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DESIGNING TOOLS FOR AUTOMATED DATA COLLECTION FOR IoT ROAD CONDITION MONITORING SYSTEMS

The object of the research is the data collection processes on road conditions in monitoring and maintenance systems based on Internet of Things (IoT) technologies. A concept of data collection and aggregation from sensors is proposed to ensure their effective processing at the IoT network edge, with the possibility of integration into smart city systems based on IoT. The proposed approach of automated data collection using embedded devices in vehicles enables dynamic monitoring of road conditions with minimal resource consumption. To implement the proposed concept, a complex of hardware and software has been developed in the form of an experimental prototype of an IoT road condition monitoring system. Experiments have proven that the proposed tools enable rapid response to road defects in any terrain, and the aggregated data format is appropriate for further analysis, including intelligent analysis. The proposed tools can be used in smart city maintenance systems to improve driving quality and prevent critical situations related to poor road conditions.

***Keywords**: IoT; SmartCity; monitoring system; road condition; STM32.*
Fig: 6. References: 16.

1. Introduction.

As modern technologies for device connectivity, big data processing, and intelligent analytics continue to advance, the Internet of Things (IoT) technology is developing and increasingly influencing society in all spheres of activity. Under the influence of the huge potential and capabilities of IoT, smart cities are rapidly evolving. The Internet of Things represents a relevant paradigm for the development of a new generation of smart cities, aiming to establish complex interconnections among all sectors within these cities.

Modern smart cities are already implementing a wide range of tasks in areas such as urban mobility, safety, maintenance, healthcare, and management [1]. Monitoring the state of road conditions is one of the relevant tasks for the technical maintenance of a smart city. An effective monitoring system will enhance driver comfort and enable timely response to problematic road sections, ultimately improving overall quality of life and reducing the use of human and material resources that could otherwise be spent on repairs and development [2]. However, this is an incredibly complex task that requires simultaneous control over thousands of kilometers of road surfaces, which can be damaged by various natural and man-made factors. Various transportation systems for technical control and monitoring are described in literature sources [1–3]. Traditionally, monitoring systems are based on a large number of IoT sensors that generate a vast amount of measurements and communicate with each other and analytics servers [4]. The most pressing challenges in the development of IoT systems are associated with improving the capabilities of modern IoT data analytics, which is driven not only by frequent data anomalies and their massive volume but also by the need for high-complexity computations in near-real-time mode [4]. Current trends in moving a significant portion of analytics to the edge level of IoT further emphasize the relevance and necessity of enhancing IoT system architectures, particularly in terms of data collection and aggregation. This is also applicable to road condition monitoring systems, which are sensitive to data processing time.

Thus, the article focuses on the current challenges of improving the efficiency of road condition monitoring systems based on IoT technologies, which can be easily integrated into smart city maintenance systems.

2. Analysis of Literature Data and Problem Statement.

Among the known methods of monitoring, the most common is the use of specialized mobile road laboratories that collect information on the quality of the road surface and roadsides. The vehicles of these mobile laboratories are equipped with a wide range of equipment and sensors, including video cameras, GPS trackers, three-dimensional laser scanners, soil analysis sensors, and positioning devices [2, 5]. The analysis of the collected data is carried out by qualified specialists using specialized tools and modern modeling techniques in laboratory settings [5]. These professional laboratories offer detailed information about the current condition, damages, and problematic sections of roads and roadsides. However, the wide-scale implementation of such laboratories has certain drawbacks, including high costs, substantial resource and time requirements, and the need for trained personnel and specialized equipment.

Methods of automatic data collecting that simplify, accelerate, and lower the costs of these operations are becoming more important as IoT becomes more widely adopted [2]. The use of video footage acquired by vehicles' cameras is a popular approach of automatically detecting road potholes. In the works.[3, 6] Methods for detecting object outlines based on points within the object are considered, but intensity variation within the object's internal zone is seen as a defect. Among the drawbacks, it is worth noting the high probability of errors in video recordings and the high cost of video equipment and paid analytic services. Additionally, it should be mentioned that standardized placement of video cameras on all vehicles is necessary to obtain high-quality data.

Another widespread solution is the use of client mobile applications and services for monitoring road damages, which are installed on drivers' smartphones. Most modern smartphones are already equipped with various sensors such as a camera, accelerometer, and GPS. The authors of works [7, 8] propose utilizing the built-in accelerometers and geolocation of mobile devices. They describe useful applications that automatically update real-time road condition information by gathering data from users and displaying it on a map. Users of these applications contribute to automated data collection, and developers obtain thousands of mobile data collection units. This is the most cost-effective solution in terms of material expenses, but technically, these local systems have the potential to be integrated into smart city systems for technical monitoring. Significant drawbacks include high energy consumption due to continuous active GPS sensor operation and the requirement for constant static device positioning throughout the entire movement. For technical monitoring systems, this can result in a decrease in the quality and reliability of the collected data, which are subject to analysis and decision-making on a city management scale. For users, the inability to use their mobile phones for their primary purpose may also cause more inconvenience than benefits.

