An IoT-Based Autonomous Waiter Robot

Un robot camarero autónomo basado en IoT

Um robô garçom autónomo baseado em IoT

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Recibido: 17/10/2024 Aceptado: 26/01/2025

Summary. - The widespread adoption of automation and robotics across various sectors has driven innovations in service delivery, particularly in the hospitality industry. This paper presents the design, development, and implementation of an IoT-based waiter robot aimed at enhancing efficiency and customer satisfaction in restaurants. The robot employs an ESP32 microcontroller, ultrasonic sensors, and a touchscreen interface for autonomous navigation, order processing, and food delivery. Unlike traditional path-planning approaches, this robot adapts dynamically to its environment, offering flexibility and reliability in service. Detailed evaluations demonstrate the system's effectiveness in optimizing operations, reducing delays, and improving overall customer experience. The proposed solution is cost-effective and scalable, making it suitable for diverse restaurant settings.

Keywords: IoT, ESP32, Robot, Automation, Ultrasonic Sensors, Real-time Navigation

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Memoria Investigaciones en Ingeniería, núm. 28 (2025). pp. 154-167
https://doi.org/10.36561/ING.28.11
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *La adopción generalizada de la automatización y la robótica en varios sectores ha impulsado innovaciones en la prestación de servicios, particularmente en la industria hotelera. Este artículo presenta el diseño, desarrollo e implementación de un robot camarero basado en IoT destinado a mejorar la eficiencia y la satisfacción del cliente en restaurantes. El robot emplea un microcontrolador ESP32, sensores ultrasónicos y una interfaz de pantalla táctil para navegación autónoma, procesamiento de pedidos y entrega de alimentos. A diferencia de los enfoques tradicionales de planificación de rutas, este robot se adapta dinámicamente a su entorno, ofreciendo flexibilidad y confiabilidad en el servicio. Las evaluaciones detalladas demuestran la eficacia del sistema para optimizar las operaciones, reducir los retrasos y mejorar la experiencia general del cliente. La solución propuesta es rentable y escalable, lo que la hace adecuada para diversos entornos de restaurantes.*

Palabras clave: *IoT, ESP32, Robot, Automatización, Sensores ultrasónicos, Navegación en tiempo real.*

Resumo. - *A adoção generalizada da automação e da robótica em vários setores impulsionou inovações na prestação de serviços, especialmente na indústria hoteleira. Este artigo apresenta o projeto, desenvolvimento e implementação de um robô garçom baseado em IoT que visa aumentar a eficiência e a satisfação do cliente em restaurantes. O robô emprega um microcontrolador ESP32, sensores ultrassônicos e uma interface touchscreen para navegação autônoma, processamento de pedidos e entrega de alimentos. Ao contrário das abordagens tradicionais de planejamento de trajetória, este robô se adapta dinamicamente ao seu ambiente, oferecendo flexibilidade e confiabilidade no serviço. Avaliações detalhadas demonstram a eficácia do sistema na otimização das operações, na redução de atrasos e na melhoria da experiência geral do cliente. A solução proposta é econômica e escalável, tornando-a adequada para diversos ambientes de restaurantes.*

Palavras-chave: *IoT, ESP32, Robô, Automação, Sensores Ultrassônicos, Navegação em Tempo Real.*

1. Introduction. - Technological advancements have significantly transformed various industries, leading to the integration of robots into daily operations. In healthcare, robots assist in delicate surgeries, while in manufacturing, they optimize production lines from assembly to packaging [1, 2]. Recently, the service sector has embraced robotics, introducing IoT-based waiter robots to revolutionize dining experiences in restaurants, coffee shops, and similar setups [3]. These robots aim to improve order processing efficiency, ensure timely food delivery, and navigate safely through congested aisles. Furthermore, they provide restaurant owners with opportunities to reduce operational costs and enhance employee productivity, creating a seamless and technologically advanced customer experience [4].

Conventional food delivery systems in restaurants rely heavily on human labor, resulting in inefficiencies such as delayed service, order mix-ups, and high operating costs. These limitations underscore the need for automated solutions. Leveraging IoT technology enables real-time data transfers, paving the way for autonomous systems capable of performing tasks without human intervention [5-9]. This study proposes an IoT-based waiter robot to address these challenges by integrating advanced navigation algorithms, real-time obstacle avoidance, and decision-making processes. Table 1 compares existing waiter robots, emphasizing their features and limitations.

