International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 05 May 2026
Page No: 3383-3389
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0436

A Reconfigurable Computing Framework For Environmental Monitoring In Space Application

Surya B[1], Sugumar M[2], Arun Kumar M[3] S. Alwyn Rajiv[4]
[1,2,3] UG Scholar, Dept. of ECE, Kamaraj College of Eng. & Tech., Virudhunagar, Tamilnadu, India
[4]Assistance professor, Dept. of ECE, Kamaraj College of Eng. & Tech., Virudhunagar, Tamilnadu,India
Emails: *suryabaskaran2004@gmail.com[1], sugumarm2605@gmail.com[2], mjarunkumar279@gmail.com[3], alwynece@kamarajengg.edu.in[4]*

Abstract
The space mission environment is a hostile environment where the continuous monitoring of various parameters is essential for the safe operation of space vehicles[1]. The existing techniques employed for monitoring are inflexible, expensive, and cannot be easily changed after deployment. The reconfigurable computing technique, which uses Field Programmable Gate Arrays, is highly flexible, powerful, and efficient[2]. Therefore, this technique is suitable for space vehicles. In this paper, a suitable framework is suggested for the monitoring of environment parameters by using the reconfigurable computing technique with a Field Programmable Gate Array. The suggested framework consists of a temperature sensor, Analog to Digital Converter, reconfigurable computing, and microcontroller for secure data transmission. The suggested framework is highly suitable for space vehicles, where real-time data acquisition, secure data transmission, and remote monitoring of environment parameters are achieved by using a web interface[6]. A suitable encryption technique is suggested for secure data transmission between space vehicles[11].

Keywords— *FPGA, EnvironmentalMonitoring, Secure Communication, Encryption, ESP32, IoT, Cloud Computing*

1. Introduction

The space mission and satellite systems are also influenced by extreme environmental conditions such as temperature variations, exposure to radiation, vibration, and pressure changes [3]. All these extreme environmental conditions are of critical importance in influencing the performance of electronic systems in space missions. Therefore, it is of critical importance to monitor these extreme environmental conditions to ensure the safe execution of space missions. In the traditional space mission system, the monitoring system is inflexible, costly, and difficult to change[1]. However, reconfigurable computing using Field Programmable Gate Arrays is flexible, computational, and efficient in terms of hardware utilization [2],[10]. All these are critical requirements for space mission systems. In this paper, a framework for reconfigurable computing for environment monitoring using an FPGA device has been proposed. Data acquisition and cloud monitoring are part of the proposed framework [5],[7].

2. Proposed System

2.1 System Overview

The proposed system will have the ability to monitor the environment safely and effectively with the help of a reconfigurable system that uses an FPGA. The system will have various components that will be integrated into one environment. These components will include sensors, data acquisition, processing, encryption, and communication. The system will mainly concentrate on real-time monitoring as well as data transmission. This will be essential for use in space. The proposed system will have an FPGA that will help process the data faster. The system will have light encryption that will help prevent the data from being compromised by unauthorized individuals. The system will have the ability to acquire data continuously, thus providing a faster means of detecting unusual changes that may occur in the environment. This will make the spacecraft reliable.

2.2 System Architecture

The components of the system which are involved in the proposed system are the LM35 temperature sensor, MCP3008 Analog to Digital Converter, FPGA processor, UART communication module, ESP32 microcontroller, and cloud monitoring system. These components of the system are very important. The role of the temperature sensor in the proposed system is to detect the environmental temperature. The detected environmental temperature is sent in analog form. Since the proposed system has a processor that processes digital information, it is necessary to convert analog information into digital information. Analog information is converted into digital information with the aid of the MCP3008 Analog to Digital Converter. Analog information is converted into 10- bit digital information. The most important component of the system is the FPGA processor. The processor processes the digital information that is sent by the MCP3008 Analog to Digital Converter. The processor encrypts the sent digital information with the aid of the LRBC algorithm. Once the digital information is encrypted, it is sent with the aid of the UART communication module. The digital information is sent at a certain baud rate. The ESP32 microcontroller will receive the encrypted data, decrypt it, and send it to the cloud server for processing with the help of WiFi. The cloud will store the data, and real-time monitoring will be done through a web interface. This project will be helpful for space missions, aerospace, etc shown in Figure 1.

