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Original Article

Design of an Electronic Module for the Unification of Industrial Networks with ESP32 for Industry 4.0

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Abstract - *This article presents the design and development of an electronic module based on the ESP32 microcontroller for the purpose of unifying and interconnecting various industrial networks. The architecture integrates protocols widely used in today's industry, such as Modbus RTU using the ADM485 transceiver, Modbus TCP/IP through the ENC28J60 Ethernet controller, CAN Bus communication using the MCP2551 transceiver, and DeviceNet networks using a combination of the MCP2515 and MCP2551, using the ESP32 microcontroller. It also incorporates compatibility with Profibus networks using the MAX14770 transceiver, as well as integration of smart instrumentation using the HART protocol employing the AD5700 modem and serial protocols such as RS232 and RS485.The electronic module enables bidirectional communication between industrial equipment using the most commonly used communication protocols in the industry today, facilitating the modernization of industrial equipment such as frequency converters, PLCs, or input and output expansion modules in existing systems without the need to completely replace this equipment. The module contributes to unification by selecting the appropriate network for a device or equipment and to the digitization of processes in Industry 4.0, achieving improvements such as interoperability, robust connectivity, and integration into multiple equipment without the need to make changes to their hardware. The electronic module adapts to an industrial environment and integrates 75% compatibility between devices such as PLCs, frequency converters, and I/O expansion modules.*

Keywords - *Industrial gateway, ESP32 microcontroller, Industrial network integration, Protocol conversion, Smart manufacturing systems.*

1. Introduction

Currently, industrial automation is undergoing a transition driven by new market dynamics and Industry 4.0 technologies, particularly regarding the integration of industrial network modules. In this context, device connectivity, control modernization through digitalization, and interoperability between systems are key areas where the lack of devices capable of connecting various industrial networks remains a significant challenge. In certain cases, production environments require equipment capable of integrating smart devices or modules, monitoring platforms, industrial networks, and real-time analysis systems. However, a large part of the industry still operates with equipment using outdated technology and integrates devices with limitations to a single communication protocol in PLCs, frequency inverters, remote expansion modules, and field instrumentation, which use point-to-point or serial communication protocols and were not always compatible with one another. Currently, the coexistence of multiple industrial networks-such as Modbus RTU, CAN Bus, Profibus, DeviceNet, HART, and Industrial Ethernet, among others-creates challenges due to the integration of equipment from different manufacturers within a single control architecture. This limitation directly impacts the adaptability and compatibility of SCADA systems, increases modernization costs due to the use of new technologies, and hinders the transition to current solutions connected to modern industrial networks or IoT technologies. This is why there is a need to develop an electronic interoperability module that unifies industrial protocols using robust electronics controlled by the ESP32 microcontroller. These components enable bidirectional data exchange between legacy and current protocols, facilitating the gradual modernization of control panels and systems such as SCADA in industrial plants without completely replacing the existing architecture. The module is capable of integrating various industrial protocols using dedicated integrated circuits, enabling communication between PLCs, drives, remote modules, and smart instrumentation within an industrial environment that aligns with current systems focused on Industry 4.0.

2. Related Words

Currently, with the advancement of technology, automation is affected by multiple protocols to be used in [1].

Multiprotocol gateway architectures based on advanced congestion control algorithms, such as BBR, have been proposed to optimize bandwidth usage and reduce latency. These solutions enable the management of massive long-term connections and support multiple protocols such as MQTT, CoAP, HTTP, and specific energy standards, facilitating the migration of industrial devices to scalable, high-performance digital environments. In [2], the literature also includes recommendations for standardization and best practices for the design and implementation of embedded systems in industrial environments, providing technical and methodological criteria for their development. In addition, practical cases of industrial networks implemented with commercial hardware are presented, covering wired, wireless, long-distance connections, and multiprotocol configurations, thus consolidating a theoretical and applied basis that supports the use of embedded systems as a key platform for interoperability in industrial automation. For [3], industrial gateways have been proposed as intermediate solutions capable of connecting serial devices to cloud services, reducing costs and implementation complexity.