The most promising class of solutions is the monitoring systems embedded in vehicles. The viability and effectiveness of such tools are supported by their adoption by major automobile manufacturers, including Volvo, Ford, and Jaguar. According to information from open sources [9], these companies propose similar concepts for monitoring road conditions, utilizing sensors and detectors placed under the vehicles. The sensors communicate with the onboard computer, which, upon detecting problematic areas, generates control actions to enhance driving comfort on uneven roads, such as reducing speed or adjusting the suspension configuration. Simultaneously, information about identified road issues is sent to cloud storage with location coordinates. This information is used to provide early warnings to other drivers about traffic complications on specific road segments. Among the implementation challenges is real-time responsiveness, which is complicated by the reliance on cloud services to access previously collected information. This incurs significant time costs for data retrieval and decision-making, which is critical for proactive response systems. The advantages of the discussed concept, when vehicles exchange information about poor road sections through a shared database, include hypothetical easy integration into smart city systems based on the Internet of Things. However, existing commercial solutions can be problematic for widespread use, as both the reviewed technologies and cloud data storage are localized for each individual automobile brand and not readily accessible.

Both built-in vehicle diagnostic systems and mobile devices commonly utilize measurements of linear acceleration from accelerometers to detect problematic road sections [2, 7, 8]. However, the main challenge associated with using accelerometers to assess linear acceleration is the inability to accurately evaluate the road conditions solely based on accelerometer measurements [10]As a result, classification of accelerometer data is required to determine the nature of road defects [10].

To address the complex tasks of analyzing a large number of measurements and classifying accelerometer data, modern literature sources describe intelligent data processing methods [6, 11, 12]. The authors of these works emphasize the importance of specific data preprocessing for analysis, the relevance of modern methods of intelligent analytics using neural networks, dataset preparation, and neural network training.

In existing road condition monitoring systems, there are common problems such as equipment inconvenience, the complexity of data collection and analysis processes, additional energy consumption, high equipment costs, and significant labor requirements. In terms of operational efficiency, challenges include processing large volumes of data in real-time, accuracy, and reliability of the obtained results. The localization and commercialization of existing solutions also pose obstacles to integrating monitoring systems into the paradigm of smart cities based on IoT technologies. Based on the aforementioned issues, conducting research in the development and improvement of road condition monitoring systems with integration capabilities into smart city maintenance systems based on IoT is relevant and justified.

3. The research's purpose and goals. The aim of the research is to develop approaches and tools for automated data collection from IoT devices for road condition monitoring systems. The implementation of the research goal aims to improve the efficiency of data collection, transmission, and aggregation from sensors in road condition monitoring systems. The objectives are to enhance the convenience of data collection approaches, increase the accuracy and reliability of measurements, and generate aggregated datasets for further real-time processing by intelligent analytics systems. Achieving the research goal and objectives will help improve the architecture of smart city monitoring systems based on IoT technologies and enhance the performance of time-critical applications, particularly for road condition monitoring.

To achieve this aim, the following tasks were set:

– Develop an architectural and functional concept of a road condition monitoring system with the ability to integrate into scalable IoT networks capable of efficient data collection and aggregation for real-time processing at the IoT network edge.

– Develop a complex of software and hardware tools for data collection and aggregation from IoT devices to implement the architectural and functional concept of the road condition monitoring system.

4. Data and methods of the research

4.1. Justification for sensor selection for monitoring linear acceleration indications.

The object of the research is the processes of data collection and processing related to the quality of road surfaces in IoT networks. Considering the need for automated collection of a large number of parameters from IoT sensors and the high computational complexity of real-time processing algorithms, the task arises to select hardware for effectively addressing these challenges. The solutions to these tasks are based on choosing software and hardware that meet the requirements of accuracy, high performance, ease of configuration and programming, low cost, mass production, and availability in the electronics market.

The quality and accuracy of the final results significantly depend on the reliability of the data obtained from IoT sensors. Accelerometers are typically used to measure linear acceleration. Three-axis MEMS (Micro-Electro-Mechanical Systems) accelerometers belong to the modern family of "nano" MEMS and cover a wide range of tasks. The efficiency of MEMS accelerometers in terms of measurement quality and integration into IoT systems has been investigated in [13], and their usefulness has been justified. Among the advantages are small size and low cost compared to analogues, high accuracy of the sensors suitable for projects of any complexity, and wide usage in the microelectronics market.

For the research, the LIS3DSH accelerometer from STMicroelectronics (a European multinational company based in France and Italy) [14] was used. The company's products are known for their high quality and come with openly available official documentation. According to the documentation [14], the LIS3DH is a high-performance three-axis linear accelerometer with low power consumption, compact size, and affordable price. The LIS3DH accelerometer has a standard I2C/SPI digital serial interface and can measure acceleration with data output rates ranging from 1 Hz to 5.3 kHz simultaneously along three axes. The available scales of ±2g/±4g/±8g/±16g can be dynamically configured for different power-saving modes or other needs. The device also features low-power, extended energy-saving modes, and smart embedded functions, withstanding overloads up to 10,000 g. The selectable measurement scales are a specific advantage for the research, providing the ability to dynamically configure different ranges of boundary values. The SPI serial peripheral interface allows for connecting a large number of peripheral devices.

4.2. Justification of technologies for the implementation of a device for collecting and aggregating IoT data from peripheral sensors

The efficiency of implementing hardware solutions for data collection and aggregation in IoT is another important factor that determines the speed of result generation. The choice of data processing processor requires high-speed performance, low power consumption, speed and ease of configuration and software development, wide availability, and affordable cost. For real-time task solutions, efficient interrupt handling mechanisms for a large number of peripheral devices and high-speed communication means are critical for processors.

