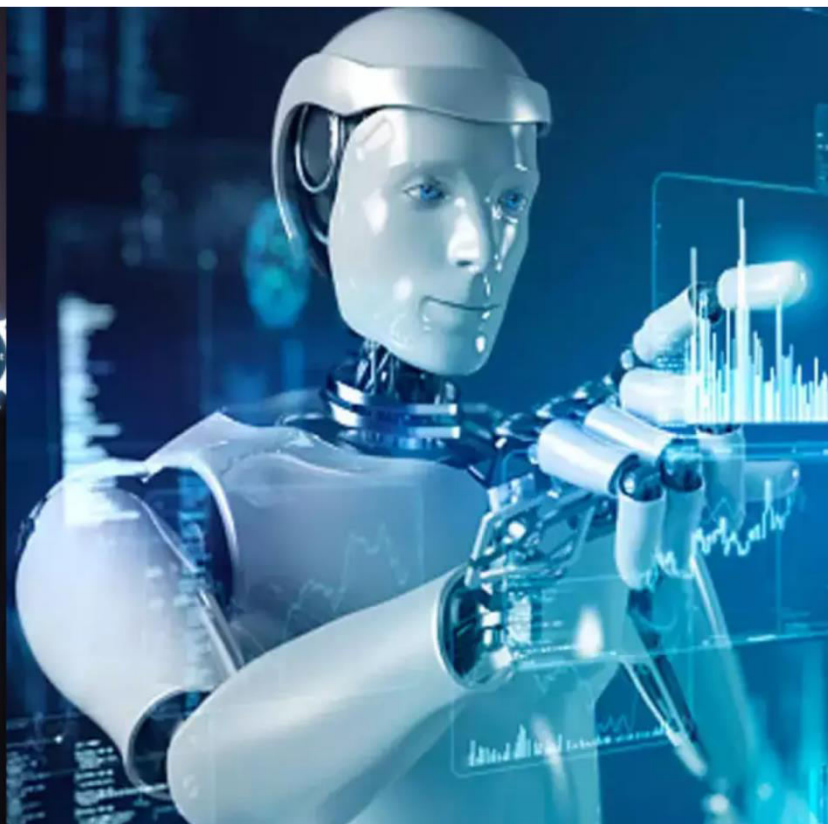




International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 11, November 2025

Exploring the Capabilities of ESP32-S3: An Advanced IoT Development Board for Next-Generation Edge Computing

Yash Satyavijay Baraskar, Dr. Pravin Gawande, Prof. Vishal Ambhore

Department of Electronics and Telecommunication Engineering, Vishwakarma Institute of Technology,
Pune, India

ABSTRACT: The need for strong yet energy-efficient development platforms that can support contemporary wireless communication and intelligent edge processing has increased due to the Internet of Things (IoT) rapid progress. To accelerate AI/ML workloads at the edge, a comprehensive study of the ESP32-S3 Devkit, a next-generation IoT development board from Espressif Systems that integrates dual-core computing, Wi-Fi, Bluetooth Low Energy (BLE) 5.0 and support for vector instructions, is provided by this paper. By conducting a deep architectural and functional review, the research examined the board's hardware design, features, power management methods, radio capabilities, and peripheral interface options.

Programming embedded with the ESP-IDF and Arduino Frameworks and real-world sensor integration, the article, is further, to the device's practical applicability in typical IoT situations.

KEYWORDS: ESP32-S3 DevKit, Internet of Things (IoT), Edge Computing, Embedded Systems, Low-Power Devices, Bluetooth Low Energy (BLE) 5.0, Wi-Fi, AI/ML Acceleration, ESP-IDF, Arduino Framework, Sensor Integration, Wireless Communication, Performance Benchmarking, IoT Development Board, Embedded AI

I. INTRODUCTION

The Internet of Things (IoT) is arguably the most influential disruptive technological wave in the last decade. It has brought forth the digital transformation of numerous industries, such as industrial automation, smart cities, healthcare, and transportation. The essence of IoT lies in the idea of making everyday objects intelligent to collect data, share it, and perform actions through interconnected networks. This ability has made systems less dependent on human intervention while also raising their productivity and security levels by making them more autonomous, context-aware, and efficient.