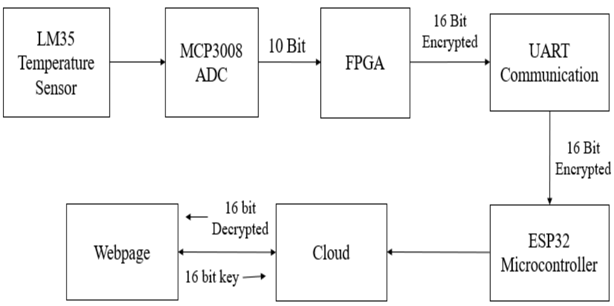

Figure 1 Block Diagram of The Proposed System

The overall architecture of the proposed system is shown in Fig. 1. The proposed system uses the LM35 temperature sensor as the first component. This sensor detects the environment's temperature. The output of this sensor is proportional to the environment's temperature. This proportional value is then sent to the MCP3008 Analog-to- Digital Converter. This converter converts the analog value to a digital value. This value is a 10-bit value. The 10-bit value is sent to the FPGA module. This module is considered the main component of this system. This module encrypts the value using a lightweight encryption technique. This results in a 16-bit value. The 16-bit value is sent to the ESP32 microcontroller using UART communication. This value is then decrypted by this module. This module uses Wi-Fi to send this value to the cloud server. The flow of the data in this system follows a sequential pipeline, from sensing to cloud visualization. The process begins with the sensing of the data, followed by its processing and encryption in the FPGA. The flow of the data has been made as it is, with a focus on minimizing loss of data, especially for real-time data. The inclusion of the encryption process in the FPGA has made this system suitable for space missions as well. In addition to that, the modules are able to communicate effectively. This is ensured by the use of the UART protocol. This protocol ensures that there is easy communication between the FPGA and the ESP32 microcontroller. The microcontroller acts as a gateway to the hardware and the cloud. This ensures that there is wireless communication. The gateway to the cloud ensures that the user can access the environment anywhere. This is because the user can be anywhere while monitoring the environment.

3. System Implementation

The proposed system will be implemented by utilizing a combination of hardware and software in order to effectively provide a system of monitoring the environment. The implementation of the proposed system will be composed of several modules in order to effectively handle the data to be used by the system.

3.1. Sensor Data Acquisition

The proposed system will be utilizing the LM35 temperature sensor in order to effectively acquire data pertaining to the temperature of the environment. The LM35 temperature sensor will produce an analog voltage which will be proportional to the temperature of the environment. Since the system will be utilizing

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an FPGA to effectively process digital data, the analog voltage produced by the temperature sensor will be effectively converted into digital data by utilizing the MCP3008 Analog to Digital Converter. The digital data produced by the MCP3008 Analog to Digital Converter will have a resolution of 10 bits. The temperature will be computed by utilizing the following formula:

$$\text{Temperature} = (\text{ADC Value} * 100) / 1023 \quad (1)$$

$$V_{out} = 10mv \times T \quad (2)$$

3.2. FPGA Processing and Encryption

The task of the FPGA will be to serve as the processing and control unit of the proposed system. The digital data will be provided to the FPGA by the MCP3008 ADC. The processing of the digital data will be done in real time. The advantage of using the FPGA will be that it will provide a device that will process the data at a high speed. This device will have the capability of being used in space. The data will be provided to the encryption block after processing.