Two technologies have been considered, which belong to different product lines in terms of performance and functional purpose. Firstly, the use of affordable and popular Arduino boards [10] has been examined, which meet the requirements of low cost, ease of development, and open-source software. However, their usage would require complex assembly of additional functional modules, including connecting the accelerometer to the board using wires. On the other hand, Raspberry Pi mini-computers [15] have been explored, which are based on quad-core ARM Cortex-A processors. This satisfies the requirement for high performance and the execution of computationally intensive tasks by being capable of running general-purpose operating systems. The Raspberry Pi board has a wide range of IoT applications and is based on energy-efficient technologies. It is often used for implementing audio systems, weather stations, personal computers, and servers. However, the Raspberry Pi board clearly exceeds the needs for solving the given tasks. In both cases, there is an increase in cost and development complexity.

STM32 controllers are specialized high-performance systems equipped with digital signal processors and designed for real-time signal processing [16]. These controllers are characterized by high performance and low power consumption. They have efficient interrupt-handling capabilities and high-speed interfaces for data exchange. The developer also provides high-level APIs for programming in languages like C and C++, as well as other tools for configuration, programming, and debugging.

For the aggregation and preliminary processing of IoT data obtained from the accelerometer, the STM32F407vg family controller is used. The STM32F407vg controller already has the LIS3DSH digital accelerometer integrated. Additionally, this controller includes the necessary interfaces for data exchange and provides a large number of general-purpose input/output ports. Choosing products from the same manufacturer simplifies the configuration, development, and programming of the system.

4.3. Deploying the development environment and configuring the controller

For the development of hardware drivers, the Keil uVision development environment and the low-level programming language C was used. The Keil uVision development environment includes a set of specialized utilities for programming microcontrollers, including those from the STM microcontroller family. The choice is justified by the convenience of working with the development environment and the optimization of compiled code, which ensures high speed and minimal delays in the operation of the drivers.

The STM32CubeMX development environment was used to configure the STM32F407vg controller. Controller configuration refers to setting up the device in its operational state, configuring the appropriate values in the processor's software registers, setting the clock frequency, activating interfaces, defining the operating modes of input/output ports, and performing a set of other configurations. STM32CubeMX is a graphical interface tool developed by STMicroelectronics specifically for automatic configuration of STM32 devices and generating C language source code for the ARM Cortex-M core.

5. Results of the study of automated IoT data collection tools

5.1. Development of the architectural concept of the IoT road surface condition monitoring system and hardware for its implementation

According to the proposed architectural concept, the IoT monitoring system is considered at an architectural level, which describes the composition and interaction of the main structural components of the system. The functional components of the system are implemented through a combination of hardware and software. An overview of the system architecture is presented in figure 1.

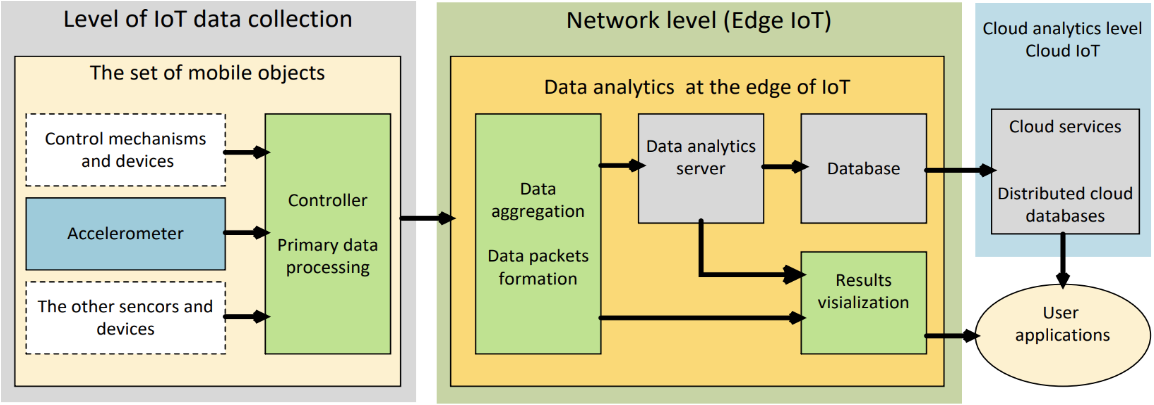


Figure 1. Structural diagram of the IoT road condition monitoring system

At the data collection level, there is a set of mobile objects, each of which contains a sensor that measures linear acceleration or other sensors and actuators. Each of these objects contains a controller that reads data from the accelerometer, performs filtering, and forms data packets that are transmitted to the analytics server for further processing. The role of the mobile object is performed by a vehicle that carries the appropriate equipment and moves in any direction within a specific IoT infrastructure area.

The data collection device is implemented on the STM32F4 DISCOVERY board. The structural diagram of the data collection subsystem is presented in Fig. 2. The STM32F4 DISCOVERY board includes necessary components, including the LIS3DSH accelerometer sensor. The sensor is interfaced with the system using the Serial Peripheral Interface (SPI). The SPI bus enables fast communication between the controller and peripheral devices and allows for the connection of multiple sensors, facilitating potential expansion of the monitoring system's functionality. The micro USB port on the board is used to transmit information to the server. A cable is used to connect the micro USB port on the board to the USB port of a computer. The server reads the data in COM port mode.

