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ALGORITHMIC DESIGN AND SOFTWARE FOR A MICROCONTROLLER-BASED WEARABLE BIOMEDICAL SENSOR MONITORING SYSTEM VIA ESP-NOW PROTOCOL

Abstract. This paper presents a hardware-software implementation of a microprocessor-based distributed system for monitoring human motion biomechanics using wireless communication for real-time data transmission. The main objective of the work is to develop an energy-efficient, reliable, and low-cost system capable of autonomously collecting, transmitting, synchronizing, and storing data from inertial sensors in real time. The proposed approach is based on the use of ESP32 microcontrollers, which support direct data exchange via the ESP-NOW protocol. This protocol enables high-speed, low-latency data communication without connection establishment, ensuring fast response and reduced power consumption. A functional system prototype has been developed, consisting of a base station and a set of sensor modules powered by standalone battery sources. The study introduces a specialized algorithm for synchronized data transmission, which includes packetization of inertial measurement unit (IMU) readings and data caching using a circular buffer. This significantly reduces packet loss even under interference and high channel load conditions. The paper describes the loss-handling mechanism, retransmission process, and methods for clock synchronization and maintaining continuous packet numbering in the event of a module or base station restart. A series of tests were conducted in various operating modes, with different numbers of modules, at different distances, and under obstacle-induced interference. Experimental results show that the average packet loss rate when using the proposed algorithm does not exceed 1%, and the probability of severe losses (over 10%) is effectively eliminated. The system has also demonstrated stable performance under real-world conditions and supports scaling up to 20 modules. The obtained results confirm the efficiency and feasibility of using the ESP-NOW protocol in distributed biomedical IoT systems focused on motion monitoring, patient rehabilitation, biomechanical studies, and prosthetic adaptation support.

Keywords: biomechanics; wearable electronics; inertial sensors; wireless communication; ESP-NOW; data packetization; caching; distributed system; monitoring.

Introduction

According to the World Health Organization, approximately 1.71 billion people (22%) worldwide suffer from musculoskeletal disorders that lead to temporary or permanent limitations in mobility, work, and social life [1]. These disorders encompass more than 150 different diseases and conditions associated with impairments in the function of muscles, bones, joints, and adjacent connective tissues. They include both acute conditions, such as fractures or ligament sprains accompanied by pain and functional limitations, and chronic disorders, such as osteoarthritis or primary lower back pain. Lower back pain is one of the most common health issues throughout a person’s life: about 80% of people over the age of 35 experience it, leading to reduced productivity and diminished quality of life.

The measurement of human biomechanics plays a crucial role in diagnosing musculoskeletal disorders and planning treatments. For this purpose, state-of-the-art tools are used, including non-invasive electronic devices, electromechanical systems, smart clothing, and exoskeletons. In recent years, numerous studies [2–7] have been conducted on the use of such devices for biomedical research, diagnostics, therapy, correction, and prevention.

The study of human biomechanics is critical not only for diagnosing and treating musculoskeletal diseases but also for rehabilitation and prosthetics. Due to the ongoing full-scale military invasion, active combat operations, and horrific terrorist attacks on the civilian population in Ukraine, the number of limb amputations has reached levels comparable to those during World War I. According to Ottobock (Germany), the world's largest prosthetics manufacturer, around 50,000 Ukrainians have lost limbs [8].

The measurement of movement parameters, load distribution, and muscle activity allows for the adaptation of prosthetic devices to the individual characteristics of users, improving comfort and reducing the risk of complications. This significantly contributes to faster recovery, pain reduction, and more effective adaptation following amputation.

Research Objective and Tasks. Timely and accurate diagnosis during treatment and rehabilitation is a key factor in significantly reducing the risk of developing musculoskeletal disorders. If diagnosis is conducted with sufficient duration, regularity, and precision, it can not only accelerate treatment and rehabilitation but also substantially decrease the likelihood of unhealthy deviations, pathologies, and associated complications. However, engaging qualified medical personnel to ensure continuous monitoring under such conditions is highly costly for the patient and reduces the quality of diagnostics and the efficiency of specialists' work due to the high number of patients or limits the number of patients who can be monitored in real time.

