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ПРОТОТИП НА СИСТЕМ ЗА СЛЕДЕЊЕ НА СЕИЗМИЧКИ НАСТАНИ ПРЕДИЗВИКАНИ ОД МИНИРАЊА НА ПОВРШИНСКИ КОПОВИ

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Апстракт: *Во овој труд е претставен прототип на систем дизајниран за следење на сеизмички настани предизвикани од минирање на површински копови. Овој систем за аквизиција на сеизмички податоци се одликува со висока прецизност и резолуција и е дизајниран како за следење на сеизмички настани во реално време, така и за складирање, далечински пристап, пренос, и визуелизација на добиените податоци. Покрај примарната намена, системот може да се користи и за други апликации, како што се геофизички истражувања, следење на сообраќај, индустриска безбедност и многу други примени. Целта е да развиеме високо автономна, а во некои аспекти и независна станица за следење на сеизмички настани. Во оваа работа ќе бидат претставени структурните компоненти, функционалноста и карактеристиките на овој прототип систем.*

Клучни зборови: *површински копови, сеизмика, аналогна дигитална конверзија, сигнал*

PROTOTYPE SYSTEM FOR MONITORING BLAST-INDUCED SEISMIC EVENTS FROM OPEN PIT MINES

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Abstract: *In this paper, a prototype system designed for monitoring seismic events induced by blasting in open-pit mines is presented. This seismic data acquisition system (DAQ) features high precision and resolution and is designed both for real-time monitoring of seismic events and for storage, remote access, transmission, and visualization of the obtained data. In addition to its primary purpose, the system can also be used for other applications, such as geophysical surveys, traffic monitoring, industrial safety, and many other uses. The goal is to develop a highly autonomous, and in some aspects independent, standalone, monitoring station for seismic events. This work will present the structural components, functionality, and characteristics of this prototype system.*

Key Words: *open pit mines, seismic, analog-to-digital conversion, signal*

1. INTRODUCTION

Geophysical research involves studying Earth's physical properties and processes, such as seismic activity and magnetic fields, through data collection and computational methods. Computer science plays a crucial role in this field by developing algorithms and tools for efficient data analysis. Geophysical techniques, like seismic imaging, aid in various applications such as hazard detection and structural integrity assessments. Seismology, a key branch of geophysics, focuses on monitoring seismic waves to understand Earth's structure, assess seismic risks, and contribute to disaster prediction and resource exploration.

Induced seismic waves from blasting in open-pit mines have a significant impact on both the structures within the open-pit mine and the surrounding environment. From a mining perspective, the most important concern is the impact on the stability of the open pit mine slopes. However, it is also necessary to consider other structures that may be endangered by 'uncontrolled' blasts.

Blasting is often used to excavate and break up rocky material in mines. However, this activity induces seismic waves, which can pose potential security risks. Data gathered from monitoring seismic activity can be used to analyze the characteristics of these waves, which is crucial for the implementation of various preventive and safety strategies [8].

Based on the gathered data from monitoring seismic waves, various analyses can be performed using different techniques [18], all with the purpose of extracting information that can potentially help optimize the blasting and drilling process while minimizing negative effects on the environment.

Seismic waves generated by blasting are essentially ground vibrations caused by the sudden release of energy during the detonation of explosives. Our goal is to develop a high-precision, high-resolution seismic data acquisition system (DAQ) for real-time monitoring, processing, and visualization of these induced seismic activities. We aim to design a mobile, autonomous, and portable station that consolidates all components into a single box, enabling seismic data collection at any location. Additionally, the system will be capable of establishing a scalable network of seismic stations.

Modern computer technologies, especially Single Board Computers (SBCs) like the Raspberry Pi 4/5, are essential for developing our prototype, managing tasks such as data acquisition, remote access, preprocessing, and transfer. The Raspberry Pi 4/5, an SBC built on a single printed circuit board, functions similarly to a standard PC but in a more compact form. For our application, it's crucial to use advanced Analog-to-Digital Converters (ADCs) with high resolution, such as the Raspberry Pi HAT (Hardware Attached on Top) ADS1263, which offers 32-bit resolution. ADCs convert continuous analog signals, such as those from geophones or seismometers measuring seismic activity, into digital data for efficient processing, analysis, visualization, and storage. In addition to the hardware components, the prototype includes a Global Positioning System (GPS) module for precise location determination, time synchronization, and accurate geolocation data. To ensure continuous operation, the prototype is equipped with a built-in Uninterruptible Power Supply (UPS) that allows it to function autonomously for a limited period. At this stage, the station still relies on the power grid and network connectivity for operation. More detailed information will be provided in the following sections.

