Arduino-based triaxial measurement system for vibration monitoring in mobile machinery*

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Abstract

Vibration is one of the primary causes of damage and loss of functionality in engineering structures during operation. Early detection and monitoring of vibrations can significantly reduce the risk of structural failure and prevent accidents. This paper presents the design and implementation of a compact measurement and recording system (MRS) for registering three-axis vibration accelerations in selected nodes of load-bearing structures of mobile agricultural machinery, such as combine harvester frames, sprayer booms, and tractor semi-trailers. The MRS integrates an MPU-6050 triaxial accelerometer with an Arduino Nano microcontroller, a DS1302 real-time clock module, and MicroSD data storage, providing autonomous operation, precise timestamping, and reliable data logging. Power is supplied via lithium-polymer batteries with voltage stabilization through a boost converter, and the system is housed in a lightweight, 3D-printed enclosure. The software architecture implements initialization, filename encoding, periodic data acquisition, and fault-tolerant storage routines, while the modular hardware design allows easy adaptation and replication. Testing with manual loading demonstrated the successful acquisition of vibration datasets with time-resolved measurements on all three axes. The proposed system ensures low operational mass, minimal influence on the monitored structures, and flexible configuration for real-time monitoring or subsequent data analysis, offering a cost-effective solution for field applications in vibration measurement and structural health monitoring.

Keywords

vibration, triaxial accelerometer, measurement, embedded systems, Arduino, prototyping, coding, mobile machinery, agricultural machines, vehicles.

1. Introduction

One of the primary causes of damage and loss of functionality in engineering structures during operation is vibration. Early detection and monitoring of vibration processes can significantly reduce the probability of structural failure and prevent accidents.

The rapid advancement of digital technologies, the expansion of the microelectronics component base, and the availability of appropriate libraries enable the implementation of new approaches to vibration analysis, based on the development and application of microprocessor devices for vibration measurement and recording.

To design sufficiently functional and cost-effective devices for vibration acceleration registration, the use of an Arduino microcontroller in combination with an accelerometer – a three-axis digital acceleration sensor capable of measuring both static (gravity) and dynamic (motion, vibration) accelerations in three dimensions – appears to be highly promising.

These devices are often considered for developing inexpensive vibration analyzers. Many researchers have demonstrated that such paired devices exhibit satisfactory performance in vibration

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measurement and possess commercialization potential [1].

Such systems are increasingly applied in engineering (industrial equipment, automobiles, agricultural and aviation machinery), construction (bridges, buildings), medicine, experimental physics, and even music.

In particular, in [1] and [2], a low-cost vibration monitoring system was implemented using an Arduino Mega microcontroller and an ADXL345 accelerometer to detect anomalies in water pump operation. Vibration signals were sampled at 530 Hz and transmitted to cloud storage for analysis. Both Fast Fourier Transform and spectrogram techniques were applied to distinguish between normal and abnormal pump conditions. The results confirmed that this configuration provides an effective and economical solution for anomaly detection in rotating machinery.

In [3], a monitoring system for rotating machines was proposed based on lateral vibration measurements of a rotor–bearing setup. Vibration data were collected under normal and defective bearing conditions at different rotational speeds using accelerometers mounted on bearing brackets. An Arduino-based microcontroller transmitted the data to LabVIEW for processing and spectral analysis. The study demonstrated that the developed system can effectively identify bearing defects through vibration spectrum evaluation.

In [4], an online vibration monitoring system for rotating machinery was developed using a 3-axis MEMS accelerometer. The architecture integrates multiple Arduino microcontrollers for data acquisition and transfer, including vibration signals from accelerometers and rotational speed data from a TCRT5000 sensor. Wireless communication via NodeMCU enables real-time transmission to a computer, where data are processed and visualized in LabVIEW. Experimental results demonstrated stable data transfer with an average delay of less than 200 ms, confirming the system's suitability for real-time monitoring of machine vibrations.

In [5], an artificial neural network (ANN)-based fault diagnosis system was developed for a pulley–belt rotating setup. Vibration signals were acquired using two MEMS accelerometers (ADXL335) connected to an Arduino Mega 2560 and processed in LabVIEW to extract time-domain features, including root mean square, kurtosis, and skewness. The ANN model was trained to classify healthy operation and five fault types, such as pulley unbalance, belt wear, and misalignment. Experimental results demonstrated the system's high accuracy and reliability in detecting multiple fault conditions.