Feature	Robo Waiter	Savioke Relay	Bear Robotics Penny	Pudu Bot	Bella Bot
Manufacturer	Robo Waiter	Savioke	Bear Robotics	Pudu Tech	Pudu Tech
Country	Denmark	USA	USA	China	China
Navigation System	Lidar	Lidar, Camera	Lidar, Camera	Lidar, Camera	Lidar, Camera
Interaction Method	Buttons	Touch Screen	Touch Screen, Voice	Touch Screen	Touch Screen, Voice
Payload Capacity	2 kg	5 kg	12 kg	30 kg	10 kg
Battery Life	8 hours	24 hours	12 hours	10-12 hours	12-16 hours
Charging Time	2 hours	2 hours	4 hours	4 hours	4 hours
Max Speed	0.5 m/s	1.1 m/s	0.9 m/s	1.2 m/s	1.2 m/s
Obstacle Detection	Basic IR sensor	Advanced sensor	Advanced sensor	Advanced sensor	Advanced sensor
Connectivity	Bluetooth	Wi-Fi	Wi-Fi, Bluetooth	Wi-Fi	Wi-Fi
Cost	Low	High	Medium	Medium	Medium
Additional Features	Basic voice responses	Can call the elevator, SLA	Advanced voice recognition	Multi-robot collaboration	Facial recognition, AI
Application	Simple table service	Hotel service, Delivery	Restaurant service	Restaurant service	Restaurant service

Table I. Comparison table for different bots

Following are the key contributions of our work.

1. Combining IoT technologies with robotics and real-time data processing.
2. Significantly improves service efficiency and reduces operational delays.
3. Features a scalable architecture that adapts to various restaurant sizes and needs.

Recent advancements in waiter robots reflect substantial progress in automation, efficiency, and technology integration. Table 2. Demonstrate the comparative analysis of significant studies and technological improvement in comparison to the proposed model

References	Limitations	Proposed Work
[10]	Robots followed only designated paths with IR sensor arrays; and high-voltage HUB motors.	Utilized lithium-ion batteries for better energy efficiency; implemented advanced mapping for improved navigation.
[11]	Used RFID tags for table identification.	Adopted advanced mapping for flexible and efficient table navigation.

[12]	RFID is used for order management, but it has limited obstacle-detection and path-finding capabilities.	Enhanced with ultrasonic sensors for obstacle detection; used mapping for path finding; integrated order processing and billing.
[13]	Designed an IoT-based robot with real-time tracking and mobile app control.	Showcased ESP32's real-time capabilities and ease of integration with mobile apps.

Table II. Comparative analysis of significant studies and technological improvement

The remainder of this paper is organized as follows: Section II describes the Proposed Architectural Model and Methodology of the system. Section III presents the results and discussion, highlighting the system's performance. Finally, Section IV concludes the paper with a summary of the key findings and the implications for the future of automated restaurant services.

2. Proposed Architectural Model and Methodology. - The development of the IoT-based waiter robot involved a series of well-structured steps to ensure its efficiency and reliability. The robot's architecture and specifications are illustrated in the block diagram in Figure I and the system process diagram in Figure III.

2.1 System Overview. - The IoT-based waiter robot's architecture integrates hardware and software components to ensure autonomous navigation and efficient task execution. For the robot, the ESP32 microcontroller [14] is used for its multi-functionality and an in-built Wi-Fi module which is very essential in IoT and is used to control robots, appliances, and other attributes to ensure perfect interaction between the robot, the kitchen, and the customers.

For navigation and obstacle detection purposes, the robot uses ultrasonic sensors with a range of up to 21 meters which allows the robot to smoothly operate at the restaurants. Further, using the TCRT5000 infrared sensor [15], the robot can identify when the trays placed for the customer's food have been taken and only then return to the kitchen.

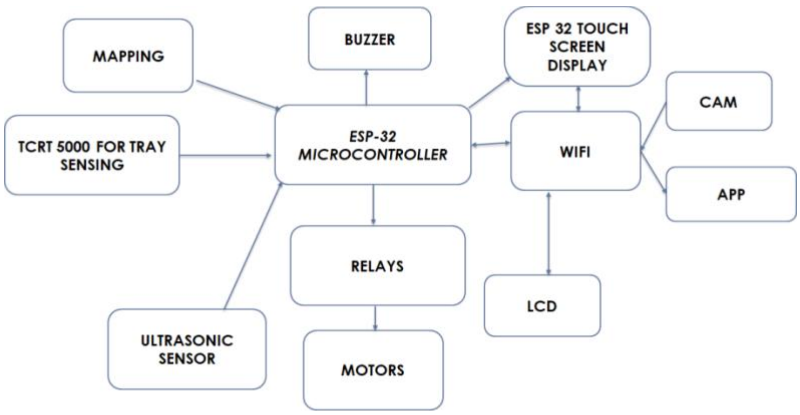


Figure I. Block Diagram

The robot has a touch-based LCD, with ESP32 (connections can be seen in Figure II) at the customer interface and the kitchen interface. In the kitchen, such a display gives instructions to the robot to move to the customer's table to take an order. Once at the customer's table, the robot provides the customer with the menu where the customer makes his/her order which is sent back to the kitchen through the WiFi. The chef then prepares the order and places it on the robot's tray.