However, they have limitations in the simultaneous management of multiple protocols, which hinders interoperability in heterogeneous environments. Recent research has proposed multiprotocol gateway architectures based on open-source environments, implementing protocols such as Modbus, CAN Bus, MQTT, and REST, and allowing for the future incorporation of new protocols. Also, in [4], the implementation of devices with multiprotocol communication capabilities is presented as a strategic solution to simplify information exchange and improve interoperability in heterogeneous industrial environments. This proposal also evaluates parameters such as device energy consumption, demonstrating its viability as a flexible solution for data acquisition and control in modern industrial systems. In [5], optimization frameworks based on artificial intelligence have been proposed for IoT devices, integrating multiprotocol adaptation, reinforcement learning for routing and anomaly detection, as well as energy optimization techniques and advanced cybersecurity mechanisms such as blockchain. Evaluations through simulation and real-world testing demonstrate significant improvements in latency, performance, energy efficiency, and threat detection compared to traditional IoT architectures. These proposals demonstrate the trend toward modular, scalable, and collaborative IoT systems between the edge and the cloud, geared toward next-generation smart grids. Likewise, in [6], IoT technology is used to facilitate communication between PLCs from multiple vendors and IoT gateways, enabling the seamless integration of local control systems under standard protocols. Experimental cases demonstrate the viability of this approach in multi-protocol environments, integrating industrial control stations and wireless devices within a unified architecture. The results of functional and performance tests show that this approach is a scalable and cost-effective alternative for modern industrial automation in heterogeneous environments. In [7], in response to a crisis of unification and constraints, recent research has proposed software-defined gateway architectures that decouple functions through modular layers, allowing protocol analysis and data conversion to be encapsulated in configurable graphical components. Case studies in SCADA systems and real industrial applications demonstrate their practical effectiveness, proposing a reconfigurable and easily maintainable paradigm that strengthens the adaptability and scalability of modern industrial automation systems. For [8], according to a 2-node link, there are improved UDP protocols that incorporate additional reliability mechanisms, such as CRC verification, retransmission, transaction identifier matching, and congestion control using exponential backoff. On this basis, lightweight gateway architectures have been developed that are capable of bidirectional conversion between advanced versions of Modbus over UDP and Modbus RTU, experimentally demonstrating significant reductions in latency and improvements in reliability compared to traditional solutions based on standard TCP or UDP. Likewise, [9] incorporates multitasking parallel processing mechanisms and reliable transmission through interruption recovery, as well as communication modules such as NB-IoT to ensure connectivity in demanding industrial environments. They also integrate cloud encryption and authentication schemes to strengthen information security. The reported experimental results show improvements in efficiency, stability, and adaptability, validating the viability of these architectures for industrial applications with high-performance and reliability requirements. Similarly, [10] includes the design of specific software architectures for data format transformation and the incorporation of intermediate conversion layers within existing protocols. Mechanisms such as virtual IPv6 addressing have also been implemented to integrate nodes without native IPv6 support into IP or non-IP networks. Experimental validations with real nodes demonstrate the technical feasibility of these solutions as an effective strategy for achieving interoperability between IIoT industrial standards.

3. Methodology

The proposed electronic module is designed to be used as an ESP32-based multiprotocol equipment that enables unification and interoperability between various industrial networks used in current industrial automation, facilitating the integration of devices such as PLCs, frequency converters, and expansion modules in different industrial architectures or systems. It offers the following features:

- Modbus RTU communication via RS-485 interface using the ADM485 IC.
- Modbus TCP/IP connectivity over industrial Ethernet using the ENC28J60 IC.
- CAN Bus communication via the MCP2551 IC.

- DeviceNet via the CAN MCP2515 IC, together with the MCP2551 IC.
- Compatibility with the Profibus protocol using the MAX14770 industrial IC.
- Integrate reading for sensors in instrumentation using the HART protocol using the AD5700.
- Robust electronic design resistant to electrical noise that could interfere with the operation of the ESP32.
- Digital integrated circuits for protocol selection.
- Correct adaptation of protocols through testing between PLCs, drives, and real industrial modules.

Table 1. Components to be used

Type	Model	Quantity
Microcontroller	ESP32	1
Modbus RTU	ADM485	1
Modbus TCP/IP	ENC28J60	1
CAN bus	MCP2551	1
DeviceNET	MCP2515+MCP2551	1
Profibus	MAX14770	1
HART	AD5700	1
RS232	MAX232	1
RS485	MAX485	1
Electronic card	PCBA 1	1
Electronic card	Peripheral	1
Peripheral	OLED 0.96”	1
Encoder	KY-040	1
Adapters	RJ45, RS232, Terminal blocks, etc.	1

The electronic module is based on the PCBA 1 electronic card designed in the EAGLE 9.6 program, which integrates dedicated integrated circuits for industrial protocols such as Modbus RTU, TCP/IP, RS485, RS232, Profibus, DeviceNET, CAN Bus, and HART, using dedicated connectors for communication and electronic selection via a peripheral. The module has a power supply with protection against external electrical noise and a switching power supply with a standard voltage of 24V as the main voltage, regulated to 10V, 5V, and 3.3V. The ESP32 microcontroller is used as the main core for the development of the electronic card's logic. It is programmed using ARDUINO IDE software, and simulation is performed on the WOKWY platform to visualize the module's control peripheral. Similarly, physical simulation is performed on a breadboard to integrate several protocols at once, rule out errors in the initial assembly, and verify the programmed control logic.