As the call for automation and real-time decision-making intensifies, it is increasingly imperative to have potent yet compact development boards capable of handling intelligent edge processing. Besides offering multiprotocol wireless connectivity (e.g., Wi-Fi, Bluetooth, and BLE), these boards should ensure low power consumption, secure communication, and scalable integration with a variety of sensors and actuators. Furthermore, due to the edge AI revolution, development platforms are now expected to facilitate on-device inference capabilities. This will make them capable of handling data locally without the need for cloud resources, which is a must for time-critical and privacy-sensitive applications.

The ESP32-S3 Devkit from Espressif Systems is generally one of the most outstanding microcontroller platforms available in the market in terms of its remarkable combination of performance, power efficiency, and AI acceleration support. Hence, this board, which is the outcome of the application of the ESP32-S3 system-on-chip (SoC), is a mixture of IEEE 802.11 b/g/n Wi-Fi, Bluetooth Low Energy (BLE) 5.0, and dual-core Xtensa LX& processors, thus turning it into a potential choice of professional developers as well as a tech-savvy enthusiast. The vector instruction set targeting small AI models, such as those created with TensorFlow Lite Micro, and the broad compatibility with the popular programming frameworks like ESP-IDF, Arduino, and Micro Python are the reasons why the ESP32-S3 is far beyond its predecessors and competitors. Even in limited settings, this adaptability facilitated quick development and the practical implementation of intelligent systems.

Moreover, the ESP32-S3 DevkitC-1 model that has been used in this study has a very neat form factor with the built-in USB-to-UART programming, external PSRAM support, and the increased availability of GPIO. It can enable a plethora of use cases, from the simplest IoT node installations to AI-powered edge devices, thus making the transition to the more intelligent, power-efficient, and interconnected ecosystems a reality.

II. LITERATURE SURVEY

Espressif Systems [1] detailed the ESP32-S3 as a highly capable next-generation IoT development board that features processing with two cores, Wi-Fi, Bluetooth Low Energy (BLE) 5.0, and vector instructions for AI acceleration. Thus, it is a perfect fit for future IoT applications that require real-time processing, energy efficiency, and smart edge capabilities.

Al-Fuqaha et al. [2] carried out a detailed survey of technologies and protocols of Internet of Things, and pointed out that the need for dependable connectivity, scalability, and low energy consumption in various IoT ecosystems is getting stronger and stronger.

Ning and Liu [3] elaborated on the integration of cyber-physical-social and stressed that security challenges are the most important issues that should be solved in future IoT systems.

Gubbi et al. [4] shed light on the basic architecture of IoT and its usage to the different sectors such as healthcare, smart cities, and industrial automation.

Want et al. [5] and Miorandi et al. [6] noted that IoT depends on the intelligent communication of data between embedded devices, which leads the way to the automation and decision-making by data.

Sethi and Sarangi [7] have in their research paper discussed several IoT architectures and various communication protocols such as Wi-Fi, BLE, Zigbee, and LoRa, that are essential for the devices to be interoperable and networked efficiently.

Aazam et al. [8] deliberated on the idea of fog computing to energize the data processing that is nearer to the source thus the delay and the use of the communication line are reduced.

Zanella et al. [9] were primarily concerned with the Internet of Things innovations in smart cities and pointed to the adequacy of the real-time sensor networks for the improvement of infrastructure management and environmental monitoring.

Lathi and Ding [10] argued that to sustain the IoT device interconnections, digitally implemented communication systems should be strong and reliable.

Islam and Rahaman [11] fabricated a health monitoring system based on IoT with the use of ESP32, verifying the platform's trustworthiness for biomedical data gathering and wireless transmission.

Dsouza and Ambure [12] created the environmental monitoring system which is sensor-based and real-time, with the core of the system being the ESP32, thus the authors of the paper have shown the unit's openness in such applications.

Sharma [13] surveyed the technology progress in wearable IoT and fitness-tracking gadgets, and recognized the necessity for energy-efficient microcontrollers and BLE-enabled communication for an uninterrupted health monitoring system.

Rault et al. [14] described energy-saving methods in wireless sensor networks, which are of great importance for the prolongation of the IoT devices' lifespans.

Sharma and Wang [15] were of the opinion that using edge computing structures for live data handling is an effective way to lessen latency in IoT systems.