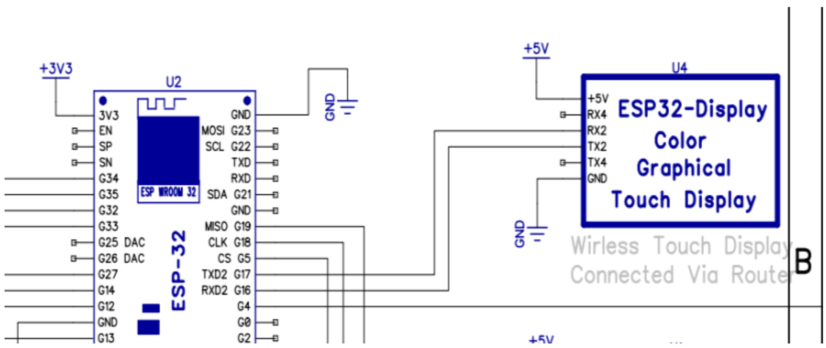


Figure II. Connection of ESP 32 with TOUCH LCD

Upon order completion, the chef commands the robot to deliver the meal to the customer. The robot uses its ultrasonic sensors to navigate, halting if an obstacle is detected until the path is clear. After the customer takes their meal, detected by the TCRT5000 sensor, the robot returns to its initial position in the kitchen, ready for the next task.

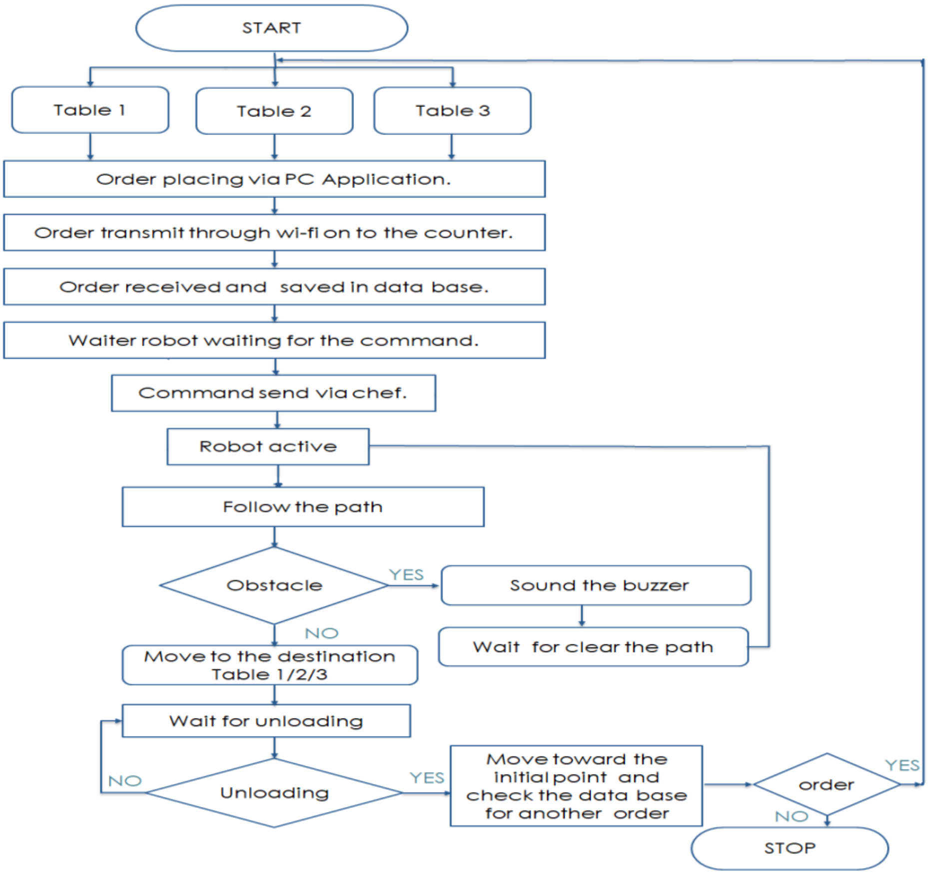


Figure III. System Process Diagram

The robot is powered by a 24V lithium-ion battery, which provides energy to the DC-geared motors [16] through a 4-channel relay module. The relay module, connected to the ESP32, allows precise control of the robot's movements (see Figure IV).