The module consists of three stages: power supply, PCBA 1 card, and peripheral card, developing the functions corresponding to the electronic cards. The first is dedicated to supporting industrial electrical noise through an EMI filter and providing a standardized voltage of 24V with linear reductions of 10V, 5V, and 3.3V. Likewise, the PCBA 1 electronic card consists of integrated circuits for the connectivity and interoperability of protocols, unifying these industrial networks, and finally, the peripheral card is responsible for displaying, selecting the type of protocol to be used, and possible connection or disconnection errors through alerts.

The module is designed for easy mounting on control panels where DIN rail mounting is required. This case is designed in AUTOCAD 3D software to provide the necessary robustness in terms of space distribution and easy connection between the dedicated connectors for each protocol. The case is intended to protect the control panel from dust that may become embedded in it, and adequate visualization for selecting the corresponding protocol when communicating.

To better identify the operating stages of the electronic module, a stage diagram is shown (see Figure 1), starting with the selection of protocols to be used. The microcontroller will provide the respective selection to perform this unification. According to the protocol used, Modbus TCP/IP is taken as an example, which requires an RJ45 connector connected from a PLC for the purpose of enabling an old drive with serial protocols such as RS232 or RS485, or by default to a Device IP is used as an example, which requires an RJ45 connector connected from a PLC for the purpose of enabling an old drive with serial protocols such as RS232 or RS485, or by default to a DeviceNet device.

The purpose is to provide sufficient robustness to send the respective data in terms of distance, if required, and to unify a network to adapt to equipment upgrades or serial equipment adaptations. After this stage of identifying the problem, the requirements of the module are obtained, which must meet certain objectives, such as communication of multiple industrial protocols, compatibility between equipment such as PLCs, drives, and expansion modules, and operability in industrial environments with electrical noise.

As for the module design and hardware selection stage, the PCBA 1 electronic card is developed using dedicated software, which includes the integrated circuits mentioned for the industrial networks of choice. The ESP32 microcontroller is used, whose UART and SPI buses are used for protocol enablement, the 24V industrial power supply with linear voltage reductions to avoid imbalance due to high frequency switching in the module, together with its respective line filtering, finalizing the correct distribution and selection of connectors for each protocol to be used without causing a conflict, as each one is an independent connection, using respective serial communications for writing and controlling the electronic module through the peripheral card. The firmware development stage allows the ESP32 microcontroller to act as a gateway, through dedicated integrated circuits for each industrial protocol. Each integrated circuit was tested individually to verify its effectiveness when unifying several protocols into one module. In the functionality testing stage, the module is verified through field tests, obtaining evaluated parameters of latency, robustness against electrical noise, and compatibility.

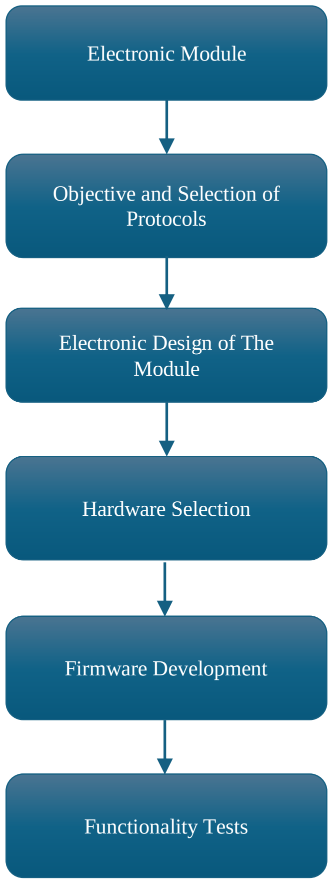


Fig. 1 Phased development of the proposed system

4. Developed System

The electronic module consists of the creation of a card that unifies several protocols based on the ESP32 microcontroller, designed to act as an industrial gateway capable of interconnecting different communication networks used in industrial automation environments. The main objective of the system is to enable the unification of devices that deliver control or logic data through different types of hardware, such as PLCs, drives, expansion modules, industrial instrumentation devices, etc. The module integrates multiple dedicated integrated circuits for the desired communication, allowing bidirectional data compatibility between different protocols, facilitating network convergence between current and existing serial networks for architecture compatibility in Industry 4.0.