$$ADC = Vref/Vin \times (2n-1) \quad (3)$$

The process of encrypting the data will be done through the use of the Lightweight Randomized Block Cipher (LRBC)algorithm. This algorithm will be used for the proposed hardware system, which will be considered resource constrained. This algorithm will be used because it will provide low complexity, power consumption, and hardware utilization. This algorithm will process data blocks of a certain size. The size of the data block will be determined by a predefined key.The encryption of the data by making use of the LRBC encryption process is done in a number of rounds. In each round, a number of processes are included, which are substitution, permutation, linear, and function. All these processes are important so that confusion and diffusion can be achieved. The repetition of these processes adds complexity to the encryption process. The complexity ensures that the encryption process is not subjected to a number of attacks. The encryption process also includes another process, which generated in the form of 16 bits. The output can be sent to the ESP32 microcontroller by making use of the UART protocol shown in Figure 2.

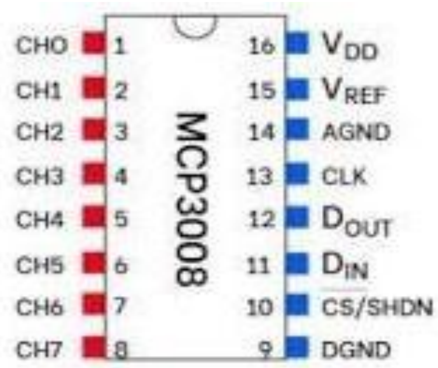

Figure 2 Structure of MCP3008

$$Ri = PBox(SBox(P \oplus Ki)$$

Table 1 PBox

FBox	- Function Box
SBox	- Substitution Box
PBox	- Permutation Box
LBox	- Linear Transformation Box

FBox or Function Box is used for major operations in rounds of the encryption algorithm. SBox or Substitution Box is used for non-linearity. The input is replaced by different values for non-linearity. PBox or Permutation Box is used for data diffusion. LBox or Linear Transformation Box is used for non-linearity shown in Figure 3.

$$C = E\,(P,K) \quad (5)$$

- P= Plaintext
- K= Key
- C= Ciphertext

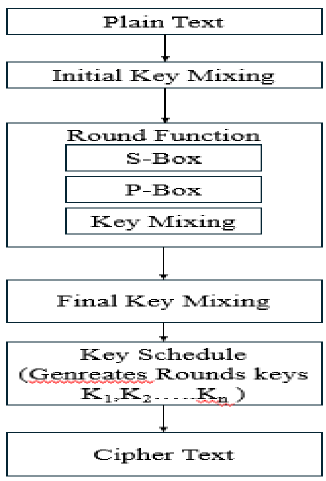

Figure 3 Block Diagram of LRBC

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https://doi.org/10.47392/IRJAEH.2026.0436

The Figure 3 shows a step-by-step representation of the process of the Lightweight Randomized Block Cipher Algorithm. As shown in the diagram, the process begins with a combination of plaintext and a secret key through an initial key mixing operation.

LRBC Algorithm:

Input: Plaintext P, Key K Output: Ciphertext C

Step 1: Perform initial key mixing $P = P \oplus K$

Step 2: For each round i = 1 to n:

- Apply substitution using S-Box
- Apply permutation using P-Box
- Apply linear transformation
- Perform key mixing with Ki

Step 3: Generate final ciphertext C

Step 4: Send encrypted data to UART module

3.3.UART Communication

The data sent by the FPGA in the form of an encrypted message is sent to the ESP32 microcontroller through UART Communication.

Data rate = BER x Bit Per Frame (6)

The UART protocol is a serial communication protocol to send data from one digital device to another. The UART communication frame is as follows:

- Start bit
- Data bits
- Stop bit

The communication between the FPGA and the ESP32 microcontroller takes place at a baud rate of 9600 bits/sec. The transfer of data through UART is asynchronous, suggesting that there is no need to use a clock signal during communication between the FPGA and ESP32. The simplicity in hardware makes this system less complex. UART communication is reliable as it uses start and stop bits to transmit each frame of data.results were obtained, showing that the FPGA received the sensor data correctly, performed the required operations, and implemented the LRBC algorithm for the encryption process

