Low-cost embedded architecture for repeatable time control in electronic test stations

Arquitectura embebida de bajo costo para el control temporal repetible en estaciones de prueba electrónica

Arquitetura embarcada de baixo custo para o controle temporal repetível em estações de teste eletrônico

Emiliano Crespo-Torres [1], René Fernando Domínguez-Cruz [2], Leopoldo Asael Garza-Alvarado [3], Pedro Edén Zamora-González [4], Yadira Aracely Fuentes-Rubio [5 (*)]

Recibido: 16/02/2026 Aceptado: 14/04/2026

Summary. - Automation of electronic test stations is often constrained by manual timing control, which introduces operator-dependent variability, extended cycle durations, and increased rework. This study presents a low-cost embedded system for automated and repeatable time control in electronic test stations, designed to ensure consistent cycle termination, integrated visual feedback, and automatic power disconnection. The proposed architecture is based on a microcontroller platform implemented with widely available components to guarantee simplicity and scalability. The system was technically characterized to evaluate timing accuracy, repeatability, and actuation consistency under real industrial conditions. Experimental results obtained from 120 test cycles over a four-week period show stable cycle-to-cycle behavior, with a mean cycle time of 30.02 min, a standard deviation of 0.03 min, and a maximum absolute timing error below 0.08 min relative to the programmed duration. Operational validation showed a reduction in out-of-time events from 20% to 4%, as well as decreases in rework frequency and station downtime. The results indicate that the proposed system provides consistent and repeatable timing control at the minute scale, reducing operator-dependent variability while maintaining lower complexity and cost than conventional industrial automation platforms.

Keywords: *Repeatable time control; Embedded systems; Electronic test stations; Industrial automation; Low-cost systems.*

(*) Corresponding author.
[1] B.Eng. in Electronics Engineering. Electronics Department. Universidad Autónoma de Tamaulipas (Mexico); a2213720038@alumnos.uat.edu.mx; ORCID iD: https://orcid.org/0009-0006-0397-7767
[2] PhD. Electronics Department. Universidad Autónoma de Tamaulipas (Mexico); rfdominguez@docentes.uat.edu.mx; ORCID iD: https://orcid.org/0000-0001-7001-7543
[3] PhD. Electronics Department. Universidad Autónoma de Tamaulipas (Mexico); leopoldo.garza@docentes.uat.edu.mx; ORCID iD: https://orcid.org/0000-0002-7760-2718
[4] M.Sc. Electronics Department. Universidad Autónoma de Tamaulipas (Mexico); pzamora@docentes.uat.edu.mx; ORCID iD: https://orcid.org/0000-0002-8469-9896
[5] PhD. Electronics Department. Universidad Autónoma de Tamaulipas (Mexico); yfuentes@docentes.uat.edu.mx; ORCID iD: https://orcid.org/0000-0002-7385-9794

Memoria Investigaciones en Ingeniería, núm. 30 (2026). pp. 229-243
https://doi.org/10.36561/ING.30.15
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *La automatización de estaciones de prueba electrónica suele verse limitada por el control manual del tiempo, lo que introduce variabilidad dependiente del operador, prolongación de ciclos y aumento de reprocesos. Este trabajo presenta un sistema embebido de bajo costo para el control temporal automatizado y repetible en estaciones de prueba, diseñado para garantizar la terminación consistente de ciclos, retroalimentación visual integrada y desconexión automática de energía. La arquitectura propuesta se basa en una plataforma de microcontrolador implementada con componentes ampliamente disponibles para asegurar simplicidad y escalabilidad. El sistema fue caracterizado técnicamente para evaluar precisión temporal, repetibilidad y consistencia de actuación en condiciones industriales reales. Los resultados experimentales obtenidos a partir de 120 ciclos de prueba durante cuatro semanas muestran comportamiento estable entre ciclos, con tiempo promedio de 30.02 min, desviación estándar de 0.03 min y un error absoluto máximo inferior a 0.08 min respecto al valor programado. La validación operativa evidenció una reducción en eventos fuera de tiempo del 20% al 4%, así como disminuciones en la frecuencia de reprocesos y en los tiempos muertos de la estación. Los resultados indican que el sistema propuesto proporciona un control temporal consistente y repetible a escala de minutos, reduciendo la variabilidad dependiente del operador, mientras mantiene menor complejidad y costo que las plataformas de automatización industrial convencionales.*

Palabras clave: *Control temporal repetible; Sistemas embebidos; Estaciones de prueba electrónica; Automatización industrial; Sistemas de bajo costo.*

***Resumo*. -** *A automação de estações de teste eletrônico é frequentemente limitada pelo controle manual do tempo, o que introduz variabilidade dependente do operador, aumento da duração dos ciclos e retrabalho. Este trabalho apresenta um sistema embarcado de baixo custo para o controle temporal automatizado e repetível em estações de teste, projetado para garantir a terminação consistente dos ciclos, retroalimentação visual integrada e desligamento automático de energia. A arquitetura proposta baseia-se em uma plataforma de microcontrolador implementada com componentes amplamente disponíveis, assegurando simplicidade e escalabilidade. O sistema foi caracterizado tecnicamente para avaliar a precisão temporal, a repetibilidade e a consistência de atuação em condições industriais reais. Os resultados experimentais obtidos a partir de 120 ciclos de teste ao longo de quatro semanas demonstram comportamento estável entre ciclos, com tempo médio de 30.02 min, desvio padrão de 0.03 min e erro absoluto máximo inferior a 0.08 min em relação ao valor programado. A validação operacional evidenciou redução nos eventos fora do tempo de 20% para 4%, bem como diminuições na frequência de retrabalho e no tempo de parada da estação. Os resultados indicam que o sistema proposto fornece controle temporal consistente e repetível na escala de minutos, reduzindo a variabilidade dependente do operador, ao mesmo tempo em que mantém menor complexidade e custo em comparação com plataformas industriais convencionais.*