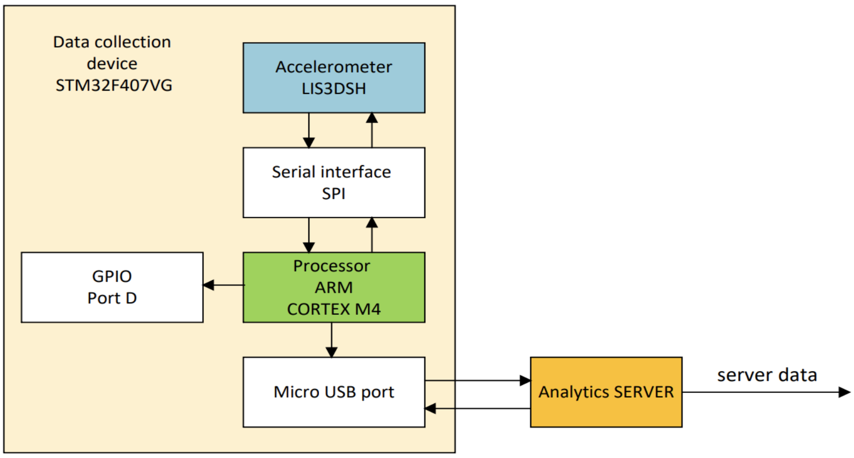


Figure 2. Block diagram of the data collection and analytics system

During the initialization of the data collection subsystem, its functionality is checked. By querying the control bits and the working state of the ports, the subsystem verifies its operability. Peripheral devices are configured, the SPI bus is initialized, and communication with the server is established. In the case of non-critical errors, the system is restarted, while in critical situations, the system operation is halted. In emergency situations, a red LED on the board is activated to indicate a system malfunction.

For the adequacy and accuracy of the data obtained based on accelerometer measurements, as mentioned earlier, the device's horizontal position is critical. The accelerometer sensor should be oriented parallel to the road surface in the vehicle. LED indicators on the board are used for device position calibration. The correct position is considered when all four LEDs are turned off, indicating that the readings obtained from the sensor can be considered relevant. Calibration of the correct device position for data collection is performed after board firmware and system initialization.

Figure 3 illustrates experiments that demonstrate the proposed methodology of using LEDs for device calibration during changes in position relative to the horizontal axis. In the correct device position, all LEDs are turned off. In positions "A" and "B," the sensor is tilted relative to the x-axis, while in positions "C" and "D," it is tilted relative to the y-axis. If one or more LEDs are lit, it indicates incorrect board placement, requiring manual adjustment of its position.

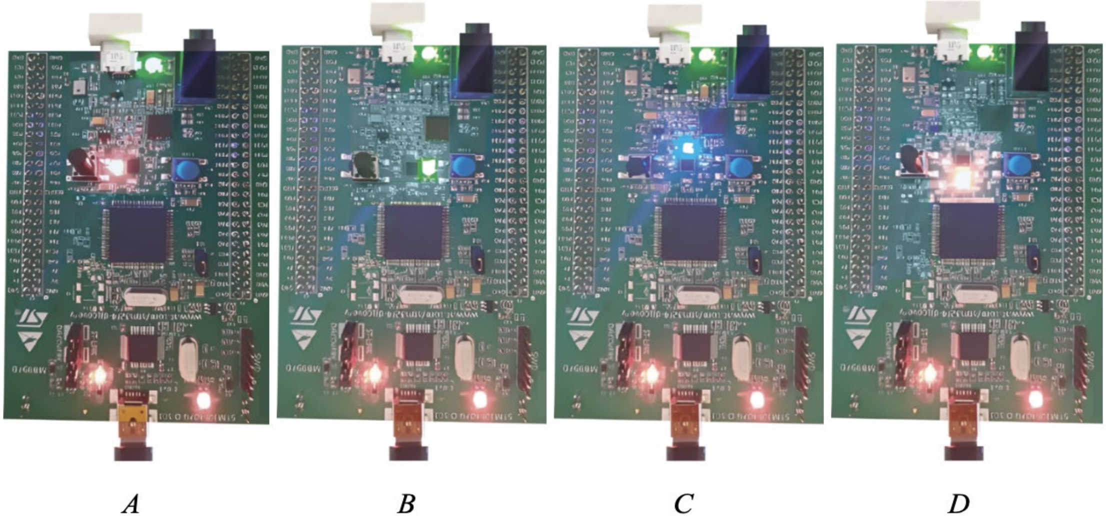


Figure 3. Calibration of the correct device position:
A – tilt to the left relative to the X-axis; B – tilt to the right relative to the X-axis;
C – tilt backward relative to the Y-axis; D – tilt forward relative to the Y-axis

Data collection from the linear acceleration sensor begins after the device has been configured and calibrated. The controller reads linear acceleration values from the three-axis accelerometer and transmits data packets through the SPI bus via the micro USB port to the data analytics server in serial COM port mode. On the server side, the data is converted to standard measurement units. The data received on the COM port is in hexadecimal format and is then converted to decimal values in units of measurement of $g=9.8$ m/s^2. Next, frames of sequential accelerometer measurements of the appropriate size are formed and aggregated in the server's database for further analysis.

The aggregation, analytics, and visualization server (server) is implemented on a personal computer (PC) during the experimental stage. To operate the server software, it is necessary to connect the device to the computer via the USB interface.

