Remote Monitoring of the Technical Condition of Military Facilities using Wireless Communication

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Abstract

This research addresses the challenges related to the collection and transmission of measurement data during the monitoring of military and other strategically significant objects. The solution involved creating a proprietary distributed system that operates on Wi-Fi technology and leverages the national military radio communication system for long-distance data transfer. Measurements were gathered for several key parameters, including the distance between cracks and joints, magnetometer readings, and the position and potential tilt of objects across three axes based on accelerometer and gyroscope data. A significant aspect of the study was the server setup, which allowed for the creation of new data reception channels. These channels were essential for the further processing and analysis of measurement results. This system is capable of addressing complex issues such as predicting the technical condition of strategically important objects. The thoroughness of the analysis enables the identification and diagnosis of potential errors, as well as the detection of delays within the communication system. Additionally, optimizing energy consumption parameters extended the duration of research activities at remote locations, which ultimately prolongs the lifespan and maintenance intervals of the control system. The flexibility in programming the module boards and compatibility with various electronic measuring sensors make it possible to adjust the system for a wide range of applications. This adaptability significantly broadens the scope of research, expanding it to diverse fields such as agriculture, ecology, energy, healthcare, meteorology, and more.

Keywords: wireless communication, remote monitoring, gyroscope, accelerometer, magnetometer, distance sensor, server.

1. Introduction

The advancement of autonomous systems for technical diagnostics of load-bearing structures, including construction and bridge facilities, requires incorporating modern measuring sensors and wireless data transmission devices. These devices must demonstrate high precision, noise resistance, and ultra-low energy consumption.

A critical component of any technical diagnostics system for military construction sites or bridges is continuous monitoring. This process revolves around measuring the stress-strain characteristics of load-bearing structures and determining key parameter levels. An essential subsystem within such technical diagnostics systems is data collection, which involves transmitting the gathered measurements to a centralized information hub. For these systems, especially those with numerous sensors, the ability to wirelessly transmit the collected data is vital for their effective operation.

The necessity of obtaining objective data on the technical state of structures and implementing specific decisions has become a pressing issue in the development of modern inspection methods. As noted by Alekseev O.V., Viktorov A.D., and Kutuzov V.M., the term "monitoring" emerged in the scientific literature in the late 1960s. Initially, it referred to observing environmental changes and assessing the impact of hazardous factors on nature [1]. Starch T.A., Yevtushenko M.P., and Starch M.P. later expanded the term’s meaning to include the monitoring of construction sites to prevent potential destruction. This type of monitoring is often applied to unique or critical structures where operational safety is paramount, such as nuclear power plants, dams, underground control centers, and bridges [2].

In their studies, Aktan A., Katbas F., Grimmelsman K., and Pervizpour M. introduced their interpretation of "object monitoring," defining it as the control of an object’s operational stage or technical condition based on reliable measurement results and analytical studies, often supported by mathematical models [3]. During monitoring, heuristic methods are utilized to provide quantitative assessments and enable proactive warnings to safeguard an object from reaching critical thresholds.

According to Tanenbaum E. and Van Steen M., monitoring systems are distinguished from traditional systems primarily by their ability to incorporate sensors of various types and brands without altering the overall structure of the measuring system. This flexibility in sensor integration allows for dynamic data management and the system's adaptation to rapidly changing requirements, whether related to functionality, fault tolerance, or scalability [4].

Frolova M.V. proposed a concept for designing a monitoring system, highlighting three key elements [5]:

The monitoring target, characterized by a set of time-dependent parameters. A distributed remote sensing system, comprising various sensors, is tasked with capturing these parameter values. Sensor configurations can be adjusted remotely if necessary.

The system core, or server, represents the software and hardware needed to collect, store, and process monitoring data, ensuring smooth communication between clients and monitoring objects.

The client, the end user of the measurement data, can also perform remote configuration of the monitoring system.

This framework enables remote monitoring of technical facilities to preempt serious accidents by tracking the dynamics of parameters such as crack development, temperature and humidity influences, object position, and potential changes in tilt angles. Moreover, utilizing distributed wireless systems for monitoring military infrastructure allows the establishment of wireless connections, not only with clients but also between the access points themselves [6]. This capability facilitates the deployment of wireless networks over long distances and scales the system to meet user or researcher requirements.

The concept of a "distributed wireless system" implies autonomy, granting the system independence from conventional wired communication networks and power sources. According to S. Franklin and A. Gresse, autonomy means that the software agent is self-regulating. In this context, a software agent is an independent system situated within an environment, capable of perceiving and responding to external signals. The agent initiates its action program and governs its operations, embodying the property of "self-activation" [7].

2. Analysis of literature data and formulation of the problem

In [8], the findings from a study that employed a wireless tilt angle sensor node to monitor the structural condition of various objects are presented. The research demonstrated that two systems—one operating at 2.4 GHz and another utilizing a code division multiple access (CDMA) system—were used together to overcome limitations in communication distance. However, with many countries phasing out CDMA in favor of newer wireless technologies, the implementation of the development outlined in [8] is now less feasible due to the CDMA method's limitations in distributed systems. Consequently, when implementing remote monitoring systems, it is preferable to choose universal wireless technologies that are widely compatible with existing devices and systems. Wi-Fi technology stands out as a potential solution to several challenges. By employing Wi-Fi, sensors and modules can be linked to an access point, which in turn can quickly connect to the national military radio communication network. The receiving end can be situated remotely, as all data is transmitted to a server within the communications network used by law enforcement, with access strictly limited to authorized personnel.

Modules and boards programmed via the Arduino development environment were selected for programming and managing the distributed data collection system. This choice is justified due to the compatibility of Wi-Fi technology with Arduino-compatible boards, modules, and sensors. The capabilities of these boards, as well as their compatibility with various sensors, are discussed in [9, 10]. The versatility of Arduino-programmed boards for developing remote monitoring, data collection, and transmission systems is further elaborated in [11, 12]. These sources confirm the advantages of using this platform, as it enables the creation of a wireless system capable of capturing a range of sensor parameters. For instance, the system described in [11] monitors parameters such as temperature, air and soil humidity, precipitation, and water levels. However, one important issue—energy consumption—remains unresolved. In that case, a wired power supply was used, meaning the system cannot be considered fully wireless. On the other hand, [12] proposed an economical system for monitoring sensor data, including soil moisture, temperature, humidity, and light intensity. Yet, the work remained at the simulation stage without creating a practical prototype, leaving the question of energy consumption inadequately addressed.

This highlights the need for research and experimental work not only on transmitting sensor data but also on optimizing energy consumption [18].