The module incorporates the ESP32 as the central processing unit, which performs the logic necessary for the module to function. It selects the protocol to be used, acquires and retains data, validates connectivity, and displays alerts with communication peripheral failure histories on a 0.96" display.

The electronic card incorporated in the module unifies several industrial protocols through dedicated integrated circuits such as the ADM485 for MODBUS RTU communication, the ENC28J60 for the MODBUS TCP/IP protocol, the MCP2551 for CAN BUS, the MCP2515 and MCP2551 integrated circuits for DEVICENET, the MAX14770 for the PROFIBUS protocol, the AD5700 for HART communication for industrial instrumentation devices, and the MAX485 and MAX232 for serial communication of outdated technology devices. These integrated circuits are distributed independently on the electronic card, meaning that each one will have a corresponding terminal block, connector, or plug for the respective communication required. In addition, the module incorporates a 24VDC industrial power supply with 10V, 5V, and 3.3V linear voltage reducers. The power supply consists of an EMI filter that protects the electronic module and prevents it from rebooting due to electrical noise in the industrial field. The PCB is optimized according to IPC-2221, IPC-7351, and IPC-2152.

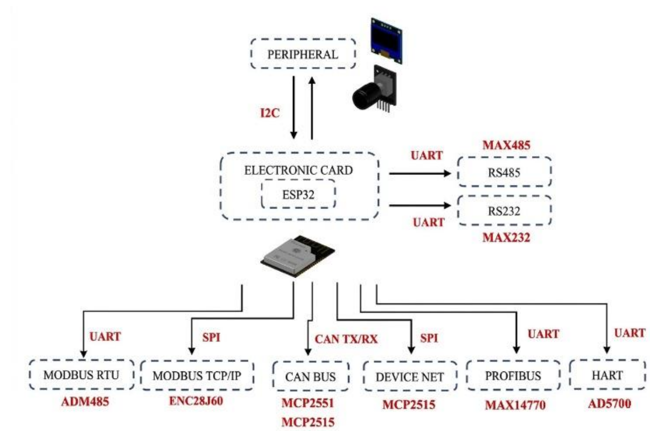


Fig. 2 Electronic module operating stage

In accordance with the module stages, the power supply design consists of the UC3843B integrated circuit, which reduces the 220VAC input voltage filtered from the corresponding EMI to obtain a voltage of 24VDC. This power supply is separate from the PCBA1 card and has a compact design located in an area where it can dissipate its heat without any problems. According to the required voltages, the PCBA1 card will have an auxiliary regulation stage, which will reduce the voltage from 24VDC to 10VDC, 5VDC, and 3.3VDC using linear regulators such as the 7810, 7805, and AMS1117-3.3 (see Figure 3).

Regarding the design stage of the PCBA1 electronic card, the IPC-2152 standard is taken into account for data transmission and the correct distribution of tracks and traces according to the application or current required. Likewise, adequate space for the pad and correct orientation of SMD components are taken into consideration in accordance with the IPC-7351 standard. For the development of the electronic card, dedicated integrated circuits are used for each protocol.