A promising solution in this context is the use of automated monitoring systems capable of continuously tracking the biomechanics of a patient’s movements without the direct involvement of medical personnel. Such systems help reduce costs, improve diagnostic quality, and enable a more personalized approach to rehabilitation.

The main objective of this article is the hardware and software implementation of a distributed human biomechanics monitoring system using the ESP-NOW protocol for wireless data transmission from sensors, as well as the development of an effective operational algorithm for the system.

Overview of Existing Solutions. With the development of computing technologies, the use of commercial microcontrollers (MCUs) in various industrial and domestic applications has been steadily increasing [9, 10]. The advancement of Internet of Things (IoT) systems also contributes to the widespread adoption of such MCU-based solutions [11]. The IoT paradigm can be applied across many fields, including healthcare [12, 13]. As noted in [3], the development of mobile medicine and related new technologies, such as intelligent sensing, along with the growing popularity of personalized health concepts, has accelerated the advancement of smart wearable devices [4].

Some of these technologies have become an integral part of everyday life in the form of accessories such as smartwatches, wristbands, and smart glasses [5]. In the healthcare sector, wearable medical electronic devices that can be worn directly on the body are used for recording and analyzing biomedical data and supporting health monitoring to aid in disease treatment through various medical-oriented IoT systems [6].

By intelligently integrating mechanical functional elements with the computing capabilities of microelectronic devices into a unified monitoring system, wearable devices can be used for immediate symptom detection, collection of laboratory indicators, and providing instructions for physical exercises, medication reminders, and more. This enables multiparametric detection and analysis of physiological and pathological information about a person in real-time [7].

Key features of such systems include decentralized data processing, the presence of distributed input-output systems, enhanced fault tolerance, and a standardized unified database structure [14].

To reduce the cost of system implementation and improve its efficiency, it is advisable to use specialized data transmission protocols, particularly ESP-NOW. This protocol was developed as a low-cost, low-power solution optimized for Internet of Things (IoT) devices operating in the industrial, scientific, and medical (ISM) 2.4 GHz frequency band. ESP-NOW is already widely used in various industrial [15, 16] and agricultural systems [17], where wireless communication protocols enable many devices to establish links using affordable IEEE 802.11 standard transceivers.

At the physical layer, ESP-NOW relies on the general IEEE 802.11-1999 standard [18] and incorporates a specialized Long-Range mode developed by Espressif, which allows transceivers to achieve higher sensitivity by reducing the data transmission rate.

It is also important to note that, unlike traditional Wi-Fi, ESP-NOW does not require connection establishment and maintenance between devices, which significantly reduces data transmission latency and improves energy efficiency [19].

All these features make ESP-NOW a highly relevant choice for synchronizing modules in distributed systems, particularly those used in wearable biomedical electronics, where the combination of energy efficiency, compactness, and low cost is critical.

Research results

1 Distributed Human Biomechanics Monitoring System. The main requirements for the system include:

1) support for simultaneous operation with at least five sensor modules;

2) a sensor polling frequency of no less than 100 Hz.

Data obtained from a single sensor typically have a size of 16 bits. In practice, three-axis sensors of two types (sometimes — three types, including magnetometer) are used: an accelerometer and a gyroscope, which result in a data volume of 12 bytes per measurement. Thus, each sensor generates approximately 1200 bytes of useful data per second. Additionally, it is necessary to account for the volume of auxiliary information required to ensure communication and system operation (headers, checksums, identifiers, special data packets). Typically, this overhead accounts for 10% to 15% of the payload.

The typical components of a distributed monitoring system include:

1. Base Station — performs synchronization and polling of sensors, stores incoming data on a storage device (SD card), provides control over the monitoring process, and visualizes the current status of sensors, their connections, and received data. The base station is implemented using a specialized microcomputer based on an ESP32 microcontroller, equipped with additional RAM, control interfaces (keyboard), and a display. The station operates autonomously, powered by an internal battery.