3.4. ESP32 Cloud Communication

The ESP32 is a microcontroller that accepts the encrypted data received from the FPGA through the UART. The ESP32 microcontroller will receive the original data by performing the decryption operation on the received data from the FPGA. The ESP32 microcontroller utilizes the internet facility to transmit the received data to the cloud server. The cloud server will store the environmental data received from the ESP32 microcontroller into the database to monitor the data received in real time. The users can view the temperature values by using the web interface, which accepts the environmental data received from the cloud server. The users can monitor the environmental parameters by using the internet facility shown in Figure 4.

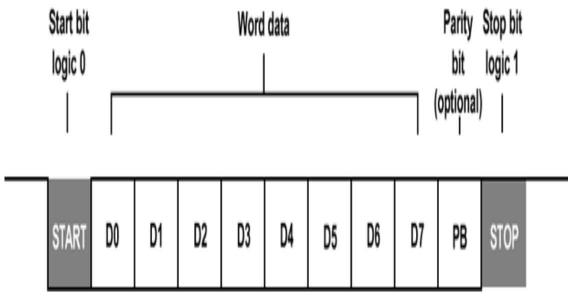

Figure 4 UART Data Frame

4. Results and Discussion

The proposed system was implemented, and the results were obtained by utilizing the FPGA hardware platform with the ESP32 module for the communication process. The LM35 temperature sensor was used to detect the environmental temperature, and the analog signal was obtained according to the temperature value. This analog signal was converted into a digital signal by utilizing the MCP3008 Analog-to-Digital Converter, and the obtained signal was sent to the FPGA for further processing. The simulation the users. The users can view the environment online without accessing the hardware system. The obtained encrypted data by the proposed system was sent to the ESP32 microcontroller by utilizing the UART communication protocol with a specific baud rate. The ESP32 received the data correctly, performed the decryption operation, and obtained the original value of the temperature. The results revealed that the proposed system was communicating with the FPGA and ESP32 successfully, showing a stable and reliable result, where no information was lost during the communication process. The proposed system improved the security of the system by implementing the encryption and decryption operation for the sensor data shown in figure 5.

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Figure 5 FPGA Temperature Result

The decrypted data is then sent by the ESP32 microcontroller to the cloud platform. The ESP32 microcontroller uses the Wi-Fi network to send the data to the cloud platform. The ESP32 microcontroller establishes an internet connection. The ESP32 microcontroller sends the data to the cloud server using a communication protocol. The cloud platform receives the data sent by the ESP32 microcontroller [4]. The cloud platform stores the received data in a database. The stored data enables the users to log the data and view the data online. The stored data enables the users to access the data online, and the temperature values are displayed to From the experimental results, it is clear that the proposed system is effective in acquiring the sensor data accurately, ensuring security in the data communication process, and performing the monitoring activity in an efficient manner. Hence, it can be concluded that the proposed framework can be effectively implemented in the field of space missions, aerospace monitoring systems, satellite systems, and other types of environmental monitoring systems where the security aspect in data communication is important shown in Figure 6-8.

