Flipping the Switch: Leveraging Pinball Machines to Teach PLC Programming and Control Systems

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***Abstract*—Teaching Programmable Logic Controllers (PLCs) requires both theory and hands-on practice, yet traditional training setups are often costly and less engaging. This paper presents a novel, cost-effective approach using a PLC-controlled pinball machine. A BRX PLC handles game logic, sensors, and flippers via ladder logic, while Python integration through Modbus enables real-time data analysis. A self-playing AI mode further enhances learning. The system bridges PLC theory and application, exposing students to automation, data analytics, and Industry 4.0 practices.**

I. Introduction

Programmable Logic Controllers (PLCs) are a cornerstone of industrial automation, widely used in manufacturing, robotics, and process control. Mastering PLC programming requires a combination of theoretical knowledge and practical application, yet traditional training environments often present significant barriers to student engagement. Industrial training setups can be costly, complex, and intimidating, particularly for those new to automation concepts. As a result, educators face challenges in bridging the gap between abstract PLC theory and hands-on experience.

This paper presents a novel approach to PLC education by leveraging pinball machines as interactive and cost-effective teaching tools. Pinball machines inherently incorporate core PLC-controlled components, including solenoids, sensors, actuators, and switches, making them an ideal platform for hands-on learning. By modifying and programming a pinball machine, students can gain practical experience with ladder logic, sequential control, input/output handling, and real-time troubleshooting in an engaging, gamified environment.

The objectives of this project are to:

- Develop a PLC-controlled pinball machine that demonstrates automation concepts.
- Provide a structured, interactive learning experience for students.
- Evaluate the effectiveness of this approach in enhancing student engagement and comprehension.

To showcase real-time control and automation principles, a custom-built pinball machine (seen in Figure 1) will be developed, powered by a BRX PLC[1]. The system features programmable gameplay, real-time data logging, and a self-playing AI mode, all of which support an engaging and practical learning environment.

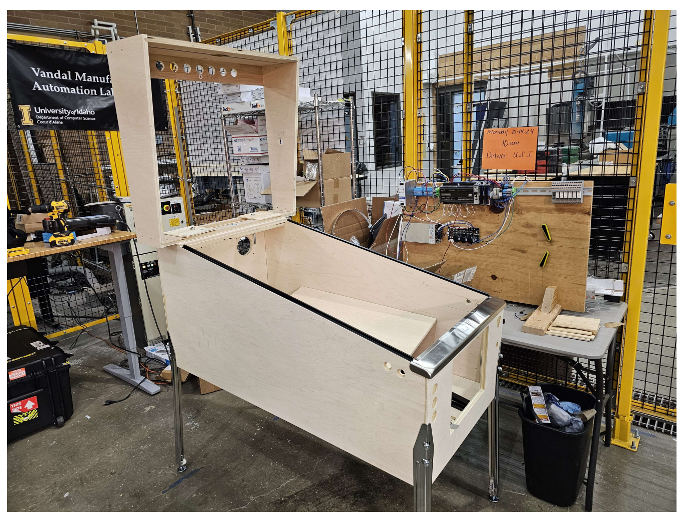

Fig. 1. Custom Pinball Cabinet

II. Background & Related Work

A. Challenges in PLC Education and Training

PLC education is critical to industrial automation and control, yet several challenges persist in existing training offerings. One frequently cited shortcoming is the limited opportunity to train on real-world components, which is widely regarded as essential to student learning and skill development [7][3][8]. However, the cost of industrial-grade PLC hardware can be prohibitive, making hands-on experience difficult to scale [7].

Beyond cost, educators have noted a lack of integration between control theory and practical implementation in PLC instruction. For instance, [10] highlights the importance of control algorithms in graduate education and proposes a PLC training kit that incorporates methods such as particle swarm optimization. Similarly, [8] includes several hands-on control projects, including PID loop implementations, to reinforce theoretical concepts.

Another common issue involves the absence of physical construction and system integration in many PLC kits. Studies [7], [3], [4], and [8] address this by designing curriculum components that include building, setup, and wiring knowledge, enabling students to work with physical hardware directly. Additionally, motivational and instructional barriers have been identified, including limited instructional resources [2][3] and the need to better engage student creativity and interest [3][4].

Despite these challenges, all reviewed studies that implemented physical PLC kit builds (where outcomes were measured) reported improved student engagement and learning outcomes [7][2][10][3]. These findings underscore the value of physical interaction, hands-on troubleshooting, and real-time system feedback in automation education.