In [13], an overview of the ecological status of smart cities is provided to develop an indoor air quality monitoring system. Although [13] examines more than 100 sources, it does not specify methods for measuring magnetic field data, which is important for evaluating the seismological condition of buildings and cities. Introducing a magnetometer into the system described in [13] could significantly broaden the scope of such a system.

Meanwhile, [14] presents a vibration spectrum monitoring and analysis system based on a Raspberry Pi 3 microcomputer and an ADXL345 triaxial digital accelerometer. This system, designed for real-time operation, is still relevant today and performs well with a wired connection. However, adding additional sensors to measure other parameters requires reprogramming both the Arduino and the microcomputer boards, complicating system setup and configuration. Furthermore, if the monitoring relies on wireless technology, transmitting data to a centralized server or accessing results via mobile devices, laptops, or tablets introduces additional challenges. Therefore, this approach may not be ideal for remote monitoring based on wireless systems.

In [15], a novel monitoring system for structural health is proposed, incorporating various accelerometers, strain gauges, and deformometers. While the sensors have been experimentally validated, issues concerning the long-term reliability and consistency of the system have not been fully resolved. The authors of [15] have taken these factors into account, ensuring that their system is designed with longevity and reliability in mind.

It is important to note that systems measuring and transmitting parameters such as those discussed in [11, 12] should not fundamentally differ in structure or function from systems monitoring other parameters, as described in [13, 15].

In conclusion, all remote monitoring systems should be autonomous, easy to configure, and energy-efficient. Additionally, these systems must reliably collect and transmit data wirelessly, ensuring secure and dependable communication channels. Results should be accessible to authorized users via different devices, whether during long-term or periodic monitoring.

Therefore, it would be prudent to develop a single distributed system with these characteristics to ensure the reliability of collected data for monitoring the technical condition of structures and military installations. To address specific challenges in these research fields, it is necessary to establish a communication channel within the distributed system and collect relevant sensor data, including the distance between cracks and joints, magnetometer readings, and the position or tilt of objects based on accelerometer and gyroscope measurements.

3. Purpose and objectives of the study

The purpose of this work is to develop a distributed wireless Wi-Fi data collection and transmission system with energy saving and information protection for monitoring the technical condition of bridge structures, military buildings and structures.

This will allow conducting research to obtain measurement results and improve quality with practical remote monitoring of the technical conditions of various objects in all weather conditions and time. The low cost of connected devices and their programming availability does not impair the reliability of the entire system, which increases the advantages of the wireless system being developed. Proper server configuration ensures ease of operation from a practical point of view. This is due to the fact that an authorized user who has access to all the measured data needs to have access to the communication system of law enforcement agencies and work on the created server channels to process the results of the study.

To achieve the goal, the following tasks were set: to select, program and configure the operation of devices that are part of a distributed wireless system for collecting and transmitting measurement results using Wi-Fi technology; get experimental results on the server and export data for subsequent processing and analysis of the distributed wireless system to conduct full-fledged monitoring of the technical condition of bridge structures and military facilities; use energy-saving methods when configuring Wi-Fi modules that are part of a distributed system; ensure the security of the transmitted data.

4. Materials and methods for studying the parameters of a distributed wireless Wi-Fi system

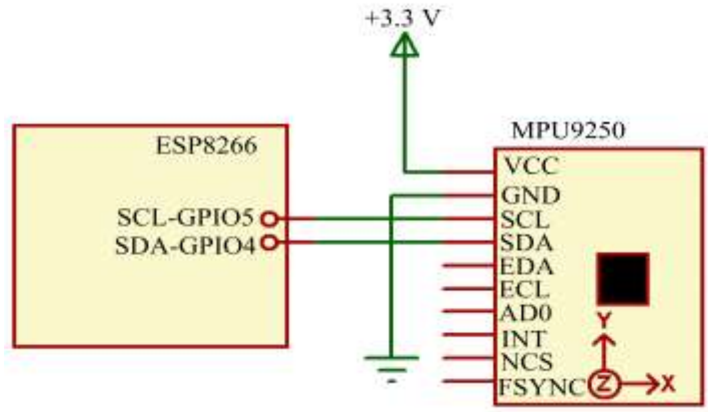
The MPU-6050 and MPU-9250 sensors are compact modules that incorporate gyroscopes, thermometers, and accelerometers. Both sensors are capable of measuring data across the X, Y, and Z axes. In addition to these features, the MPU-9250 also includes a built-in magnetometer, which records magnetic field data on all three axes.

To transmit the gathered data to server channels in a distributed wireless system, the NodeMCU V3 Wi-Fi module is utilized. This module, based on the ESP8266 board, is well-suited for the task due to its ease of programming and relatively low power consumption, which can be adjusted depending on the configured energy-saving mode. The server used for data storage and analysis was hosted on the platform ThingSpeak (https://thingspeak.com/), which offers extensive configuration options for users.

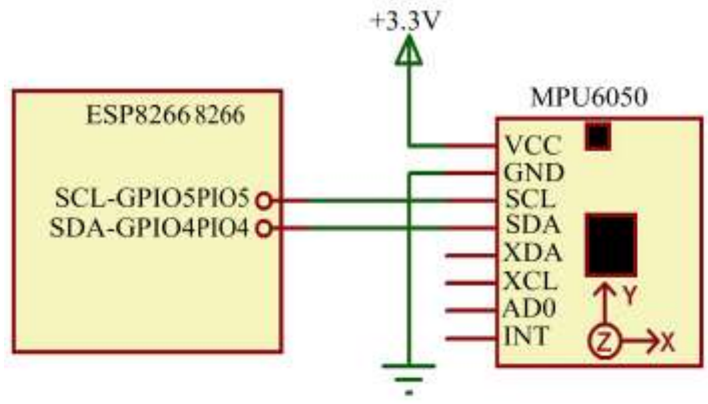
Given the specifications of the sensors and Wi-Fi module, they were selected as the primary components for determining spatial position, inclination angles, and magnetic field measurements of the monitored objects. All data measured by the sensors is transmitted to designated server channels.

Figure 1, part (a), illustrates the connection diagram of the MPU-6050 sensor with the ESP8266-based Wi-Fi module. The sensor's VCC pin is connected to a 3.3V power source, and the GND pin to one of the three ground ports available on the Wi-Fi module. The SCL pin serves as the data line, while the SDA pin handles synchronization. Both SCL and SDA are used for connecting I2C devices, simplifying the connection scheme and enabling smooth data transmission and management. The INT pin is a configurable interrupt, and the AD0 pin is linked to the I2C address. When wiring the sensor, note that pulling the AD0 pin to ground sets the device address to 0x68, while connecting it to the power pin changes the address to 0x69.