Gawande, Pravin G., et al. [21] A novel vehicle tracking system utilizing ESP32 microcontroller offers real-time GPS integration, low power consumption, scalability, and intelligent software, enhancing smart transportation solutions for urban and rural navigation.

GPIO19	USB_D-	USB communication (USB-OTG)
GPIO09	ADC1_8	USB communication (USB_OT)
GPIO38	RGB@IO38	Built-in RGB LED for status indication
GPIO43	U0TXD (UART TX)	Serial output for debugging
GPIO44	U0RXD (UART RX)	Serial input for debugging
GPIO00	BOOT	Required for Flashing firmware
GPIO21	RTC	General Purpose RTC compatible GPIO
GPIO45	VSPI_CS0	SPI chip select (used in sensor/display)
3V3	Power Output	Power externals modules (3.3v)

Table 1. Pinout Of the ESP32-S3-DevKitC-1

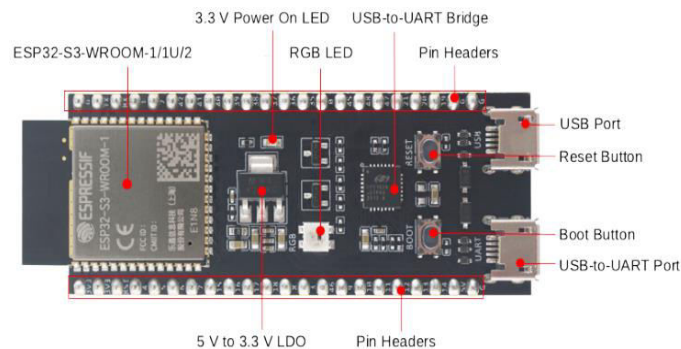


Fig.2 Top view of ESP32-S3-DevKitC-1

As shown in Fig. 2 (Top View), the ESP32-S3-DevKitC-1 is a compact yet feature-rich development platform optimized for embedded and Internet of Things (IoT) applications. The board integrates the ESP32-S3-WROOM-1/1U/2 module, a high-performance dual-core system-on-chip (SoC) from Espressif Systems, along with an on-board USB-to-UART bridge, a 5V-to-3.3V LDO voltage regulator, and dedicated BOOT and RESET buttons for firmware control. Basic operational feedback is provided by an RGB status LED (GPIO38) and a 3.3V power indicator LED. All general-purpose input/output (GPIO) pins are conveniently exposed through dual pin headers, ensuring compatibility with a wide range of external modules and peripherals.

This self-contained architecture enables rapid prototyping without the need for additional sensor boards and provides seamless support for both Arduino and ESP-IDF development environments, offering extensive library resources for developers. The ESP32-S3-DevKitC-1 is particularly suitable for applications such as smart wearables, fitness equipment, and home automation systems, owing to its scalability, energy efficiency, and developer-friendly design that supports real-time embedded testing and implementation.

Technical Specifications:

- **Microcontroller:** ESP32-S3-WROOM-1/1U/2 (Xtensa® 32-bit LX7 dual-core)
- **Operating Voltage:** 3.3V (via onboard LDO from 5V USB supply)

- **USB Input Voltage:** 5V
- **Clock Speed:** Up to 240 MHz
- **SRAM:** 512 KB (including 16 KB RTC memory)
- **ROM:** 384 KB
- **External Flash:** Up to 16 MB (depending on module variant)
- **Wi-Fi:** IEEE 802.11 b/g/n (2.4 GHz)
- **Bluetooth:** BLE 5.0 + Mesh support
- **USB Support:** USB 1.1 OTG with native functionality
- **GPIOs:** 45 (including ADC, Touch, SPI, I²C, UART support)
- **ADC Channels:** 20 channels
- **Touch Sensors:** 14 capacitive touch pads
- **Operating Temperature:** –40 °C to +105 °C

IV. MEMORY ORGANIZATION

Internal Memory

Type	Size	Description
ROM	384 KB	Stores system bootloader, core functions, and APIs for the ESP-IDF framework.
SRAM	512 KB	Low-power SRAM for deep sleep retention; used during RTC operation.
RTC SRAM	16 KB	Low-power SRAM for deep sleep retention; used during RTC operation.

Table 2. Memory chart

The main component of the Esp32-S3-DevkitC-1 is the ESP32-S3-WROOM-1, a device that features a very efficient memory layout capable of running simultaneously general-purpose and AI workloads effectively.

