SEVEN publicações acadêmicas

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MICROSENSORES Y MICROACTUADORES EN SISTEMAS IOT CON ESP32 PARA MONITOREO Y CONTROL

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ABSTRACT
The rapid advancement of the Internet of Things (IoT) has driven the need for intelligent systems capable of combining miniaturization, energy efficiency, and high computational performance. In this context, this article analyzes the integration of microsensors and microactuators, largely based on MEMS (Micro-Electro-Mechanical Systems) technology with the ESP32 microcontroller. The ESP32 platform stands out as a suitable solution for low-cost IoT applications due to its dual-core architecture, processing flexibility, and multiple connectivity options, such as Wi-Fi, Bluetooth, and LoRa, enabling the development of compact, efficient, and connected systems.

Keywords: Microsensors. Microactuators. IoT Systems. Monitoring.

RESUMO
O avanço acelerado da Internet das Coisas (IoT) tem impulsionado a necessidade de sistemas inteligentes capazes de aliar miniaturização, eficiência energética e elevado desempenho computacional. Neste contexto, este artigo analisa a integração de

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microssensores e microatuadores, em grande parte baseados na tecnologia MEMS (Micro-Electro-Mechanical Systems), com o microcontrolador ESP32. A plataforma ESP32 destaca-se como uma solução adequada para aplicações IoT de baixo custo, devido à sua arquitetura dual-core, à flexibilidade de processamento e às múltiplas opções de conectividade, como Wi-Fi, Bluetooth e LoRa, possibilitando o desenvolvimento de sistemas compactos, eficientes e conectados.

Palavras-chave: Microssensores. Microatuadores. Sistemas IoT. Monitoramento.

RESUMEN

El rápido avance del Internet de las Cosas (IoT) ha impulsado la necesidad de sistemas inteligentes capaces de combinar miniaturización, eficiencia energética y alto rendimiento computacional. En este contexto, este artículo analiza la integración de microsensores y microactuadores, en su mayoría basados en la tecnología MEMS (Micro-Electro-Mechanical Systems), con el microcontrolador ESP32. La plataforma ESP32 se destaca como una solución adecuada para aplicaciones IoT de bajo costo, gracias a su arquitectura de doble núcleo, su flexibilidad de procesamiento y sus múltiples opciones de conectividad, como Wi-Fi, Bluetooth y LoRa, lo que permite el desarrollo de sistemas compactos, eficientes y conectados.

Palabras clave: Microsensores. Microactuadores. Sistemas IoT. Monitoreo.

1 INTRODUCTION

The Internet of Things (IoT) has emerged as one of the main technological paradigms of contemporary digital transformation, characterized by the interconnection of intelligent physical objects endowed with sensing, processing, and real-time data communication capabilities. This approach has promoted profound changes across multiple domains, including advanced manufacturing within Industry 4.0, smart cities, precision agriculture, environmental monitoring, and connected healthcare systems, enabling increased automation, operational efficiency, and data-driven decision support (Abdulhussain, 2025; Jing, 2023; Gazis, 2025).

From an architectural perspective, IoT systems are composed of multiple functional layers in which the interaction between the physical environment and the digital domain is primarily enabled by interface devices such as microsensors and microactuators (Senturia, 2000). These components are critical to the success and scalability of IoT applications, since data acquisition quality and actuation accuracy directly affect overall system performance (Witczak, 2024).

Microsensors play a fundamental role in the acquisition of physical, chemical, and biological variables, such as temperature, pressure, vibration, humidity, and gas composition, providing essential information for continuous and distributed monitoring. Microactuators, in turn, are responsible for active intervention in the environment, enabling control actions, adjustments, and automated responses, and are widely employed in positioning systems, micromirrors, acoustic devices, and biomedical applications (Amara, 2025; Ahmad, 2024; Islam, 2025).

The growing demand for compact, energy-efficient, and low-cost IoT devices has significantly driven advances in Micro-Electro-Mechanical Systems (MEMS) technologies. The miniaturization enabled by these systems allows the integration of sensors and actuators at micrometer scales while maintaining high sensitivity, low power consumption, and high reliability (Cheng, 2025). Recent studies highlight that advances in functional materials, fabrication techniques, and transduction structures have enhanced MEMS device performance, making them increasingly suitable for large-scale IoT deployments and operation in challenging environments (Fang, X., 2025; Jung, Y., 2025; Wan, Z., 2025; Ferreira, 2024).