Figure 1, part (b), shows the connection setup for the MPU-9250 sensor with the same ESP8266-based Wi-Fi module.



a



b

Fig. 1. Connection diagram of sensor terminals to the Esp8266 family Wi-Fi module: a – MPU-9250 sensor; b – MPU-6050 sensor

The primary distinction between the MPU-6050 and MPU-9250 sensors lies in the presence of XCL and XDA pins on the MPU-9250, which serve as additional I2C interfaces for connecting an external magnetometer. Otherwise, all other pins on these sensors have the same functional properties. Both sensors are integrated into a distributed wireless system, and their operation follows a specific workflow.

Multiple sensors are installed at various locations on the structure or object under investigation, strategically positioned based on the object's height and width. Each sensor is connected to a dedicated module that supports Wi-Fi communication. The modules are configured with a power-saving mode, as continuous data transmission is unnecessary. When no measurement is being taken, the devices remain inactive, conserving energy.

The sensors measure data along three axes (X, Y, Z) at their respective positions on the object, providing separate readings for gyroscope, accelerometer, and magnetometer parameters. Thanks to the scalability of the distributed system, the number and placement of sensors can be adjusted as needed.

To ensure a robust data set for analysis and to minimize inaccuracies, measurements are recorded every 15 seconds. After each interval, the sensors transmit their data to the server via predefined channels. On the receiving end, authorized users responsible for data analysis can log into the system through their respective channels and retrieve the data using a computer or any other internet-enabled device.

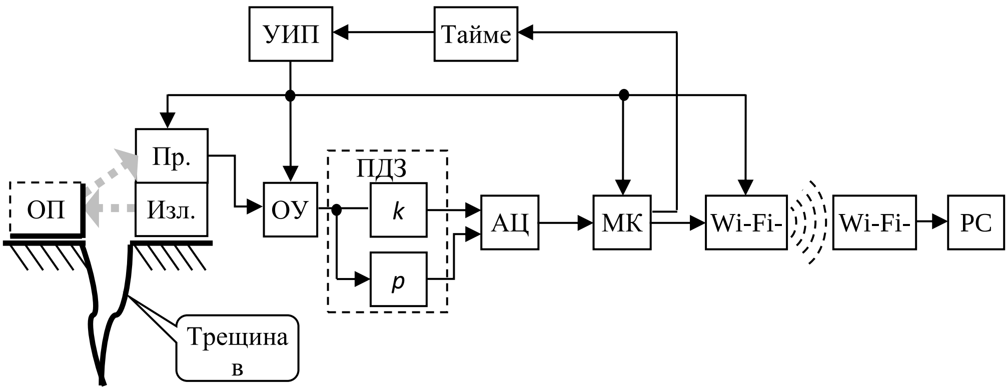


Fig. 2. Block diagram of a wireless device for monitoring the condition of cracks and joints of buildings and structures: an optical sensor consisting of a reflecting panel (OP), an emitter (Isl) and a receiver (Pr), an operational amplifier (OP), an analog-to-digital converter (ADC), a proportional-differentiating link (PDZ), microcontroller (MC), Wi-Fi transmitter (Wi-Fi-1), Wi-Fi receiver (Wi-Fi-2), personal computer (PC), controlled power supply (UIP) and timer.

Figure 3 shows the connection diagram of the distance sensor to the wireless module.

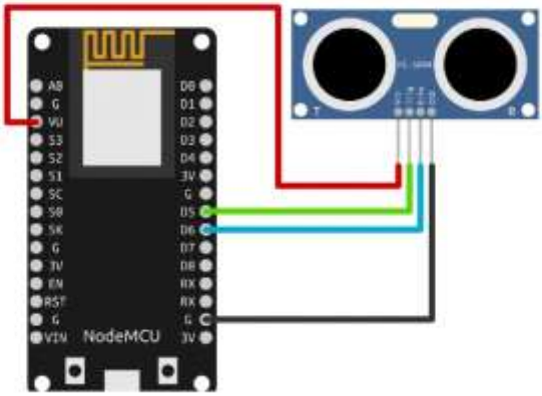


Fig. 3. Schematic diagram of the connection of the distance sensor to the Wi-Fi module

This device functions as part of a distributed wireless system designed for analog data acquisition and transmission using dual-processor Wi-Fi transmitters. In this setup, the HC-SR04 ultrasonic distance sensor is utilized to measure distances, while the NodeMCU V3 Lua Wi-Fi module serves as the wireless communication module. The system requires a 5V power supply, but since the Wi-Fi module itself does not have direct outputs for this voltage, a 4.7 kOhm resistor is incorporated into the circuit. This resistor adjusts the voltage, allowing for accurate distance readings without errors.

The sensor features four standard 2.54 mm terminals: a positive power contact (+5V), Trig (T) for the input signal, Echo (R) for the output signal, and a GND ground contact.

The NodeMCU Wi-Fi module was selected because of its ability to support various power-saving techniques. It is compact, versatile, and includes multiple operational modes, including a sleep mode that can be accessed through both hardware and software adjustments. The NodeMCU V3 ESP8266 operates in the following power modes:

Active mode: In this mode, the entire chip is fully operational, allowing data reception and transmission. This is the most energy-consuming state.

Modem standby mode: The CPU remains active, but the Wi-Fi function is disabled. This mode is useful in applications where the processor performs tasks like pulse width modulation, and the Wi-Fi modem can disconnect when connected to a Wi-Fi access point without active data transmission, optimizing power usage.

Standby mode: Both the CPU and peripherals are suspended, but the system can wake up upon external interrupts. In this mode, the Wi-Fi modem is also disconnected, reducing power consumption significantly when data is not being transmitted.

Deep sleep mode: Only the real-time clock (RTC) remains active while all other chip components are disabled. This mode is ideal for scenarios where data transmission occurs at predefined intervals.

Table 1 outlines the characteristics of these energy-saving modes, highlighting their power consumption levels.

Table 1. Characteristics of the power-saving modes of the NodeMCU Wi-Fi module

Name		Modem Standby mode	Standby mode	Deep sleep mode
Wi-Fi		Turned off	Turned off	Turned off
System clock		Included	Turned off	Turned off
RTC		Included	Included	Included
CPU		Included	Waiting	Turned off
Substrate current		15 мА	0,4 мА	20 mcA
Average current	DTIM=1	16,2 мА	1,8 мА	–
	DTIM=3	15,4 мА	0,9 мА	–
	DTIM=10	15,2 мА	0,55 мА	–

5. Results of studies of the parameters of a distributed wireless Wi-Fi system

5. 1. Connecting and configuring devices included in a wireless distributed system

Once the devices are connected to the wireless distributed data collection and transmission system, the process of configuring and programming the Wi-Fi module begins. A custom program sketch is developed for this purpose (Figures 4-6). At the start of the sketch, details such as the Wi-Fi network credentials, the personal channel on the server, and the data transfer rate are specified. The sketch also defines the conditions for successful Wi-Fi connection, as well as instructions for handling cases where the connection fails.