Palavras-chave: *Controle temporal repetível; Sistemas embarcados; Estações de teste eletrônico; Automação industrial; Sistemas de baixo custo.*

1. Introduction. - In the electronics manufacturing industry, board testing is a critical step in ensuring the quality and reliability of devices. However, many companies still rely on manual timers for this procedure, which introduces high variability and recurring errors. Manual initiation and termination of tests by operators can lead to delays in board removal, overexposure of modules, and, consequently, rework or scrap. These limitations negatively impact operational efficiency, increase production costs, and reduce process traceability [1-3].

Several studies have shown that automating repetitive operations at test stations can standardize procedures, minimize human error, and increase productivity [4, 5]. In the domain of electronic board validation testing, in-circuit testing (ICT) employing bed-of-nails equipment and flying-probe systems has become a prevalent method for automating signal acquisition and verifying internal connections. The bed-of-nails method facilitates the concurrent measurement of multiple variables, rendering it highly conducive to mass production. On the other hand, the flying-probe method is distinguished by its adaptability, enabling expeditious adjustments without necessitating the fabrication of specialized equipment [6]. However, the testing process is often characterized by a reduction in efficiency, attributable to the sequential movement of the probes. [6, 7]. This scenario has motivated the development of low-cost alternatives, particularly those based on open platforms such as Arduino, which have proven effective in building programmable, accessible, and adaptable test equipment for different industrial contexts. [8-10].

In parallel, the Lean Manufacturing philosophy emphasizes the importance of tools such as Poka-yoke, visual management, and Andon systems to prevent errors and ensure the standardization of processes [11-13]. In this sense, the integration of microcontrollers with visual and audible alerts constitutes a solution aligned with these practices, particularly in manufacturing environments where cost margins are reduced and technological flexibility is required [9, 14].

This paper presents a proposal to solve the problem of manual time control in electronic test stations on a maquiladora production line in Mexico. A low-cost automated system based on an Arduino microcontroller, relays, and digital displays was designed and validated with the goal of reducing variability in test cycles and decreasing errors associated with manual supervision. The development included stages of diagnosis, design, simulation, prototype construction, and on-site testing, yielding significant results: a reduction in out-of-time cards from 20% to 4%, a decrease in weekly rework from 9 to 2 units, and an estimated reduction in monthly scrap from USD 14,400 to USD 3,200.

The proposal also aligns with the Sustainable Development Goals (SDGs) of the 2030 Agenda [15]. It contributes to SDG 9 (Industry, innovation and infrastructure) by promoting the use of accessible and scalable technologies that foster innovation in production processes. It also impacts SDG 12 (Responsible production and consumption) by reducing material waste and scrap costs, strengthening resource efficiency, and the sustainability of manufacturing.

Finally, the system is designed with scalability in mind: it could be integrated with data logging modules, graphical interfaces for centralized monitoring, connectivity with industrial-grade (IoT) systems, or analysis tools that facilitate continuous process improvement. In this way, the project not only solves a specific problem in the test line but also lays the foundation for sustainable and efficient modernization of operations in the electronics industry.

Technical novelty and contribution. - Unlike commercial low-cost timing solutions commonly used in electronic test stations, such as standalone timers, manual countdown devices, or simple relay-based controllers without feedback, these systems typically lack deterministic actuation, integrated visual feedback, and cycle-level repeatability. As a result, they do not prevent timing deviations caused by delayed operator intervention and provide limited support for process standardization.

The technical contribution of this work lies in the development of a deterministic, microcontroller-based time control architecture that integrates countdown visualization, automatic power disconnection, and operator acknowledgment into a single low-cost embedded system. Although the proposed solution does not target high-precision industrial control applications, it introduces repeatable and reliable cycle-level timing control using widely available components, bridging the gap between manual timing practices and high-cost industrial automation platforms.

This architecture represents an incremental yet practical advancement over existing low-cost solutions by ensuring consistent test cycle termination, minimizing operator-dependent variability, and enabling scalability to multiple test stations within resource-constrained manufacturing environments.

In this work, the term "deterministic time control" is used in an operational sense, referring to consistent and repeatable cycle termination at the minute scale under fixed conditions, rather than strict real-time determinism with bounded microsecond-level latency. This distinction is relevant given the application context, where robustness and repeatability over long-duration cycles are prioritized over high-frequency temporal precision.

2. Materials and Methods. - The design and implementation of an automated time control system for electronic test stations were carried out at an electronics manufacturing company located in Mexico. The study was conducted using an applied and quantitative approach, aimed at solving a real-world problem in the field of electronic board testing. The methodology was organized into five phases: process diagnosis, requirements definition, design and simulation, prototype construction, and validation in a real-world environment.