5.2. Software complex for collecting and aggregating IoT data

As part of the functional implementation of the architectural concept, a software suite has been developed, which consists of the following components:

– Data collection software: drivers for connecting the accelerometer to the controller, a data collection device from the accelerometer on the controller, and communication tools between the data collection device and the server.

– Server software: data aggregation and monitoring system server, server software for testing and visualization of results with a graphical user interface.

The data collection device is implemented on the STM32F4 controller. After configuring the controller, an executable project file called main.c is obtained, which represents the working block of the program. The file contains the main() function, which is executed at project start, as well as functions for initializing general input/output ports, the SPI interface, system clock settings, and error monitoring functions. To flash the controller, the board is connected to the host computer. The compiled project is then loaded onto the STM32F4 DISCOVERY board using the programming tools provided by the STM32CubeMX development environment.

The server software consists of software modules for data aggregation, analytics, and visualization of results (Fig. 1). The aggregation module creates frames of sequential accelerometer measurements, which are stored in the server's database. The data visualization software module displays the data read from the COM port in a convenient graphical format.

The server for experimental data analytics consists of a roughness classification module (classifier). The classifier processes the aggregated data frames on the server and classifies them using simplified experimental algorithms. The purpose of this classifier is to assess the suitability of the prepared data formats for further processing, including the application of trained neural networks. The classifier generates specific analytical results, which are stored on the server and can also be transmitted to the cloud for further use and analysis. The operation of the classifier is described in detail in reference [10].

Software with a graphical user interface has been developed for visualizing the results of data aggregation and experimental processing on the analytics server. The results are displayed in the form of graphs showing the change in vertical acceleration along the three axes of the accelerometer. The developed software has communication interfaces with both the analytics server tools and the data collection device, in the form of user buttons within the graphical interface.

The server-side software is implemented using the PyQt library for graphical user interface development in the Python programming language. The pySerial library is used for communication with the COM port, and the mathplotlib library is used for graphical representation of data. The Qt Designer program was utilized to configure the visual display of the classifier's results, which offers a wide range of options for customizing the graphical interface.

The graphical interface consists of a menu for selecting the COM port, scales for displaying linear acceleration values on different coordinate axes, a dynamic graph of the acceleration values along the Z-axis, and digital indicators displayed above it. The data is presented in real-time in various visualizations. The overall layout of the graphical interface for the Accelerometer Port Monitor module, which displays the state and classification of road surfaces, is shown in Figure 4. On the left side, the measurement results along the three accelerometer axes are displayed, and real-time graphs are plotted for the three projections. On the right side, there are four indicators representing the condition of the road surface: green for a level road, yellow for speed bumps, railroad crossings, or potholes, orange for small potholes or cobblestones, and red for accident zones or large potholes. The classification is implemented using a software classifier model, which is described in detail in the reference [10]. The indicators are illuminated according to the identified types of road surface irregularities determined by the classifier.

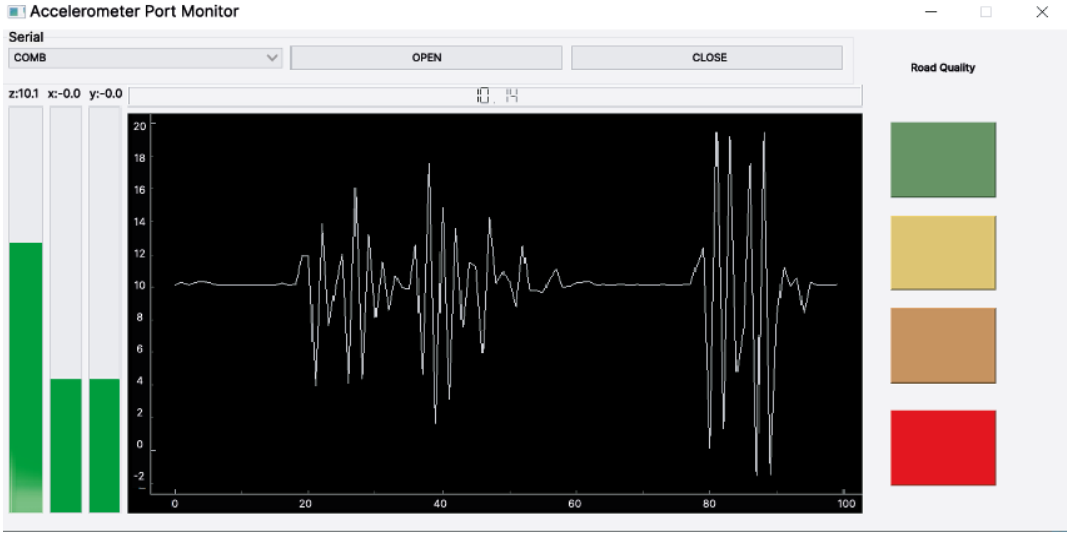
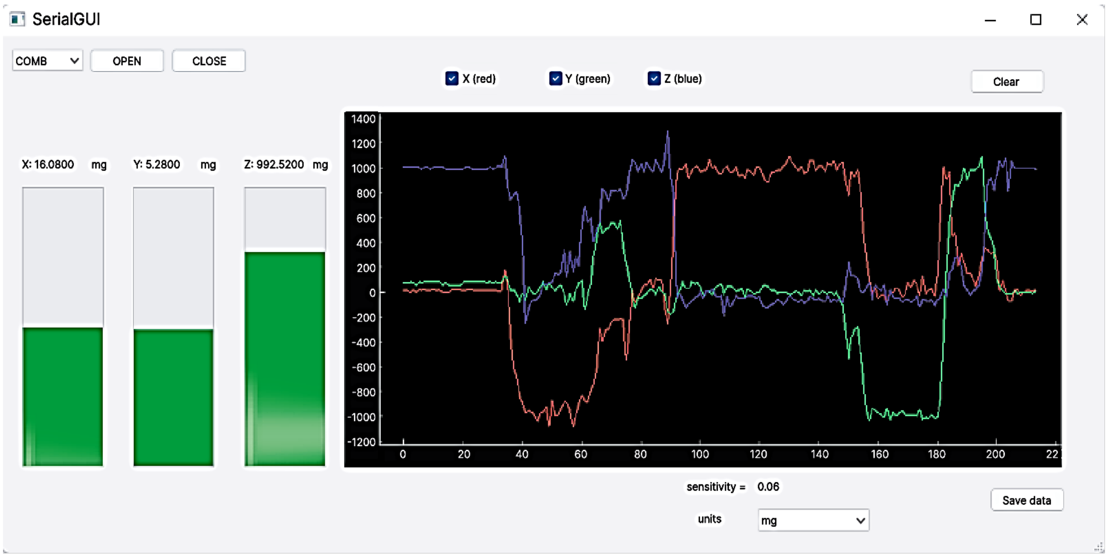


