Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

Roadmap to Build Low-cost Ground Motion Monitoring Sensing Unit

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ABSTRACT
Building a low-cost Ground Motion Monitoring Unit is a challenging process, and many challenges exist, such as choosing the proper seismic sensor, analog-to-digital converter, and digital data processing. To analyze, store, and send real-time seismic data to a data center, we need to construct various libraries to operate the hardware of the Ground Motion Monitoring Unit. This paper presents a detailed roadmap that demonstrates the challenges of building a low-cost Ground Motion Monitoring Unit to benefit the research community and has a positive influence through knowledge sharing. The major goal of this study was to save researchers time and effort, especially those who wish to learn about the design of low-cost Ground Motion Monitoring devices.

Keywords: *Ground Motion Monitoring, Geophone, MEMS, ObsPy., PROMAT*

1. Introduction

Historically, the Ground Motion Monitoring Unit (GMMU) has recorded velocity and acceleration associated with seismic events without engaging in any sophisticated seismic data analysis With significant advancements in seismic sensors and digital signal processing, GMMU is now performing extremely complex functions, making the design process difficult, expensive, and time-consuming. In 2019, the authors built their first GMMU, PRO-MATE [1]. After three years of work, much effort was put into finishing the PRO-MATE. The authors decided to share their experience with the research community by providing a detailed roadmap shown in Fig.1 to help developers build their own GMMU. The fundamental zone covers the basics of earthquakes , electronic components, circuits, and software fundamentals. The design zone covers building sensor and analog-to-digital converter (ADC) interface circuits, connecting electronic components, fundamental operating modules required to extract data from the ADC, event detection, event data processing, and real-time data handling. The applications of GMMU are discussed in the application zone.

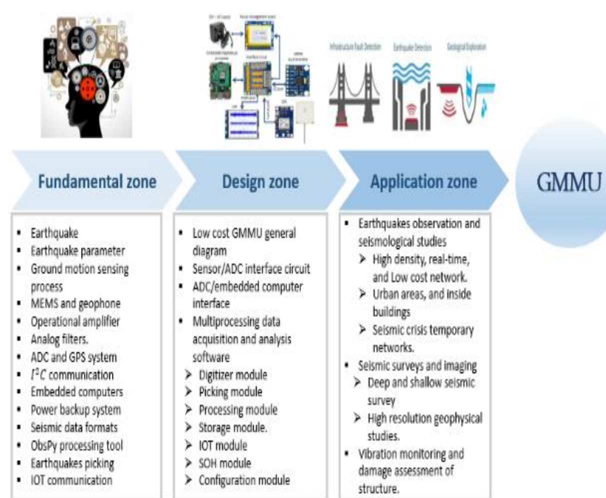


Fig.1. Basic building blocks for GMMU's proposed roadmap

I. FUNDAMENTALS ZONE

A. Earthquakes

An earthquake is an event resulting from plate tectonics' movement and collision. Two types of seismic waves combine earthquakes: body waves (Primary or P-waves and secondary or S-waves), and surface waves (Rayleigh and Love waves) Fig.2 [2].

Fig.2. Types of seismic waves: p-waves; S-waves; Love waves; Rayleigh waves

P-waves travel in the direction of propagation as a sequence of compressions and rarefactions. P-waves are followed by the S-waves. Rotation is caused by Rayleigh waves, which spread as ripples close to Earth's surface. In contrast, love waves move parallel to the Earth's surface but orthogonally to the direction of propagation [3].