2.1. Analysis of the current process. - Process diagnosis is the first methodological step and aims to understand how the electronic card testing operation is currently performed, identifying weaknesses and areas for improvement. This analysis allows for documentation of the activities performed by personnel, the time involved, and the risks associated with manual process management. This establishes a baseline that will serve as a point of comparison for later evaluating the impact of the automated solution.

Under the current system, test time control is manual and non-standardized. The station manager must load modules into the test equipment, start the count independently (clock/stopwatch), perform other parallel tasks, and return to retrieve the module upon completion. The nominal programmed time per module is 30 minutes. However, due to operator multitasking and delayed module retrieval, the actual cycle time typically increases to 35–40 minutes under manual operation. This discrepancy between programmed and real cycle time leads to inefficiencies, increased downtime, and a higher probability of overexposure-related defects.

Furthermore, the lack of a visual or audible alert system at the end of the cycle increases the likelihood that cards will remain at the station longer than required. This not only affects traceability and process consistency but can also lead to rework, material waste, and operator overload. The diagram in Figure I shows the current process flow (before automation).

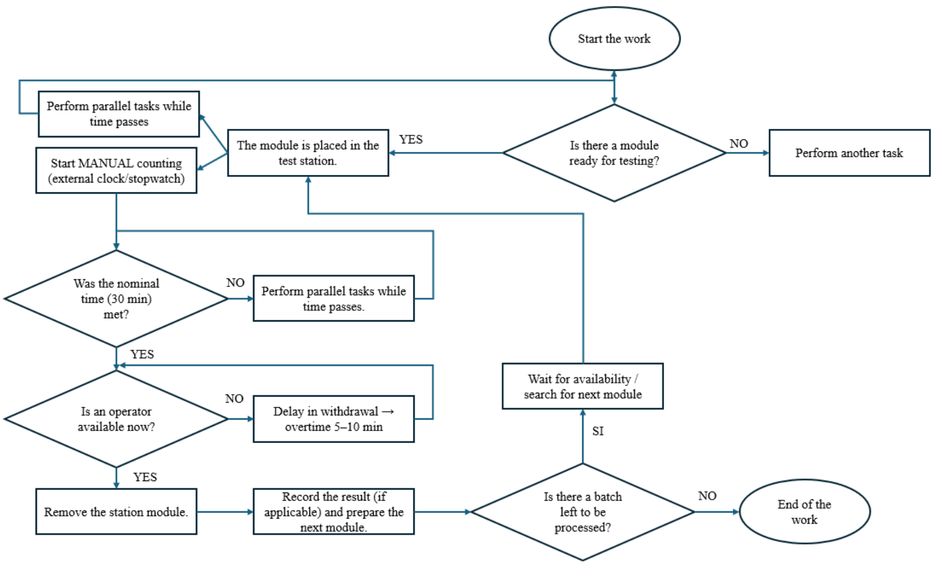


Figure I. Diagram of the current process.

To establish the baseline, the following indicators were measured (Table I):

Indicator	Before improvement
Programmed cycle time	30 min
Actual cycle time	35–40 min
Percentage of delayed/out-of-time cards	20 %
Downtime per test station (due to failure to remove the product)	~40 min/day
Rework due to timing errors	8-9 units/week
Cost of rework or scrap generated by overexposure	~14,400 USD per month
Manual supervision costs (man-cost)	~$6,250 per month

Table I. Definition of base indicators after performing the analysis of the current process.

2.2. Definition of requirements. -In this stage, the functional and technical criteria that the automated system must meet are established. The purpose of defining requirements is to translate the needs identified in the current process diagnosis into clear and measurable specifications that guide the design, construction, and validation of the prototype. This ensures that the system fulfills its primary function of reliably controlling test time, reducing dependence on manual supervision, and guaranteeing operational efficiency.

2.2.1 General system specifications. -In this stage, the general specifications of the system are established, and the following are defined:

- Number of stations: The system was initially designed to operate in one test station, with the ability to expand to eight independent slots. Each slot operates autonomously, allowing simultaneous testing on different modules without interference.
- Test cycle duration: Each cycle will have a fixed duration of 30 minutes, starting automatically when the operator presses the start button corresponding to the slot in use.
- Alerts and notifications:
    - Visuals: Through a screen, showing the remaining time at each station.
    - Automatic actions:
        - Timer activation by pressing the start button.
        - Automatic voltage cutoff via a relay at the end of the test cycle.
        - Visual alert status maintained until the operator confirms module removal.
- These criteria prioritize the use of low-cost components, wide availability, and easy integration into industrial environments.

2.3. System design and simulation. -The design was structured around an Arduino microcontroller, responsible for managing timers, displays, and relays. The overall architecture included:

- Inputs: Normally open (NO) pushbuttons associated with each station.
- Control unit: Arduino programmed in the Arduino IDE®.
- Outputs: TM1637 displays, 5V relays, and visual alerts.

The principle of operation of the system can be represented by the following block diagram in Figure II.