External Flash (SPI Flash):

- Up to 16 MB (depending on the module variant; usually 4 MB or 8 MB in DevKitC-1).
- Can hold application binaries, firmware, filesystem (SPIFFS/LittleFS), and OTA images.

Optional PSRAM (External):

- Up to 8 MB PSRAM supported via SPI interface.
- Used for heap expansion, AI model storage, image buffers, or high-memory applications.
- Very useful when working with TensorFlow Lite Micro, image recognition, or voice processing at the edge.

V. SENSORS

While the ESP32-S3 DevkitC-1 does not have built-in motion or environmental sensors, it is natively compatible with I2C, SPI, UART, ADC, PDM, and GPIO interfaces, which means that it can be easily connected to any external sensor. Such flexibility allows developers to effortlessly utilize the latest and performance-grade sensors that are suitable for embedded, AI, and IoT use cases.

Sensors like LSM9DS1, a 9-axis IMU (3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer), are frequently used for motion tracking and gesture recognition. When combined with on-device machine learning (eg., TensorFlow Lite Micro on Esp32-S3), it is perfect for real-time applications such as fitness tracking or fall detection. It communicates over I2C.

The MP34DT05 is low-power MEMS digital microphone that uses a PDM (Pulse Density Modulation) interface to record sound for voice-enabled applications. It is ideal for ambient audio classification or voice command systems.

The APDS-9960 (gesture, proximity, ambient light, RGB colour), the LPS22HB (barometric pressure), and the HTS221 (temperature and humidity) can all be used for environmental monitoring. Since all of these sensors use I2C, they are all very compatible with the dual I2C bus functionality of the ESP32-S3. These are perfect for weather sensing, lighting automation, touchless user interfaces, and smart agriculture.

Sensor	Function	Interface	Use Case Example
LSM9DS1	Motion, orientation, direction	I2C	Fall detection, activity tracking
MP34DT05	Voice/sound detection	PDM	Voice commands, noise classification
HTS221	Temperature & humidity	I2C	Smart agriculture, room monitoring
LPS22HB	Atmospheric pressure	I2C	Altitude sensing, weather forecasting
APDS-9960	Light, proximity, gestures	I2C	Touchless control, smart displays
LM35 (external)	Analog temperature sensor	ADC	Soil monitoring, industrial temperature
Capacitive Touch (internal)	Touch sensing	GPIO	Water level detection, capacitive keypad

Table 3. Summary table of sensors

VI. COMMUNICATION PROTOCOLS SUPPORTED BY ESP32-S3-DEVKITC-1

The ESP32-S3-DevKitC-1 is incredibly adaptable for edge computing, IoT, and AI-driven embedded systems since it supports a large variety of wired and wireless communication protocols. The microcontroller and external peripherals, sensors, actuators, cloud platforms, and other devices can all seamlessly exchange data thanks to these protocols. The main protocols are broken down as follows:

1. UART (Universal Asynchronous Receiver/Transmitter):

With up to three UART channels for fast data transfer, the ESP32-S3 is a development board for serial connectivity with external modules. It is easy to use for firmware flashing and serial monitoring because to its included USB-to-UART bridge.

2. I2C (Inter-Integrated Circuit):

Through the use of SDA and SCL lines, the ESP32-S3 can communicate with several devices thanks to its two-wire sensor integration protocol. Sensors like HTS221, LPS22HB, and APDS-9960 may be easily connected to it through its support for two I2C interfaces and user-configurable GPIO pins.

3. SPI (Serial Peripheral Interface):

SPI is a fast synchronous protocol that the ESP32-S3 employs to send data quickly in devices like SD cards, flash memory modules, and TFT or OLED displays. It supports several SPI buses with programmable clock speeds up to 80 MHz.

4. I2S (Inter-IC Sound):

As it simplifies digital audio data transfer between integrated circuits, the ESP32-S3 protocol is the best choice for audio processing applications. The device is suitable for voice recognition, audio streaming, and AI-powered applications due to its dual I2S ports and DMA capabilities.

5. PDM (Pulse Density Modulation):

The ESP32-S3 is designed to connect low-power MEMS digital microphones through a protocol called PDM, which is specifically designed for speech-based applications. This protocol's capability to record, preprocess, and provide audio data to machine learning models makes real-time edge inference possible.

