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HARDWARE AND SOFTWARE OF THE "SMART" BOAT OAR FOR THE APPLIED FORCE MEASUREMENT SYSTEM

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Assessment of the volume and quality of a rower's efforts during training plays an important role in preparing for competitions and improving his results. The article reviews existing commercial solutions, such as rowing simulators and individual sensor devices. It was determined that such proposals allow recording the frequency or trajectory of movement, but do not measure force. They also have limited functionality in real water conditions or high cost. Therefore, it is proposed to bring rowers' training into the realm of modern technologies for measuring and analyzing information in real time. For this purpose, a device mounted on an oar for numerically assessing individual aspects of rowing technique and corresponding software are proposed. Approaches to creating an embedded system for measuring force, orientation, and vibration response of an oar are investigated. The hardware part of the device is developed based on the Seeed XIAO nRF52840 board with low power consumption, built-in Bluetooth, accelerometer, and gyroscope. A strain gauge in combination with an analog-to-digital converter HX711 was used as a force sensor. The disadvantages of previous solutions based on Arduino Nano and the HC-05 module are described, in particular, high power consumption, unstable communication, and non-compliance with modern requirements. The choice of a real-time operating system is described. The capabilities of Zephyr OS, FreeRTOS, and Mbed OS are compared. FreeRTOS is preferred as a system with a minimalist kernel sufficient for flow control and stable operation of sensors in real time. The device's power consumption in different modes is analyzed. The use of sleep modes for the microcontroller, sensors, and other components is proposed. A battery discharge curve is constructed that takes into account the nonlinear relationship between voltage and residual charge, which allows for accurate determination of the charge level in field conditions without external indicators. The article also describes the principle of device calibration. A multi-point force calibration method with interpolation between key points is presented.

Keywords - Embedded, IoT, Bluetooth®, Realtime OS, microcontroller board, training evaluation, force measurement,

Problem statement

Quantitative and qualitative assessment of an athlete's efforts during training is an important part of the process of preparing for competitions and improving their own results.

In fact, the success of a team or individual rowers in competitions depends on three main factors: their physical strength, endurance, and compliance with the technique of movements.

Devices for measuring rowing statistics are divided into two types: stationary and mobile. Stationary devices act as exercise machines installed in sports halls, allowing you to simulate rowing movements and measure certain sports parameters. RowErg rowing machines (Sybertz, n.d., 2023) from Concept2 dominate this category. However, stationary simulators are not able to fully reproduce the circumstances of real competitions on the water. The conditions of real boat movement with other team members on board, wave resistance, coordination and synchronicity of actions, real physical movement over a distance and other real factors are very important for training. In addition to the purely physical difference between training in the water and on stationary simulators, there is also a psychological factor of teamwork, as well as observation of the surrounding environment during training. For these trainings, there is a type of device specifically designed to measure the performance of rowers during training in the water. For example, Waaka Cadence (Vaaka Ltd., n.d.) – the device is attached to the oar and measures the frequency of the rower's movements, has the ability to connect to an application for a smartphone or smartwatch. However, this device does not measure the applied force. There is also POD PaddleMate (Paddlemate Kft., n.d.) – the device consists of two components: a base and a capsule. The base is attached to the oar with superglue and contains a load sensor. A capsule containing the main processor, accelerometer and gyroscope is inserted into the base. The battery life is 5 hours. It connects to the smartphone app via Bluetooth. However, it should be noted that the superglue mount and the relatively short length of the device may lead to measurement distortions in the long term and require regular recalibration of the sensor. Also, equipment that can be temporarily installed on a boat to collect statistics during a full-fledged training session is expensive and usually requires calling a team of specialists to take measurements.

Therefore, at the moment, most rowing training on the water takes place without the ability to assess the rower's performance in specific numbers. Coaches have to rely only on their own vision and feeling of how much effort the athlete puts in to achieve the result. The situation is complicated by the fact that rowing is a team sport, where there are 6 (and sometimes more) rowers in one boat, who must be monitored at the same time.