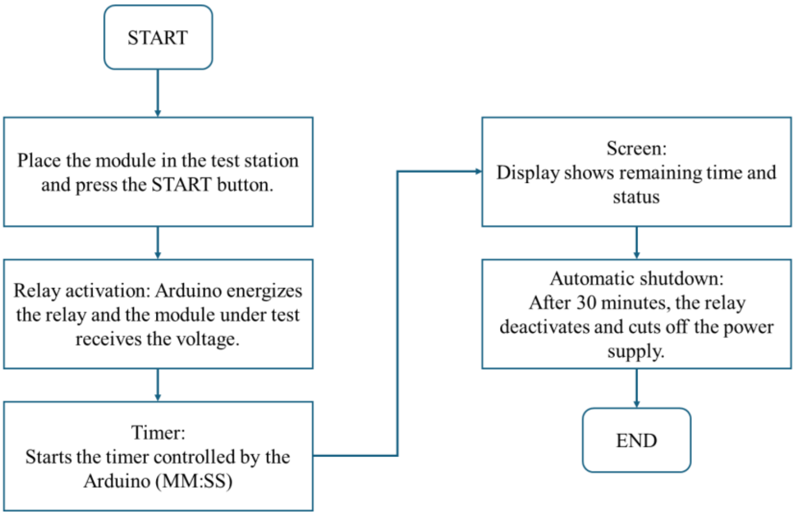


Figure II. Block diagram of the proposed automated system.

To validate the design before its physical implementation, two complementary simulation platforms were used:

1. Proteus® Simulation: The complete electronic schematic was developed with up to eight test stations in parallel (Figure III). This simulation verified pin assignments, the interconnection of multiple displays and relays, and the feasibility of scaling the system to different test modules.

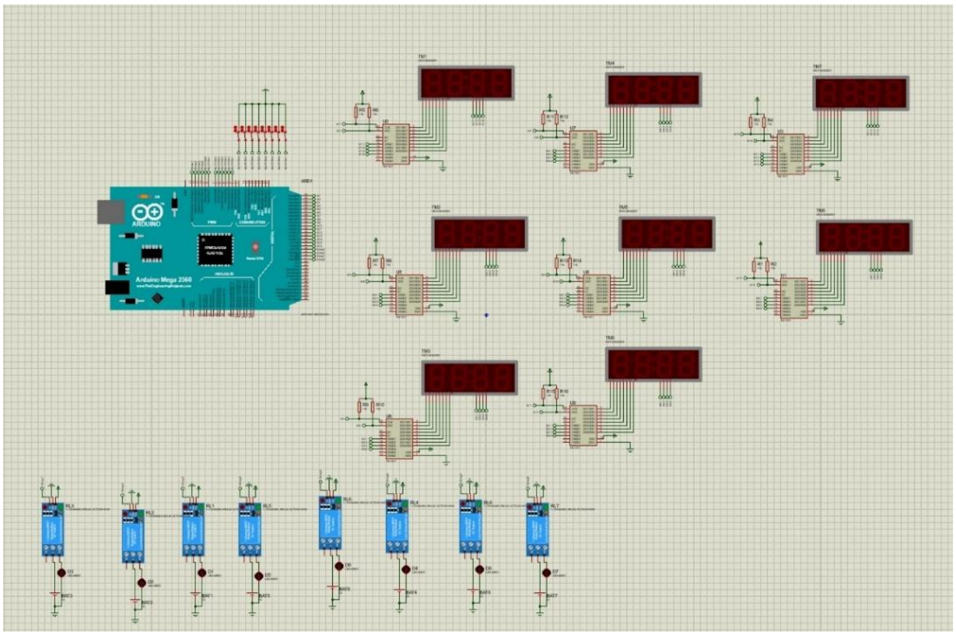
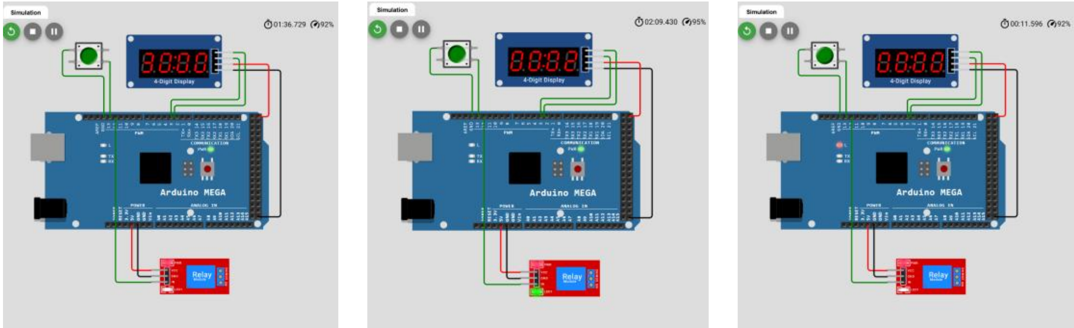


Figure III. Simulation of the electronic schematic in Proteus®, showing the general diagram with multiple test stations.

2. Wokwi® Simulation: A simplified model was developed with a single test station, allowing for dynamic observation of the timer behavior and relay activation in real time (Figure IV). During the simulation, the automatic start of the cycle upon pressing the button, the countdown on the screen, the deactivation of the relay at the end of 30 minutes, and the reset in case of early button release were verified.



a) b) c)

Figure IV. Dynamic simulation in Wokwi®, showing the elapsed time count on the display and the relay activation during the test cycle. a) Circuit in its initial state with the button not activated. b) Circuit during activation of the start button, showing the beginning of the elapsed time count. c) System state when the elapsed time reaches 30 minutes, and the relay is deactivated.