Figure 4. An example of the graphical interface

The developed module for visualizing road conditions on Google Maps is designed to visualize the experimental results of data processing in user applications. However, the current experimental prototype lacks a GPS sensor and a wireless network interface for communication with the server. To accommodate the experimental implementation, certain abstract simplifications have been made. For example, communication with the server is realized using a COM port, and GPS navigation data is obtained from the server-side PC to determine the position.

During the experimental testing of the device with accelerometer measurements visualization, it was assumed that the acceleration readings are influenced by inertial forces that cause the device to deviate from its equilibrium state. In figure 5, which visualizes the rotations and tilts of the board, the displacement of the graphs along different axes can be observed during the tilting of the board in corresponding directions.

To indicate the position of the data collection device, LEDs were used on the board. This function was implemented for system calibration during initialization (Figure 3). Experiments involving tilting the board and visualizing it in the graphical interface determined, for example, that the green LED LD4 is activated when the device deviates along the X-axis by more than -200 units (one unit corresponds to 0.06 mg according to the documentation). Therefore, the calculated sensitivity of the adjusted system to tilts is 12 mg, which corresponds to 0.1176798 m/s^2. Tilts of the device were performed backward and forward along the X-axis, and the corresponding changes along that axis were displayed in the console (Figure 6). The maximum acceleration of 10110 units was recorded during tilting the board backward along the X-axis, and the maximum acceleration of 13395 units was recorded during tilting it forward along the X-axis. Thus, the calculated acceleration values were 606.6 mg and 803.6 mg due to inertial effects along the X-axis, representing the maximum and minimum deviations from the equilibrium state.

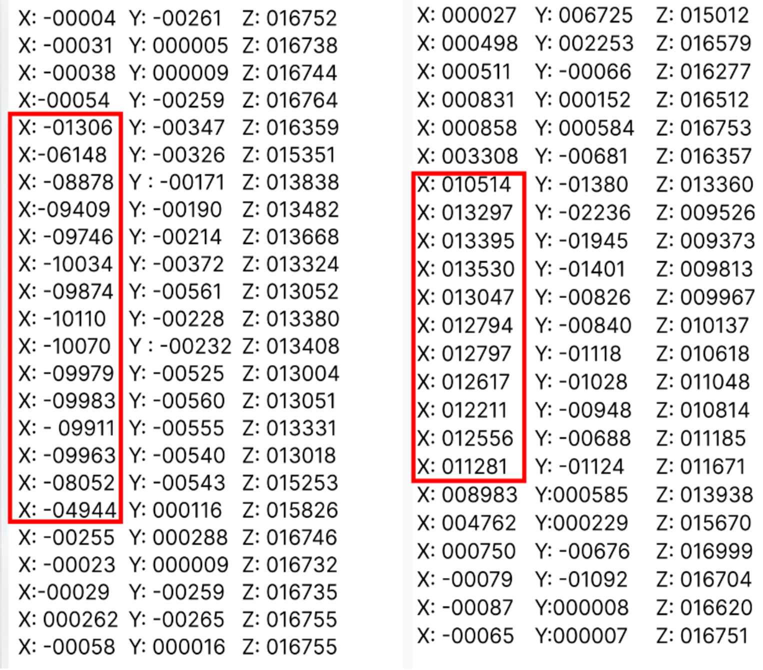


X: 16.0800 mg
Y: 5.2800 mg
Z: 992.5200 mg

sensitivity = 0.06
units mg

Figure 5. Influence of inertial forces on acceleration rates

The results of similar experiments along the Y-axis showed that the maximum and minimum acceleration deviations from the equilibrium state along the Y-axis correspond to 444.46 mg and 414.48 mg, respectively. Thus, the characteristics of the inertial forces affecting the device have been assessed.