Furthermore, recent research indicates that the combined use of MEMS-based microsensors and microactuators fosters the development of intelligent systems with a higher degree of autonomy, enabling the implementation of advanced control strategies and predictive maintenance. In particular, applications involving vibration, temperature, and environmental variable monitoring have directly benefited from the integration of these devices into low-power IoT platforms (Kolok, 2025; Gazis, 2025).

In parallel with the advancement of MEMS devices, there has been significant evolution in embedded processing platforms used in IoT systems. System-on-a-Chip (SoC) microcontrollers have increasingly incorporated advanced wireless connectivity, processing capabilities, and power management features, thereby reducing both hardware and embedded software complexity (Hercog, 2023). Within this context, the ESP32 platform stands out for offering low-power Wi-Fi and Bluetooth connectivity, adequate computational performance, and widespread adoption in both academic and industrial applications.

Moreover, the integration of the ESP32 with long-range, low-power communication technologies such as LoRa significantly expands the application scope of IoT systems, enabling the monitoring and control of distributed devices over large geographical areas. Recent studies demonstrate that this combination is particularly effective in scenarios such as precision agriculture, predictive maintenance, and remote environmental monitoring, where communication reliability and energy efficiency are critical requirements (Le, 2021; Kolok, 2025; Gazis, 2025).

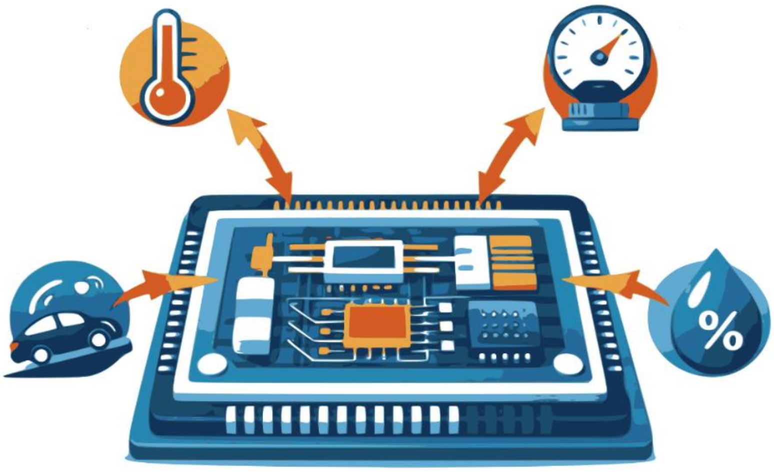
Within this context, this article proposes an analysis of the integration of MEMS-based microsensors and microactuators with the ESP32 platform, evaluating aspects such as technical feasibility, robustness, and energy efficiency of the proposed solution. The objective is to demonstrate that this approach represents a promising alternative for the development of practical monitoring and control systems within the Internet of Things framework, in alignment with recent trends reported in scientific literature.

2 THE MINIATURIZATION OF COMPONENTS

The convergence of component miniaturization and the increasing ubiquity of the Internet of Things (IoT) has driven the development of intelligent systems capable of autonomously perceiving, processing information, and interacting with the environment. In this context, microsensors and microactuators play a central role as interface elements between the physical world and the digital domain, enabling data acquisition and the execution of control actions. Frequently based on Micro-Electro-Mechanical Systems (MEMS) technology, Figure 1, these devices allow the efficient integration of sensing and actuation functions into compact, energy-efficient systems suitable for large-scale distributed applications.

Figure 1

MEMS (Micro-Electro-Mechanical Systems)



Source: Produced by the author, 2025.

MEMS are miniaturized systems that integrate mechanical components, sensors, actuators, and electronic circuits onto a single substrate, typically fabricated in silicon using processes derived from microelectronics. This integration enables the sensing and actuation of physical quantities such as pressure, acceleration, temperature, sound, and electric or magnetic fields with high precision and low power consumption. Owing to their small size, low cost in mass production, and high reliability, MEMS have become essential in a wide range of modern applications, including mobile devices, automotive systems, medical equipment, industrial instrumentation, and IoT solutions, contributing significantly to system miniaturization and the increasing intelligence of advanced technological systems.

