

Developing a serial production optical inspection system for electrical components based on ESP32 controller

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Abstract – In this paper, we present the process of designing and developing a programmable logic controller (PLC)-like system based on the ESP32 microcontroller intended for use in industrial environments. The work demonstrates the complete design flow, starting from the initial idea and system-level requirements, through schematic development, component selection, simulation and PCB design, to the final realization of a fully functional prototype integrated into an optical inspection system. The developed system performs optical inspection of electronic components transported on a conveyor belt. Defect detection is carried out using pattern-recognition algorithms and machine-learning tools integrated into state-of-the-art Cognex industrial cameras.

Keywords - PCB, PLC, development, ESP32.

I. INTRODUCTION

Automation and quality control represent fundamental pillars of modern industrial production. As manufacturing processes become faster, more complex and increasingly demanding in terms of reliability, the need for flexible, compact and programmable control systems continues to grow. Traditional industrial PLCs (Programmable Logic Controllers) remain the standard solution for implementing logic control, but their high cost, limited adaptability and proprietary architecture often make them unsuitable for small-scale or specialized applications where custom hardware is required.

The design methodology used in this work follows a structured engineering flow, starting from the definition of functional requirements and system-level abstraction, and continuing through the decomposition process [1], component selection, electrical schematic development and simulation, up to the physical PCB layout and prototype testing. Simulation tools such as LTspice are used to verify the behavior of the power converters and input-conditioning stages, while KiCad is employed for schematic capture and PCB layout design. The system's decision logic is implemented using the OpenPLC environment and ladder logic, ensuring compatibility with standard industrial programming practices.

II. BACKGROUND AND SYSTEM REQUIREMENTS

Modern industrial production increasingly relies on Andrija Brzaković is with the University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 4, Niš, Email: razlii@elfak.rs.

automated optical inspection (AOI) to ensure product quality and reduce manual supervision. Smart vision systems such as Cognex cameras provide real-time classification of components and generate discrete OK/NOK signals, which must be processed by a reliable control unit and activates the right output (valve, indicator lights). To replace a conventional PLC with a compact and cost-efficient alternative, this work proposes an embedded controller based on the ESP32 microcontroller, supported by isolated digital inputs, relay-based outputs and a robust multi-stage power supply. The system must operate from an industrial 12/24 V source, withstand electrical noise, ensure galvanic isolation of inputs and provide sufficient current to drive motors, pneumatic valves and signal lamps.

TABLE I
SYSTEM REQUIREMENTS AND DESCRIPTION

Requirements	Description
Power supply	System must operate from a 12–24 V industrial DC source with regulated 5 V and 3.3 V outputs for logic and MCU.
Input Conditioning	Digital inputs must be isolated and compatible with 24 V industrial signals from camera and photo sensor
Output control	System must provide relay-based outputs for driving actuators such as motors, pneumatic valves and signal lamps.
Processing & Logic	ESP32 must execute deterministic control using ladder logic

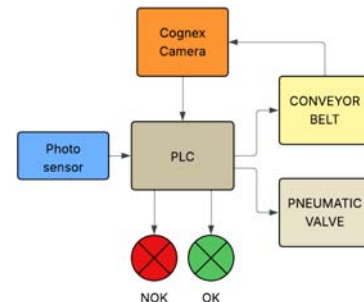


Fig. 1. Block diagram of optical inspection system

III. HARDWARE DESIGN OF THE PLC SYSTEM

Using concepts such as domain of description, levels of abstraction, decomposition and iterative development for each of these modules [1].

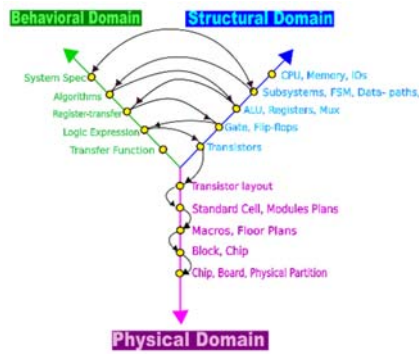


Fig. 2. Y diagram

The hardware architecture of the proposed PLC-like controller is designed to consists of four key hardware independent modules: the power supply stage, the optocoupler input-conditioning stage, the output-driving and relay stage and the ESP32 central processing unit.