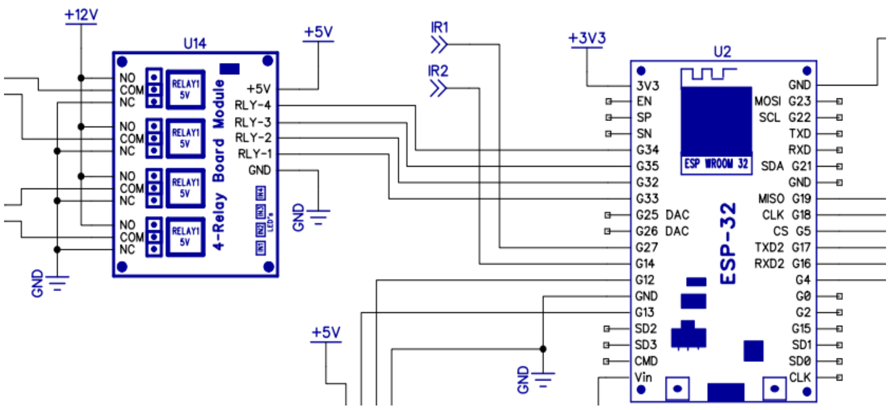
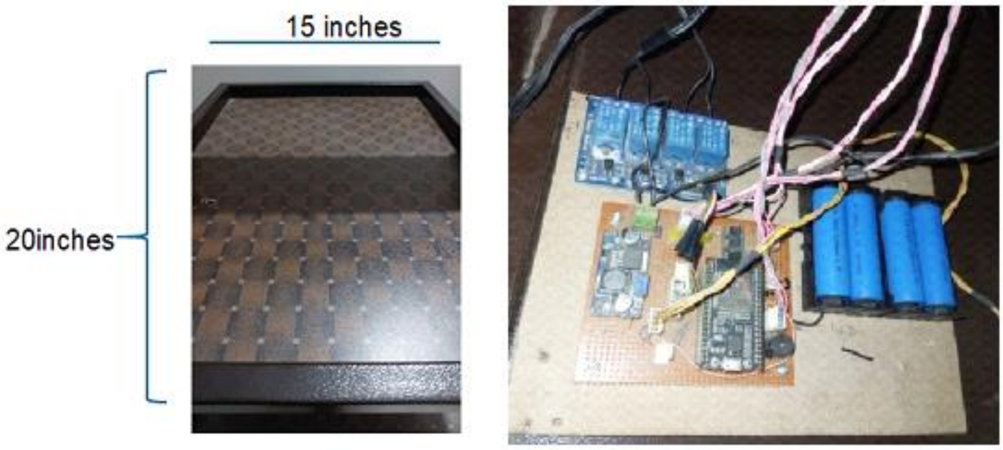


Figure IV. Connection of ESP 32 with relay

The robot's base is constructed from an 8mm steel laminated sheet, chosen for its durability and cost-effectiveness. Measuring 20 inches by 15 inches, the base supports all components and ensures stability during movement (in Figure Va). It houses the battery mechanism, which includes four Li-ion batteries, and a buck converter that steps down the voltage from 16V DC to 3-5V for various components (in Figure Vb).



(a) (b)

Figure V. (a) Dimension of the base, (b) Base circuitry

On top of the robot, a 2.8-inch ESP32 touch display LCD, with resolutions between 240x320 and 480x320 pixels, enables user interaction and order placement. A webcam is also installed to monitor the robot's position and detect obstacles, allowing real-time visibility of any obstructions (see Figure VI).