Analysis of Recent Studies and Publications

The article by Hohmuth et al. (2023) describes a wireless rowing measuring system (WiRMS). It is capable of measuring the oar bending as well as the pressure applied by the fingers of a rower. It also collects the acceleration information, resulting in comprehensive and wide statistical analysis. The research by Labbé et al. (2019) analyses the relations between oar length, blade size and overall rowing efficiency. The results show that to go fast without paying attention to the energy consumed, short oars with big blades are a good fit. But if minimizing required power is an important factor, then using long oars with smaller blades is a better option. he article by Ungricht et al. (2023) conducts a testing of FlexOmega oar bending measuring system and states that the system is precise enough to be used in evaluation of rower’s performance. It demonstrates that strain gauges can effectively measure the desired parameters in this application. The research by Holt et al. (2020) shows that the greatest modifying effects were found for stroke rate, mean and peak force, and power output before adjustment, and for catch angle after adjustment for stroke rate and power. The research was conducted on multiple athletes of female and male sexes, as well as pairs of athletes. The article by Held et al. (2020) concludes that the stroke rate had a high impact on WPS (work-per-stroke) during boat measurement, compared to no high impact during ergometer-measurements. This demonstrates that ergo machines are not capable of fully representing real on-water conditions. The article also states that is it hard to find an optimum stroke rate, gearing and drag factor for maximum power in rowing. The research by Lintmeijer et al. (2018) concludes that rowers’ power output was underestimated with 12.3 % on average when determined using the common proxy, which is to estimate on-water power output as the time average of the dot product of the moment of the handle force relative to the oar pin and the oar angular velocity. The article by Mpimis et al. (2023) describe the system aims at recording critical kinetic and kinematic parameters for sport performance evaluation and rowing technique improvement, but only for one person.

Thus, the development of a system for measuring the applied force and spatial orientation of a oar with Bluetooth communication is an urgent task. The proposed system can also be useful in the process of rehabilitation of the musculoskeletal system. Since during the rehabilitation process it is important to correctly dose the load on the muscles and joints in order to avoid overexertion or injury. The force measurement system will allow an objective assessment of the patient's efforts, which helps doctors and physiotherapists adjust the training program in real time.

Formulation of the Article’s Objective

Therefore, the goal of the work is to improve the efficiency of the coach's assessment of the personal athletic skills of rowing team members by introducing a system for measuring the applied effort, spatial orientation and vibration response of the oar with Bluetooth communication. The main requirements are to create a cheap, compact, reliable and energy-efficient system that could be installed on rowers on a permanent basis, so that each rower's performance could be assessed in specific numbers at each training session. The device must withstand immersion in water, be frost-resistant, and not require frequent recharging or other maintenance.

Main Results

System modeling

Analysis and justification of the main hardware components of the system

Initially, for the development of the prototype, the Arduino® hardware platform was chosen (Arduino® Nano (Arduino S.r.l., n.d.)). Since the board lacks a Bluetooth® module, an external module - HC-05 (Guangzhou HC Information Technology Co., Ltd., n.d.) was selected for communication.

The applied force is measured using a strain gauge sensor. The working principle of this sensor is as follows: a flexible strain gauge is mounted on a resilient element (usually metal). When the resilient element is loaded, micro-deformation of its surface occurs, causing deformation of the attached strain gauge. The deformation of the strain gauge, in turn, results in a proportional change in resistance, from which the fact and degree of deformation of the resilient element can be determined. The applied force is calculated using the formula $F = kx + s$, where s is the linear offset of the strain gauge (tare), k is the multiplication coefficient for converting from arbitrary units to real physical units, and x is the raw measured value. The determination of s and k is carried out through calibration, first without load (s), and then with a known load on the oar blade (k). The measurement error is ±5 % relative to the ideal calibration values.

Since the change in resistance during the deformation of the shaft is slight, the HX-711 (SparkFun Electronics, n.d.) board is used, which serves as an amplifier and an analog-to-digital converter.

A test model of the device was developed, allowing measurement of the load, calculation of the basic offset (tare), and calibration coefficient (divider). After experiments with the test model, the following conclusions were made. The HX-711 ADC meets the requirements for measurement accuracy and stability. In combination with a 20 kg strain gauge, the "noise" range is <10 g after calibration. The increase in "error" with an increase in weight is insignificant and can be corrected using multiple calibration dividers for different loads. The HC-05 module does not meet the requirements for stability and the overall communication model. The communication being via UART and control using AT commands leads to a large number of incorrectly transmitted bytes, slow and unreliable command execution. The situation is further complicated by the fact that the module does not adhere to the BLE standard specification regarding the communication model by dividing data streams into services and characterristics. The Arduino Nano board also does not meet the project's needs, as it has too big power consumption (~40 mA) for this application, a relatively slow processor (16-bit with a frequency of 16 MHz), and lacks accelerators for crypto operations necessary for message authentication.