Next, the program includes the necessary configurations for linking the system to specific channel elements that handle data from the gyroscope, accelerometer, and magnetometer, covering all parameters and axes. Additionally, the sketch configures the output text displayed by the serial port monitor when the receiving device connects to the sensor via a USB cable. This step is essential for verifying the accuracy of sensor readings and ensuring that they are functioning correctly before data is transmitted wirelessly.

In the final portion of the sketch, further software adjustments are made to enable all the necessary operations of the distributed system, which is designed to measure and determine tilt angles and spatial orientation.

Fig. 4. Part of the software sketch designed to read the measured data of the gyroscope and accelerometer and transmit them to the server via Wi-Fi

Fig. 5. Part of the software sketch designed to read the measured magnetometer data and transmit it to the server via Wi-Fi

Fig. 6. Part of the software sketch for transmitting data from a distance sensor via a Wi-Fi module and configuring the board to connect to the server

A unique program code is developed in the Arduino IDE software environment to connect the Wi-Fi module and the distance sensor. This code, comprising numerous lines of programming, ensures the accurate reading, transmission, and reception of all measured data on the server. Additionally, it was decided to display the measurement results on the serial monitor for real-time verification.

It is important to note that after the board is configured and flashed, all data can be transmitted to the server without requiring a direct connection to a computer—only a power source is needed to keep the device operational.

This sketch enables data transmission both to the Arduino IDE serial monitor (Figure 7), which helps in verifying sensor functionality, and to the dedicated server channel via Wi-Fi (Figures 8 and 9).

Fig. 7. Output of measured distance data to the monitor of the Arduino Ide environment port

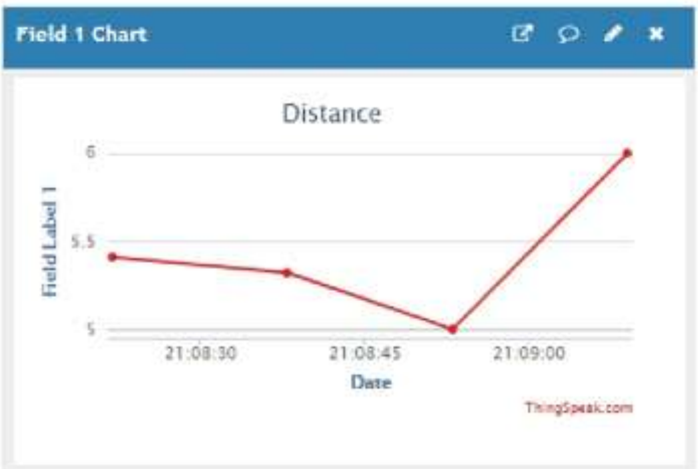


Fig. 8. Graph of measured distance data on the server

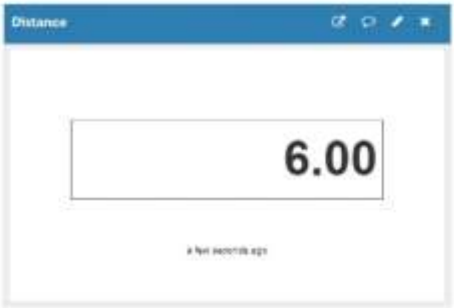


Fig. 9. Display of the last distance measurement on the server

The distance sensor operates based on the following principle: it is positioned at a remote location and measures the distance to an object using the triangulation method. This sensor is part of the structural and functional system described in [16], where it is connected to a Wi-Fi module. The module periodically collects the distance measurements at intervals that can be customized by the user according to their requirements. After collecting the data, the module transmits the distance values to the server via Wi-Fi using a router.

Both the distance sensor and Wi-Fi module are technically compatible and can work together seamlessly in the same system. The process of collecting and transmitting distance data is similar to the procedure used for sending measurement data from the MPU-6050 and MPU-9250 sensors, with the primary difference being the unique programming sketches tailored for each device.

Figure 10 demonstrates an example of how the distance sensor is wired to the Wi-Fi module.

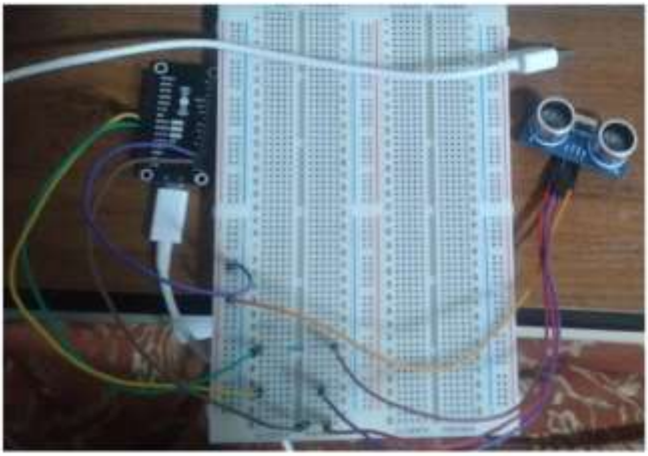


Fig. 10. Connection of the distance sensor to the Wi-Fi module in the developed distributed wireless system

5.2. Receiving the results of the study on the receiving side (in the server)

All data (Figures 11-17) is transmitted to the server, which offers the convenience of tracking the time and date each value is received. This feature allows users to monitor and analyze how the values fluctuate over time when observing a remote object. Based on the collected data, conclusions can be drawn about changes in the object's parameters throughout the monitoring process.

Figures 11 and 12 illustrate the specific dates and times when the minimum and maximum distance measurements were recorded.

Fig. 11. The minimum value of the measured distance value with a detailed description of the date and time

Fig. 12. The maximum value of the measured distance value with a detailed description of the date and time

Figure 13 displays the available formats for exporting distance measurement data, while Figure 14 presents the data in XML format, based on research results. This format enables users to process the information for future integration into a separate HTML file. HTML files are commonly used for creating local web pages via an MQTT server, offering enhanced options for monitoring and collecting data on the receiving end.