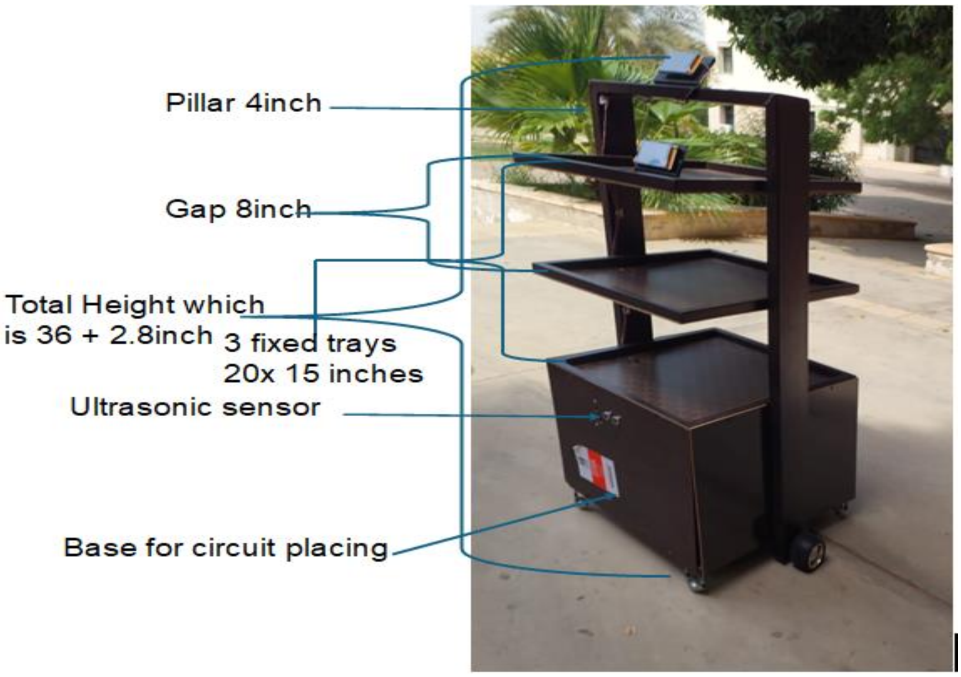


Figure VI. Structure with dimensions

2.2 Navigation Algorithm. - The robot employs an A* path-planning algorithm to ensure optimal navigation in dynamic environments. The algorithm processes input from ultrasonic sensors to identify obstacles and dynamically adjust the robot's trajectory. The A* algorithm calculates the shortest path based on cost functions that account for distance, obstacle proximity, and time. The robot's movement is controlled by precise motor commands derived from these calculations.

2.3 Software Architecture and Real-Time Obstacle Avoidance. - The IoT-based waiter robot is designed with a robust software architecture consisting of three primary modules: the Data Acquisition Module, the Processing Unit, and the Communication Module. The Data Acquisition Module is responsible for continuously gathering sensor data, such as distance measurements and tray status, while the Processing Unit handles the navigation algorithm, processes sensor inputs, and generates motor control commands. The Communication Module facilitates Wi-Fi connectivity, enabling interaction between the robot, the kitchen interface, and the customer touchscreen. This integrated system allows for real-time data processing and dynamic decision-making. Furthermore, the robot's obstacle avoidance system employs ultrasonic sensors to detect potential collisions. Upon detection, the A* algorithm recalculates the robot's path to avoid obstacles, and the motor controller adjusts the movement accordingly. Continuous monitoring ensures that the robot can navigate efficiently and reliably, even in crowded environments.

3. Results and Discussion. - In the kitchen setup, an ESP32-controlled display allows the chef to dispatch the robot to the customer's table to take an order. Upon arrival, a display on the robot presents menu options categorized as follows: Appetizers (FOOD A), Desserts (FOOD B), and Grilled Items (FOOD C) as shown in Figure VII. The customer makes their selection through the display (Figure VIII and Figure IX), which is then transmitted to the kitchen display via Wi-Fi. After placing the order, the display shows a "Thank You" message (Figure X), and the robot returns to the kitchen. The chef prepares the meal, places it on the robot's tray, and commands the robot to deliver it to the customer's table.

Figure VII. Chefs command the robot to take the order

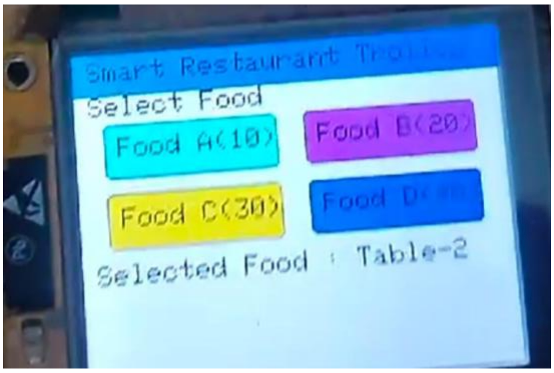


Figure VIII. Menu Display

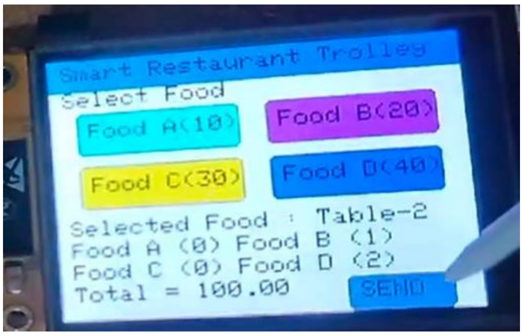


Figure IX. Selection of Food by the customer

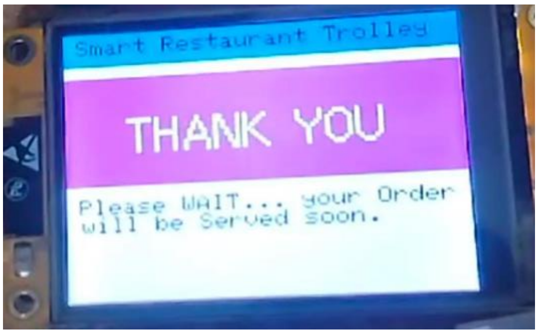


Figure X. After taking the order

During meal delivery, the robot follows the command from the chef to navigate to the customer's table. Once there, the customer retrieves the meal trays, and the TCRT 5000 sensor detects the tray's removal, signaling that the meal has been received. The ultrasonic sensor continuously scans for obstacles, with the robot stopping and sounding a buzzer if an obstacle is detected, resuming its journey only when the path is clear. After the customer has taken their meal, the TCRT 500 sensor confirms the absence of the tray, prompting the robot to return to its original position in the kitchen, ready for its next task.