B. Pinball Machines as an Educational Platform

This project builds on that body of research by addressing several of the noted gaps in PLC education. First, it provides a low-cost and engaging alternative to traditional trainers using widely available pinball machine components. Second, it offers students an integrated learning experience that includes physical construction, wiring, ladder logic programming, and real-time control. Third, it incorporates a diverse set of sensors and actuators—similar to the strategies employed in [4] and [8]—to simulate a broad range of industrial input/output scenarios.

Moreover, the pinball-based platform addresses student motivation and classroom engagement concerns highlighted in [3] and [4]. By using a familiar and fun, game-based interface, students are invited into a playful but rigorous learning environment where they can build, program, and control a physical machine. This novel format bridges the gap between theoretical concepts and real-world application, making PLC education more accessible, interactive, and impactful.

C. Existing Work in Gamified PLC Training

Several initiatives have attempted to gamify PLC education, including:

- Virtual PLC simulation games, which allow students to program and debug automation scenarios.
- Industry-grade PLC trainers, which simulate real-world production lines.
- Project-based learning approaches, where students design automation projects using PLCs.

However, most of these methods lack the dynamic, unpredictable environment provided by a physical system like a pinball machine. The integration of real-time control, mechanical actuation, and sensor feedback creates a richer learning experience that closely mirrors industrial automation challenges.

D. Contribution of This Work

This project builds on prior research by introducing a physical, interactive learning platform that bridges the gap between theoretical instruction and hands-on PLC training. The pinball-based PLC trainer is:

- Cost-effective: built from widely available, low-cost components.
- Interactive: offers immediate feedback and hands-on control.
- Customizable: supports modification of game logic and behaviors.

By designing a PLC-controlled pinball machine, this work demonstrates how automation principles can be taught in an engaging, scalable manner, making PLC education more accessible and immersive.

III. System Design

The development of a PLC-controlled pinball machine requires careful integration of mechanical, electrical, and software components to create a functional and interactive system. This section outlines the overall architecture, hardware selection, PLC programming approach, and data processing methods used in the project.

A. Overall Architecture

- Mechanical Structure – The physical pinball machine, including the playfield, flippers, bumpers, and ramps.
- Sensors & Input Devices – Switches, optical sensors, and proximity detectors that track ball movement and user interactions.
- Actuators & Output Devices – Solenoids for flippers and bumpers, LEDs for visual feedback, and a speaker for sound effects.
- PLC Control System – A BRX PLC programmed in ladder logic to handle game logic, input processing, and actuation.
- Data Logging & AI Module – A system that collects gameplay data for analysis and can enable an autonomous self-playing mode.

Figure 2 gives an overview of the systems communication between various systems The hardware components used in the system include a BRX Do-more PLC, optical sensors, mechanical switches, solenoids, and LEDs, as shown in Figure 2. These components were selected for their accessibility and relevance to industrial automation training.

B. Pinball Playfield

The pinball machine includes:

- Flippers controlled by solenoids.
- Bumpers and slingshots that activate on ball impact.
- Ball sensors to track position and scoring events.
- Launch mechanism for controlled ball entry.

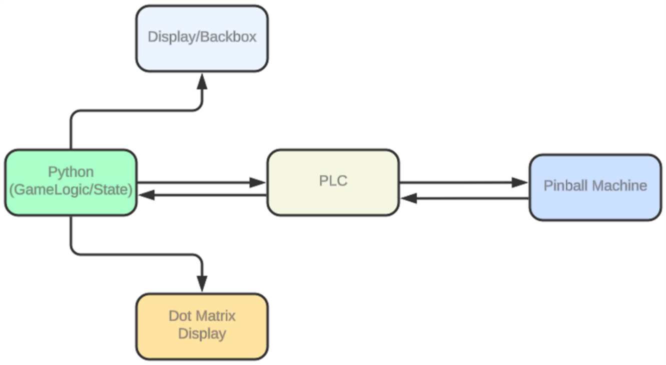

Fig. 2. Block Diagram of Architecture

C. PLC Controller

- Model: BRX Do-more PLC
- I/O Modules:
  - Inputs: Optical sensors, mechanical switches, limit switches.
  - Outputs: Solenoid drivers, LED indicators, sound signals.
- Communication Interface: Ethernet (for logging and remote monitoring)

D. Sensors & Actuators

- Optical sensors: Detect ball position and scoring events.
- Mechanical switches: Register player interactions.
- Solenoids: Control the flippers and bumpers.
- LEDs & Sound System: Provide visual and auditory feedback.