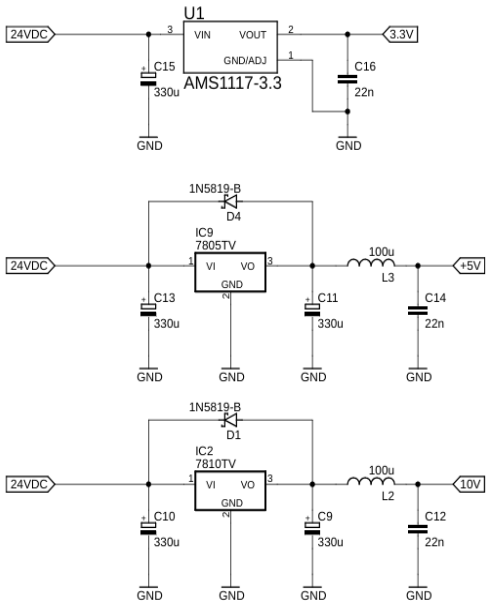
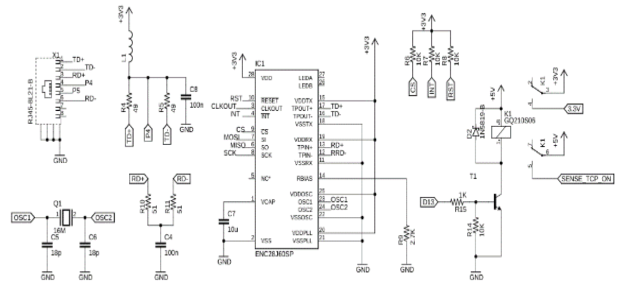
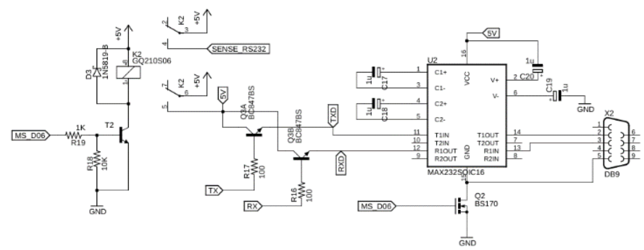


Fig. 3 Power supply in PCBA1

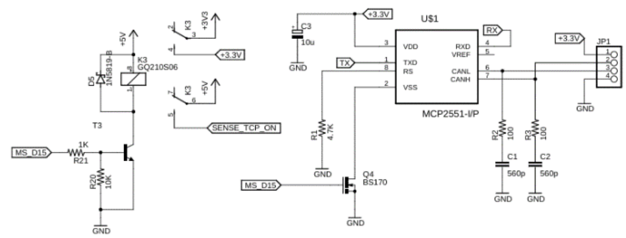
This involves the use of connectors associated with each circuit, such as RJ45 for Modbus TCP/IP, DB9 for RS232, MODBUS RTU with 2-pin terminal blocks, etc. The purpose of dividing into several connectors is to be able to make a single link for each type of protocol and thus avoid a conflict by using external adapters that can perform this function. The functionality of the module implies that it can make a change autonomously when it is necessary to perform the logic between two protocols, through commands that can be configured from the 0.96" OLED incorporated in the module. The ESP32 is configured to serve as a bypass between each protocol, providing optimal reading between two indistinct protocols, whether from RS485 to MODBUS TCP/IP or vice versa, achieving compatibility with older and current devices by integrating an Industry 4.0 architecture. Digital selectors such as the integrated 74HC126, mini relays, and MOSFETs are used to limit power in circuits where they are not required. The ESP32 uses the SPI and I2C pins to communicate between the different electronic circuits dedicated to a protocol, using a short-distance serial network. If monitoring is required through the module's UART port and PC, the PCBA 1 electronic card must have the correct distribution of connectors, which must be accessible for proper connection between the communication cables of the device to be intercommunicated. There is a peripheral stage where the protocol to be used can be selected using a KY-040 rotary encoder, which provides easy maneuverability for selecting multiple variables in a selection menu. The electronic cards have two layers, each with the ground layer distributed according to the IPC-7351 standard for better performance of the electronic components. Below are some electronic diagrams specific to the PCBA 1 electronic card (see Figure 4).



(a)



(b)



(c)

Fig. 4 Example circuit (MODBUS TCP/IP), RS232, CAN bus

The module case design must be compact and allow for proper handling and attachment to an electrical panel using a DIN rail. It must also display the values to be set and configured using the 0.96" OLED and the encoder. Figure 5 shows the correct internal and external distribution of the module on a DIN rail.