In [6], an Arduino-based vibration monitoring prototype was developed using four ADXL345 triaxial accelerometers. The system integrates an Arduino Mega, Wi-Fi module, and LCD display to acquire, analyze, and validate vibration data against a reference device. Collected measurements are transmitted wirelessly for further inspection and can be stored on a personal server for extended analysis. The results demonstrate the effectiveness of the setup in detecting structural vibrations and assessing their potential impact on machinery and buildings.

In [7], an Arduino-based accelerometer toolkit was developed to support undergraduate education in civil engineering, particularly for seismic response analysis of structures. The system, built with an Arduino Uno, ADXL345 MEMS accelerometer, and microSD card module, enables vibration data acquisition, storage, and visualization. A total of 15 devices (ACCE_edu) were produced for classroom use, integrating Arduino and Python programming for data processing, filtering, and analysis. The toolkit enhances practical learning by allowing students to directly measure and interpret structural vibrations, thereby reinforcing earthquake engineering concepts.

In [8], a short-span footbridge in Barcelona was instrumented with four Low-cost Adaptable Reliable Accelerometers (LARA) to evaluate the feasibility of Arduino-based devices for Structural Health Monitoring (SHM). The system addressed common drawbacks of low-cost sensors by introducing automated data acquisition, wireless synchronization, and systematic data management. Operational Modal Analysis (OMA) was performed using Frequency Domain Decomposition (FDD) and Covariance Stochastic Subspace Identification (SSI-cov), and the results were compared with a digital SAP2000 bridge model through the Modal Assurance Criterion (MAC). The measured eigenfrequencies showed strong agreement with those from a high-precision commercial sensor, confirming the reliability of the low-cost system.

In [9], a low-cost IoT-based system was developed to measure the frequency of hand tremors with high precision. Flex sensors detected finger bending, while an accelerometer and gyroscope measured vibration and angular position, respectively. An Arduino Pro Mini with an ESP8266 Wi-Fi module processed the raw sensor data to calculate tremor frequency, which was then transmitted to a cloud server. A web application, built with HTML, PHP, and MySQL, enabled remote monitoring by doctors, supporting medical assessment and patient care.

In [10], a novel Arduino-based hardware design was introduced for measuring liquid helium (LHe) levels in cryogenic experiments. The system detects thermoacoustic oscillations in a capillary tube using an accelerometer, automating the process of identifying level changes. Tests on 100 L and 120 L Dewars demonstrated a measurement error below 1 cm compared with standard niobium–titanium sensors. The approach offers a reliable and cost-effective alternative to conventional superconducting level sensors for LHe monitoring.

In [11], a tactile notification system for live-electronics performance was investigated using a display driven by an Arduino-controlled PWM signal with eccentric mass actuators. Physical measurements and user studies were conducted to evaluate vibrotactile perception thresholds and spectral characteristics. The results provided design guidelines to ensure robust perceptual discrimination between tactile stimuli, enabling improved tactile cue design within the CIRMMT Live Electronics Framework (CLEF).

In [12], a risk management methodology based on the use of geographic information systems, which provide the necessary tools and capabilities for collecting, analyzing and visualizing spatial data, is presented. A risk management system framework has been developed to ensure the safe operation of pipelines under geodynamic influences.

In [13], an approach to developing a computer system for automated construction of a basic ontology is presented. Mathematical support for the functioning of intelligent agents for planning activities based on ontologies is developed, which allows formalizing their behavior in the state space.

It should be noted that the majority of studies focus primarily on the analysis of accelerations in limited cases – either moving or stationary objects and processes. Research related to the development of devices for analyzing vibration accelerations in the load-bearing structural elements of mobile machinery is practically absent.

As presented in our earlier works [14–16], investigations of the load-bearing structural elements of mobile machines were carried out using a universal measuring system equipped with an analog-to-digital converter (ADC) providing eight channels in total: five universals, two for single-axis accelerometers, and one for angular velocity measurement. The system was powered either from an alternating current mains supply of 220 V at 50 Hz or from a direct current supply of 12 V.

However, the limited number of measuring channels, the absence of three-axis vibration acceleration registration, and other shortcomings of the universal measuring system somewhat constrained the authors in their studies of mobile machinery, for example, in conducting experimental investigations [17] aimed at assessing fatigue life of load-bearing structures [18].

Therefore, the objective of this work is to develop a measuring system for recording vibration accelerations at selected points of load-bearing structures of mobile agricultural machines, such as the frame of a harvesting combine, the boom of a field sprayer, or the chassis of a tractor or semi-trailer truck.