E. Software Development

The software for the PLC-controlled pinball machine will be developed using ladder logic, a standard programming language in industrial automation. The primary functions of the ladder logic program will include managing game logic, processing inputs from sensors, controlling solenoids for mechanical actuation, and handling scoring mechanisms. The PLC will continuously monitor sensor inputs to detect ball position, player interactions, and scoring events. When a player activates the flipper buttons, the program will trigger the corresponding solenoids, ensuring real-time response to user input. Additionally, the PLC will regulate timed events, such as releasing the ball at the start of the game and activating bumpers based on predefined conditions.

Beyond manual control, the system will include an autonomous self-playing mode, where the PLC will follow a predefined sequence of operations to simulate gameplay. This mode will leverage historical gameplay data to optimize flipper activation timing and shot accuracy, demonstrating AI-driven automation in a real-time control environment. The implementation of this feature will showcase how PLCs can be used beyond traditional industrial applications, extending into automation-driven gaming.

To enhance the system's educational value, a data logging module will be implemented, allowing the PLC to record sensor activations, player inputs, and score progressions over multiple game sessions. This data will later be analyzed to assess player behavior, optimize machine performance, and evaluate student interactions with the system. The logging functionality will provide insights into how students engage with PLC programming concepts, offering a measurable way to assess the effectiveness of the pinball machine as a learning tool.

Additionally, Python will be integrated with the system through Modbus communication[9], enabling students to interact with the PLC using a high-level programming language. Using Python, students will develop custom dashboards to visualize real-time game performance, track sensor activations, and analyze gameplay statistics. Libraries such as pymodbus will allow Python programs to retrieve real-time data from the PLC, providing a deeper understanding of how control logic influences the physical system. Python will also facilitate advanced data analysis, enabling students to apply machine learning techniques to detect trends, predict gameplay behaviors, and optimize control strategies. This integration will bridge the gap between traditional PLC programming and modern industrial automation practices, enhancing both data-driven decision-making and real-time system monitoring in an engaging learning environment.

IV. Methodology

The development and implementation of the PLC-controlled pinball machine will follow a structured methodology, including system design, hardware integration, software development, and testing. The process will be iterative, incorporating feedback and refinements to enhance both functionality and educational effectiveness.

A. Design and Prototyping Process

The project will begin with a literature review on pinball machine mechanics and PLC applications in automation training. This research will guide the selection of key components, including solenoids for flippers, optical sensors for ball detection, and a BRX Do-more PLC for control logic. A CAD-based design of the pinball machine layout will be created to ensure optimal placement of sensors, actuators, and scoring mechanisms.

Once the design is finalized, hardware components will be procured and assembled. The integration process will involve mounting sensors and actuators on the playfield, wiring input and output connections to the PLC, and configuring power management for solenoid-driven components.

B. PLC Programming and System Integration

The software development phase will focus on programming the PLC using ladder logic. The control program will be structured to manage sensor inputs, trigger solenoid outputs, and regulate scoring mechanisms in real time. Special attention will be given to optimizing response time for flipper activation, ensuring seamless interaction between player input and mechanical actuation.

During integration, extensive debugging will be performed to resolve timing inconsistencies, optimize sensor thresholds, and refine the game logic. The system will be tested in both manual and autonomous modes, with iterative improvements made to enhance stability and performance.

C. Testing and Performance Evaluation

A comprehensive testing phase will be conducted to evaluate the reliability and responsiveness of the system. This will include hardware validation, where individual sensors and actuators will be stress-tested under repeated cycles, and software verification, ensuring the PLC logic handles all game states correctly. Real-time debugging tools will be used to monitor input-output operations, diagnose issues, and fine-tune ladder logic parameters.

User testing will also be carried out to assess the educational effectiveness of the pinball machine as a PLC training tool. Students will be given structured exercises, requiring them to modify game logic, troubleshoot sensor failures, and interpret real-time system behavior. Observations from these sessions will provide valuable insights into how effectively the machine facilitates hands-on learning of PLC concepts.