For the robot's movement, we selected wheels with a diameter of 4 inches (see Table III). Using smaller wheels than this diameter would cause the robot to slip on the surface, leading to increased power consumption during rotation. On the other hand, using larger wheels would raise the cost and result in higher power usage, making the 4-inch diameter an optimal choice for balancing performance and efficiency.

Name of Equipment	Circumference of Wheel (cm)	RPM	RPS	Time (sec)	Distance (cm)	Speed (cm/sec)	Accuracy Based on Perfect Turning
Wheel (Gear Motor)	31.92	15	0.3	60	479.04	7.984	Best
Wheel (Gear Motor)	31.92	20	0.3	45	479.04	10.645	Better
Wheel (Gear Motor)	31.92	25	0.4	36	479.04	13.324	Very Good
Wheel (Gear Motor)	31.92	30	0.5	30	479.04	15.968	Good

Table III. Wheel configuration

The robot has been tested across various testing scenarios to validate its performance. Some of the key scenarios include the following,

3.1 Load Vs Ampere. - It is observed that the IoT Base Waiter Robot's current consumption varied with different weight loads. Specifically, with a load of approximately 2 kg, the robot drew 1.68 mA. When the weight was increased to around 4 kg, the current consumption rose to 1.75 mA. With a maximum load of 6 kg, the current increased further to 1.91 mA. These findings are illustrated in Figure XI.

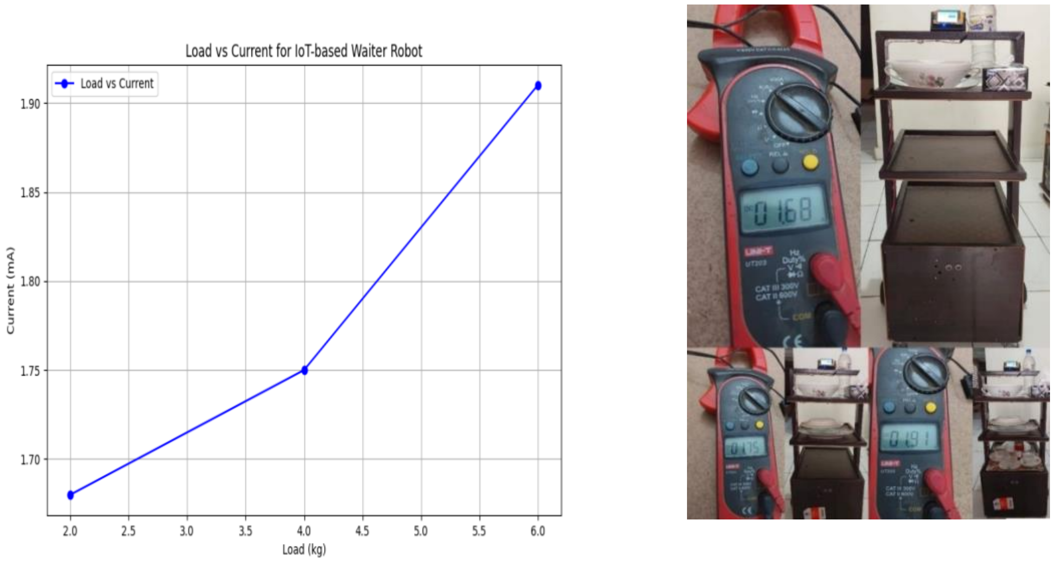


Figure XI. Comparison of Load Vs Amp for the proposed system model

3.2 Distance over time. - The performance of the robot under varying weight loads was assessed by measuring the distance covered over time (see Figure XII). With a 2 kg load, the robot traveled 2.17 meters in 20 seconds. Increasing the weight to 4 kg resulted in a distance of 1.78 meters covered in 20 seconds. At the maximum load of 6 kg, the robot covered 1.50 meters in 20 seconds.