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X: -00004  Y: -00261  Z: 016752
X: -00031  Y: 000005  Z: 016738
X: -00038  Y: 000009  Z: 016744
X:-00054   Y: -00259  Z: 016764
X: -01306  Y: -00347  Z: 016359
X:-06148   Y: -00326  Z: 015351
X: -08878  Y : -00171 Z: 013838
X:-09409   Y: -00190  Z: 013482
X: -09746  Y: -00214  Z: 013668
X: -10034  Y: -00372  Z: 013324
X: -09874  Y: -00561  Z: 013052
X: -10110  Y: -00228  Z: 013380
X: -10070  Y : -00232 Z: 013408
X: -09979  Y: -00525  Z: 013004
X: -09983  Y: -00560  Z: 013051
X: - 09911 Y: -00555  Z: 013331
X: -09963  Y: -00540  Z: 013018
X: -08052  Y: -00543  Z: 015253
X: -04944  Y: 000116  Z: 015826
X: -00255  Y: 000288  Z: 016746
X: -00023  Y: 000009  Z: 016732
X:-00029   Y: -00259  Z: 016735
X: 000262  Y: -00265  Z: 016755
X: -00058  Y: 000016  Z: 016755
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X: 000027   Y: 006725   Z: 015012
X: 000498   Y: 002253   Z: 016579
X: 000511   Y: -00066   Z: 016277
X: 000831   Y: 000152   Z: 016512
X: 000858   Y: 000584   Z: 016753
X: 003308   Y: -00681   Z: 016357
X: 010514   Y: -01380   Z: 013360
X: 013297   Y: -02236   Z: 009526
X: 013395   Y: -01945   Z: 009373
X: 013530   Y: -01401   Z: 009813
X: 013047   Y: -00826   Z: 009967
X: 012794   Y: -00840   Z: 010137
X: 012797   Y: -01118   Z: 010618
X: 012617   Y: -01028   Z: 011048
X: 012211   Y: -00948   Z: 010814
X: 012556   Y: -00688   Z: 011185
X: 011281   Y: -01124   Z: 011671
X: 008983   Y:000585    Z: 013938
X: 004762   Y:000229    Z: 015670
X: 000750   Y: -00676   Z: 016999
X: -00079   Y: -01092   Z: 016704
X: -00087   Y:000008    Z: 016620
X: -00065   Y:000007    Z: 016751
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Figure 6. Changes in the X-axis values when the position of the of the data acquisition device: forward and backward tilt

Based on the visualization of the processed aggregated accelerometer measurements in the SerialGUI software interface, as shown in the graph (Figure 5), it was possible to identify the device's position and state at different time intervals as follows:

– Tilting of the board in different directions is identified as sinusoidal patterns. The gradual increase in values corresponds to an increase in the tilt angle, while the decrease in values corresponds to returning to the equilibrium state.

– Shaking of the board is identified as segments on the graph with sharp changes in values.

– Flipping of the device is characterized by a sudden change in the Z-axis value from 1000 mg to -1000 mg.

– Resting state is characterized by values close to zero for X and Y axes, and close to 1000 mg for the Z-axis.

– Impacts on the board are characterized by sudden variations along one of the accelerometer axes and a return to the initial state within a short time interval.

6. Analysis of the results of the study of IoT data collection and aggregation tools

The proposed architectural and functional concept of the IoT monitoring system is designed to be easily integrated into a large-scale smart city maintenance system based on IoT technologies. As depicted in Figure 1, the proposed concept aligns perfectly with the IoT paradigm. At the data collection and aggregation level, there is a set of sensors, detectors, and control devices for feedback. The Internet level facilitates communication between the hardware and server components, as well as connectivity with cloud services and technologies. Modern IoT technologies strive to implement edge computing, so the implementation of the server component for intelligent data analytics is considered at the edge of the IoT network.

Within the proposed concept, the task of automating the collection of data on road quality is addressed by installing inexpensive devices on user vehicles, in contrast to the approaches discussed in references [6, 9]. An autonomous embedded system has been implemented to collect and perform initial processing (aggregation) of acceleration measurements from the accelerometer. The hardware implementation is based on high-performance and cost-effective off-the-shelf boards. These boards feature specialized processors and high-precision embedded accelerometers. As a result, the developed IoT data collection device conforms to standard IoT network integration methods while meeting the requirements of low cost and availability.

The data collection devices are installed on user vehicles or public transportation vehicles for the purpose of collecting and transmitting data to the server for further analysis. Unlike local monitoring systems [6-9], these mobile nodes, moving through different regions, address the task of dynamic and scalable monitoring of large and, in general, technically unlimited volumes of road surfaces. Data on the state of the road surface, along with the vehicle's coordinates, are transmitted to the server for generating analytical insights. The analytical information is stored on the server and in distributed cloud databases for future use. The road surface database can be utilized by road authorities to assess road conditions and also by user applications to provide drivers with early warnings and alerts.

The implementation of network interfaces and the specifics of network communication between the data collection device and the server are beyond the scope of the research topic, so certain abstract simplifications have been made. For example, communication with the server is implemented using a COM port (Figure 2), and GPS navigation data is obtained through the server PC. As a continuation of the research, there are plans to migrate the server component to specialized hardware. In the context of further research, there is a need to develop distributed intelligent analytics tools to address the scalability of the IoT monitoring system, which was conceptually considered based on the proposed methods in this study. The conditions for seamless integration into IoT systems, which are met by the developed tools, will enable the realization of such scalable monitoring systems in the future.