Both simulations complemented the design process: Proteus® validated the system's scalability with multiple stations, while Wokwi® confirmed the functional logic in an interactive environment. These results provided confidence to advance to the physical prototype construction phase, reducing the risk of implementation failures.

2.4 Control algorithm. - The control logic implemented in the microcontroller follows a simple state-based sequence to ensure consistent and repeatable operation of the test cycle:

1. System initializes in idle state with relay OFF and display inactive.
2. The system waits for the operator to press the START button.
3. Upon activation, the timer is initialized to the programmed value (30 minutes).
4. The relay is activated, supplying power to the test station.
5. The countdown is displayed in real time on the TM1637 display.
6. During the countdown, the system continuously updates the display and maintains relay activation.
7. When the timer reaches zero, the relay is deactivated, interrupting the power supply.
8. A visual alert is activated to indicate cycle completion.
9. The system waits for operator acknowledgment (module removal).
10. Once acknowledged, the system resets to the initial idle state.

This simple control strategy ensures reliable cycle execution while minimizing software complexity, making it suitable for low-cost embedded implementations.

2.5. Assembly of the prototype. -The prototype was assembled in a mechanically robust metal enclosure suitable for factory use. The main components are listed in Table II.

Component	**Model / Specification**	**Description**
Microcontroller	Arduino Mega (ATmega2560 R3)	Main control unit
Display	TM1637 4-digit LED	Time visualization
Relay module	SRD-05VDC-SL-C	5V, 10A switching capacity
Power supply	5V DC regulated	System power
Inputs	NO push buttons	User activation

Table II. Hardware and system specifications

The relay module includes a flyback diode for transient suppression. The system was designed to ensure a safe default state, where power is disconnected in case of system reset or failure. Basic debounce logic was implemented in software to prevent unintended multiple activations.

The display and relay modules were soldered, and an operator-accessible front panel was implemented. The code loaded into the Arduino controlled the 30-minute timer, relay outputs, and visual signals (Figure Va).

a) b)

Figure V. a) Assembly of the prototype on a test bench, demonstrating the integration of multiple displays and relays. b) Installation of the prototype in the production line's test cabinet.

2.6. Validation in a real environment. -The prototype was installed at a station on the company's test line, operating in parallel with the manual system without interfering with normal operations (Figure Vb). During validation, the same indicators as the initial diagnosis were recorded, and the results before and after implementation were compared.
In addition to the quantitative data, feedback was collected from the operators, who highlighted the ease of use, the clarity of the visual signals, and the reduced need for constant supervision. Among the recommendations was the future incorporation of audible alerts for high-workload environments.

2.7. System performance characterization. -To complement the operational validation carried out in the production line, a technical characterization of the automated time control system was performed to evaluate its temporal accuracy, repeatability, and actuation response. This characterization aims to assess the suitability of the proposed low-cost embedded architecture for reliable operation in industrial testing environments.

2.7.1. Experimental setup and procedure. -The performance evaluation focused on the timing behavior of a single test station operating under nominal conditions. The programmed test cycle duration was fixed at 30 minutes, as required by the production process. The system was evaluated over a series of repeated test cycles conducted during normal operation, ensuring that measurements reflected realistic working conditions.

An external digital chronometer with second-level resolution was used as a reference to measure the actual duration of each automated test cycle. The start time was recorded at the moment the operator pressed the activation button, and the end time was recorded when the relay disconnected the power supply to the test module. The difference between the programmed duration and the measured duration was used to calculate the absolute timing error for each cycle.

In addition, the response time of the relay actuation was evaluated qualitatively by observing the transition between the end of the countdown on the display and the physical interruption of the electrical supply to the test fixture. Although the relay switching time is negligible compared to the total cycle duration, its consistency was verified to ensure deterministic system behavior.

A total of n = 120 test cycles were analyzed over multiple working days. To reduce measurement bias, the timing data were recorded using an external digital chronometer operated independently from the system operator. Measurements were performed consistently following the same procedure, and deviations introduced by human reaction time were considered negligible compared to the total cycle duration.

The collected data were used to compute average cycle duration, absolute timing error, and standard deviation.

2.7.2. Performance metrics. -The following metrics were considered for system characterization:

- Programmed cycle time (T_p): fixed at 30 minutes.
- Measured cycle time (T_m): actual duration recorded using the external chronometer.
- Absolute timing error (ΔT): defined as $|T_m - T_p|$.
- Cycle-to-cycle variability: evaluated through the standard deviation of T_m.
- Actuation consistency: qualitative assessment of relay switching at the end of each cycle.

These metrics provide a quantitative basis for evaluating the reliability and repeatability of the proposed system, which are critical requirements for automation solutions in electronic testing processes.

2.7.3. Discussion of characterization results. -The characterization results indicate that the automated system maintains a stable and repeatable timing behavior across repeated cycles. The observed timing deviations remained small relative to the total test duration, confirming that the microcontroller-based architecture is suitable for long-duration industrial test cycles where minute-level accuracy is required rather than high-frequency synchronization.