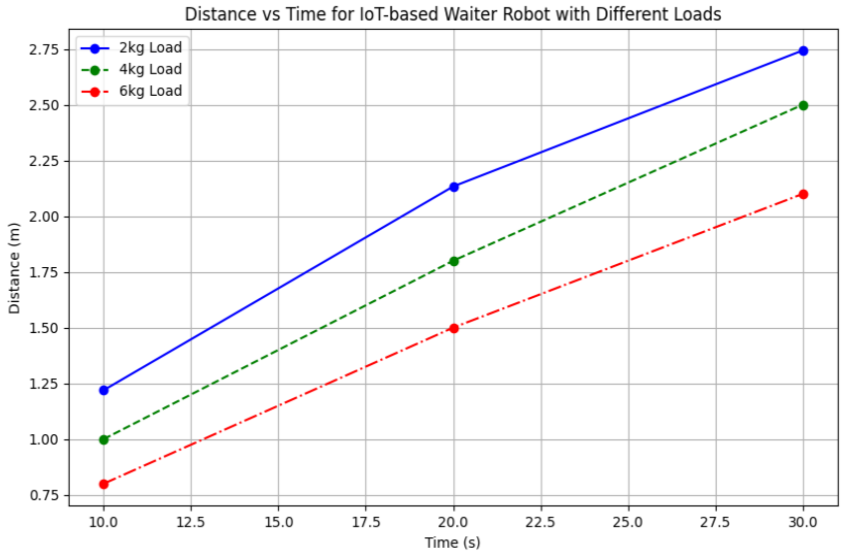


Figure XII. Comparison of distance covered over time for the proposed system model

3.3 Speed Vs torque. - Table IV shows the statistical relationship between speed and torque for the IoT-based waiter robot under different weight loads (2 kg, 4 kg, and 6 kg). It highlights an inverse relationship: as torque increases (due to heavier loads or higher resistance), the robot's speed decreases. The yellow line (2 kg) indicates the highest speed at lower torque (see Figure XIII), while the red line (6 kg) shows the lowest speed, reflecting the significant impact of heavier loads. This analysis demonstrates the robot’s load-dependent performance, providing insights into optimizing its operation for varying weights.

Weight (kg)	Speed (m/s)	Torque (Nm)
2	1.5	0.5
2	1.2	0.7
2	1.0	0.9
4	1.2	0.8
4	1.0	1.0
4	0.8	1.2
6	1.0	1.1
6	0.8	1.3
6	0.6	1.5

Table IV. Speed vs Torque

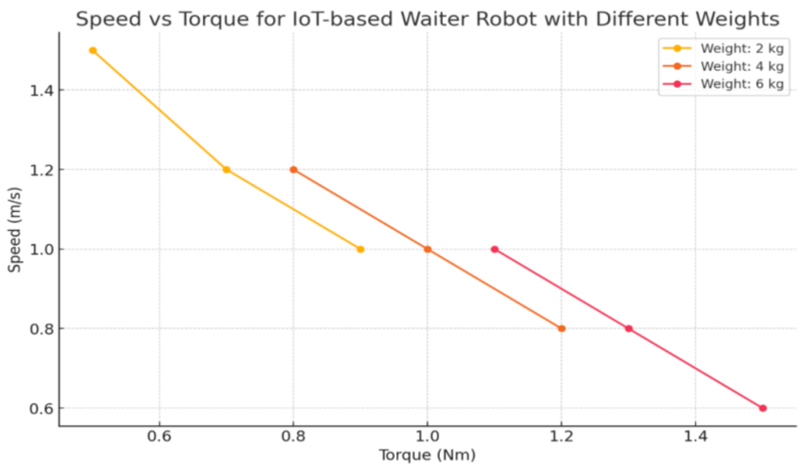


Figure XIII. Speed vs torque

Memoria Investigaciones en Ingeniería, núm. 28 (2025). pp. 154-167
https://doi.org/10.36561/ING.28.11
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

There are a lot of other parameters that were considered during the testing of this prototype system. The graphs in Figure XIV, we obtain as the result of those tests in which we kept the 4 Kg weight constant. It can be seen that the graph of battery life versus distance traveled shows a sharp decline in battery life as distance increases, indicating higher energy consumption over longer trips and the need for efficient power management. Similarly, the response time improves with more orders, while success rates decrease as obstacle density increases, underscoring the need for advanced navigation algorithms. Customer satisfaction rises with service speed but plateaus beyond an optimal point, and energy consumption increases significantly with heavier loads. Higher network latency reduces navigation accuracy, while increased bandwidth reduces processing time, though improvements diminish after a certain point. Idle time decreases with longer working hours, and collision rates rise at moderate speeds but decline at higher speeds. Maintenance costs increase with usage duration, highlighting the importance of proactive maintenance strategies.