Since the use of Arduino for the selected task showed shortcomings, the following directions for evaluating components were established for the subsequent selection of the board. Since rowing conditions do not allow convenient recharging of the battery, its frequency should be reduced to a minimum. Therefore, low power consumption is important. Ideally, this should be once every two weeks or less, depending on the characteristics of power consumption. The approximate capacity of the battery is 3000 mAh. Since the integrity of the transmitted data is a decisive factor in the operation of the device, and the external Bluetooth module demonstrated unreliability and low controllability, it was decided to consider only boards with built-in Bluetooth modules.

The analysis of widely available Arduino Nano 33 BLE, Seeed XIAO ESP32C3, Seeed XIAO nRF52840 boards was carried out. The comparison is presented in Table 1.

Table 1

Comparison of potential main board characteristics

Characteristic	Arduino Nano 33 BLE	Seeed XIAO ESP32C3	Seeed XIAO nRF52840
Active state power consumption	30 mA	100 mA	1-2 mA
Sleep power consumption	20 uA	4 mA	5-10 uA
Dimensions	45 mm x 18 mm	21 mm x 17.5 mm	21 mm x 17.5 mm
Chip	nRF52840	ESP32-C3	nRF52840
Architecture	ARM 32 bit	RISC-V 32 bit	ARM 32 bit
Frequency	64MHz	160 MHz	64MHz
Memory	1MB Flash, 256KB SRAM	400KB SRAM, 4MB Flash	1MB Flash, 256KB SRAM, 2 MB QSPI flash
Communications	UART, SPI, I2C, PWM, ANALOG, DIGITAL	UART, SPI, I2C, PWM, ANALOG, DIGITAL	UART, SPI, I2C, PWM, ANALOG, DIGITAL
Bluetooth® antenna	Embedded	External (included)	Embedded
Crypto function accelerators	AES, ChaCha, SHA1, Sha2, RNG, HMAC, RSA, ECC	AES, SHA1, SHA2, RNG, HMAC, ECC	AES, ChaCha, SHA1, Sha2, RNG, HMAC, RSA, ECC
Additional functions	Embedded LSM9DS1 accelerometer, gyro and compass	Embedded WIFI-module, OTA-updates functionality	Embedded LSM6DS3 accelerometer and gyro

Considering ultra-low power consumption, built-in Bluetooth® module and antenna, compact dimensions, built-in accelerator of SHA and HMAC-operations, built-in gyroscope, accelerometer and voltage level reader, Seeed XIAO nRF52840 is chosen as the most optimal option among analogs.

Analysis and justification of the main software components of the system

Single-threaded cyclic execution of instructions is not a desirable operational model for the device, as it has several disadvantages. Firstly, delays in obtaining readings from individual sensors halt the entire system's operation. For sports involving fast movements, such delays are a critical issue, as they may result in the analysis of entire segments of the rower's actions not being performed. Secondly, there is no ability to predict a strictly fixed periodicity for the execution of specific instructions. For certain tasks, such as calculating the orientation of the oar in space using gyroscope and accelerometer data, a high frequency and fixed periodicity of calculations are crucial for their accuracy.

For comparison, the following widely used real-time operating systems were selected: Zephyr OS (The Linux Foundation, 2024), FreeRTOS (Amazon.com, Inc., n.d.), Mbed OS (Arm Holdings plc, n.d.). A comparison of the characteristics of these systems is presented in Table 2.

Table 2

Comparison of realtime operating systems

Characteristic	Zephyr OS	FreeRTOS	Mbed OS
Developer	Linux Foundation	AWS	Arm
Architecture	ARM, x86, RISC-V, MIPS, SPARC	ARM, AVR, x86, RISC-V	ARM (Cortex-M)
Thread time splitting	Preemptive / Cooperative + priorities	Preemptive round-robin + priorities	Round-robin + priorities
Kernel type	Microkernel until v.1.6, now monolithic	Microkernel	Hybrid
State	Active development	Active development	Maintenance

Mbed OS was rejected due to the low number of supported architectures (which would make it difficult to potentially port to other platforms if needed) and the partially abandoned state of the project. Although updates are released for this OS, there have been no big improvements or changes for several years, and the developer audience is gradually moving to other OSes.

Choosing between Zephyr OS and FreeRTOS is a more difficult task. Zephyr OS is a more comprehensive system with more configuration options and a more advanced kernel. FreeRTOS focuses specifically on the microkernel, it is plainer and more minimalistic. Since, in fact, only thread management solution is required from the OS to perform the tasks of this device, a choice was made in favor of FreeRTOS.