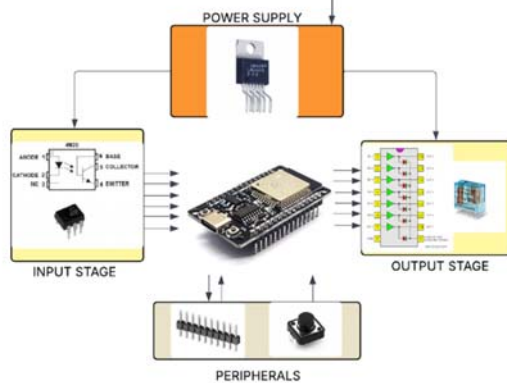


Fig. 3. Block diagram of electrical system

The first stage uses a LM2678 buck converter [2] to reduce the input voltage to 5 V DC. This converter is selected due to its high efficiency up to 92%, wide input voltage range and simplicity of designing [2].

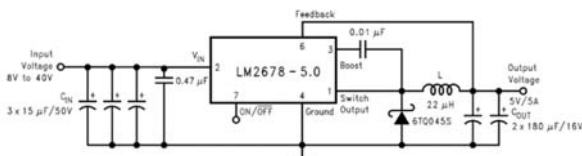


Fig. 4. Model for input module [4]

Based on the datasheet the inductance of the circuit depends on the maximum input voltage and maximum load current and is determined by the graph in Fig. 5. Every other parameter in the circuit (input and output capacitance and a catch diode) is determined by the induction. Following this stage, a 3.3 V LDO regulator (LM3940) provides clean, low-ripple power to the ESP32 module, ensuring stable operation of the microcontroller [3]. The input module conditions external 24 V industrial signals and converts them to safe logic-level voltages suitable for

the ESP32. To achieve galvanic isolation and noise immunity, each input channel uses an optocoupler (4N25) followed by a Schmitt-trigger inverter (74HC14) [3]. Fig. 3 shows the simulation for this module.

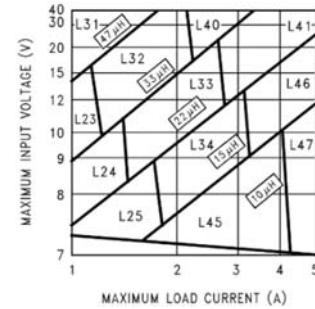


Fig. 5. Inductance indicator graph

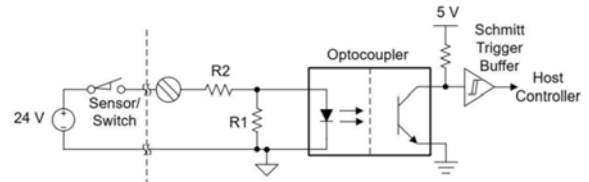


Fig. 6. Model for input module [4]

The parameters that needs to be taken into consideration when designing this stage are the resistors R2 and R1 for biasing the circuit and providing a CTR (current transfer ratio) [5] that can saturate the BJT. In this project 4N25 optocoupler is chosen.

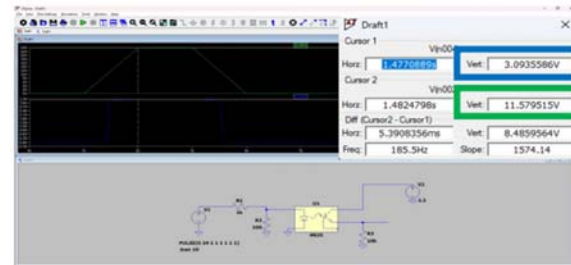


Fig 7. Input voltage vs output voltage simulation result

In Fig. 7 for resistances of $1k\Omega$ (R_2) and 100Ω (R_1) a logic high of 3.09V is generated for a voltage that is 11.5V on the input. Based on forward current Fig 8 the calculated CTR is 18%.