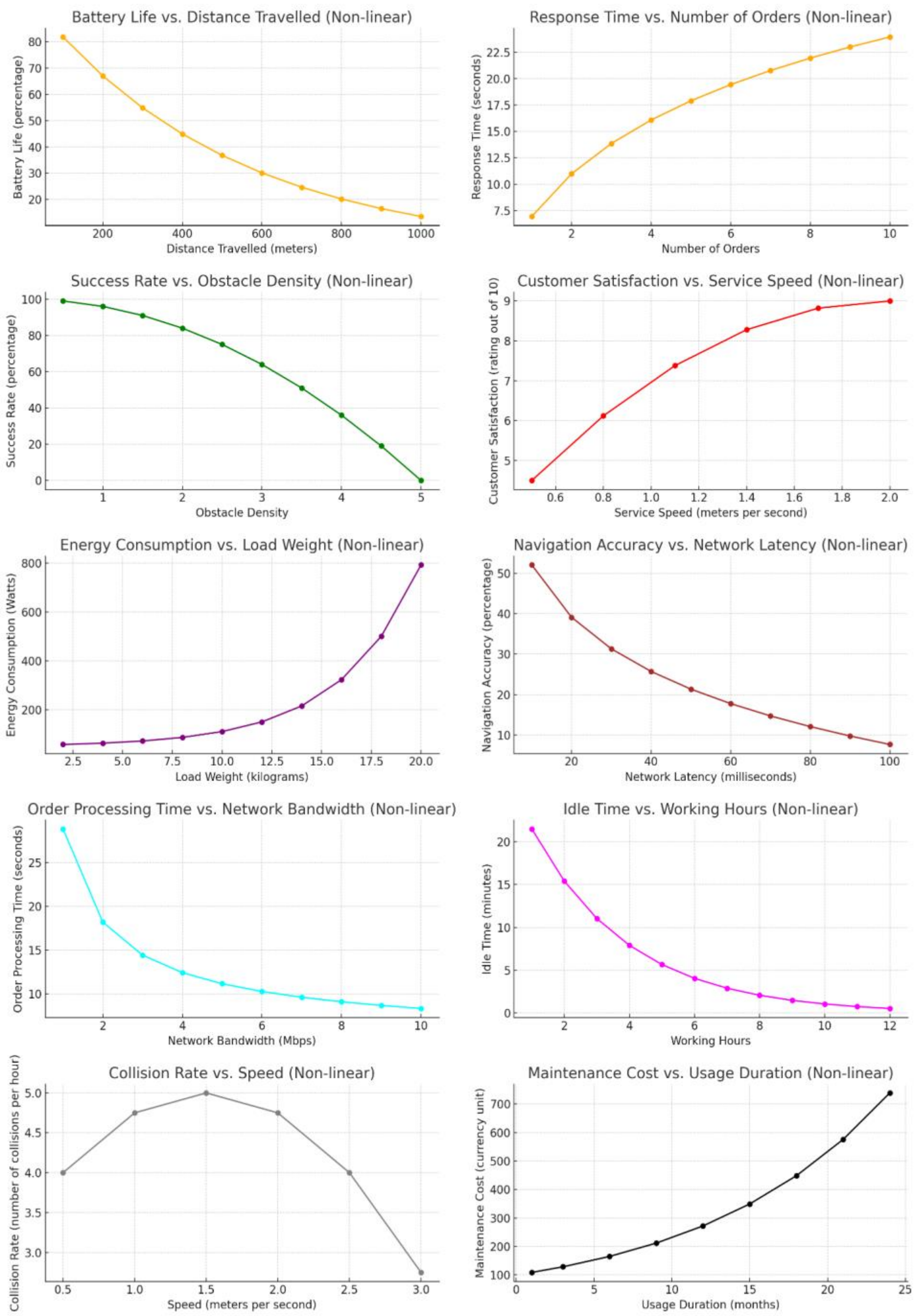


Figure XIV. Comparison of different parameters for the proposed system model

4. Conclusion and Future Work. - The IoT-based waiter robot proposed in this study can potentially transform the restaurant business positively. The system which operates with the ESP32 microcontroller and is utilized with the help of modern sensors and convenient interfaces helps increase the level of service, decreasing the time of service and, thus, increasing satisfaction of the customers. The self-orienting capability, real-time computing, and modularity of the designed robot enable it to be easily integrated into various restaurant contexts and thus economically efficient. Future upgrades would bring enhancements like SLAM for better navigation of the floor and introducing enhanced customer interaction as other enhancements would improve the efficiency of the robot and the service it provides. These enhancements coupled with the possibility of payment system integration distinguish the adaptability of the system as well as the application of IoT and robotics in revitalizing the processing of meals and the food chain.

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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

SUR has contributed to: 1, 2, 3, 4, 5 and 6.

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