Analysis and justification of the communication components of the system

The distinctive feature of the implementation of the "smart" oar is that the oar is a public device. It does not belong to a specific rower, but is attached to the boat and can be used by anyone who wants to start training with it. This condition does not allow using the built-in Bluetooth pairing function, since this function: slows down the initial connection to the oar, starts displaying a system dialog, and also leaves the oar in the list of known devices on the smartphone. This is problematic for users connecting to a large number of different oars and not wanting to see them in the list of known devices.

Factors complicating signal transmission include the presence of at least 5 identical oars within a radius of several meters and the location of the antenna inside the oar body, partially blocking radio waves. A popular communication method for public devices is the integration of mobile communication modules. However, in the case of "smart oars", this technology is not optimal in terms of either energy consumption or stability under conditions of use. Table 3 compares the key aspects of mobile communication compared to the Bluetooth® Low Energy (BLE) protocol.

Table 3.

Comparison of BLE and LTE/GSM protocols

Method	Data path	The time of data arrival on the smartphone	Use at 1 km from the shore	Power consumption
BLE	Oar – smartphone	< 100 ms	Possible (on smartphone)	low
LTE/GSM	Oar – base station – smartphone	From 200 ms, worsens with increasing distance from the base station	Complicated	high

The BLE protocol was chosen for communication with the "smart" oar because it meets a number of needs that mobile communication methods could not satisfy. It is worth noting that we are talking about BLE - an updated version of the technology, characterized by low energy consumption and other methods of building communication. BLE is the optimal alternative that allows you to compensate for most of the shortcomings of LTE / GSM.

Developed system

As a result, a system for measuring the applied force, movement and vibration response of a oar with Bluetooth communication was obtained, consisting of the following components:

- the sensors module on the oar (nRF52840 controller, gyroscope + LSM6DS3 accelerometer, HX711 ADC, strain gauge);
- the subsystem for the operation of the "smart" oar;
- the mobile application for processing and visualizing data from the "smart" oar.
- Device software was developed using the C++ programming language, Arduino SDK and nRF52840 SDK, with SoftDevice software component.

To track and visualize the data received from the "smart" oar, a cross-platform mobile application was developed using the Flutter framework. Built-in mechanisms of the Android and iOS operating systems were used to communicate with Bluetooth devices. Data coming from the oar to the application is immediately sent to the server via a TCP socket. The server code is written in Dart for unification with the mobile application. The PostgreSQL database is used to save user data and achievements, as well as to save information about assigning oars to boats.

Experimental research

Sensor calibration

The current oar model is equipped with a strain gauge, an accelerometer and a gyroscope. Load cell tare calibration and gyroscope calibration are combined into one rest calibration function. The user needs to leave the oar stationary. The idle calibration process takes 5 seconds. During this time, the oar constantly records the measured readings of the strain gauge and the gyroscope. At the end of the sampling period, the average value of each of the readings is used to calculate the corresponding calibration parameters.

Finding the multiplication factors for a known weight is a more complicated process. At least in the particular model of strain gauges used in the par, one multiplication factor is not enough to construct a correct graph. Sensor readings are not completely linear. Instead, they gradually deviate with increasing applied force. Since the oar must measure both a 5 kg load and a 100 kg load with the same accuracy, the ability to set several key points of the multiplier calibration has been added. For each point, the administrator sets a known weight, attaches this weight to the handle of the oar, waits 5 seconds, and the oar itself calculates such a multiplication factor that will reduce the value measured during calibration to the desired weight. Between key points, the calibration factor is linearly interpolated to prevent "jumping" readings when passing through key points. The degree of interpolation and the nearest key points are chosen based on the raw values measured by the strain gauge.

Power consumption

The built-in function is used to monitor the charge level by obtaining the voltage at the input pins. As the battery discharges, the voltage level decreases, allowing the calculation of the charge level based on this parameter. Since the voltage change during battery discharge is not linear, a curve was measured and plotted to reflect the real relationship between voltage and the remaining charge level in the battery (Fig. 2).

This curve is used to calculate the actual percentage of oar charge, providing users and water station personnel with an understanding of how many days of operation can be expected from it.