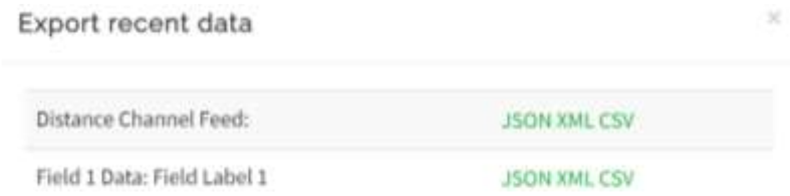


Fig. 13. Choosing a format for exporting measured distance readings


```xml
<channel>
  <id type="integer">1085729</id>
  <name>Distance</name>
  <latitude type="decimal">0.0</latitude>
  <longitude type="decimal">0.0</longitude>
  <field1>Field Label 1</field1>
  <created-at type="dateTime">2020-06-20T11:27:40Z</created-at>
  <updated-at type="dateTime">2020-06-20T11:27:40Z</updated-at>
  <last-entry-id type="integer">29</last-entry-id>
  <feeds type="array">
    <feed>
      <created-at type="dateTime">2020-06-22T15:08:22Z</created-at>
      <entry-id type="integer">1</entry-id>
      <field1>5.41 </field1>
    </feed>
    <feed>
      <created-at type="dateTime">2020-06-22T15:08:38Z</created-at>
      <entry-id type="integer">2</entry-id>
      <field1>5.32 </field1>
    </feed>
    <feed>
      <created-at type="dateTime">2020-06-22T15:08:53Z</created-at>
      <entry-id type="integer">3</entry-id>
      <field1>5.00 </field1>
    </feed>
    <feed>
      <created-at type="dateTime">2020-06-22T15:09:09Z</created-at>
      <entry-id type="integer">4</entry-id>
      <field1>6.00 </field1>
    </feed>
    <feed>
      <created-at type="dateTime">2020-06-22T15:14:26Z</created-at>
      <entry-id type="integer">5</entry-id>
```


Figure 14. Output of all measured data in Xml format

Figures 15-17 show the experimental results obtained using MPU-9250 sensors. During the experiments, the position of a mock-up, representing a military structure or a strategically important object, was adjusted in the laboratory every 15 seconds. The change in the tilt angle and spatial orientation was measured along three axes, and the results were transmitted from the sensors to the server via a Wi-Fi network.

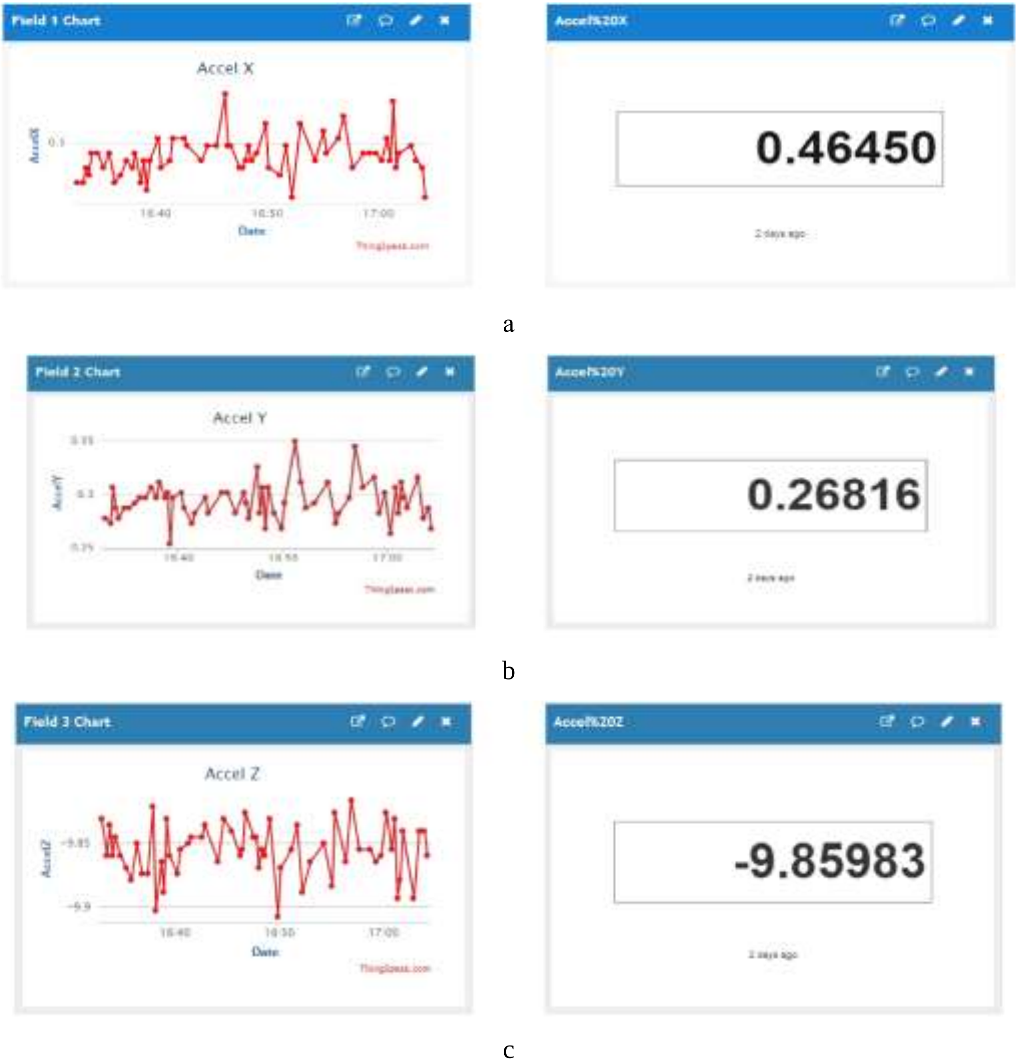


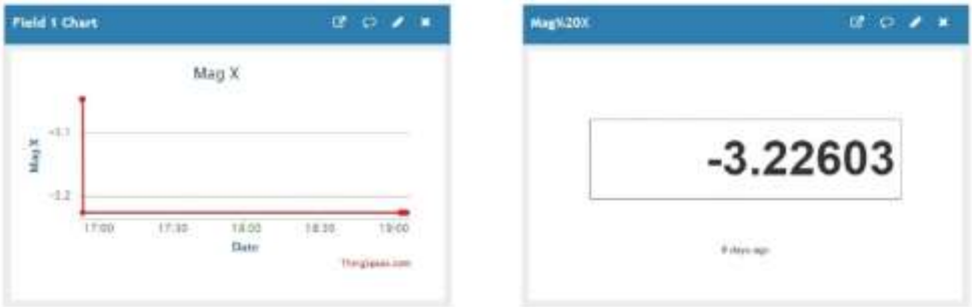
Fig. 15. Accelerometer readings over time: a – on the X axis; b – on the Y axis; c – on the Z axis