(I) Microsensors and MEMS Technology

Microsensors are transducer devices responsible for converting physical quantities—such as temperature, pressure, acceleration, or humidity—into electrical signals that can be measured and processed. These components form the foundation of sensing in modern systems and play an essential role in applications that require continuous and accurate monitoring. MEMS technology is widely used in the fabrication of most contemporary microsensors, as it enables the integration of mechanical structures, sensing elements, and electronic circuits for signal conditioning and processing onto a single silicon substrate, with dimensions ranging from micrometers to millimeters. Table 1 presents a comparison of commonly used microsensors in IoT projects, highlighting their typical applications and associated operating principles.

Table 1

Comparison of Common Microsensors in IoT Systems

Sensor	Measured Quantity	Operating Principle	Typical Applications
DHT22	Temperature and Humidity	Capacitive (Humidity), Thermistor (Temperature)	Environmental Monitoring, Smart Greenhouses
BMP280	Barometric Pressure and Temperature	Piezoresistive	Weather Stations, Indoor Navigation (Altitude)
MPU-6050	Acceleration and Angular Velocity	Piezoresistive (Accelerometer), Gyroscope (Coriolis Effect)	Predictive Maintenance (Vibration), Robotics, Drones
MQ-X	Gas Concentration (e.g., CO, Methane)	Semiconductor (Resistance Variation)	Air Quality Monitoring, Industrial Safety

Source: Produced by the author, 2025.

The operating principles of MEMS-based microsensors may vary depending on the physical quantity to be measured and the intended application. Among the most common mechanisms is the piezoresistive principle, widely employed in pressure sensors and accelerometers, in which the electrical resistance of a material changes when subjected to mechanical deformation. Another frequently used principle is the capacitive mechanism, typical of accelerometers and humidity sensors, which is based on variations in capacitance between electrodes caused by mechanical displacement or the presence of a variable dielectric medium. In addition, thermal sensors exploit phenomena related to heat transfer or voltage variation with temperature and are commonly used in flow sensors and thermocouples.

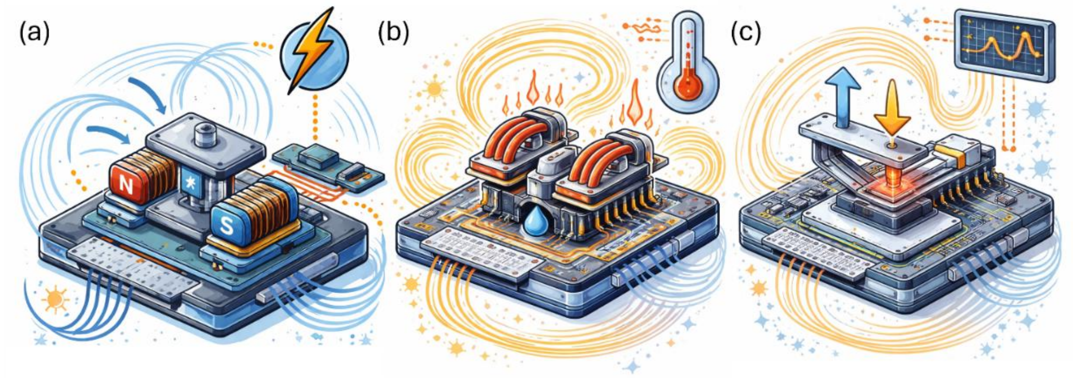
The miniaturization enabled by MEMS technology provides benefits that extend beyond simple reductions in size and cost. Miniaturized sensors generally exhibit higher sensitivity, faster response times, and lower power consumption—features that are fundamental for embedded and distributed systems. These advantages make MEMS-based microsensors particularly well suited for Internet of Things (IoT) applications, in which large numbers of devices must operate efficiently, reliably, and with extended energy autonomy.

(II) Microatuadores e o Controle de Sistemas

Microactuators are components responsible for converting electrical control signals generated by the embedded system into physical or mechanical actions in the environment. They play a fundamental role in microelectromechanical systems, enabling digital decisions to produce tangible effects in the physical world. These principles are illustrated in a didactic manner in Figure 2.

Figure 2

Microactuators: (a) Electromagnetic, (b) Electrothermal, and (c) Piezoelectric



Source: Produced by the author, 2025.

Like sensors, many actuators benefit from MEMS technology, which enables the fabrication of devices with high precision, reduced dimensions, and low power consumption. These characteristics make microactuators particularly suitable for embedded applications and miniaturized systems. Among the main types of microactuators are electromagnetic actuators, which use the Lorentz force to generate motion and are widely employed in micro-relays and microvalves. Electrothermal actuators are also prominent; they are based on the thermal expansion of materials, such as thermal bimorphs, and are commonly used in microvalves and optical shutters.