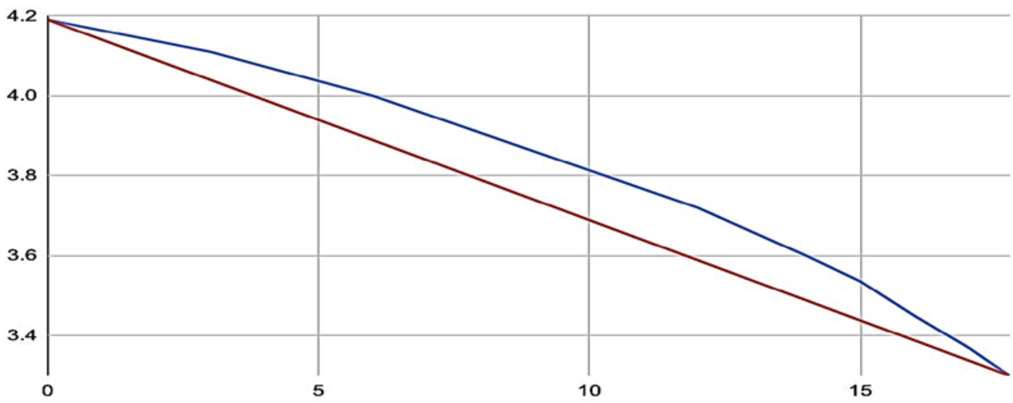

Fig. 1. Battery discharge curve x axis – days without recharging,
y axis – battery voltage, blue line – measured curved values, red line – perfect linear values

The usage specification of smart oars involves their operation in a cold and humid environment. Regular recharging of the device's batteries or regular recalibration of its sensors is also not easy. The following software methods are used to optimize the device's energy consumption:

- the 2-second interval between sending oar advertisement packets when no device is connected to it;
- transition of threads into sleep $mode and minimization of the number of operations performed by the device without necessity;
- utilization of built-in sleep modes in nRF52840, HX711, and LSM6DS3 for power use reduction.

Conclusions

During rowing team training, it is important to evaluate the force application of each athlete. For this purpose, a system was developed that allows measuring the main characteristics of interaction with the boat oar during training. The basis of the system is a "smart" oar - a unique device based on a set of sensors, the data from which is then transmitted via Bluetooth technology to mobile devices with the appropriate software for analysis and visualization.

Development of prototypes and research have shown that the most optimal option for creating a "smart" oar is the Seeed XIAO nRF52840 board. This option was chosen because the board has low power consumption, a built-in Bluetooth module and antenna, compact dimensions, a built-in SHA and HMAC accelerator, a built-in gyroscope, accelerometer and voltage level reader. FreeRTOS was chosen as the operating system. A watchdog timer was used for the automatic restart of the controller in case of a critical error, although the occurrence of such errors is unlikely. Scalability for a large number of simultaneously used devices and protection against radio interference is achieved through the characteristics of Bluetooth itself, which includes mechanisms for filtering and channel switching to maintain communication in environments with a high number of identical devices nearby.

Experimental studies confirmed that, based on the selected components, the device meets the requirements, especially energy efficiency. The resulting "smart" oar can operate for months on a single battery charge, and its waterproof design makes it resistant to harsh environmental conditions. Thus, the proposed "smart" oar can be successfully used in a system for measuring applied force in real conditions. This system is initially important for training athletes. But it can also be further used to assess the applied force to determine the effectiveness of patient rehabilitation programs.

REFERENCES

Amazon.com, Inc. (n.d.). *About FreeRTOS Kernel*. Retrieved from https://www.freertos.org/RTOS.html

Arduino S.r.l. (n.d.). *Arduino® Nano Product Reference Manual*. Retrieved from https://docs.arduino.cc/resources/datasheets/A000005-datasheet.pdf

Arm Holdings plc. (n.d.). *Mbed OS Features Overview*. Retrieved from https://os.mbed.com/mbed-os/

Guangzhou HC Information Technology Co., Ltd. (n.d.). *HC-05*. Retrieved from https://www.sgbotic.com/products/datasheets/wireless/HC05_datasheet.pdf

Held, S., Siebert, T., & Donath, L. (2020). Changes in mechanical power output in rowing by varying stroke rate and gearing. *European Journal of Sport Science, 20*(3), 357–365. https://doi.org/10.1080/17461391.2019.1628308

Hohmuth, R., Schwensow, D., Malberg, H., & Schmidt, M. (2023). A wireless rowing measurement system for improving the rowing performance of athletes. *Sensors, 23*(3), 1060. https://doi.org/10.3390/s23031060

Holt, A., Aughey, R., Ball, K., Hopkins, W., & Siegel, R. (2020). Technical determinants of on-water rowing performance. *Frontiers in Sports and Active Living, 2*, Article 589013. https://doi.org/10.3389/fspor.2020.589013

Labbé, R., Boucher, J.-P., Clanet, C., & Benzaquen, M. (2019). Physics of rowing oars. *New Journal of Physics, 21*, 093050. https://doi.org/10.1088/1367-2630/ab4226

Lintmeijer, L. L., Hofmijster, M. J., et al. (2018). Improved determination of mechanical power output in rowing: Experimental results. *Journal of Sports Sciences, 36*(18), 2138–2146.