2. Sensor Module — collects data directly from individual sensors (typically an accelerometer and a gyroscope) and may support additional sensors such as a magnetometer. The module is designed for attachment to the human body and includes its own power supply for autonomous operation. A typical module consists of a microcontroller with integrated support for wireless protocols (Wi-Fi, ESP-NOW, etc.), an inertial measurement unit (IMU) connected via I2C interface, a power management unit (PMU), and a battery.

3. Software for Post-Processing — runs on a PC and enables resampling of the collected data, calculation of additional parameters based on sensor readings (e.g., rotation angles), and saving the processed data in a synchronized format (across different sensor modules) suitable for further analysis and research. The structural diagram of the monitoring system is shown in Fig. 1.

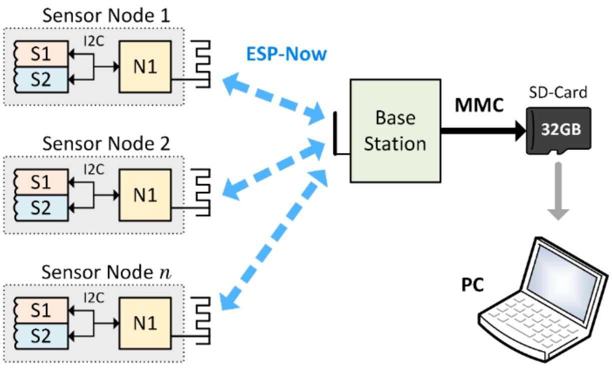

Fig. 1. Structure of the Monitoring System

2 Synchronized Packet Exchange Algorithm. Data exchange is carried out using the wireless ESP-NOW protocol. The base station maintains a list of trusted modules that are authorized to connect to the system and transmit data. Modules are distinguished by their unique 6-byte MAC addresses.

After connection, each module is assigned its own time quantum for data transmission (typically 1000 ms), which is divided into three parts: synchronization waiting (100 ms), actual data transmission (~800 ms), and transmission completion (~100 ms). Time quanta are sequentially distributed by the base station among all connected modules (Fig. 2). At the beginning of each time quantum, the base station sends a packet containing a timestamp used for synchronizing the internal clocks of individual modules, as well as the allocated time quantum size for the module permitted to transmit data. During each synchronization step, only one module receives a non-zero time quantum and is authorized to transmit its data during that interval.

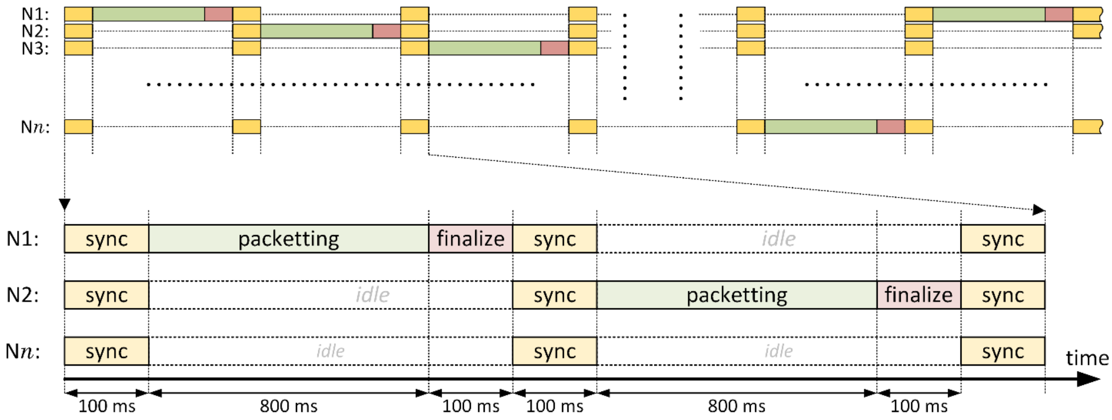

Fig. 2. Time Quantum Allocation Among Modules

After receiving a packet containing a timestamp, the module performs synchronization of its internal clock by calculating the difference between its local time and the received timestamp. Immediately afterward, the module sends a packet to the base station containing technical information about its current status, including: supply voltage level, CPU load, sensor and CPU temperatures, available RAM size, packet format information, IMU operating frequency, and the received timestamp. This data allows the base station to assess the module's current condition and estimate the data transmission delay to the module. If the received time quantum value is greater than zero, the module waits for 100 ms — this delay is necessary to avoid conflicts during the synchronization process of other modules. After the delay, the module begins transmitting the previously accumulated IMU data packets. Transmission continues until either the queue is fully emptied or the allocated time quantum is exhausted. Once transmission is completed, the module switches to standby mode.