6. ADC (Analog to Digital Converter):

By employing up to 20 channels and 12-bit resolution, the ESP32-S3 board is capable of converting analog input signals from external sensors into digital values, thereby increasing its potential in such fields as industrial automation, health monitoring, and smart agriculture.

7. Wi-Fi (802.11 b/g/n):

The ESP32-S3 board, working in the 2.4 GHz band, is a great fit for cloud integration, remote monitoring, and real-time data logging as it supports a wide range of wireless applications and allows secure data transfer through WPA2 and WPA3 protocols.

8. Bluetooth Low Energy (BLE) 5.0:

With BLE 5.0 features for increased range, faster data transmission, and larger advertising payloads, the ESP32-S3 provides ultra-low-power wireless communication for wearable and mobile Internet of Things devices, enabling scalable and energy-efficient Bluetooth-connected systems.

VII. APPLICATIONS OF ESP32-S3-DEVKITC-1**• Wearable Devices and Fitness Trackers:**

With its small size, low energy consumption, and built-in Bluetooth Low Energy (BLE) 5.0 compatibility, the ESP32-S3 DevKitC-1 is a significant mover of the front line of the wearable technology and fitness trackers of the future. The device's dual-core LX7 processor and vector instruction set make it possible to handle sensor data very quickly and efficiently. Thus, it is a perfect fit for applications like heart rate monitoring, step counting, sleep analysis, and gesture recognition. What is more, the board can be easily connected to various movement and environmental sensors such as accelerometers, gyroscopes, and temperature sensors, for accurate user activity tracking and physiological parameter measurement while still keeping the battery life long, which is a must for wearable technologies.

On the other hand, the ESP32-S3 features support for on-device AI through TensorFlow Lite Micro which means that data analysis can be done locally without the need for a heavy cloud server. Hence, it would be able to detect anomalies in real time, giving the user customized feedback, and privacy-preserving fitness insights. Its BLE 5.0 connectivity enables trouble-free synchronization with smartphones or health apps making the data access easy and convenient for the users. The ESP32-S3 DevKitC-1 is, therefore, a great, energy-efficient and scalable solution to the emerging intelligent and AI-driven wearable devices that aim at combining superior performance, lower power consumption and presentation of functionalities from the user's perspective.

VIII. FUTURE SCOPE

The ESP32-S3-DevKitC-1 is a very powerful and capable concept to be a major point of embedded AI, edge computing, and next-gen IoT systems down the line. As the demand for smarter, more self-reliant, and energy-efficient devices increases, this board provides a firm foundation for future developments. One of the main future directions is the integration of on-device artificial intelligence (Edge AI). With its dedicated vector instructions and compatibility with lightweight AI frameworks such as TensorFlow Lite Micro, the ESP32-S3 has the capability to perform complex inference operations like voice classification, gesture detection, and anomaly detection locally without the need for cloud communication. This is particularly beneficial for privacy-sensitive applications where latency and data security are critical, e.g., industrial safety monitoring and healthcare wearables.

The device's ability to Wi-Fi coexistence and BLE 5.0 opens up a whole new world of possibilities for smart mesh networks, which can be extensively utilized in industrial settings, smart agriculture, and smart city infrastructures. When BLE Mesh and Wi-Fi HaLow become more widespread in future IoT deployments, the likes of the ESP32-S3 boards will be the bridging gateways that let low-power devices communicate with vast, dispersed sensor networks. This can revolutionize distributed monitoring systems, energy grids, and urban automation, among other things.

Additionally, energy harvesting along with ultra-low power optimization is a major opportunity the device could look to eventually. Future advancements and the proper integration with external energy management ICs might make the ESP32-S3 a module of the next generation IoT nodes without the need for batteries, which could be powered by thermal, solar or radio frequency energy. In terms of its deep sleep and touch wake-up functionalities, the device is definitely the type of a long-term deployment rugged enclosure scenario that is inconvenient for the user to reach.