KThe hardware and software complex was implemented as an experimental prototype system for monitoring the condition of the road surface. The software consists of server programs for data processing based on a neural network, which includes a classifier module, a system control module, a visualization module with a graphical interface, a navigation module, and a user application. Experiments were conducted to configure the hardware and software and test the proposed means of aggregating accelerometer data for further analysis. The experiments showed that the developed prototype is functional and responds promptly to road irregularities in real time. The graphs in Figure 4 display the road surface profile during vehicle movement, and the classifier detects the type of irregularities and displays them using indicators on the graphical interface. During testing, it was demonstrated that the highlighting of the classifier indicators is reflected on the map by marking the corresponding color (Figure 5). Thus, drivers in the user application can choose a route based on the quality of the road surface, while municipal services can use the application to track problematic areas that require repair. The database can also be used for planning vehicle routes, taking into account poor road conditions.

Based on the obtained research results of linear acceleration indicators and testing of the prototype, it can be concluded that the proposed solution demonstrates excellent performance compared to analogs. The embedded system has very low power consumption compared to smartphone-based systems. The accuracy of the monitoring system is sufficiently high, and expanding the database of linear indicators will allow for the enlargement of the training dataset, thus further enhancing the precision of intelligent analytics.

One of the drawbacks is the need for proper device placement to obtain relevant results. This issue was addressed by fixing the device in place. However, as an assumption for further research, it was assumed that when the device deviates from its balanced state, inertial forces occur, which affect the acceleration indicators. This assumption was experimentally validated using the developed visualization programs on different datasets. The investigation of the impact of inertial forces on the acceleration indicators during device deviations along the X and Y axes allowed for the identification of changes in the board's position in the absence of fixation. The obtained data requires further research and validation to incorporate the consideration of inertial forces for improving the classifier's accuracy and reducing dependence on device placement in the vehicle. Based on the consideration of inertial forces, certain correction mechanisms are planned to be implemented by recalculating the acceleration indicators relative to the static coordinate system.

7. Summary

1.The proposed architectural-functional concept of the road condition monitoring system allows for the improvement of existing monitoring systems by:

– Automating the collection and processing of information about the road condition, minimizing human and material resources.

– Enabling dynamic and scalable monitoring, analyzing and storing reliable information about the road condition in large and virtually unlimited databases, and creating an overall map of the road condition.

– Utilizing autonomous, inexpensive, and widely accessible embedded systems for collecting IoT data about the road condition, providing a cost-effective and straightforward integration into a large IoT network, particularly in smart city maintenance systems.

– Enhancing real-time data processing efficiency by performing data aggregation for implementing analytics at the IoT network edge, including intelligent analytics.

2.The architectural concept of the IoT road condition monitoring system has been implemented as a complex of hardware and software tools for data collection and aggregation. Based on this concept, an experimental prototype of the monitoring system has been developed. The experiments demonstrated that the proposed IoT monitoring tools are capable of promptly detecting road defects.

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ПРОЄКТУВАННЯ ЗАСОБІВ АВТОМАТИЗОВАНОГО ЗБИРАННЯ ДАНИХ ДЛЯ СИСТЕМ IoT МОНІТОРИНГУ СТАНУ ДОРОЖНЬОГО ПОКРИТТЯ

Моніторинг стану дорожнього покриття – одне з актуальних завдань технічного обслуговування розумного міста. Ефективна система моніторингу дозволить підвищити комфорт водіїв, якість життя та зменшити використання людських та матеріальних ресурсів.

У відомих системах моніторингу стану дорожнього покриття наявні загальні проблеми, на кшталт незручності користування устаткуванням, складності реалізації процесу збирання та аналізу даних, додаткових енерговитрат, високої вартості устаткування та значних трудовитрат. Серед проблем ефективності функціонування, значними є проблеми швидкодії обробки великих обсягів даних у реальному часі, точності та достовірності отриманих результатів.

Метою дослідження є розроблення підходів та засобів до автоматизованого збирання даних з IoT пристроїв для систем моніторингу стану дорожнього покриття.

Для досягнення мети основним було розробити архітектурно-функціональну концепцію системи моніторингу стану дорожнього покриття з можливістю інтеграції в масштабовані мережі IoT та розробити комплекс програмно-апаратних засобів для збирання та агрегації IoT даних.

Запропонована архітектурно-функціональна концепція системи моніторингу стану дорожнього покриття, забезпечує можливість вдосконалення існуючих систем моніторингу шляхом автоматизації збирання та обробки інформації про стан дорожнього покриття, динамічного та масштабованого моніторингу, використання автономних, дешевих та широкодоступних вбудованих систем для збирання IoT даних про стан дорожнього покриття, підвищення ефективності обробки даних в реальному часі. Архітектурна концепція реалізована у вигляді комплексу програмно-апаратних засобів для збирання та агрегації IoT даних, на базі яких розроблено експериментальний прототип системи моніторингу.

Розроблені засоби дозволяють оперативно реагувати на нерівності дорожнього покриття на довільній місцевості, а формат агрегованих даних придатний для подальшого аналізу, в тому числі інтелектуального. Запропоновані засоби можуть бути використані в системах технічного обслуговування розумними містами з метою покращення якості водіння та упередження критичних ситуацій, пов'язаних з неякісними дорожнім покриттям.

Ключові слова: *IoT; SmartCity; система моніторингу; дорожнє покриття; STM32.*

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