Such a measuring system should ensure reliable long-term registration of vibration accelerations and provide a sufficient number of measuring devices (around a dozen or even several dozens). The measuring devices, in turn, should be compact and lightweight, equipped with autonomous power supply, integrated data recording modules, and the capability for time synchronization.

2. Basic Diagrams

A compact measurement and recording system (MRS) has been designed, incorporating all the necessary functionalities for reliable acquisition of vibration acceleration data from the object under study. The MRS is intended to be cost-effective and easily replicable in the required quantities. The block diagram of the proposed measurement and recording system is shown in Fig. 1.

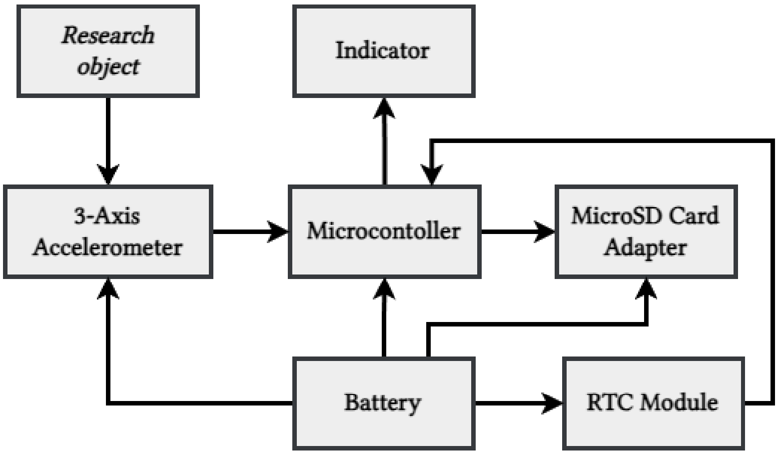

Figure 1: Basic block diagram.

Based on the block diagram shown in Fig. 1, a component diagram of the proposed MRS has been developed, representing all system elements and the interconnections between them (Fig. 2).

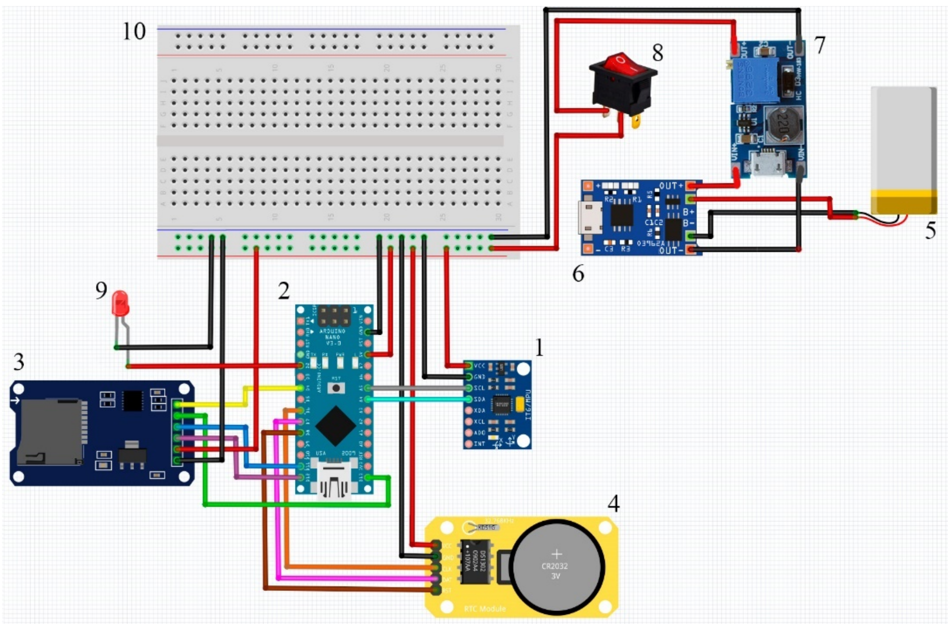

Figure 2: Basic component diagram.

The structural diagram of the MRS comprises the following components (Fig. 2 reference numbers):

1 – A motion tracking module that functions as a 3-axis accelerometer.
2 – A microcontroller development board, serving as the main computing platform.
3 – A module that enables data storage by interfacing with a MicroSD card.
4 – A real-time clock module used for precise timekeeping.
5 – Rechargeable Battery, that provides portable power supply for the system.
6 – A battery charging controller module used for safe recharging.
7 – A step-up power converter that increases voltage to the required level (5V).
8 – A simple two-position switch for turning the device on and off.
9 – A light-emitting diode used to indicate device operation.
10 – A breadboard for assembling and testing electronic circuits without soldering.