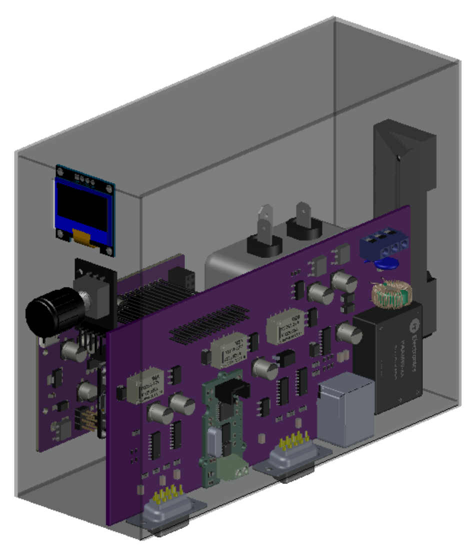
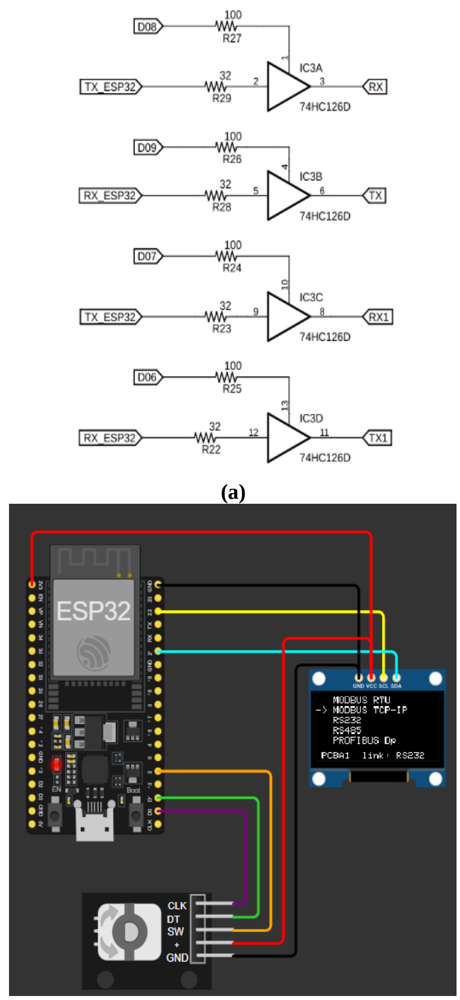


Fig. 5 Built-In 3D module

The functionality of the electronic module seeks to facilitate the link between two different protocols. This is achieved thanks to the ESP32 using several layers under a multitasking modular scheme, obtaining a physical layer where the UART and SPI interfaces manage the use of the integrated circuits dedicated to each protocol, in addition to the use of the I2C serial protocol for peripheral connectivity, a protocol layer that implements the appropriate logic for handling protocols such as MODBUS RTU and TCP/IP, CAN and DEVICENET structures, HART signal processing, and basic PROFIBUS communication management. The Gateway layer performs data conversion between protocols, evaluating commands and states to enable interoperability. Some examples of operation include reading records from a DEVICENET drive and converting them to MODBUS TCP/IP. The supervision layer allows system diagnostics, historical monitoring, and configuration through the peripheral.

Its mode of operation allows a device connected to a network to send a request and transmit data, while the ESP32 receives the information through the corresponding interface, which interprets the original protocol and converts it to a format required by the destination network. The operation process is to receive the data from a source protocol, decode the information through dedicated integrated circuits to convert the new data structure according to the destination protocol, which is then transmitted to the target device. The configuration is done on the module's 0.96" OLED screen, which displays a submenu indicating the protocols to be used for input and output. It also generates a history of connection failures, data loss, and disconnections. The ESP32 allows enablement through the 74HC126 integrated circuit for data acquisition (see Figure 6), in addition to voltage enablement through a MOSFET and relay for supplying voltage to the integrated circuit corresponding to the protocol used.

The industrial application allows for cost reduction through equipment upgrades and facilitates the transition to Industry 4.0 technology. Some limitations of the electronic module include the non-certified implementation of industrial protocols, limited performance for more protocols due to the resources offered by the microcontroller, applications for part-time use, such as 8 to 12 hours of continuous operation in critical situations, and in partially active operations, the duration may be extended. Its industrial-level scope allows for the functional integration of industrial networks within automation environments, enabling the interoperability of devices from different manufacturers and technological innovation in existing serial technologies. The application is geared towards implementation in manufacturing plants, automation lines, and control systems where there is outdated control of processes far removed from Industry 4.0, allowing it to be applied in PLCs, frequency converters, expansion modules, instrumentation, and supervision systems. The implementation significantly reduces the costs of commercial industrial gateways, avoids replacing an entire infrastructure, and takes advantage of existing devices. The module was applied for communication between a PLC logo and an HMI to a drive (see Figure 7) of equipment for HVOF metallization applications in an industrial plant located in Cerro Colorado, Arequipa.



(a)

(b)

Fig. 6 UART selection with 74HC126 and selection from the peripheral in Wokwy

Fig. 7 PLC and HMI configuration

5. Tests and Results

The electronic module developed demonstrates optimal performance in industrial applications, allowing the integration of various protocols, monitoring, and modernization of older serial networks such as RS232 and RS485.