a

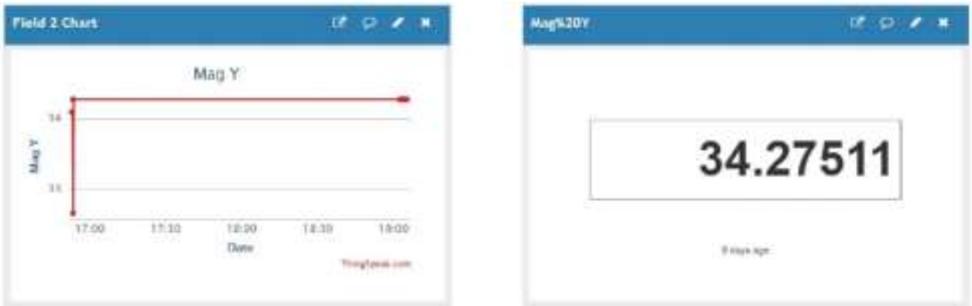
b

c

Fig. 16. Gyroscope readings over time: a – on the X axis; b – on the Y axis; c – on the Z axis



a



b

c

Fig. 17. Magnetometer readings over time: a – on the X axis; b – on the Y axis; c – on the Z axis

The resulting measurements provide users on the receiving end with a clear view of all deviations, spikes, and potential errors within the network, represented in the form of graphs. By processing the measurement data, it was possible to correct any inaccuracies or errors that occurred during network operation. The successful setup and testing of sensors and devices within the wireless distributed network, along with the construction of the network itself, demonstrate that these sensors can be installed on any military structure or bridge.

Figures 18 and 19 illustrate the available formats for exporting the measurement results from the gyroscope, accelerometer, and magnetometer along the axes, gathered during the laboratory experiments.

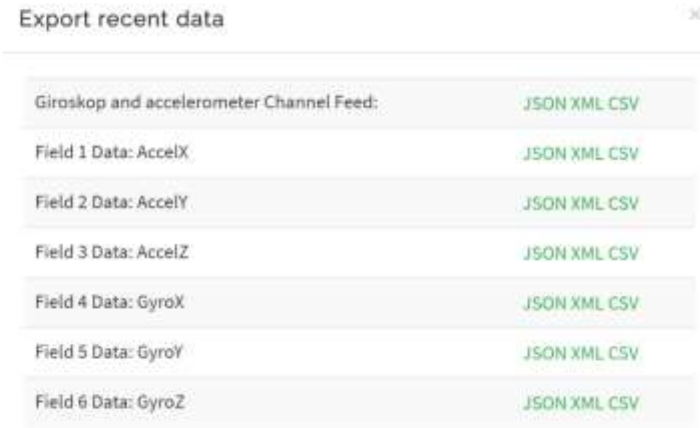


Fig. 18. Export of the received gyroscope and accelerometer data in 3 formats

Fig. 19. Export of the received magnetometer data in 3 formats

5. 3. Features of modes, methods of operation and ways to ensure the reliability of a distributed system

The measurements conducted on the distributed system revealed the following key features:

All analog sensor data is automatically digitized using the built-in ADCs and displayed as results on the designated server channel. When creating a channel, users must specify its name and set the number of graph windows (referred to as "fields" in the settings) to receive data from sensors or other inputs. As shown in Fig. 20a, the maximum number of graphs for data collection is 8, while Fig. 20b shows the created channels, with a maximum of 4 channels allowed. This setup enables one account to manage up to 32 parameters simultaneously, and when using multiple accounts, the number of parameters can increase significantly.

The ability to select any point on the graph and view the corresponding date and time of the measurement.

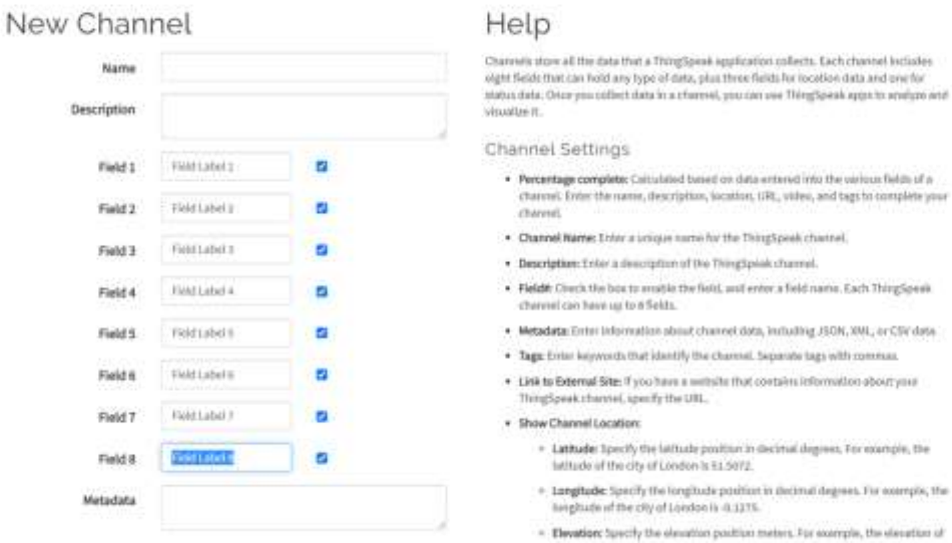
Options to choose the desired power consumption mode.

The server automatically generates a coordinate system to display the results as graphs.

Data export is available in three formats: JSON, XML, and CSV.

Display of the most recent result in the form of a measuring device, a numerical display, or an indicator light.

Capability to process measurement data directly within the Matlab software environment without leaving the platform or needing to install Matlab on a local machine (Fig. 21, 22).