The system operation algorithm is shown in Fig. 3.

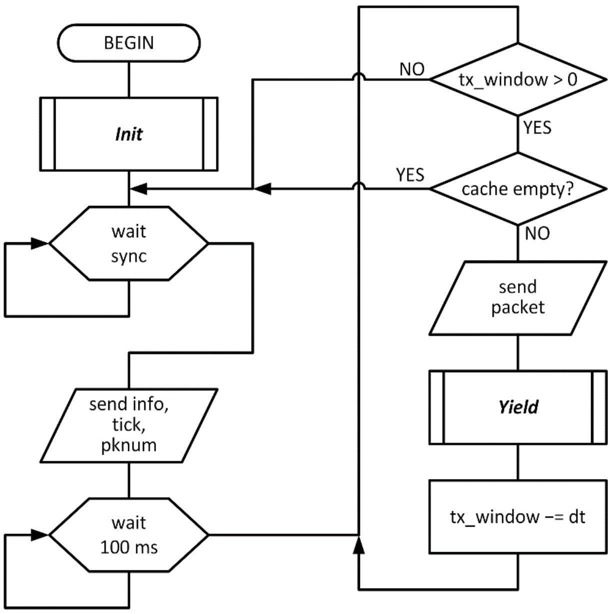

Fig. 3. System Operation Algorithm Diagram

While one module is transmitting data, other modules remain in standby mode without transmitting. Upon receiving each packet, the base station verifies the continuity of the packet sequence based on a unique sequential number contained in each IMU packet, which increments by 1 for each subsequent packet.

If a discontinuity is detected — that is, if the number of the newly received packet exceeds the previous one by more than one – the base station sends a request for retransmission of the missing packets.

Upon receiving such a request, the sensor module checks the cache for the presence of packets with the requested sequence numbers and retransmits them if they are found.

To support this functionality, each module implements caching of IMU data in the form of a circular buffer controlled by three pointers (Fig. 4): a pointer to the position for writing the new packet, a pointer to the last formed packet, and a pointer to the last transmitted packet. The search for missing packets is performed in reverse order, starting from the position of the last transmitted packet.

On the selected hardware platform (ESP32 microcontroller), the cache can store a sufficient number of packets to ensure the proper functioning of the described system algorithm (up to 60 seconds of data) and can have a size of up to 128 KB.

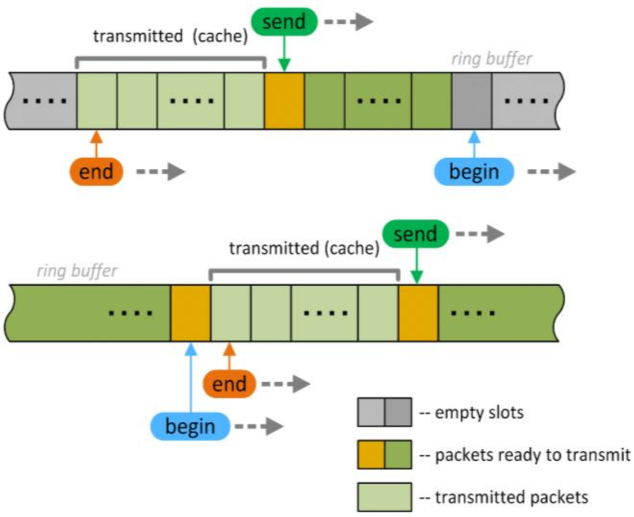

Fig. 4. Packet Cache Operation Diagram:
a – initial phase, b – working phase (cache is full)

In practice, this allows connecting up to 20 sensor modules to a single base station on a single channel, which corresponds to the client limit for the ESP-NOW protocol on the ESP32 microcontroller.