This work builds upon our previous efforts in prototyping and designing seismic data acquisition (DAQ) systems [2], introducing several key advancements and conceptual differences. While the earlier prototype focused on foundational development, this new version enhances both hardware and software capabilities, addressing limitations and incorporating additional features that will be discuses in the following sections.

2. RELATED WORK

In the current technological era, there is growing awareness and demand for geophysical science, leading to the availability of both professional and budget-friendly seismic instruments. Established companies like Kinemetrics [7], Guralp Systems Limited [6], and Nanometrics [9] produce high-end seismic equipment, while affordable alternatives such as Raspberry Shake: Earthquake [13], GEObit [5], and various Do-It-Yourself (DIY) seismometer kits are offered by different companies and educational institutions. In addition to hardware, both proprietary and open-source software tools are essential for seismic monitoring, including SeisComP [14], SAC [15], and programming frameworks like ObsPy [10] and Seismic.jl [16]. Our station is classified as a DIY seismometer kit, providing an accessible option for educational institutions, hobbyists, and enthusiasts to build and customize their own seismic monitoring devices. Notable examples of DIY systems include designs proposed by Gao et al. [4], Ramdeane et al. [11], and Attia et al. [1], which illustrate various components and approaches for developing effective seismic data acquisition systems.

3. PROTOTIP SYSTEM DESIGN

This section focuses on the components that make up our prototype system. Specifically, we emphasize the use of the SBC Raspberry Pi 4, a high-precision AD HAT ADS1263 with an extremely low-noise 32-bit analog-to-digital (A/D) converter, and EG-4.5-II geophone (Fig. 1).

Figure 1. Raspberry Pi 4, HAT ADS1263, and EG-4.5-II geophone

The Raspberry Pi 4 Model B [12] (Fig. 1) is a 4th generation Raspberry Pi single-board computer (SBC). It is widely used in many areas because of its low cost, modularity, and open design. The hardware configuration, operating system, and additional software used with the Raspberry Pi 4 are described in Table 1.

Table 1. Description of Raspberry Pi, hardware, and software

Component equipment	Raspberry Pi
Product Model:	Raspberry Pi 4 Model B
CPU	Quad-core ARM Cortex-A72
Memory	8 GB LPDDR4
OS	Ubuntu 22.04.4 LTS
Kernel Version	5.15.0
Compiler	GCC 11.4, Python3
Remote Access	SSH, WireGuard

The ADS1263 (Fig. 1) [17] (Raspberry Pi HAT) is a high-resolution, low-noise 32-bit ADC commonly used in precision measurement applications such as instrumentation, data acquisition, and sensor interfacing. With its 32-bit resolution and programmable gain amplifier, the ADS1263 offers exceptional accuracy and sensitivity, making it ideal for capturing small signals with high fidelity. Its integrated features, including an on-chip voltage reference and temperature sensor, contribute to its versatility and reliability in demanding measurement environments. The detailed specifications are described in Table 2.

Table 2. ADS1263 details specifications

Component equipment	ADS1263
Resolution	32 (Bits)
Sample rate (max)	38 (ksps)
Number of input channels	10
Interface type	SPI
Architecture	Delta-Sigma
Input type	Differential, Single-ended
Multichannel configuration	Multiplexed
Input voltage range (max)	2.5, 5 (V)
Input voltage range (min)	-2.5, 0 (V)
Features	50/60 Hz Rejection, Excitation Current Sources (iDACs), GPIO, Oscillator, PGA, Temp Sensor
Operating temperature range	-40 to 125 (°C)
Power consumption (typ)	27 (mW)
Analog supply (min)	4.75 (V)
Analog supply voltage (max)	5.25 (V)
Digital supply (min)	2.7 (V)
Digital supply (max)	5.25 (V)

The EG-4.5-II [3] vertical geophone (4.5Hz) (Fig. 1) is a conventional moving-coil geophone known for its precise working parameters, stable performance, and reliability. Its compact design and lightweight structure make it well-suited for seismic exploration across various geological environments and depths. The technical specifications are provided in Table 3.