D. Iterative Refinement and Future Enhancements

Based on test results and user feedback, modifications will be implemented to improve system performance. Adjustments may include refining sensor placement for better ball detection accuracy, optimizing solenoid timing for smoother flipper control, and enhancing the self-playing mode for more realistic AI-driven gameplay. Future iterations may also include wireless connectivity for remote monitoring and expanded gameplay customization through advanced PLC programming.

The methodology adopted in this project aims to ensure that the PLC-controlled pinball machine will function as both an interactive gaming device and a practical educational tool, bridging the gap between automation theory and hands-on experience in a dynamic, engaging format.

V. Expected Results and Evaluation

The testing and evaluation of the PLC-controlled pinball machine will focus on assessing its functionality, reliability, and effectiveness as an educational tool. The evaluation process will include hardware performance tests, software validation, and user-based assessments to determine its impact on PLC education.

A. Performance Evaluation

The system's overall performance will be measured by testing the responsiveness and accuracy of the PLC-controlled components. The solenoids for the flippers and bumpers will be tested for actuation speed and consistency, ensuring that they respond to inputs within an acceptable time frame. Sensor accuracy will be assessed by analyzing ball detection precision and minimizing false triggers. The PLC's ability to process real-time inputs and execute ladder logic commands efficiently will be a key factor in determining the reliability of the system.

To quantify performance, we will log response times, sensor activation frequencies, and actuation cycles during multiple game sessions. Any latency or failure in component operation will be analyzed to refine the control logic and hardware configuration.

B. Educational Effectiveness Assessment

To evaluate the effectiveness of the pinball machine as a PLC training tool, structured user testing will be conducted with students enrolled in automation or control systems courses. Participants will be introduced to the system through guided exercises, requiring them to modify ladder logic, troubleshoot sensor failures, and analyze real-time system behavior. Their engagement levels, comprehension of PLC programming principles, and ability to diagnose faults will be measured through surveys and performance-based assessments.

Preliminary expectations suggest that the interactive nature of the system will enhance student learning by providing real-time feedback and hands-on troubleshooting experience. Comparative studies will be conducted between students using the pinball machine and those relying solely on simulation-based PLC training to assess the impact of physical interaction on learning outcomes.

C. Self-Playing Mode and Data Analysis

The self-playing mode will be tested to ensure that the AI-driven automation functions as intended. The system will log scoring patterns, shot accuracy, and decision-making behavior to analyze how well the automated mode replicates human gameplay. Additionally, gameplay data will be used to refine solenoid timing, sensor placement, and scoring mechanics for improved overall performance.

Collected data will also be analyzed to determine trends in user interactions, identifying potential areas for enhancing the training experience. Insights gained from this analysis may inform future improvements, such as adaptive difficulty levels or additional programmable features to further enhance student engagement.

D. Iterative Improvements and Future Work

Based on the findings from performance tests and student assessments, refinements will be made to enhance system functionality. These may include improving PLC logic efficiency, optimizing sensor placement, and refining actuation timing for more consistent gameplay. Future developments may also explore wireless connectivity for remote PLC access, cloud-based data logging, and advanced AI implementations to create a more dynamic learning environment.

Ultimately, this evaluation process will determine the effectiveness of the PLC-controlled pinball machine as a hands-on educational tool, validating its potential for enhancing PLC training through interactive, real-world automation scenarios.

VI. Discussion and Future Work

The development of a PLC-controlled pinball machine as an educational tool is expected to provide students with a hands-on approach to learning automation concepts. By integrating real-time control, sensor feedback, and mechanical actuation, this system offers an engaging alternative to traditional PLC training methods. This section discusses the anticipated impact of the project, current limitations, and potential future enhancements.

A. Expanding SCADA Integration with Ignition

The integration of Ignition[5] a SCADA(Supervisory Control and Data Acquisition) platform, with the PLC-controlled pinball machine will enhance student learning by providing a real-time interface for monitoring, control, and data analysis[5]. Initially, the system will focus on basic visualization and real-time monitoring, with future enhancements including alarm notifications for system faults, and historical data tracking through Ignition's built-in historian.

Python scripting within Ignition will automate data processing and predictive analytics, reinforcing real-world industrial automation practices. The Modbus TCP/IP protocol will enable seamless communication between the PLC and Ignition, allowing students to interact with live system data via web-based dashboards.

By expanding SCADA functionality, this project will bridge PLC programming with modern industrial automation, preparing students for advanced control systems, AI-driven analytics, and industrial IoT applications.