The use of the proposed system architecture virtually eliminates the possibility of collisions during data transmission between modules.

3 Handling Module Restarts and Failures. Despite the constantly increasing reliability of microcontroller systems, it is impossible to guarantee their stable operation over extended periods, especially for low-cost systems powered by autonomous power sources.

On one hand, the use of wireless communication technologies and the absence of galvanic connections between modules generally increases the reliability of the monitoring system, as the failure of a single module does not lead to the failure of the entire system. However, on the other hand, wireless data exchange imposes certain limitations on the system's operation and prevents obtaining diagnostic information about the device's status and the cause of its failure in the event of a lost connection.

Another significant issue is that popular wireless communication protocols (Wi-Fi, Bluetooth, ESP-NOW) operate in the shared 2.4 GHz frequency band, creating the risk of mutual interference, particularly in environments with closely spaced devices. When using the ESP-NOW protocol, an additional limitation is the fixed communication channel: changing the frequency channel is impossible without a complete device restart, which reduces the system's flexibility in dynamic radio environment conditions.

Therefore, at the software level, it is essential to implement mechanisms for handling temporary sensor-module failures. To detect a module restart, synchronization is performed using the sequence number of the last successfully received packet, which the base station includes in its synchronization packet along with the timestamp. Upon receiving this packet, each sensor module computes its next packet number as the maximum from the base-station number plus one and its own current packet counter. This ensures that after a module restart, both its internal clock and packet counter are adjusted so that the sequence of packet numbers remains continuous and strictly increasing. In the event that the base station restarts, packet numbering is then initialized based on the latest sequence numbers reported by the modules.

4 Testing and Practical Use of the System. The system was tested in several stages.

In the first stage, the stability of the wireless connection between the sensor modules and the base station was checked. The base station was built using a module based on the ESP32-S3 microcontroller with an integrated antenna. The modules operated in autonomous mode (powered by batteries) and were placed at a fixed distance of 1 meter from the base station. During the experiment, which lasted approximately 1 hour, the number of readings that were not successfully transmitted to the base station was recorded. The experiment involved four sensor modules, each was based on a module with an ESP32-C3 microcontroller and equipped with BMI-160 inertial sensors [20], operating at a frequency of 100 Hz. Data transmission was performed in packets of 16 readings each. The total number of collected readings was 381608, and the average number of transmitted packets was 23810. The chosen communication channel was also used by an additional external device (Wi-Fi Router). Under these conditions, the minimum number of lost readings was 1, and the maximum was 410 (≈0.1% of the total data). The maximum deviation of the sensor module's clock from the reference value was recorded at – 1.4%.

The average power consumption of a sensor module reached 0.8 W in standby mode and 0.91 W during packet-based data transmission by a single module, rising to 1.0 W when multiple modules were active simultaneously. The average sensor startup time before beginning data transmission was 650 ms. The base station became operational within 2–3 seconds after power-up.

The next testing phase focused on evaluating reading losses during data transmission. Losses can occur for two main reasons: packet misalignment due to clock synchronization errors [21], and complete packet loss. The typical signal propagation delay from the base station to a sensor module is 4–10 ms, which roughly matches the IMU sampling interval at 100 Hz (10 ms). Consequently, misaligned packets usually lose 1–2 readings at the beginning and end of each packet. However, the majority of data loss arises from entire packet drops, given that each packet contains 16 readings.

The packet loss study was conducted under two configurations: with a single module and with four modules operating simultaneously. Each testing session lasted approximately 30 minutes. For each session, the ratio of lost readings to the total number of readings expected at the base station during that period was calculated. Between 5 and 15 trials were performed for each operating mode; the results were averaged, and the maximum loss percentage was recorded. The detailed outcomes are presented in Table 1. During these experiments, both non-packetized/non-cached and packetized/cached modes were evaluated in sequence. To further assess the impact of distance on packet loss, measurements were taken at two average separation ranges from the base station: 10–15 cm and 100–200 cm.