The proposed MRS architecture ensures the concurrent operation of multiple hardware modules, each dedicated to specific functions and integrated into a unified system. Each component is characterized by its functional purpose, interface of connection, and operational characteristics.

3. Prototyping

The prototyping of the MRS was carried out in several stages. At the initial stage, a prototype of the MRS was assembled on a breadboard, accompanied by the development of firmware for the microcontroller. Subsequently, a prototype of the casing was designed to accommodate the electrical and electronic components, taking into account their physical layout. Each prototyping stage is described in a separate subsection.

3.1. Breadbord Prototyping

Based on the component diagram shown in Fig. 2, a functional prototype of the MRS was assembled (Fig. 3).

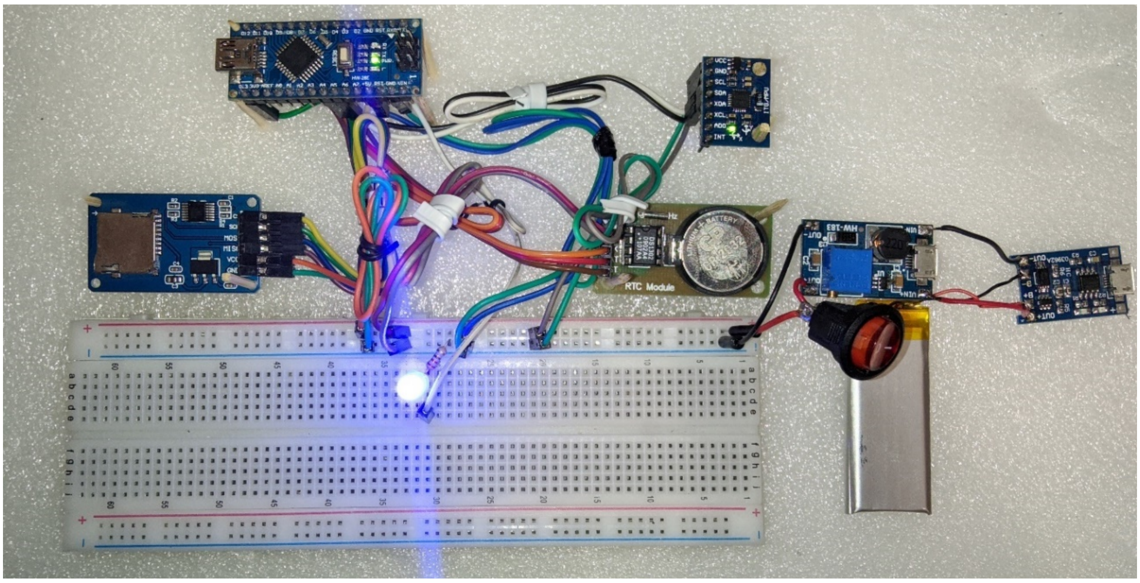

Figure 3: Breadboard prototype.

All components of the circuit were interconnected on a breadboard, which provided flexibility in testing and enabled unconstrained modifications without the need for soldering.

The primary sensor module of the system is the MPU-6050, which serves as a triaxial accelerometer. The module interfaces with the Arduino Nano microcontroller platform via the I^2C bus using the SDA and SCL lines. The accelerometer operates by measuring acceleration forces acting on the device (both static and dynamic), with a measurement range of ±2g to ±16g.

To maintain timestamps (used in file naming) and synchronization, the DS1302 RTC module was integrated, implementing real-time clock functionality. It is connected through a three-wire serial interface consisting of CLK, DAT, and RST signals, along with the VCC and GND power lines. Owing to its backup battery, the module ensures uninterrupted timekeeping even in the absence of primary power.

Collected data are stored on a MicroSD memory card through a dedicated adapter with an integrated voltage-level shifter. Data transfer is performed via the SPI bus, utilizing MOSI, MISO, SCK, and CS signals. The module enables data storage in file format for subsequent analysis.

The system is powered by a lithium-polymer battery of type 042048P (48×20×4 mm, 3.7V, 500 mAh) with an integrated protection circuit. To extend the operational time of the MRS, a 102050P battery (50×20×10 mm, 3.7V, 1000 mAh) may also be employed.

The battery is connected to a charging module based on the TC4056A controller via the B+ and B- pads. This module provides safe charging from an external power source.