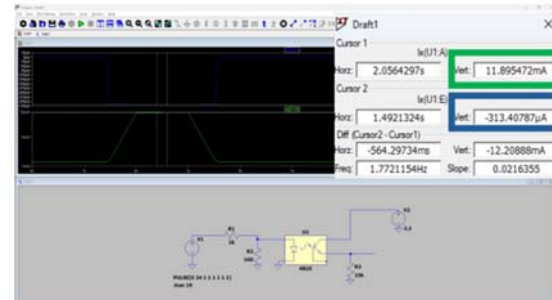


Fig 8. Input current vs output V_{ce} simulation result

The activation voltage for digital inputs in function of R_2 and R_1 is shown in table II.

TABLE II
ACCURACY AND LOSS VALUES FOR THE 4 CONFIGURATIONS

R1	R2	Time of activation	Activation voltage
100Ω	1kΩ	485ms	11.5V
100Ω	900Ω	425ms	10.1V
100Ω	800Ω	393ms	9.6V
100Ω	700Ω	328ms	7.9V

Output channels are implemented using electromechanical relays controlled by a ULN2003[4] Darlington driver array as a driver for the relay. The ULN2003 provides transistor-level amplification and includes integrated flyback diodes that protect the circuit from iFig. 5. Topology of output stage inductive spikes generated by relay coils. Fig 9 shows the concept of output module

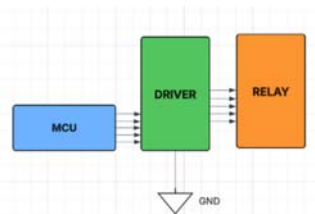


Fig. 9. Block diagram of output stage

For designing the output module, a fly-back diode is connected in parallel with the coil to limit the dI/dt and dV/dt . An indicator LED and a current-limiting resistor are also included in the circuit, as shown in Figure 10.

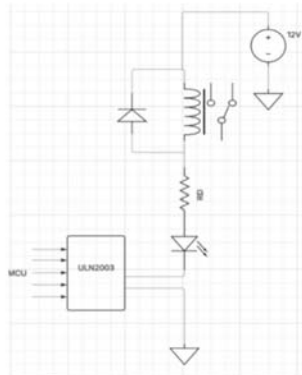


Fig. 10. Output module circuit

The following assumptions R_D is 220Ω, LED forward voltage (V_f) is 1.8V and V_{CEsat} is 1V then the calculated coil voltage current is 7.58V and 34.4mA. Figure 11. shows the following results for those assumptions and calculations

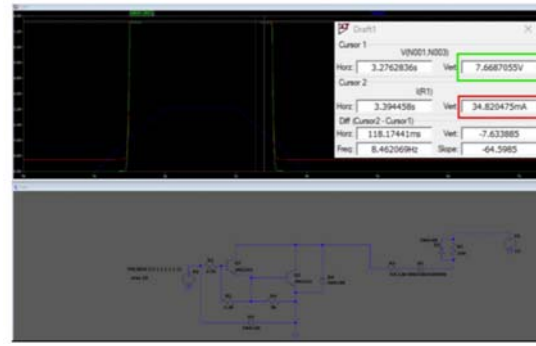


Fig. 11. Output coil voltage vs current

As the microcontroller, the ESP32 DevKitC development board is chosen as the PLC, as it already includes all the necessary peripherals and components. Only the GPIOs need to be debounced when using push buttons, and proper pull-up resistors must be used, which in this case are typically 10 kΩ. The development board is shown in Figure 12.



Fig. 12. ESP32 DevKitC

IV. PCB DESIGN

Design and generating the Gerber files necessary for fabrication, KiCad is used as an open source program. KiCad is not a standalone program it consists of two main applications, The Schematic design editor and Layout design editor and multiple support applications such as Symbol and Footprint editor, Gerber viewer. This type of structure follows a typical design flow of a PCB and can be shown in the following figure.