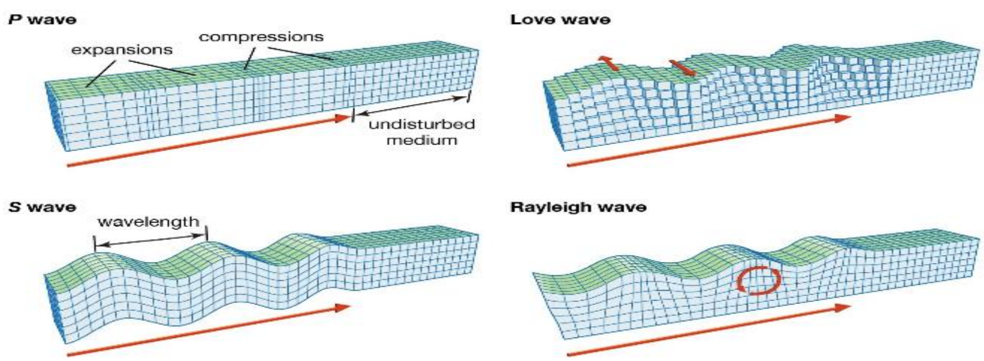


Fig.2. Types of seismic waves: p-waves; S-waves; Love waves; Rayleigh waves

B. Earthquake parameters

Earthquake intensity, which describes the effect of the earthquake on a specific area, has long been used globally to assess the shaking pattern and amount of damage imposed by an earthquake. The earthquake intensity levels were measured using the Modified Mercalli Intensity Scale. Ground motion prediction equations (GMPEs) are

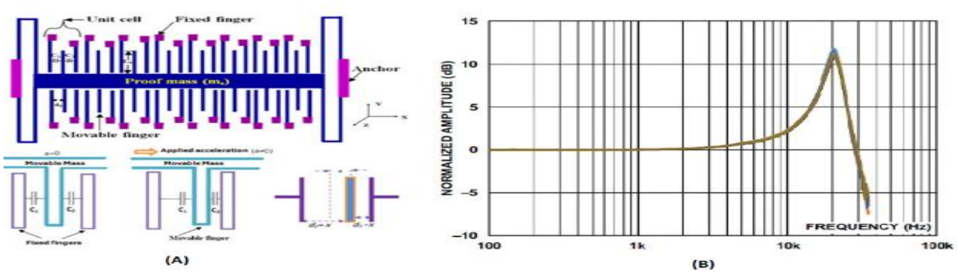


Fig.3. (A) MEMS accelerometer structure, (B) MEMS accelerometer response (low pass filter configuration)

useful tools for predicting the magnitude of an earthquake. The three ground motion parameters employed in the developed equations are Peak Ground Displacement (PGD), Peak Ground Velocity (PGV), and Peak Ground Acceleration (PGA). Equation (1), and Equation (2) present the correlation equations that Wald and Hershberger [4] developed.

$$MMI = 2.2\log(PGA_{max}) + 1 \qquad (1)$$

$$MMI = 2.33\log(PGA) + 1.5 \qquad (2)$$

The Spectral Intensity (SI) of an earthquake indicates how much destructive energy it will impart to a specific structure. Based on the velocity response spectrum (sv), the SI value is obtained using (3). The SI value is used to calculate the seismic impact of an earthquake on a building's structural integrity [5].

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} sv(T,h)dT \qquad (3)$$

The magnitude of an earthquake is an indication of the energy generated at the source, or epicenter. Its value is independent of the measurement site. Several factors affect the ability to establish a clear relationship between earthquake magnitude and intensity, including the depth of the hypocenter or focus, the composition of the ground surrounding the hypocenter, the type of soil between the epicenter and the measuring device, and the location of the device about the epicenter.

C. Overview of low-cost sensors of GMMU

The seismic wave band has a broad frequency range, from 0.00001 to 1000 Hz. Thus, creating seismic instruments that cover at least part of this broad frequency and dynamic range is challenging. In seismology, seismic sensors are employed in a variety of methods. In this section, we will focus on inexpensive sensors that are utilized to build low-cost GMMU units, such as geophones and micro-electromechanical systems (MEMS) accelerometers.

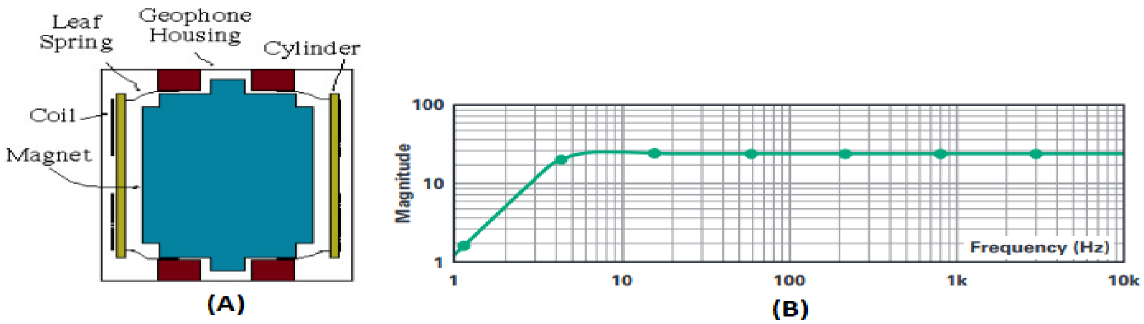


Fig.4. (A) geophone internal components, (B) geophone response (high pass filter configuration).