Table 3. EG-4.5-II geophone details specifications

Component equipment	EG-4.5-II
Natural Frequency (Hz)	4.5±10%
Coil resistance(Ω)	375±5%
Damping	0.6±5%
Open circuit intrinsic voltage sensitivity (v/m/s)	28.8 v/m/s ±5%
Harmonic distortion (%)	≦0.2%
Typical Spurious Frequency (Hz)	≧140Hz
Moving Mass (g)	11.3g
Typical case to coil motion p-p (mm)	4mm
Allowable Tilt	≦20º
Height (mm)	36mm
Diameter (mm)	25.4mm
Weight (g)	86 g
Operating Temperature Range (℃)	-40℃ to +100℃

Depending on specific conditions and requirements, different instruments for measuring seismic waves can be attached. One of the instruments we have available is the SS-1 Ranger seismometer. The SS-1 Ranger is widely known for its high sensitivity. It consists of a stationary coil and a durable permanent magnet that acts as a seismic mass. This mass is supported by annular springs located at both the top and bottom of the magnet's range of motion. The SS-1 is versatile, capable of functioning in both horizontal and vertical orientations, with the annular springs adjusted accordingly to support the seismic mass.

Figure 2 illustrates the general block diagram of our DIY seismic DAQ system. The geophone is connected to the ADC, which detects seismic activity, vibrations, or oscillations. The ADC converts the input analog signal from the geophone into a 32-bit digital representation. The ADC input range is set to ±2.5V, and a programmable gain amplifier (PGA) can be used to amplify the input signal. The ADC is configured to sample at a rate of 100 samples per second, providing high-resolution 32-bit data. The communication between the ADC and the main control unit is handled via the serial peripheral interface (SPI), with a direct connection between the ADS1263 HAT and the SPI on the Raspberry Pi 4 GPIO (General-Purpose Input/Output) pinout. The main control unit, represented by the SBC Raspberry Pi 4, preprocesses and stores seismic data. Network connectivity is established through either an Ethernet or wireless interface, enabling local access or remote configuration using software such as SSH, WireGuard, or similar tools. An additional GPS module (GY-NEO6MV2) is included for precise location determination and time synchronization. The UPS consists of a battery, smart battery charger, and DC-DC battery step-down charging board. The UPS design is still being finalized, with plans to incorporate additional components, such as a second battery and a voltage comparator, which will manage the battery power supply switch.

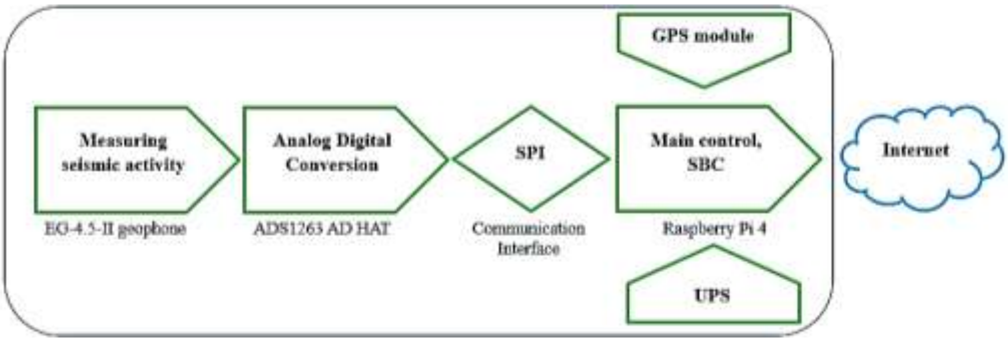

Figure 2. DAQ system general block diagram

Our goal is to design a mobile, autonomous, and portable station that integrates all components into a single enclosure, allowing for seismic data collection at any location. The design schematic enables the placement of all components and modules within one single box. Figure 3 shows the appearance of our DIY seismic DAQ station. There are additional connectors for various purposes, including Ethernet cables, power supply, a geophone connection, and a power-on button, among others.

Figure 3. Prototype of DIY seismic DAQ station

The unique structure of the device components requires a specialized programming toolset, tailored for the early experimental phase. On the SBC side, the software is developed in C++ and Python3, leveraging various libraries to meet specific requirements. For seismic data processing, the ObsPy framework is a critical component. We use the pySerial module to access the serial port, through which the SBC receives seismic data. Data visualization is handled using the Plotly library, while Pandas and NumPy are utilized for preprocessing, manipulation, and analysis of seismic data. All these elements are integrated into interactive web applications using the Dash framework. This software toolset is upgrade to the one implemented in our previous work [2].
At present, the results are saved in two formats: comma-separated values (CSV) for easy text-based access and MiniSEED (MSEED), which adheres to the Standard for the Exchange of Earthquake Data (SEED). The following section will explore seismic data processing, visualization techniques, and experimental measurements taken from seismic events.