Table 2. Comparison between modules

Parameter	Electronic module	Certified module
Multiprotocol	6	4
Latency	8-15ms	3-6ms
Real time	8 hours daily	Unlimited
Certification	No	Yes
Noise protection	Medium-high	High
Configuration	Programmable	Native software
Energy consumption	Low	Medium
Cost	Low	High

Although the design is not certified, it offers a highly competitive solution due to its low manufacturing cost, flexibility, and adaptability, especially for non-critical processes or transition processes and routine work during the workday. Comparisons of advantages are shown between a commercial module used in industry for its versatility in the industrial field among controllers. Latency comparison is measured between the time elapsed from when data is sent from an external gateway to a destination protocol. The conditions are:

Table 3. Estimated latency between modules with nodes

Units	Electronic module	Commercial module
Low load (2 nodes)	7-12ms	3-5ms
Medium load (4 nodes)	12-18ms	5-8ms
High load (x>6 nodes)	18-25ms	8-12ms

As can be seen, latency tends to increase because the module is designed for daily work shifts of 8-12 hours that do not require precision.

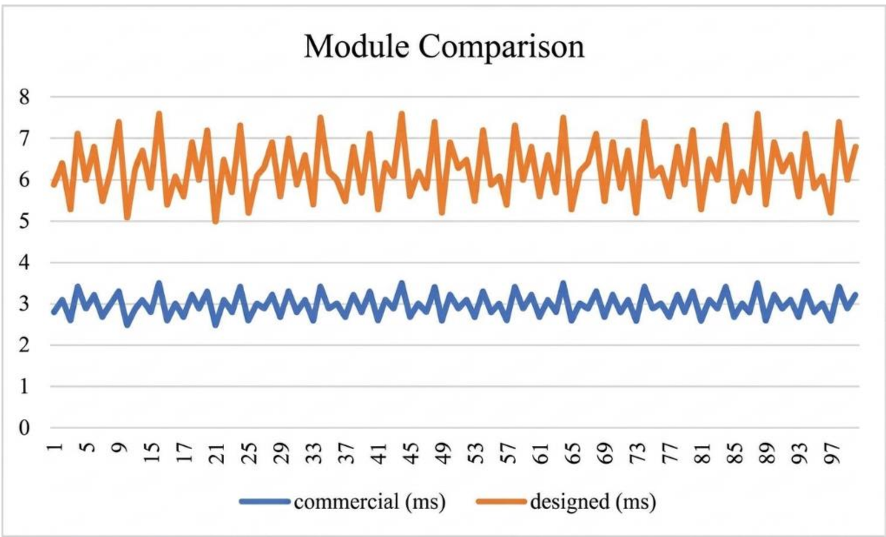


Fig. 8 Tabulated latency between modules

Due to the wide range of devices used in the Cerro Colorado industrial park, records were taken of 10 compatible PLCs, 5 drives, and 5 expansion modules, which are:

PLC
- Simatic S7-1200
- Simatic S7-200
- Simatic S7-1500
- Compact Logix
- Modicon M221
- Modicon M340
- FX5U
- Logo!
- Omron CP1E
- Delta DVP-SE

Drives
- Sinamics v20
- Powerflex 525
- Altivar 320
- HNC HV100
- CHINT NFV5

Expansion modules
- ET 200SP
- POINT I/O

- TM3 SCHENEIDER
- WAGO I/O
- ADAM 4000

Based on the data collected in the field, the comparison shown in Table 3 was taken into account, considering baud rates ranging from 9,600 to 19,200 for 20 records transmitted with low interference due to the signal filtering built into the electronic module between two nodes for the application.

Table 4. Communication latency

Components	Communication	Latency
PLC Logo!	Modbus RTU	32-12 ms
Electronic module	Modbus RTU to TCP/IP conversion	10-6 ms
Optidrive E3	Modbus TCP/IP	18-7 ms