i- MEMS accelerometer

A MEMS accelerometer is an IC package device that observes acceleration. As demonstrated in Fig.3, the proof mass with movable fingers moves both in and out of the forced direction. This movement modifies C_1 and C_2 capacitances. The applied external acceleration can be used to measure and calibrate this change in capacitances. Since the bandwidth of commercial MEMS sensors is broader due to their general-purpose design, it primarily depends on the signal conditioning electrical circuits to obtain higher sensitivity [6] [7]. Table. I list the available commercial MEMS accelerometers that several authors have utilized to construct low-cost accelerograph units.

Table. I. Commercial MEMS accelerometer used in recent publications and its specifications

MEMS	Output	Range (g)	Frequency (HZ)
ADXL335	Analog	± 3	0.5:550
LIS3DHH	Digital	± 2.5	0:440
MMA8452	Digital	± 8	0:800
MPU6050	Digital	± 16	0:260
MSV6000	Analog	± 2	0:1200
LIS344ALH	Analog	± 6	0:1800
GY-61	Analog	± 3	0.5:550

ii- Geophone

Geophones are passive sensors that measure ground velocity. The geophone shown in Fig.4, with a coil free to move around a permanent magnet, the coil is integral with an inertial mass and, in turn, anchored to the structure using springs. This geophone is sensitive and can detect very low frequencies, even of a few Hertz. Geophones typically have a mass of 20g and the generator constant is nearly always around 30 V/ms^{-1}. It is often used with circuits that will extend the frequency range. Due to its low sensitivity, it requires more amplification than the standard sensors.

D. Choosing the proper sensor

The technical parameters of the available velocity and acceleration sensors vary. The particular application will determine its specific requirements, and the following factor needs to be taken into account [8]: $10^5\ to\ 10^{-7} m.s^{-2}/\sqrt{Hz}$ noise output spectrum density; $10^2\ mV.m^{-1}.s^2$ sensitivity; $\pm 2\ and\ \pm 20\ m.s^{-2}$ observable amplitude; $10^{-2}\ and\ 10^2\ HZ$ frequency range; 10^{-2} and $10^{-3}\ m.s^2$ resolution [9]. Several factors, such as budgetary limitations, specific goals, and the scope of the application under consideration, as well as a choice from the best commercially available devices, may influence the choice of sensors.

E. operational amplifier and filtering

Operational amplifiers "op-amps" are analog electrical chips that change the output voltage from a differential input to a single-ended one. Many important characteristics and attributes are present in op-amps, including gain bandwidth product (GBP), frequency response and bandwidth (BW), input and output impedance, and open-loop gain. Selecting the appropriate op-amp for a given application requires consideration of multiple aspects [10]. Op-amps are used in seismic sensors to construct active filters, signal conditioning circuits, and signal isolation. Wideband frequency op-amps, such as LT1028, LT1128, OP-227, OP-77, LT-1012, LT1169, LM-2904, LM358, TL071, LM741, CA3094, LT1001, AD797, and AD797BR, are used in seismic sensors and are known for their high sensitivity, low noise, and superior performance. In seismology, filters are utilized for numerous purposes such as antialiasing, identifying harmonic signals, correcting instrument response, and distinguishing 'desirable' from 'unwanted' frequencies. three primary categories of filters exist band pass, low-pass, and high-pass filters

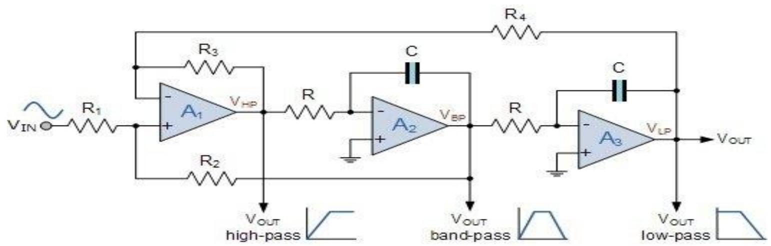


Fig.5 [11].

Fig.5 The four common filters Output: (A) a low-pass, (B) a high-pass, (C) a bandpass, and (D) a band-stop filter.