5. RESULT MEASUREMENTS AND DISCUSSION

Up to this point, all initial experimental measurements have been conducted under laboratory conditions. The experimental testing phase followed a similar evaluation process to our previous work [2], focusing on assessing the performance of the DAQ prototype system, particularly the ADC device. The evaluation included tests for field performance, frequency distortion, and click time accuracy. In addition, we will discuss certain characteristics of the ADS1263 that are relevant to the performance evaluation. Noise evaluations were not performed, as system noise is influenced by various ADC settings, such as PGA gain, data rate, digital filter mode, and chop mode. We conducted experiments to determine which settings best suit our needs, but we have yet to find the optimal configuration. Generally, the lowest input-referred noise is achieved by using the highest possible gain that aligns with the input signal range. According to the ADS1263 technical documentation [17], this ADC device meets our requirements and provides further insights on this issue.
The dynamic range represents the ratio of the maximum and minimum signals the system can accurately detect. During initial experiments, the PGA was off, and system noise determined the minimum detectable signal. Noise tests showed that sampling rate had little effect, allowing flexible frequency selection. The ADS1263 PGA extends

the ADC's dynamic range for low-level signals with programmable gains up to 32 times.
The Click Time Test assesses the system's sampling rate by detecting deviations in recorded time durations, which can signal issues such as lost or oversampled data. Such deviations may occur due to significant processing interruptions. Despite not using high-accuracy or calibrated equipment, the tests produced consistent results, confirming the data acquisition device's reliability and quality. A sampling rate of 100 Hz was tested, with a margin of error of 0.0001%, demonstrating the system's precision and suitability for our needs.
As mentioned, the station currently relies on the power grid and network connectivity for operation, allowing real-time seismic data streaming from its location. In the event of connectivity issues, the DAQ system will store seismic data in CSV and MSEED formats to prevent loss. We tested real-time data streaming (Fig. 4) using secure communication through a VPN tunnel. Additionally, a UPS is available to provide power for up to one day in case of outages, ensuring continued operation without immediate recharging.

Figure 4. Real-time seismic data streaming

One of the most significant aspects of seismic data visualization is the dayplot (Fig. 5). The dayplot provides an overview of the data collected over a day, allowing users to identify notable events and time periods of interest. This enables further detailed analysis of specific time periods identified from the dayplot.

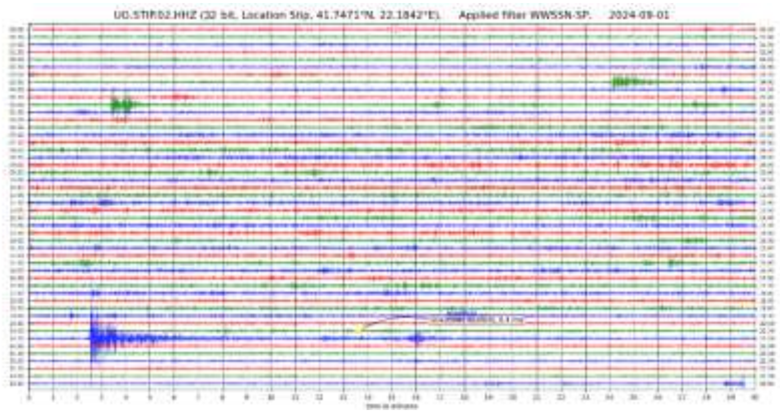

Figure 5. Seismogram (aggregate seismic data, dayplot)

A dedicated laboratory was established within the university campus for continuous seismic data acquisition using a single-channel vertical seismometer, positioned at coordinates 41.7471°N, 22.1842°E, and an elevation of 297 meters. During this phase, the system successfully detected several significant earthquakes in neighboring regions. Future testing will focus on controlled induced seismic events, such as artificial hammering, and field environment testing, particularly in open-pit mines.

CONCLUSIONS

This paper presents a prototype seismic data acquisition (DAQ) system designed specifically for monitoring seismic events caused by blasting in open-pit mines. The system offers high precision and resolution, supporting real-time monitoring, data storage, remote access, transmission, and visualization. The primary goal is to create a mobile, autonomous, and portable station that houses all components within a single enclosure, allowing for seismic data collection in any location. The design ensures that all modules are integrated seamlessly into one compact unit. This system is intended to advance geophysical research, structural health monitoring, disaster preparedness, and safety protocols, while providing valuable insights into seismic activity.

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