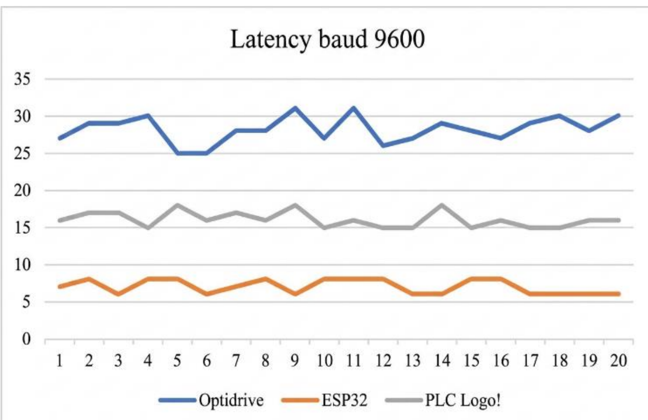


Fig. 9 Latency at 9600 baud between devices

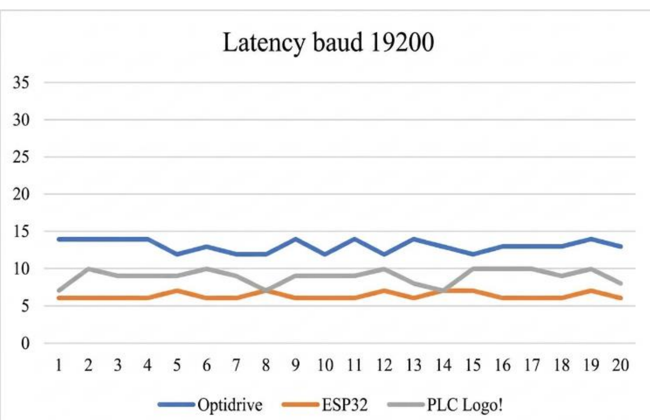


Fig. 10 Latency at 19,200 baud between devices

Of these, 13 devices have optimal functionality and compatibility, while 4 work partially due to latency issues and 3 are not compatible due to the robustness and precision required. According to the following formula, it can be inferred that:

$$compatibility\ index: \frac{(Compatible*1)+(Partial*0.5)}{Total}$$

$$CI: \frac{(13*1)+(4*0.5)}{20} = \frac{13+2}{20} = 0.75$$

Since the program is expected to include more complex functions and relatively simpler data handling, the HMI is being upgraded to a SIMATIC HMI model KTP900 (see Figure 11).

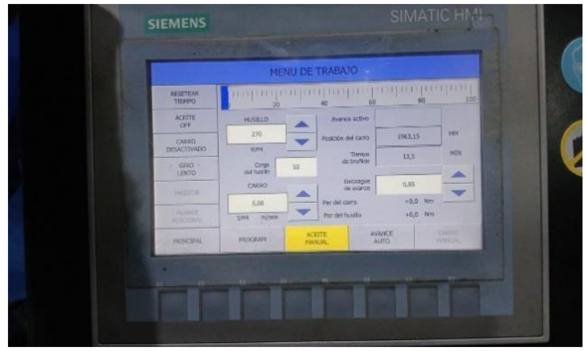


Fig. 11 Modified HMI after testing

Where the process requires faster parameter configuration and modification, as well as integration with the OPTIDRIVE drive to leverage both legacy and modern control systems, the Logo! PLC is shown on the control panel using legacy discrete logic, with modernization implemented for the respective process (see Figure 12).

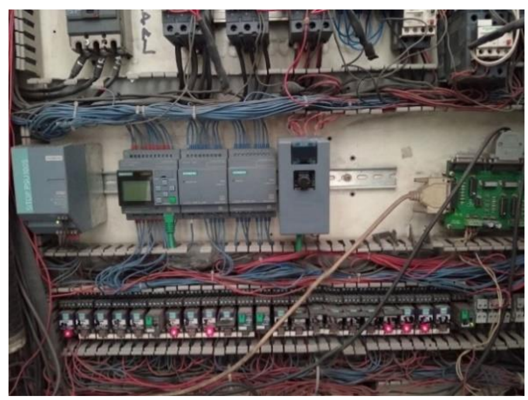


Fig. 12 Control panel with a Logo! PLC and built-in module

Device compatibility is 75% for an application in the Cerro Colorado industrial park, covering production lines such as HVOF processes, reducing the cost of purchasing a commercial expansion module and the complexity of configuration due to a protocol change in the device.

6. Conclusion

The results obtained demonstrate the functionality of the module between devices that do not share the same protocol, achieving a compatibility index of 75% determined by quantitative evaluation between devices used in industrial companies. It should be noted that it is not a certified option, but it is an appropriate and low-cost option for supervision, monitoring, and integration of serial infrastructure applications. The module's performance showed that latency under average load conditions of two active nodes was the only difference, starting with the use of three nodes, with an acceptable range of 3 ms between the real-time communication rate. Likewise, from an economic point of view, the electronic module has a considerable cost advantage, making it a viable alternative for the modernization of industrial devices. In conclusion, the module offers a viable and economically efficient technical solution for the partial unification of industrial networks in automation.

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