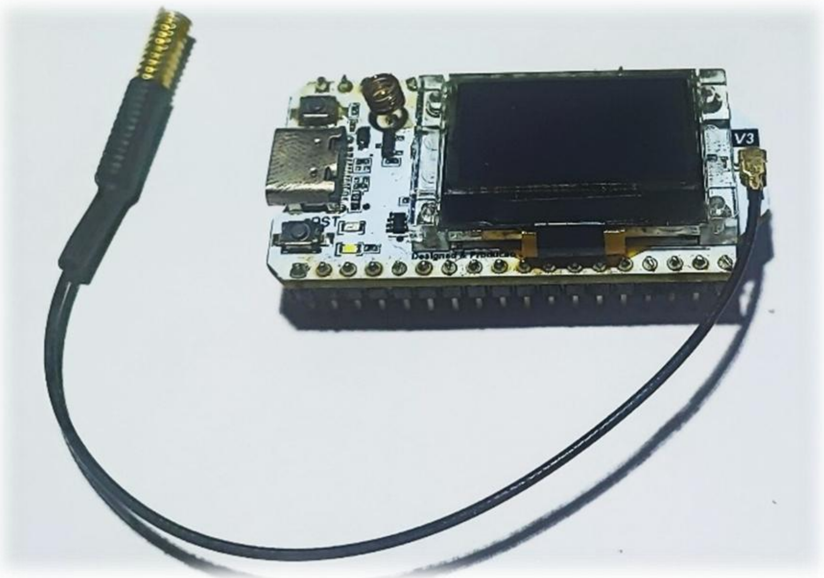
Another important class of microactuators is piezoelectric microactuators, which exploit the inverse piezoelectric effect to generate high-precision and high-force movements. These devices are essential in fine positioning systems, micropumps, and applications that require precise displacement control. In control systems, the microactuator is the element responsible for closing the feedback loop: the microsensor measures the variable of interest, the controller processes this information, and the microactuator acts on the environment, adjusting the system until the desired operating point is achieved.

(III) Runtime Optimizations

The ESP32, developed by Espressif Systems, is a System-on-a-Chip (SoC) that has become one of the leading platforms for the development of Internet of Things (IoT) prototypes and products, combining low cost, high performance, and considerable versatility. Its technical characteristics make it particularly well suited for integration with microsensors and microactuators. From a processing standpoint, the ESP32 features a microcontroller capable of executing concurrent tasks, allowing, for instance, sensor data acquisition to be handled by one core while wireless communication is managed by another core. This capability is commonly observed in applications such as the Heltec Automation LoRa 32 V3, as illustrated in Figure 03.

Figure 3

Heltec Automation LoRa 32 V3



Source: Produced by the author, 2025.

In terms of connectivity, the ESP32 integrates Wi-Fi modules compliant with the 802.11 b/g/n standards and Bluetooth Low Energy (BLE), which are essential for communication with cloud services and mobile devices. In addition, it can operate with LoRa technologies across frequency bands ranging approximately from 433 to 510 MHz and from 863 to 928 MHz, significantly extending its range for long-distance and low-power applications.

Regarding interfaces, the ESP32 provides a wide variety of peripheral options, including GPIOs, I^2C, SPI, UART, ADC, and DAC, which facilitates direct connection to most commercially available microsensors and microactuators, thereby reducing the need for complex external circuitry.

The combination of processing capability, multiple connectivity options, and low power consumption makes the ESP32 a robust solution for monitoring and control systems. These characteristics enable advanced applications such as predictive maintenance, industrial automation, and real-time environmental monitoring.