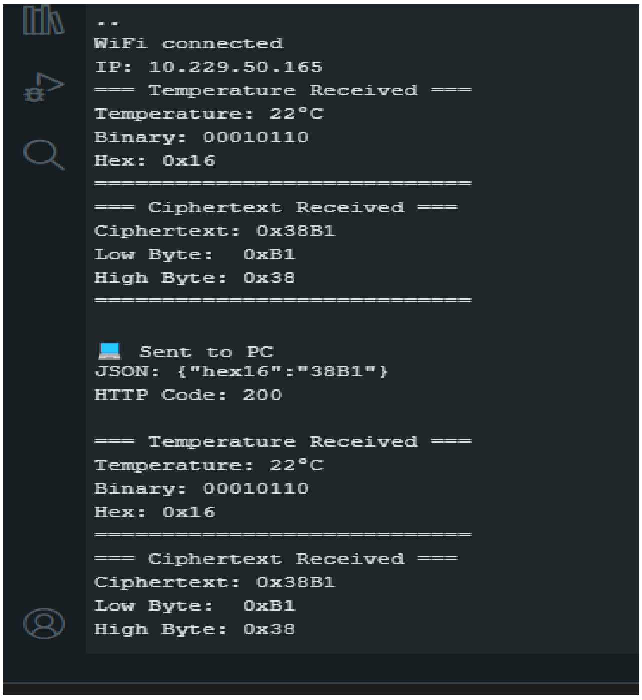

Figure 6 Data Received in ESP32

In addition to that, it is also possible to visualize and store the collected data using the cloud platform. The user can also analyze the received data and observe changes in temperature and abnormal environmental conditions [9]. It is also possible to ensure security using FPGA processing, encryption, and ESP32 cloud communication to send data from the sensing unit.

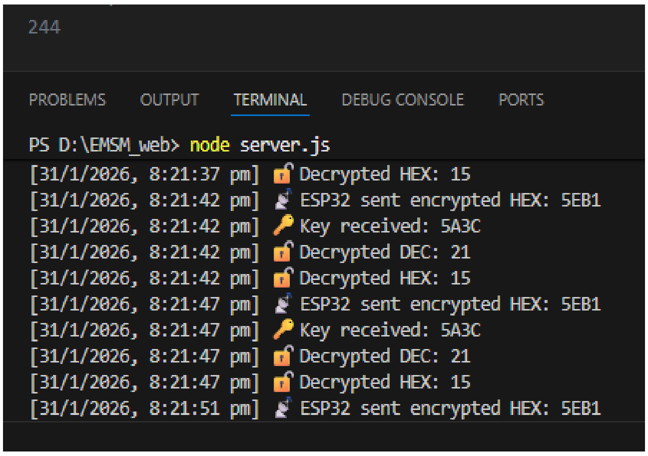

Figure 7 ESP32 To Webpage Communication

The acquisition of the sensor data was effective. The system has provided an efficient way of ensuring the security of the environmental[8].

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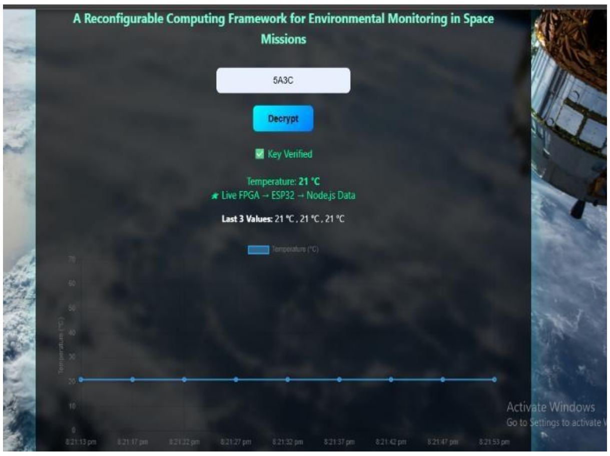

Figure 8 Webpage

Conclusion

The objective of the paper was to develop a reconfigurable framework on an FPGA platform for the development of a space mission-based environmental monitoring system. The framework is to be designed in such a manner that it can integrate a temperature sensor module, analog-to- digital conversion, an FPGA, encryption techniques, and IoT communication for the real-time and secure monitoring of the environment. The temperature is to be sensed by the LM35 sensor, while the analog-to-digital conversion is to be achieved by the analog device MCP3008. The FPGA is to be used for the encryption of the data by the LRBC algorithm. The encrypted data was successfully sent to the ESP32 microcontroller through UART monitoring system. The system can also be used to monitor extreme environments such as the environment of a space mission. The system can also be improved in several ways such as the addition of other sensors to make the system more efficient in monitoring other parameters. The system can also be improved in several ways such as the addition of fault-tolerant techniques to make the system more efficient

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