Further power distribution is managed through the OUT+ and OUT- pads of the charging module, which are connected to the VIN+ and VIN- inputs of the MT3608 boost converter. This converter raises the battery voltage (3.7V) to a stable 5V required for the operation of the remaining modules. The OUT+ and OUT- outputs of the converter supply power to the microcontroller, sensor modules, the MicroSD adapter, and auxiliary elements.

A two-position power switch is integrated into the supply chain, enabling the system to be switched on and off. An indicator LED is used to provide visual feedback on the operational state.

The system implements the following communication interfaces:

- I^2C bus – for interfacing with the MPU-6050 module;
- SPI bus – for data exchange with the MicroSD adapter;
- Three-wire serial interface – for communication with the DS1302 RTC module.

Thus, the system architecture provides autonomous power supply, data acquisition and processing from sensors, incorporating real-time clock information for file naming, and data storage on a memory card for subsequent processing.

3.2. Case Prototyping

For the convenience of use and to protect the electronics of the MRS from external mechanical influences, it is necessary to place the system in a compact enclosure.

The most efficient method of prototyping such an enclosure at present is the development of its 3D model followed by additive manufacturing on a 3D printer. A specialized CAD package, SOLIDWORKS, was employed for the design of the 3D model (Fig. 4).

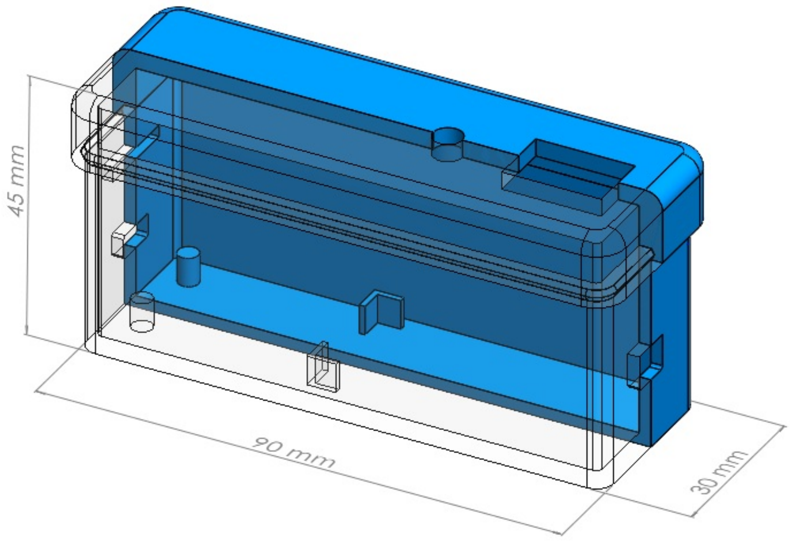

Figure 4: Enclosure prototype (longitudinal section).

Structurally, the enclosure (Fig. 4) consists of a box and a lid, which is fixed onto the box by means of a sealing flange located along the entire perimeter of the upper outer edge.

The end surfaces of the box include openings that provide access to MRS connectors. On one side, a single opening is provided for the microcontroller connector, while the opposite side contains two shaped openings for the battery charging board and the memory card slot. The lid is equipped with two openings for the LED indicator and the switch.

On the inner bottom surface of the box, mounting elements are provided to securely fix the accelerometer and the battery. The battery holder is designed to accommodate two types of batteries, namely 042048 and 102050. The remaining MRS components are mounted inside the box using additional elements such as standoffs.

The overall dimensions of the enclosure are 90×45×30 mm, with a wall thickness of 2 mm.

The enclosure was fabricated using a 3D printer with PLA-filament as the printing material.

3.3. Measuring-Recording System Prototyping

During the development of the prototype of the MRS, particular attention was paid to the compact arrangement of its components. The layout was designed to minimize the overall dimensions of the system while maintaining sufficient clearance between components and wiring inside the enclosure to ensure reliability and ease of assembly.

Another essential consideration in the layout was the functional placement of individual elements. Specifically, the accelerometer, as the primary sensing element, was rigidly mounted to the bottom of the enclosure, since the underside of the case serves as the mounting interface to the surface of the test object. The battery, being the heaviest component, was also fixed to the base to enhance structural stability. The microcontroller was positioned with its pins facing upward, facilitating convenient wire routing. The toggle switch and indicator LED were placed on the top cover to provide unobstructed access during experiments.

The schematic of the MRS prototype is presented in Fig. 5.