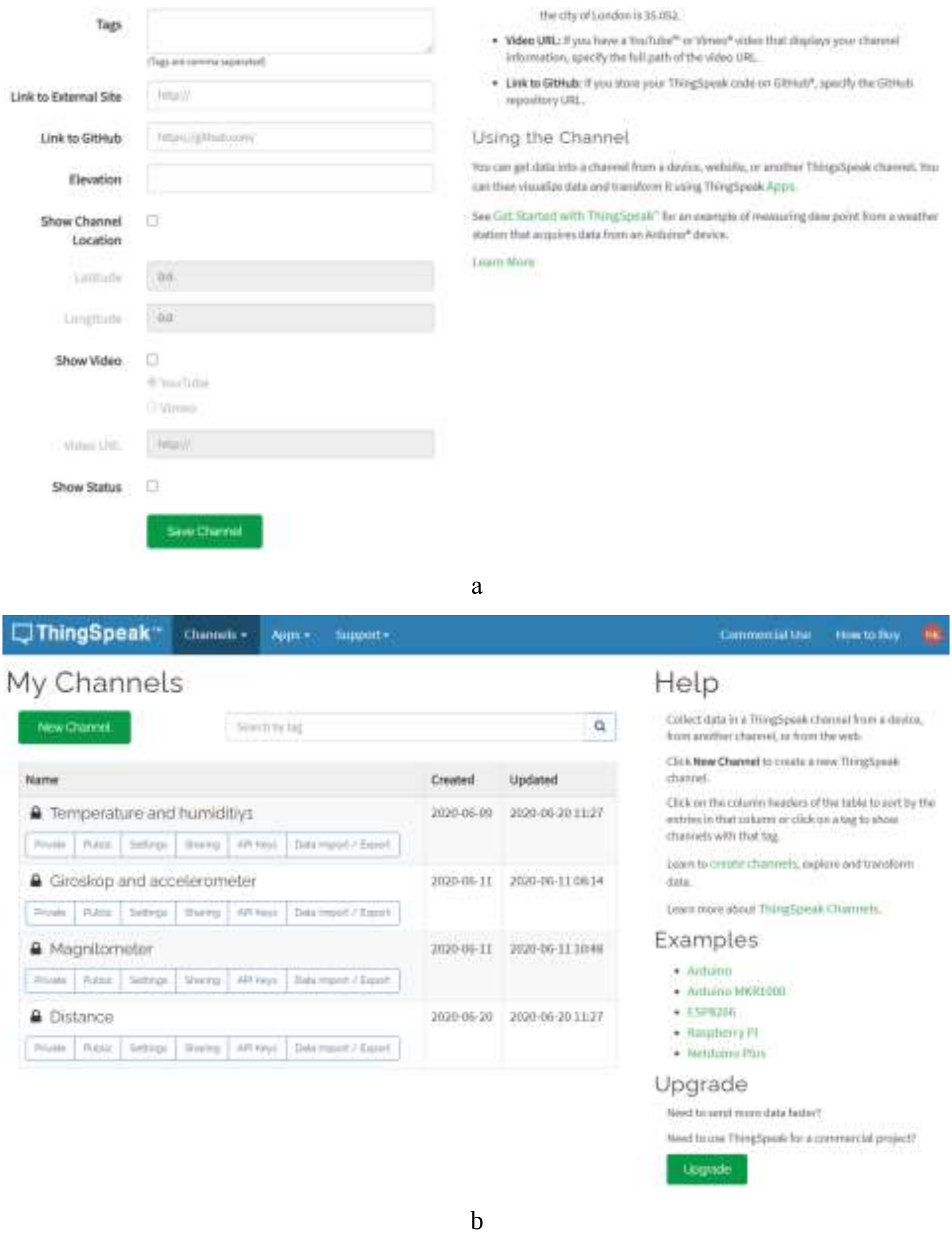


Fig. 20. Working with channels on the server to receive data: a – setting up a new channel; b – list of available channels on the server

Fig. 21. Buttons for processing the received data using the Matlab program on the server

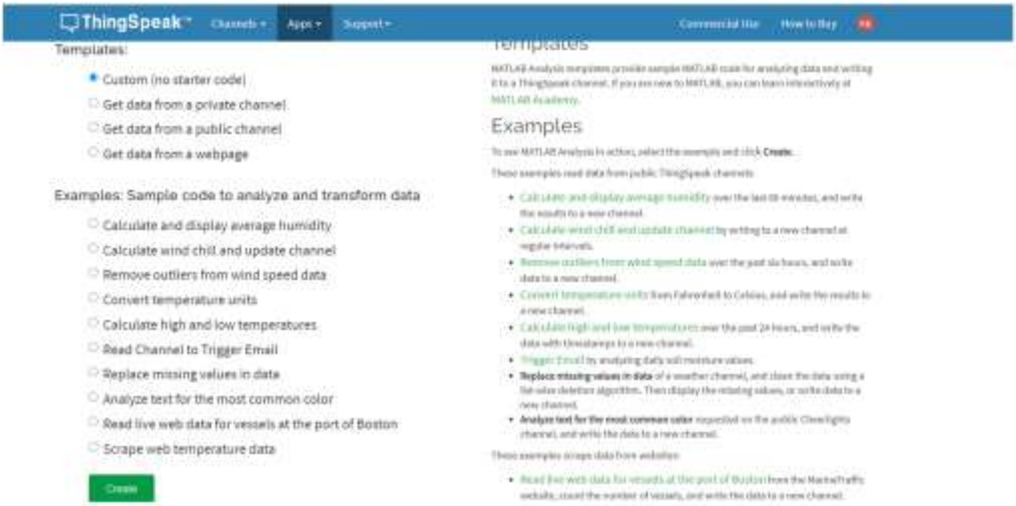
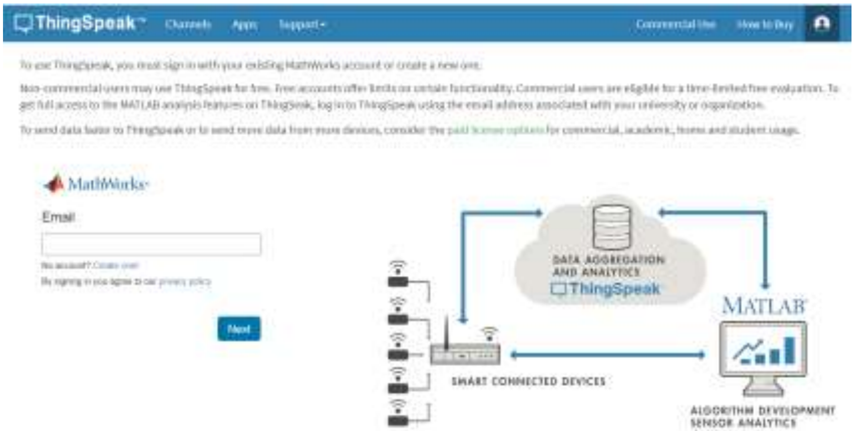


Fig. 22. Server window for data processing in the Matlab program

It is important to consider that data transmission over any network, particularly for military applications, must be highly secure. In the experimental part of this work, data protection is implemented in several stages.