B. Impact on PLC Education

The interactive nature of the pinball machine is expected to enhance student engagement and bridge the gap between theoretical instruction and real-world application. Unlike simulation-based PLC training, this system will allow students to physically interact with automation components, reinforcing key concepts such as input-output processing, ladder logic programming, and troubleshooting strategies. Additionally, the ability to modify game rules and system behavior through PLC programming will encourage experimentation and problem-solving, skills essential for industrial automation.

Another expected benefit is the accessibility and cost-effectiveness of this approach. Traditional PLC trainers can be expensive[6] and limited in scope, whereas a repurposed pinball machine provides a dynamic and adaptable learning environment. By incorporating data logging and AI-driven automation, students will also gain exposure to modern advancements in industrial automation, including predictive analytics and automated decision-making.

C. Python and Modbus Integration for Advanced Learning

Integrating Python with Modbus provides a flexible, modern complement to traditional PLC instruction. Python's wide industry adoption and rich ecosystem of libraries allow students to visualize, log, and analyze real-time data in ways ladder logic alone cannot support.

Using the Modbus protocol, students can communicate directly with the PLC to monitor sensors, control outputs, and simulate real-world automation scenarios like those in the pinball machine. This expands the scope of learning to include remote monitoring, diagnostics, and data-driven decision-making.

In this project, Python enables the creation of custom dashboards to display live system status, sensor activity, and gameplay metrics. Libraries such as pymodbus support real-time data exchange, allowing students to write programs that influence machine behavior and observe immediate results. This hands-on feedback reinforces core automation concepts while encouraging experimentation.

The integration also supports a multidisciplinary approach, combining industrial automation with data analytics. Students can analyze gameplay data—such as flipper response times or scoring trends—using Python's scientific libraries to optimize performance and detect faults. This mirrors real-world practices in Industry 4.0 environments.

By using Python alongside PLCs, students gain experience in both control logic and data analysis, preparing them for advanced industrial roles. Future enhancements may include machine learning for predictive maintenance, adaptive game tuning, and automated difficulty adjustment—demonstrating how PLC platforms can evolve into smart, responsive systems.

D. Limitation of the Current System

While the system offers an engaging learning experience, several limitations must be addressed. Hardware reliability is a concern, as repeated solenoid activation and mechanical wear may lead to maintenance issues. Consistent sensor performance and low-latency response are essential for smooth gameplay. Although the BRX PLC offers flexibility, supporting multiple PLC models may improve broader adoption.

Scalability is another challenge. While effective for introductory training, the pinball machine may not reflect the complexity of industrial systems. Future versions could include features like robotic integration, conveyor systems, or multi-axis control.

To enhance capabilities, wireless connectivity (via Wi-Fi or Ethernet) could enable remote programming and monitoring. Adaptive AI could improve the self-playing mode with dynamic gameplay. Cloud-based logging would support long-term analytics, helping instructors track progress and tailor instruction. Integrating additional industrial components—like servos or pneumatics—would expose students to broader technologies.

Finally, implementing a multi-mode learning framework with increasing difficulty would accommodate students at varying experience levels, making the system more versatile and educationally effective.

E. Broader Applications

Beyond its application in PLC education, this project has potential for use in automation research, human-machine interaction studies, and game-based learning initiatives. The integration of real-time control with AI-driven decision-making could lead to further exploration in autonomous gaming systems, predictive maintenance in automation, and user-interactive industrial training modules.

By addressing the current limitations and implementing the planned enhancements, the PLC-controlled pinball machine will continue to evolve as a robust, interactive platform for teaching automation concepts. The future work outlined in this section will ensure that the system remains a valuable educational tool, fostering a deeper understanding of industrial automation and real-time control systems.

VII. Conclusion

This paper presented the design and implementation of a PLC-controlled pinball machine as a cost-effective, hands-on educational tool. By leveraging the mechanical and electronic systems of a pinball machine, the project allows students to apply ladder logic, manage I/O, and troubleshoot real-world automation scenarios.

The system integrates modern tools such as Python, Modbus, and AI-driven control to expose students to data logging, analytics, and Industry 4.0 practices. Planned evaluations will assess the system's effectiveness in enhancing student engagement and comprehension.

Ultimately, this platform offers an engaging bridge between PLC theory and practical application, making automation education more accessible and interactive.

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