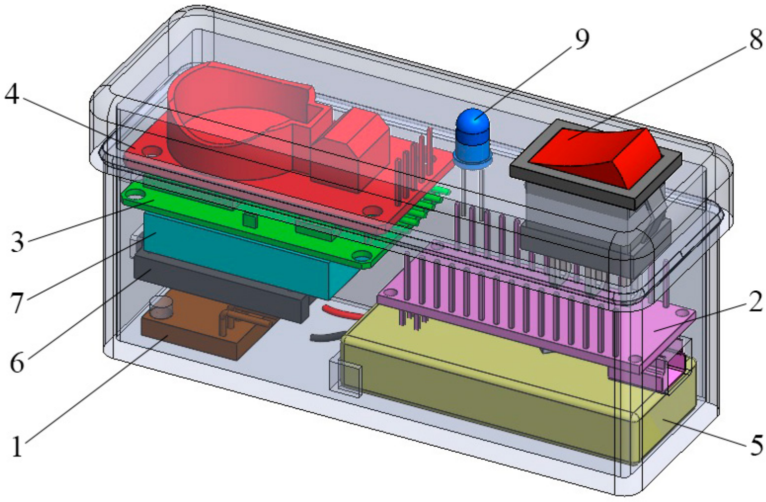

Figure 5: MRS prototype diagram.

The reference numbers of the components in Fig. 5 correspond directly to those shown in Fig. 2. The overall appearance of the completed MRS prototype is illustrated in Fig. 6.

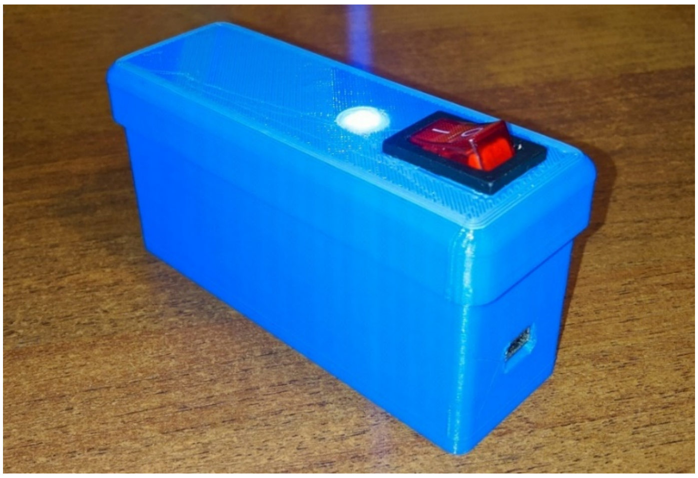

Figure 6: MRS prototype.

Weight measurements of the enclosure (Fig. 7a) and the fully assembled prototype (Fig. 7b) demonstrated that the operational weight of the device is approximately 100 g. when equipped with a 500 mAh battery, with the enclosure accounting for approximately 40% of the total mass.

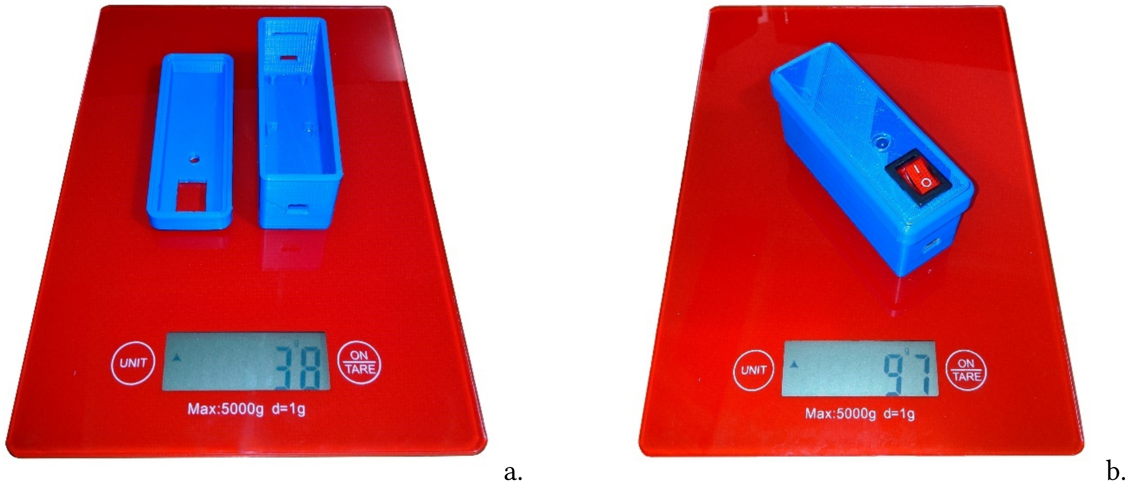

Figure 7: Case weight (a) and measuring system weight (b).