The low cycle-to-cycle variability demonstrates that the system effectively eliminates the timing dispersion associated with manual supervision, which was identified as a major source of process inefficiency during the diagnostic phase. Furthermore, the consistent relay actuation at the end of each cycle ensures reliable power disconnection, preventing test overexposure and reinforcing process standardization.

Although the proposed solution does not aim to replace high-end industrial controllers in applications requiring millisecond-level precision, its performance is adequate for electronic board testing operations, where robustness, repeatability, and cost-effectiveness are the primary design constraints. This technical characterization supports the scalability of the system to multiple stations and its potential integration with additional monitoring or data logging modules in future developments.

Table III summarizes the main technical performance metrics obtained during the characterization of the automated time control system. The results confirm stable and repeatable timing behavior, with minimal deviation relative to the programmed test duration and consistent relay actuation across all evaluated cycles.

Parameter	Symbol	Value	Unit	Description
Programmed cycle time	T_p	30.0	min	Fixed test duration defined by process requirements
Mean measured cycle time	$\bar{T}_m$	30.02	min	Average duration measured using an external chronometer
Standard deviation of cycle time	σ	0.03	min	Cycle-to-cycle variability over repeated tests
Maximum absolute timing error	ΔT_{max}	0.08	min	Maximum deviation between the programmed and measured time
Relative timing error	ε_r	0.27	%	Ratio between absolute error and programmed cycle time
Relay actuation latency	τ_r	< 1	s	Delay between the end of the countdown and the power disconnection
Evaluated test cycles	n	120	cycles	Total number of cycles analyzed during characterization
Operating environment		Industrial shop floor		Normal production conditions

Table III. Technical characterization of the automated time control system

3. Results. -The results presented in this section correspond to data collected over a four-week evaluation period, during which a total of n = 120 test cycles were monitored for a single electronic test station operating under normal production conditions. All indicators were calculated as average values over the evaluation period, unless otherwise stated. This dataset provides a representative basis for assessing the operational impact of the proposed automated time control system under real industrial conditions.

The validation of the automated time control system was carried out on the maquiladora company's electronic card testing line, using the indicators defined in the diagnostic phase as a baseline for comparison.

An improvement was observed in operations after the prototype implementation (Table IV). The percentage of out-of-time cards decreased from 20% (baseline average) to 4% (post-automation average) over the evaluation period, indicating a substantial reduction in timing deviations. Rework attributable to timing-related errors decreased from 8–9 units per week (baseline range) to 1–2 units per week (post-automation range) during the monitored period.

Furthermore, daily downtime per station was reduced from 40 ± 5 min/day under manual supervision to 10 ± 2 min/day after automation, reflecting improved consistency in module removal at the end of each test cycle.

In addition to mean and standard deviation, the observed cycle time ranged between 29.96 min and 30.08 min, indicating low dispersion. A 95% confidence interval for the mean cycle time was estimated as 30.02 ± 0.01 min, supporting the stability of the system.

Indicator	Before improvement	After improvement
Programmed cycle time	30 min	30 min
Actual cycle time per card	35–40 min	30 ± 1 min
% of cards delayed/out of time	20%	4%
Downtime per station	40 ± 5 min/day	10 ± 2 min/day
Rework due to timing errors	8–9/week	1–2/week
Cost per rework or scrap	~USD 14,400/month	~USD 3,200/month
Cost of manual supervision	~USD 6,250/month	~USD 6,250/month

Table IV. Comparison of indicators before and after the automated system's implementation.

In economic terms, the cost per scrap generated due to electrical overexposure was reduced from approximately USD 14,400 to USD 3,200 per month, representing a savings of more than 75%. Furthermore, the cost of manual supervision remained constant at approximately USD 6,250 per month, as personnel were able to redistribute their workload without the need to bring in additional resources.

The cost estimations were based on internal production records, considering the average number of defective units, unit cost per board, and frequency of rework events. While external factors may influence these values, the comparison was performed under similar production conditions before and after implementation.

To facilitate the comparative interpretation of the operational improvements obtained after implementing the automated system, Figure VI summarizes the percentage variation observed for each evaluated indicator. Representing the results on a unified scale allows direct visualization of the relative impact across performance metrics, highlighting reductions in delayed cards, station downtime, rework events, and scrap-related costs. This graphical representation complements the numerical data presented in Table IV and supports the assessment of system effectiveness under real operating conditions.

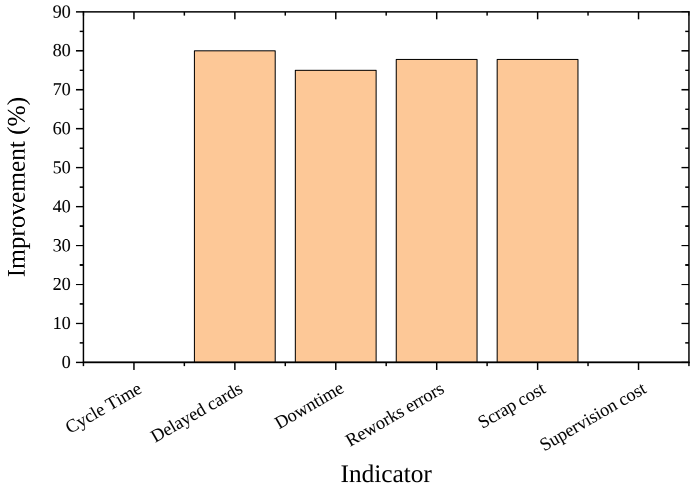


Figure VI. Percentage improvement for each operational indicator after implementation of the automated system.