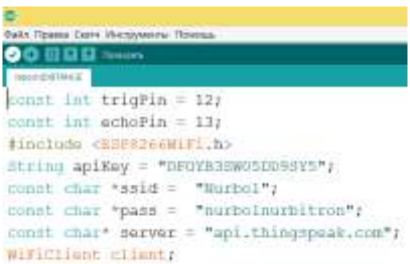
The first layer of security involves creating a login and password for the personal server account, as shown in Fig. 23a. The second layer: each channel created on the server is assigned unique encryption keys (Fig. 23b), without which the Wi-Fi module cannot establish a connection. These keys are embedded in the sketch of the Arduino IDE software environment (Fig. 23c). The third layer of protection is controlling access to the Wi-Fi network itself, where the network's login and password are also specified in the Arduino IDE sketch (Fig. 23d).

Therefore, it can be concluded that the protection against unauthorized access to the data collection system, and especially the modification of the programming sketch, is sufficiently robust.



a

b



c

Fig. 23. Data security settings: a – authentication on the server; b – channel encryption keys configuration window; c – setting the encryption key and Wi-Fi network parameters in the Arduino Ide software environment

6. Discussion of the results of the study of the parameters of a distributed wireless Wi-Fi system

The proper selection of a Wi-Fi module that supports multiple energy-saving modes significantly reduces overall power consumption. Depending on the type and frequency of monitoring, each user can choose an appropriate power mode. In the developed distributed system, the "deep sleep" mode is selected and configured to minimize energy usage. During deep sleep, the following processes occur:

The module connects to a Wi-Fi access point.

Various tasks are performed, such as reading sensor values, publishing MQTT messages, and more.

The system then enters sleep mode for a specified number of microseconds. According to the ESP8266 SDK, the device can remain in this state for a maximum of 4,294,967,295 microseconds, equivalent to about 71 minutes.

These steps can be repeated as necessary.

The small size of the selected Wi-Fi modules and sensors allows the entire system to be compact, making it suitable for use in remote or hard-to-reach areas, addressing autonomy concerns. The choice of devices was made so that the programming does not complicate the monitoring process and can be easily adjusted to new conditions without the need for professional programmers. Nevertheless, the sketches used provide a high level of data reliability, as the system is built on a universal programming environment and configured to implement multi-stage authentication and encryption (Fig. 23).

The measurement results and their processing capabilities enable real-time remote monitoring. The study's results can be viewed using any device connected to the national military radio network. This makes the distributed wireless system an effective solution for addressing the challenges of configuring and ensuring compatibility between transmitting and receiving devices.

To facilitate comprehensive analysis and data processing, the system includes a server that allows for exporting data and processing results directly within the built-in Matlab software environment (Fig. 22). The data collected by the system can be processed in various ways. For instance, users could manually record all results and build data arrays to analyze parameter changes, which would help identify any potential errors. However, manual data entry is time-consuming and prone to human error. Therefore, the system supports data export in a convenient format for processing in Matlab, eliminating the need for manual input.

Data transmission occurs at intervals of no less than 15 seconds, as data collection and reception on the server take a certain amount of time. The server cannot process data every second due to configuration limitations, but this does not affect the system’s overall performance. The measurements, such as the distance between cracks and joints, magnetometer readings, and the object's inclination in three axes based on accelerometer and gyroscope data, are periodic and do not require real-time updates every second.

In addition to the time interval, there are some limitations related to the installation of additional libraries in the Arduino IDE software. When changing sensors or upgrading to newer Wi-Fi modules, the boards must be reprogrammed to accommodate updated libraries. If system configuration is transferred to a different computer, all relevant libraries and modules must be installed on the new machine. Fortunately, this is a straightforward process, as all required libraries and boards are available in any version of the Arduino IDE, which is freely accessible.

The research conducted using this wireless distributed system has significant potential for expansion into other fields. By modifying the appropriate controls, this system can address challenges in areas such as agriculture, ecology, energy, healthcare, and meteorology. For instance, in agriculture, the system could enable remote monitoring of soil temperature and humidity. In ecology, it could track water pollution or air quality remotely. In energy, it could manage power consumption modes for remote sites based on sensor loads. In healthcare, the system could be adapted for remote monitoring of vital signs, such as heart rate, body temperature, or blood pressure. In meteorology, it could monitor climate changes.

In summary, by implementing similar studies across various industries with the developed system, it is possible to achieve reliable, remote, and efficient monitoring results across a broad range of applications.

7. Conclusion

Selection of Suitable Devices: After comparing various available options, the following sensors were selected: MPU-6050 (China), MPU-9250 (China), and HC-SR04 (China), along with NodeMCU Wi-Fi modules from the ESP8266 family. These modules operate using Wi-Fi technology, with the advantages and rationale for choosing this technology detailed in [17]. The sensors were chosen for their ability to function as gyroscopes, accelerometers, magnetometers, and distance measuring devices, particularly suited for installation in hard-to-reach locations. The selection of the Wi-Fi module was based on its capability to operate in energy-saving mode. A custom software sketch was developed in the Arduino IDE environment to establish reliable communication between the transmitting and receiving sides of the wireless distributed system. This approach to creating an automated wireless system ensures minimal power consumption and facilitates the development of efficient, low-cost systems for 24/7 autonomous monitoring of load-bearing structures in military installations. The system components contribute to monitoring the technical condition of structures, helping prevent accidents or sabotage attempts in advance, and ultimately extending service life while enhancing accuracy, informativeness, and the quality of structural condition forecasting for both bridges and military facilities.

Data Reception and Channel Configuration: Data is received through channels created on a server, each tailored to meet specific user requirements. Each channel can accept up to eight parameters, and the server allows users to create up to four channels, providing scalability as observation needs grow. The server used in this wireless distributed system stores all measured data with corresponding timestamps, ensuring that all observation results are saved and displayed as numerical values in the user’s personal channels. The ability to process these observation results helps users evaluate the quality of the wireless communication system and quickly identify and correct any errors.

Power Consumption Management: Among the four power consumption modes, the system uses the deep sleep mode. While modem standby and standby modes are useful when certain functions of the ESP8266 module are disabled, deep sleep mode is essential when rigorous power management is required. In this mode, the overall average current consumption is less than 1 mA, and at 2.5V, the current requirement drops to just 20 µA.

Data Security: The distributed system ensures data security through multiple layers of protection. Access to the data reception channel is controlled via a server that requires user authentication. Encryption keys are generated during the board flashing process to bind the sensors and server securely. Wi-Fi technology with WPA2 PSK encryption is used to secure the wireless communication line, ensuring that only authorized users have access to the transmitted data.

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