Such a relatively low weight ensures that the developed MRS does not introduce significant errors in vibration acceleration measurements when mounted on sufficiently massive and rigid structural elements of mobile agricultural machinery.

4. Coding

The software of the system was developed for the Arduino Nano microcontroller platform utilizing the Alash_DS1302 library (for RTC operation), the MPU6050 library (for accelerometer interfacing), as well as the standard SPI.h and SD.h libraries for memory card interaction. Structurally, the program consists of three functional routines implemented as C functions: system initialization, filename generation, and the main execution cycle.

4.1. System Initialization

The initial configuration of all components is performed within the setup() function (Fig. 8).

```
void setup() {
  pinMode(DIOD_PIN, OUTPUT);
  digitalWrite(DIOD_PIN, 0);

  if (!SD.begin(chipSelect)) while (1);
  if (!rtc.begin()) while (1);

  myFile = SD.open(getEncodedFileName(), FILE_WRITE);
  while (!myFile) {
    myFile = SD.open(getEncodedFileName(), FILE_WRITE);
    delay(1000);
  }

  mpu.initialize();
  mpu.testConnection();

  mpu.setFullScaleAccelRange(MPU6050_ACCEL_FS_8);
  myFile.println("Accel: 8g");

  mpu.CalibrateAccel(6);

  delay(1000);

  timer_drop = millis();
  time_prev = timer_drop;
  time_start = timer_drop;

  digitalWrite(DIOD_PIN, 1);
}
```

Figure 8: System initialization.

Specifically:

- The indicator LED is configured as an output. At system startup, the LED remains off; upon successful initialization, it switches on, signaling system readiness.
- The SD card is initialized on the SPI bus with chipSelect = 4. If initialization fails, program execution halts in an infinite loop (while(1)), thereby preventing operation without accessible storage.
- The DS1302 RTC module is started via rtc.begin(). In case of an error, the program similarly enters an infinite loop, ensuring that no incorrect timestamps are used.
- A filename for data storage is generated using the getEncodedFileName() function.

The filename is encoded from the date and time in the format YYMMDDHH.MM (e.g., 25072314.05). This approach accounts for the FAT16/FAT32 file system limitation, which supports only short filenames (8 characters + dot + 3-character extension). Encoding the timestamp into the filename also resolves the absence of file-creation metadata on SD cards, enabling automatic chronological ordering when files are sorted by name. The file is opened in FILE_WRITE mode. If opening fails, the program retries every second until successful access is established, thereby improving fault tolerance in cases of delayed SD card readiness.

- The MPU6050 module undergoes initialization and self-test procedures (mpu.initialize(), mpu.testConnection()).
- The accelerometer measurement range is configured, e.g., ±8 g (mpu.setFullScaleAccelRange(MPU6050_ACCEL_FS_8)), providing a balance between precision and the ability to capture high accelerations.
- Accelerometer calibration is performed (mpu.CalibrateAccel(6)), compensating for hardware offsets of the sensor.

Upon completion of initialization, service information (e.g., “Accel: 8g”) is recorded into the file, and the initial timestamps are stored for subsequent logging.

4.2. Filename Generation

The system employs the auxiliary function getEncodedFileName() (Fig. 9), which generates a new filename for a data file on the SD card based on the current date and time.

```
String getEncodedFileName() {
  uint8_t hour, minute, second, day, month, wday;
  uint16_t year;

  while (!rtc.getDateTime(&hour, &minute, &second, &day, &month, &year, &wday)) {
    Serial.println(F("Помилка RTC! Повторна спроба..."));
    delay(500);
  }

  char encodedTime[13];
  snprintf(encodedTime, sizeof(encodedTime), "%02d%02d%02d%02d.%02d",
           year % 100, month, day, hour, minute);
  return String(encodedTime);
}
```

Figure 9: Implementation of the getEncodedFileName() function.

This compact encoding scheme stores the year, month, day, hour, and minute, thereby ensuring compliance with FAT16/FAT32 filename constraints, reducing memory usage through short strings, and maintaining chronological ordering of records without the need for additional metadata. To increase reliability, the function incorporates a retry loop with delays, which guarantees valid timestamp acquisition in cases of temporary read errors from the RTC.

4.3. The Main Execution Cycle

The main execution cycle of the program is implemented in the loop() function (Fig. 10).

```
void loop() {
  myFile.print(millis() - time_start);
  myFile.print('\t');

  mpu.getAcceleration(&ax, &ay, &az);

  myFile.print(ax);
  myFile.print('\t');
  myFile.print(ay);
  myFile.print('\t');
  myFile.print(az);

  if (millis() - timer_flush > 5000) {
    myFile.flush();
    timer_flush = millis();
  }
}
```

Figure 10: The main execution cycle.