F. ADCs and GPS

The term "analog-to-digital conversion" refers to the process of using an ADC to convert a continuous analog signal into a discrete series of numbers representing the signal. When selecting an ADC for a certain application, it's important to keep in mind its fundamental characteristics, which include “resolution, gain, sample rate, full scale, dynamic, accuracy, noise level, nonlinearity, and input impedance”. Low-cost ADCs with GMMU architecture have been used in recent studies, several law cost ADCs that are available on the market and can be utilized for GMMU design are “NAU7802, ADS1232, CS5532, AD7793, AD4032-24, MCP3561, AD127L01, and HX710B”. GPS is used in GMMU architecture for signal timing, earthquake location, and digitizer internal clock correction [12]. A9G, L96, Adafruit P6H071316, Ublox NEO-6m, and UM980 are among some of the numerous Low-Cost GPS circuits that are on the market that can be used in GMMU design.

G. I^2C communication

The majority of Low-Cost seismic sensors are digital, and digital data is exchanged between the sensor and the GMMU maser unit's data-acquisition processor via I^2C protocols. The I^2C (Inter-Integrated Circuit) protocol is commonly used for enabling communication between integrated circuits. SDA (Serial Data) is the line used to send and receive data between the master and slave, while SCL (Serial Clock) is the line used for transmitting the clock signal. I^2C only uses these two wires to transport data between devices. The benefit of combining the I^2C protocol with digital sensors is that, as Fig.6 illustrates, one processing unit can receive data simultaneously from numerous sensing units. By averaging sensor data, the use of numerous sensors in a single GMMU improves data recording accuracy [13]

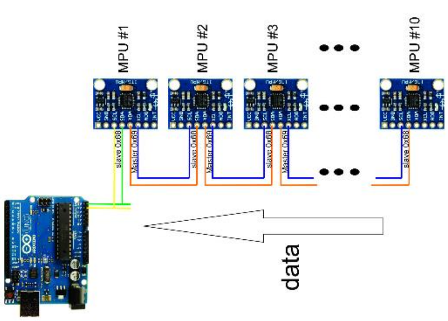


Fig 6. Multiple low-cost MEMS accelerometers connected increase measurement accuracy

Fig.7. example of microcontrollers and microcomputers to utilized in low-cost GMMU design

H. Data recording, processing, and seismic data format

Two central processing units (CPU) form a modern GMMU unit, the first used for digital data collection, storage, and packing. This type of CPU is used by remote nodes that use external computing equipment for data analysis. Examples of this kind of CPUs are microprocessors used in the Arduino microcontroller family, which is shown in Fig. 7. Time-synchronized data sampling, complex real-time data processing, communication, and real-time data transmission via data link to primary data centers are all handled by the second CPU type. This type of processing unit is used in remote units that handle large amounts of signal processing. Examples of this kind of CPU are the microprocessors found in the

Raspberry Pi microcomputer series, which is shown in Fig. 7. There are several different data formats used for waveform data sharing and storage (SEG-Y, GCF, SEED, MINISEED, etc.). However, the most complete and widely accepted standard is the SEED format and its MSEED equivalent. The SEED standard is the only one that provides the most important metadata along with the waveform data in a single file, called a SEED volume. The MSEED section of the SEED specification only includes the waveform data. All of the information that has been stored about the equipment and the location of the waveform's site is referred to as metadata.

I. ObsPy toolbox

A Python framework for handling seismological data is provided by the open-source program ObsPy. It offers clients to access data centers, parsers for popular file formats, and algorithms for processing seismological signals that enable the modification of seismological time series. It allows clients to communicate with the most significant data centers at IRIS and ORFEUS/GEOFON, and it offers read/write support for the most pertinent waveform data formats used at observatories and data centers. It also supports the standard metadata-sharing format of Dataless SEED. ObsPy can operate with XML-SEED in addition to supporting metadata stored in Dataless SEED or Full SEED volumes. It also offers an extensive list of routines for data analysis, visualization, and signal processing. Python is used in conjunction with ObsPy to give GMMU strong processing capabilities.