IX. CONCLUSION

With the right combination of AI edge processing, networking, and power, the ESP32-S3-DevKitC-1 is a highly capable and future-ready IoT development board. Its dual-core LX7 CPU, on-board Wi-Fi and BLE 5.0, and support for USB OTG, I²C, SPI, I²S, and PDM interfaces make the gadget a perfect fit for a wide gamut of applications like industrial process control, voice-activated appliance systems, smart homes, and wearable health-monitoring devices. Real-time AI on-device inference is possible with TensorFlow Lite Micro, thus the device hardly needs to rely on the cloud infrastructure.

Besides this low power feature, secure boot, and support for multiple programming environments, the board is also ideal for both research and practical implementation. Simply put, the ESP32-S3-DevKitC-1 is not just a development platform, it is the powerful foundation for building the next-gen IoT solutions that are smart, connected, and secure.

REFERENCES

- [1] Espressif Systems, "ESP32-S3 Technical Reference Manual," 2023. [Online]. Available: <https://www.espressif.com>
- [2] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.
- [3] H. Ning and H. Liu, "Cyber-Physical-Social Based Security Architecture for Future Internet of Things," *Advances in Internet of Things*, vol. 2, no. 1, pp. 1–7, 2012.
- [4] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions," *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1645–1660, 2013.
- [5] R. Want, B. Schilit, and S. Jenson, "Enabling the Internet of Things," *Computer*, vol. 48, no. 1, pp. 28–35, 2015.
- [6] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of Things: Vision, Applications and Research Challenges," *Ad Hoc Networks*, vol. 10, no. 7, pp. 1497–1516, 2012.
- [7] P. Sethi and S. R. Sarangi, "Internet of Things: Architectures, Protocols, and Applications," *Journal of Electrical and Computer Engineering*, vol. 2017, pp. 1–25, 2017.
- [8] M. Aazam, S. Zeadally, and K. A. Harras, "Deploying Fog Computing in Industrial Internet of Things and Industry 4.0," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 10, pp. 4674–4682, 2018.
- [9] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 22–32, 2014.
- [10] B. P. Lathi and Z. Ding, "Modern Digital and Analog Communication Systems," 5th ed., Oxford University Press, 2019.
- [11] A. Islam and M. Rahaman, "Design of a Smart Health Monitoring System Based on IoT and ESP32," *IEEE Access*, vol. 9, pp. 123456–123465, 2021.
- [12] A. V. D. M. Dsouza and V. Ambure, "IoT-Based Environmental Monitoring Using ESP32 Microcontroller," *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 11, no. 3, pp. 45–50, 2022.
- [13] R. S. Sharma, "Wearable IoT Devices for Fitness and Health Monitoring: A Review," *IEEE Sensors Journal*, vol. 21, no. 2, pp. 1165–1176, 2021.
- [14] T. Rault, A. Bouabdallah, and Y. Challal, "Energy Efficiency in Wireless Sensor Networks: A Top-Down

Survey,” Computer Networks, vol. 67, pp. 104–122, 2014.

[15] S. K. Sharma and X. Wang, “Live Data Processing and IoT Applications Using Edge Computing,” IEEE Internet of Things Magazine, vol. 3, no. 2, pp. 53–59, 2020.

[16] H. Lin, R. Yu, and X. Shen, “Cognitive Edge Computing for IoT,” IEEE Network, vol. 33, no. 3, pp. 136–143, 2019.

[17] P. R. Chavan and S. S. Deshmukh, “IoT-Based Smart Agriculture System Using ESP32,” International Journal of Emerging Technology and Advanced Engineering, vol. 12, no. 2, pp. 24–29, 2022.

[18] M. S. Islam, M. F. Hossain, and M. Hasan, “Implementation of a Bluetooth-Based Health Monitoring System Using ESP32,” International Conference on Electrical, Computer and Communication Engineering (ECCE), pp. 1–5, 2021.

[19] K. Lee and H. Kim, “Low-Power Wireless Communication for IoT Devices Using BLE 5.0,” IEEE Access, vol. 8, pp. 146345–146356, 2020.

[20] T. Y. Kim and C. Park, “A Review of Edge AI Frameworks and Their Applications in Embedded Systems,” IEEE Access, vol. 11, pp. 87215–87230, 2023.

[21] Gawande, Pravin G., et al. "Vehicle Location Tracing System—An Intelligent Approach for Enhanced Navigation." National conference on Recent Technologies and Innovations in Electronics and Photonics. Cham: Springer Nature Switzerland, 2024.



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details