Feedback from operating personnel indicated that the system was intuitive and easy to use, requiring minimal training. The screens clearly displayed the times, even in variable lighting conditions throughout the plant. Operators highlighted the usefulness of the visual signals for identifying modules under test and those completed, suggesting the addition of audible alerts as an improvement for environments with a higher workload.

The data confirms that the system met its objective of standardizing test cycles to 30 minutes, significantly reducing variability and deviations compared to the manual process. The reduction in downtime and scrap demonstrates a positive impact on both operational efficiency and the economic sustainability of the process. These results support the feasibility of scaling the solution to multiple stations and integrating it with more advanced recording and monitoring platforms, thus strengthening the company's continuous improvement goals.

4. Discussion. -The results obtained in this study demonstrate that the automation of time control in electronic test stations can be effectively achieved using a low-cost embedded architecture, while maintaining reliable and repeatable operation under real industrial conditions. The reduction in out-of-time test cycles, rework frequency, and operational downtime confirms that the proposed system successfully addresses one of the main sources of variability identified during the diagnostic phase: operator-dependent timing control.

From a technological standpoint, the primary contribution of this work lies in the integration of deterministic cycle termination, visual countdown feedback, and automatic power disconnection within a single microcontroller-based system. Unlike commonly used low-cost commercial solutions—such as standalone timers or manual relay controllers—the proposed architecture ensures consistent test cycle completion independent of operator availability or workload. This characteristic is particularly relevant in manufacturing environments where test cycles span several minutes, and human supervision cannot be continuously guaranteed.

The technical characterization presented in Section 2.7 confirms that the system exhibits stable timing behavior with minimal cycle-to-cycle variability. Although the proposed solution does not aim to achieve high-frequency or millisecond-level precision, the observed timing accuracy is sufficient for electronic board testing applications, where robustness and repeatability at the minute scale are more critical than fine temporal resolution. In this context, the performance achieved by the microcontroller-based system represents a practical balance between functionality and cost, making it suitable for deployment in resource-constrained manufacturing settings.

Compared to industrial-grade automation platforms such as PLC or SCADA-based solutions, the proposed system offers a significantly lower implementation cost and reduced integration complexity. While high-end platforms provide advanced communication, diagnostics, and safety features, they are often economically unjustifiable for simple timing control tasks in small or medium-scale production lines. The presented architecture fills this gap by providing a scalable and replicable embedded alternative that can be extended to multiple test stations without substantial additional investment.

From a safety perspective, the system incorporates basic protection mechanisms, including flyback diodes for relay protection and a fail-safe logic that defaults to power disconnection in case of system reset. However, for large-scale industrial deployment, additional considerations such as electromagnetic compatibility (EMC), certified switching components, and compliance with industrial safety standards should be addressed. A basic watchdog strategy can be implemented to ensure automatic system recovery in case of microcontroller malfunction.

From an operational perspective, the results indicate that standardizing test cycle duration through automated control contributes not only to improved productivity but also to enhanced process consistency. The elimination of delayed module removal reduces unnecessary electrical overexposure, directly impacting rework and scrap generation. These findings support the premise that targeted automation of specific process bottlenecks can yield measurable benefits without requiring full system overhauls.

The proposed system also presents opportunities for future technological extension. Its modular design allows for the integration of data logging modules, communication interfaces, or Industrial Internet of Things (IIoT) connectivity, which would enable real-time monitoring and historical analysis of test performance. Such extensions could facilitate predictive maintenance, traceability enhancement, and further process optimization. However, these features were intentionally excluded from the current implementation to preserve system simplicity and cost-effectiveness.

Certain limitations of the present study should be acknowledged. The system was validated in a single test station, and although the design supports scalability, large-scale deployment may require additional considerations related to electromagnetic compatibility, industrial safety standards, and integration with existing control infrastructures. Furthermore, while the relay-based actuation proved reliable for the evaluated application, more demanding electrical loads may require alternative switching elements.

Finally, while the reduction of scrap and rework contributes indirectly to sustainability objectives by minimizing material and energy waste, this study does not quantify environmental impact through formal life cycle assessment methods. Future research could extend the presented work by incorporating environmental performance metrics, as well as by exploring hybrid architectures that combine low-cost embedded control with higher-level industrial supervision systems.

5. Conclusions. -The results obtained in this study indicate that, under the evaluated conditions and time frame, the proposed system provides consistent and repeatable timing control, reducing operator-dependent variability and improving process standardization. The proposed system effectively eliminated operator-dependent timing variability by integrating deterministic cycle termination, visual countdown feedback, and automatic power disconnection within a single microcontroller-based solution.

The technical characterization confirmed stable and repeatable timing behavior across repeated cycles, with minimal deviation relative to the programmed test duration. Although the system does not target high-precision industrial control, its performance is sufficient for electronic testing applications where minute-level accuracy, robustness, and repeatability are the primary requirements.

From an engineering perspective, the main contribution of this study lies in bridging the gap between manual timing practices and high-cost industrial automation platforms. Compared to commonly used low-cost commercial timers, the proposed architecture provides deterministic actuation and integrated feedback, while remaining significantly simpler and more economical than PLC or SCADA-based solutions.