Within this function, the algorithm for periodic data acquisition and storage is implemented as follows. First, the system logs the elapsed time since startup (millis() − time_start) into the output buffer. Second, the accelerometer data are acquired from the MPU6050 using the command mpu.getAcceleration(&ax, &ay, &az), providing acceleration components along the three axes. These measurements, together with the time values, are sequentially written to the buffer using the myFile.print() function at a rate of several hundred readings per second. The buffered data are formatted using tab delimiters, which facilitates subsequent import into analysis tools such as Excel or MATLAB. Finally, the actual writing of buffered data to the SD card occurs when the command myFile.flush() is executed every five seconds. This operation transfers the accumulated data from the output buffer to the file, thereby reducing the frequency of write operations and minimizing the risk of data loss in case of a sudden power interruption.

5. Results

During the testing of the developed MRS, a dataset was obtained that corresponds to the manual loading and shaking of the system (Fig. 11).

obtained data.txt

C: > Arduino > obtained data.txt

11069	52	12556	9012
11075	3180	15544	7392
11081	3532	-5404	9360
11087	2336	-7176	7108
11094	348	-8852	10500
11100	4180	-10528	4460
11106	-1656	-6776	25628
11112	-3052	-9108	19452
11118	-6120	-8400	28196
11124	-1188	-6484	18616
11130	-32	1724	29332
11136	1876	-5388	9016
11142	-124	-5036	14580
11148	-1000	-3096	15452
11154	136	-1452	18780
11160	-4680	-4036	26844
11166	9652	-1768	-2004
11172	-7920	-3552	22928
11179	-68	3612	22564
11185	680	1280	12996
11191	-448	1292	15408
11197	-324	1776	13860
11203	-564	2520	13024
11209	-252	2376	15604

Figure 11: Excerpt from raw dataset.

The acquired dataset consists of four columns: the first column contains the measurement time (in milliseconds); the second and third columns store data from the horizontal axes of the accelerometer (longitudinal and transverse, respectively); and the fourth column contains vibration acceleration values in the vertical direction.

The data format can be configured in a way that is convenient for further processing in specialized software to be used by the end user.

An example of a graphical representation of the raw data is shown in Fig. 12.

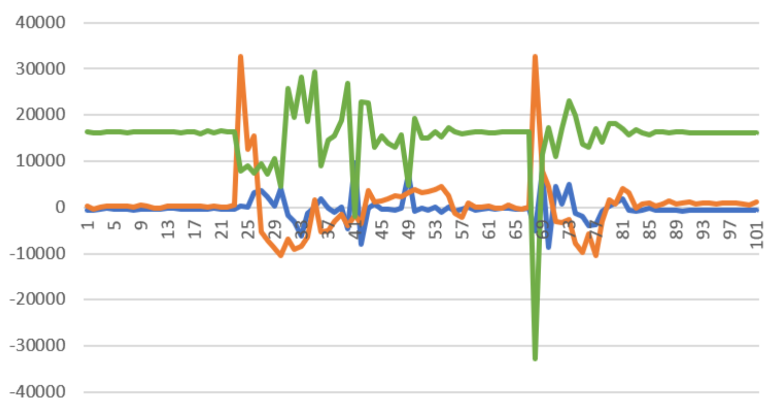

Figure 12: Time-domain plot of raw accelerometer data.

In addition, the firmware may implement a data processing algorithm, which can be customized according to the specific needs of the user.

6. Conclusion

The developed measurement and recording system successfully implements the functions described in this work, including autonomous power supply, acquisition and processing of acceleration data from the MPU6050 sensor, timestamped storage of measurements on a microSD card, and system status indication via an LED. The system enables reliable registration of vibration accelerations at specific nodes or structural elements of mobile agricultural machinery. Its compact size and low mass ensure minimal influence on the mechanical behavior of the monitored structures, while the modular design and flexible software architecture allow for straightforward adaptation and replication in larger-scale experiments or production units.

Declaration on Generative AI

The authors used Grammarly for grammar and spelling check. Additionally, the authors used X-GPT-4 to search for information regarding the characteristics and pinout of the MRS components. The author(s) did not use Chat-GPT-4 to generate text or images. After using these services, the authors reviewed and edited the content as needed and takes full responsibility for the publication's content.

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