Mpimis, T., Gikas, V., & Gourgoulis, V. (2023). Rigorous and integrated on-water monitoring system for performance and technique improvement in rowing. *Sensors, 23*(13), 6150. https://doi.org/10.3390/s23136150

Paddlemate Kft. (n.d.). *Sensors – ThePaddleMate*. Retrieved from https://thepaddlemate.com/

SparkFun Electronics. (n.d.). *24-bit analog-to-digital converter (ADC) for weight scales*. Retrieved from https://www.digikey.com/htmldatasheets/production/1836471/0/0/1/hx711.html

Sybertz, A. (n.d.). The Concept2 RowErg rowing machine is a quality, no-frills pick for the seasoned rower. *CNN Underscored*. Retrieved from https://edition.cnn.com/cnn-underscored/reviews/concept2-rowerg-rowing-machine

The Linux Foundation. (2024). *Zephyr OS Overview*. Retrieved from https://zephyrproject.org/wp-content/uploads/sites/38/2024/01/Zephyr-Overview-20240110.pdf

Ungricht, C., Graf, C., et al. (2023). Validation of a novel instrumentation (FlexOmega system) measuring oar bending moments on-water in rowing. *Current Issues in Sport Science (CISS), 8*, 009. https://doi.org/10.36950/2023.1ciss009

Vaaka Ltd. (n.d.). *Vaaka Cadence Sensor*. Retrieved from https://www.vaakacadence.com/

АПАРАТНЕ Т А ПРОГРАМНЕ ЗАБЕЗПЕЧЕННЯ“РОЗУМНОГО” ВЕСЛА ДЛЯ СИСТЕМИ ВИМІРЮВАННЯ ПРИКЛАДЕНОЇ СИЛИ

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Оцінка обсягу та якості зусиль весляра у процесі тренування відіграє важливу роль у підготовці до змагань та покращенні його результатів. У статті розглянуто існуючі комерційні рішення, такі як гребні тренажери та окремі сенсорні пристрої. Визначено, що такі пропозиції дозволяють фіксувати частоту або траєкторію руху, але не вимірюють силу. Також вони мають обмеженість функціональності в реальних умовах на воді або високу вартість. Тому пропонується вивести тренування веслярів у площину сучасних технологій вимірювання та аналізу інформації у реальному часі. Для цього пропонується пристрій, що встановлюється на весло для

чисельної оцінки окремих аспектів техніки веслування та відповідне програмне забезпечення. Досліджено підходи до створення вбудованої системи вимірювання сили, орієнтації та вібраційного відгуку весла. Розроблено апаратну частину пристрою на основі плати Seeed XIAO nRF52840 з низьким енергоспоживанням, вбудованим Bluetooth, акселерометром і гіроскопом. У якості датчика сили використано тензодатчик у поєднанні з аналого-цифровим перетворювачем HX711. Описано недоліки попередніх рішень на основі Arduino Nano та модуля HC-05, зокрема високе енергоспоживання, нестабільність зв'язку та невідповідність сучасним вимогам. Описано вибір операційної системи реального часу. Порівняно можливості Zephyr OS, FreeRTOS та Mbed OS. Перевагу надано FreeRTOS як системі з мінімалістичним ядром, достатнім для управління потоками та стабільної роботи сенсорів у реальному часі. Проведено аналіз енергоспоживання пристрою в різних режимах. Запропоновано використання режимів сну для мікроконтролера, сенсорів та інших компонентів. Побудовано криву розрядки батареї, яка враховує нелінійний зв'язок між напругою та залишковим зарядом, що дозволяє точно визначати рівень заряду в польових умовах без зовнішніх індикаторів. Також у статті описано принцип калібрування пристрою. Наведено методику багатоточкового калібрування зусиль з інтерполяцією між ключовими точками.

Ключові слова – вбудовані системи, Інтернет речей, Bluetooth®, операційна система реального часу, мікроконтролерна плата, оцінка тренувань, вимірювання сили