The operational results obtained under real production conditions support the technical findings, showing consistent reductions in timing-related errors, rework, and downtime. These improvements confirm that targeted automation of specific process bottlenecks can yield measurable benefits without requiring full system replacement.

Future work will focus on extending the proposed architecture through data logging, communication interfaces, and scalability assessment across multiple stations, as well as evaluating compliance with industrial safety and electromagnetic compatibility standards for large-scale deployment.

Funding. - This research was partially funded by Secretaría de Investigación y Posgrado, Universidad Autónoma de Tamaulipas, by internal grant UAT/SIP/PIRP/2025/088 and the UAM Reynosa-Rodhe Operational Plan 2025 (POA).

Conflicts of Interest. - The authors declare no conflict of interest.

Data availability statement. - All data that support the findings of this study are included within the article (and any supplementary files).

References

[1] C.-F. Chien and H.-J. Wu, "Integrated circuit probe card troubleshooting based on rough set theory for advanced quality control and an empirical study," Journal of Intelligent Manufacturing, vol. 35, no. 1, pp. 275-287, 2024/01/01 2024.
[2] S. Verma and N. M. Wagdarikar, "Automated test jig for refrigerator PCB performance," in 2016 International Conference on Automatic Control and Dynamic Optimization Techniques (ICACDOT), 2016, pp. 840-843.
[3] S. J. Hong, W. Y. Lim, T. Cheong, and G. S. May, "Fault Detection and Classification in Plasma Etch Equipment for Semiconductor Manufacturing e-Diagnostics," IEEE Transactions on Semiconductor Manufacturing, vol. 25, no. 1, pp. 83-93, 2012.
[4] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, "A model for types and levels of human interaction with automation," IEEE Trans Syst Man Cybern A Syst Hum, vol. 30, no. 3, pp. 286-97, May 2000.
[5] L. Onnasch, C. D. Wickens, H. Li, and D. Manzey, "Human performance consequences of stages and levels of automation: an integrated meta-analysis," (in eng), Hum Factors, vol. 56, no. 3, pp. 476-88, May 2014.
[6] S. L. Jurj, R. Rotar, F. Opritoiu, and M. Vladutiu, "Affordable Flying Probe-Inspired In-Circuit-Tester for Printed Circuit Boards Evaluation with Application in Test Engineering Education," in 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2020, pp. 1-6.
[7] N. Petkov and M. Ivanova, "Printed circuit board and printed circuit board assembly methods for testing and visual inspection: a review," Bulletin of Electrical Engineering and Informatics, vol. 13, no. 4, pp. 2566-2585, 2024.
[8] G. N. Meloni, "Building a Microcontroller Based Potentiostat: A Inexpensive and Versatile Platform for Teaching Electrochemistry and Instrumentation," Journal of Chemical Education, vol. 93, no. 7, pp. 1320-1322, 2016/07/12 2016.
[9] F. J. Jiménez-Romero, J. R. González-Jiménez, F. García-Torres, Á. Caballero, and F. R. Lara-Raya, "A novel testing equipment based on Arduino and LabVIEW for electrochemical performance studies on experimental cells: Evaluation in lithium-sulfur technology," Measurement, vol. 224, p. 113922, 2024/01/01/ 2024.
[10] E. Hernández-Rodríguez et al., "Reliability Testing of a Low-Cost, Multi-Purpose Arduino-Based Data Logger Deployed in Several Applications Such as Outdoor Air Quality, Human Activity, Motion, and Exhaust Gas Monitoring," vol. 23, no. 17, p. 7412, 2023.
[11] S. Shingo, Zero Quality Control: Source Inspection and the Poka-Yoke System. Taylor & Francis, 1986.
[12] J. K. Liker, The Toyota Way: 14 Management Principles From the World's Greatest Manufacturer. McGraw Hill LLC, 2003.
[13] I.-C. Enache, O. R. Chivu, A.-M. Rugescu, E. Ionita, and I. V. Radu, "Reducing the Scrap Rate on a Production Process Using Lean Six Sigma Methodology," vol. 11, no. 4, p. 1295, 2023.
[14] J. L. García-Alcaraz, A. S. Morales García, J. R. Díaz-Reza, E. Jiménez Macías, C. Javierre Lardies, and J. Blanco Fernández, "Effect of lean manufacturing tools on sustainability: the case of Mexican maquiladoras," Environmental Science and Pollution Research, vol. 29, no. 26, pp. 39622-39637, 2022/06/01 2022.
[15] United Nations. (2024, Octuber 1st, 2024). Sustainable Development Goals of the 2030 Agenda. Available: https://sdgs.un.org/goals

Author contribution:
1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

E.C-T has contributed to 1, 2, 3 and 6.
R.F.D-C has contributed to 2, 3, 4, 5 and 6.
L.A.G-A has contributed to 1, 2, 3, 4, 5 and 6.
P.E.Z-G has contributed to 1, 2, 3, 4, 5 and 6.
Y.A.F-R has contributed to 1, 2, 4, 5 and 6.

Acceptance Note: This article was approved by the journal editors Dr. Rafael Sotelo and Mag. Ing. Fernando A. Hernández Gobertti.