Table 1 – **Packet Loss Under Different Conditions and Operating Modes of Sensors**

Test	Testing Conditions				Packet Loss (%)	
	Num-ber of Modu-les	Distanc e (cm)	Packet Trans-fer and Cashing	Ob-stacle	Max	Min
1	1	10	-	-	0,113	0,049
2	4	10-15	-	-	3,249	1,001
3	4	10-15	-	+	15,490	4,365
4	4	10-15	+	-	0,383	0,145
5	4	10-15	+	+	0,966	0,378
6	4	100-200	-	-	14,855	6,152
7	4	100-200	-	+	25,911	6,784
8	4	100-200	+	-	0,949	0,204
9	4	100-200	+	+	2,152	0,816

Additionally, an obstacle was deliberately introduced between the station and the sensors to partially obstruct line-of-sight, effectively simulating the periodic occlusion of sensors by the human body.

Conclusions

Wearable electronic devices enable the study of human biomechanics in everyday life, rather than just in laboratory conditions.

Based on the results of the tests, it can be noted that the proposed algorithm for packetization and caching of IMU data reduces the packet loss percentage when using the ESP-NOW protocol by approximately 10 times. The average packet loss does not exceed 1% of the total number, and the use of the proposed algorithm also allows for nearly eliminating cases where data loss from a single module becomes significant and exceeds 10% (see the maximum packet loss column in Table 1).

At the same time, if the working communication channel is overloaded by more than 90%, packet losses significantly increase. Therefore, future studies should focus on developing an algorithm and procedure for automatically selecting the least congested channel during the system initialization phase, which will improve the reliability of its operation in challenging radio frequency conditions.

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Алгоритм роботи та програмно-апаратна реалізація мікропроцесорної системи моніторингу начіпних біомедичних сенсорів із застосуванням протоколу ESP-NOW

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Анотація. У статті представлено програмно-апаратну реалізацію мікропроцесорної розподіленої системи моніторингу біомеханіки руху людини із застосуванням бездротового зв’язку для оперативної передачі даних. Основною метою роботи є створення енергоефективної, надійної та недорогої системи, здатної автономне збирати, передавати, синхронізувати та зберігати дані з інерційних сенсорів у режимі реального часу. Запропонований підхід базується на використанні мікроконтролерів ESP32, які можуть здійснювати прямий обмін даними за допомогою протоколу ESP-NOW. Він забезпечує високошвидкісний та оперативний обмін даними без встановлення з’єднання, низькі затримки, високу швидкодію та зменшене енергоспоживання. Створено функціональний прототип системи, що включає базову станцію та набір сенсорних модулів з автономним живленням від акумулятора. У роботі розроблено спеціалізований алгоритм синхронізованої передачі даних, що включає пакетування відліків інерційних вимірювальних вузлів (IMU) та кешування інформації з використанням циклічної черги. Це дозволяє суттєво зменшити втрати пакетів навіть в умовах перешкод та високого навантаження на канал. Описано механізм обробки втрат, повторного надсилання даних, а також способи синхронізації годинників і підтримки неперервної нумерації пакетів після перезавантаження модулів чи базової станції. Проведено серію тестувань у різних режимах роботи, з різною кількістю модулів, на різних відстанях та в умовах із перешкодами. За результатами експериментальних досліджень встановлено, що середній рівень втрат пакетів при використанні запропонованого алгоритму не перевищує 1%, а ймовірність значних втрат (понад 10%) зводиться практично до нуля. Також підтверджено стабільну роботу системи в реальних умовах та можливість масштабування до 20 модулів. Отримані результати свідчать про ефективність і доцільність застосування протоколу ESP-NOW у розподілених біомедичних IoT-системах, орієнтованих на моніторинг рухової активності, реабілітацію пацієнтів, дослідження біомеханіки людини та підтримку адаптації протезів.

Ключові слова: біомеханіка; начіпна електроніка; інерційні сенсори; бездротовий зв’язок; ESP-NOW; пакетування даних; кешування; розподілена система; моніторинг.