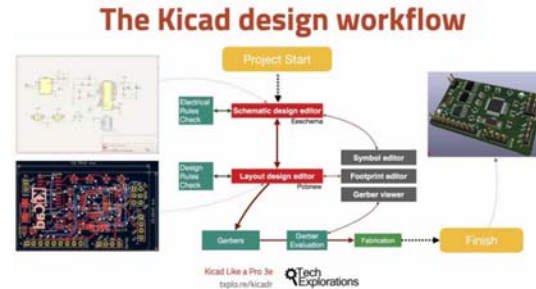


Fig. 13. KiCad structure

When designing in KiCad, every step must be verified. The Electrical Rules Check (ERC) is used during schematic capture to ensure that all necessary power flags are present and that connections between placed components are correct.

The Design Rules Check (DRC) is then used to verify that none of the defined design rules are violated. The following figure 14. show the modules described in the previous chapter in both schematic and layout editor, 3D and fabricated formats.

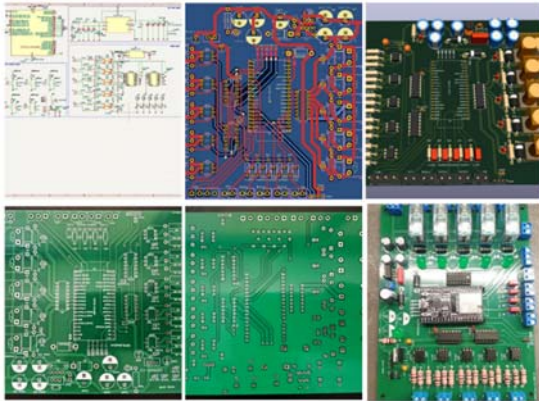


Fig. 14. PCB design flow

IV. PROGRAMING THE DEVICE AND FINAL SYSTEM

OpenPLC is used as an open-source ladder programming environment suitable for industrial applications, enabling easy implementation of the desired results for the described sequential process. in figure 1. The complete ladder for described inspection and is shown in the following figure.

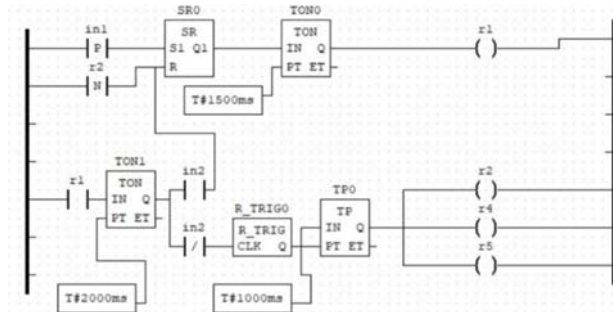


Fig. 15. Ladder program

The complete system with the implemented designed PLC can be seen in the following figure 16.

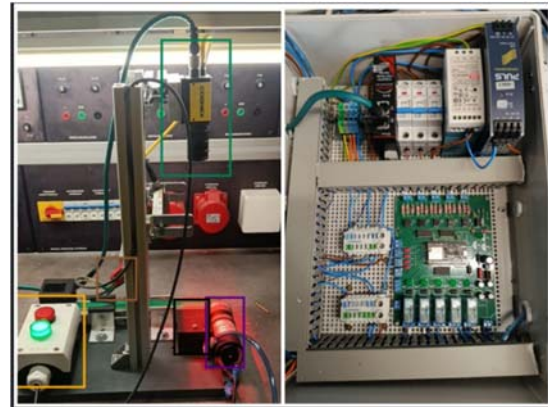


Fig. 15. Ladder program

IV. CONCLUSION

This paper presented the design and implementation of a compact PLC-like control system based on the ESP32 microcontroller for use in an industrial optical inspection application. The complete development process was demonstrated, starting from system requirements and hardware architecture definition, through schematic design, simulation and PCB layout, up to programming and final system integration. The developed system was integrated into an optical inspection setup with Cognex industrial cameras, proving its suitability for real-world automation and quality-control tasks. Overall, the results demonstrate that modern microcontrollers such as the ESP32 can serve as a viable platform for custom industrial control systems, particularly in small-scale or specialized applications where adaptability, openness and reduced cost are essential.

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