(IV) Environmental Monitoring and Control System

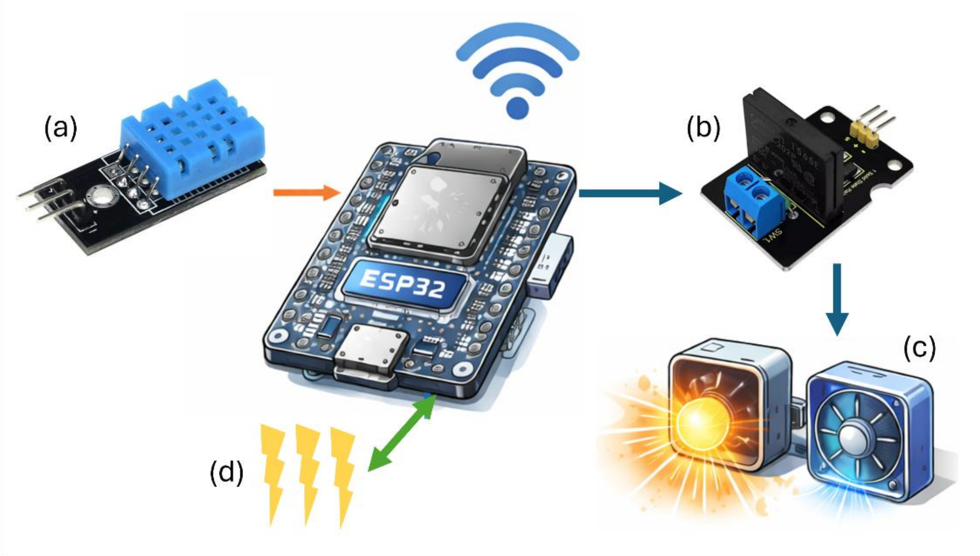
The system adopts a hardware architecture composed of a central controller, sensors, and actuators, designed for environmental monitoring and control applications. The controller used is the ESP32, which is responsible for data processing, execution of the control logic, and Wi-Fi connectivity, enabling system integration with external monitoring platforms.

As a microsensor, the digital temperature and humidity sensor DHT22, also known as the AM2302, is employed. This sensor was selected due to its good accuracy, low cost, and ease of interfacing with microcontrollers, providing reliable measurements of the environmental variables required for greenhouse control.

The system's microactuator is a solid-state relay (SSR) module, which operates as an electromagnetic microactuator. It is responsible for switching heating devices, such as a lamp, and cooling devices, such as a fan, on or off, allowing environmental variables to be adjusted according to the conditions measured by the sensor. Figure 4 illustrates the architecture of this Environmental Monitoring and Control System for a smart greenhouse.

Figure 4

Architecture of the Intelligent System: (a) DHT22 microsensor, (b) solid-state relay (SSR), (c) heating device (lamp) and cooling device (fan), and (d) power supply and communication via USB Type-C cable.



Source: Produced by the author, 2025.

The system architecture is based on the continuous acquisition of temperature and humidity data by the DHT22 sensor, the processing of this information by the ESP32, and direct actuation on the environment through the relay. In addition, the collected data are transmitted via Wi-Fi to a cloud platform, such as ThingSpeak or Firebase, enabling remote monitoring and historical data storage, as demonstrated in several recent studies on IoT systems.

The control logic implemented in the ESP32 firmware is based on a simple ON/OFF control strategy, primarily focused on temperature regulation. In this model, heating or cooling is activated when the measured variable exceeds predefined threshold limits. If an additional water flow system is integrated with the fan, this control logic can be extended to regulate humidity as well, thereby expanding the functionality of the environmental control system.

3 CONCLUSION

The architecture presented throughout this study clearly demonstrate the effectiveness of integrating microsensors, microactuators, and the ESP32 platform for the implementation of IoT-based monitoring and control systems. The synergy between the miniaturization enabled by MEMS technology and the ESP32's processing capability, connectivity options, and low power consumption yields a solution that is not only robust and scalable, but also economically viable for a broad range of applications, including environmental control, industrial automation, and predictive maintenance.

The practical case study of an environmental control system applied to a smart greenhouse further reinforces these findings. By employing a temperature and humidity microsensor (DHT22) in conjunction with a relay-based microactuator, the proposed architecture successfully closes the control loop, enabling real-time data acquisition, timely decision-making, and rapid actuation on the physical environment. This configuration demonstrates how relatively simple control strategies, such as ON/OFF control, can be effectively implemented using low-cost hardware while still achieving reliable and responsive system behavior.

Beyond the specific application presented, the proposed architecture highlights the flexibility and adaptability of the ESP32–MEMS combination, which can be readily extended to more complex control schemes, additional sensing modalities, and distributed system topologies. The integration with cloud platforms for remote monitoring and data storage further enhances the system's usability and scalability, supporting data-driven analysis and long-term performance assessment.

In conclusion, the integration of the ESP32 with MEMS-based microsensors and microactuators constitutes a solid and promising foundation for the development of next-generation IoT systems. Future work may focus on further optimizing energy consumption, implementing advanced control algorithms, and incorporating Edge Computing concepts to enable local data processing, reduced latency, and increased system autonomy, thereby addressing emerging challenges in large-scale and mission-critical IoT deployments.

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