J. Earthquake automatic detection

A trigger or earthquake detection algorithm examines variations in signals that point to an incoming earthquake. The level trigger and the STA/LTA trigger are the two most popular forms of event detection algorithms. We will only briefly outline those. Many complex and sophisticated detection algorithms, including "Scalodeep, Capsule, Vision transformer, EQCCT, Eqtransformer, Phasenet, and Generalized phase picker", have been developed as a result of the enormous advancements in artificial intelligence [14-17] . The level trigger simply searches for any amplitude exceeding a preset threshold. Recording starts whenever this threshold is reached and stops when the level is below or after a given time. This kind of trigger is used in many analog-recording accelerographs and can be used in very basic instruments. A single channel in the short-term average long-term average trigger (STA/LTA) is normally processed in this way: as in Fig. 8, the absolute average STA (short-term average) over the STA time window (usually = 0.5 sec) is calculated after the signal has been band-pass filtered. Additionally, the LTA (long-term average) throughout the LTA time range (usually 50 sec) is computed using the same filtered signal. As a result, while the STA reacts to short-term signal fluctuations, the LTA provides the long-term background signal level. An event is announced for that trace when the ratio of STA to LTA exceeds a predetermined threshold, known as the trigger level. This ratio is continuously monitored.

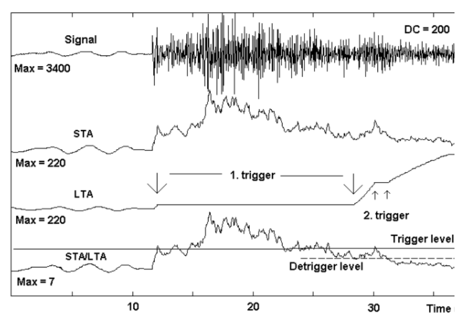


Fig.8 An illustration of how the STA/LTA algorithm uses the absolute value for the standard trigger

K. Data communication protocols

The Means of Communication is very important for GMMU to exchange real-time data with data collection centers, data download, monitor the state of health of GMMU, and change the configuration of the GMMU. Serial communication (RS-232, RS-484), WI-FI, Bluetooth, and GSM are common communication methods used in GMMU design. Most of embedded microcontrollers involve serial communication. There are low-cost communication shields available in the market for embedded controllers to increase communication capabilities shown in Fig.9.

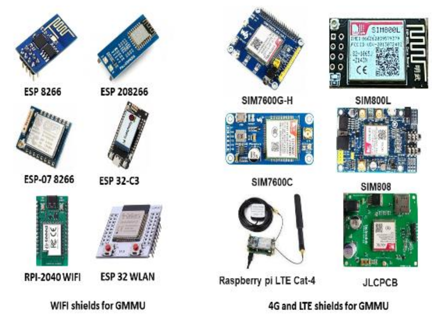


Fig.9 WIFI and 4g modules used for GMMU

2- DESIGN ZONE

A. Low-cost GMMU diagram

In the ground motion monitoring process, the GMMU continuously monitored ground vibrations. Once a seismic event occurs, data acquisition begins, and real-time data are saved on a large SD card and immediately transmitted to the data acquisition center. Authors in [5] proposed a general block diagram shown in Fig.10 for a low-cost GMMU, that is flexible for different applications.

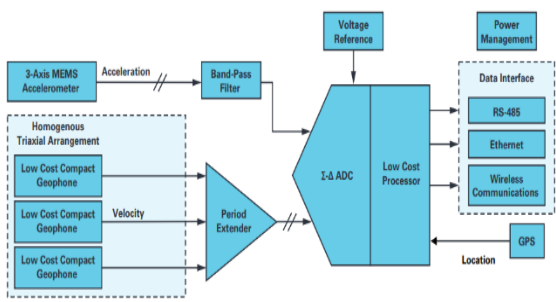


Fig.10. General block schematic of a low-cost GMMU featuring a three-axis MEMS accelerometer and three homogeneously triaxially organized geophones

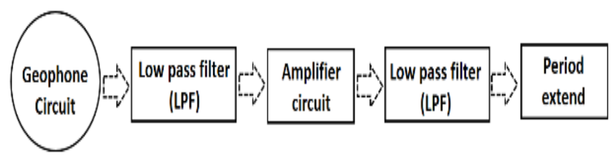


Fig.11. Geophone interface circuit diagram.

A period extender is required to extend the geophone bandwidth downward to achieve the standard instrument specification for broadband sensors. Band-pass filters improve the acceleration signal in the frequency range of interest to local seismology. The voltage reference sets the measurement range of the ADC and the output signal swing of the period extender. The sigma-delta converter takes in three-channel velocity signals from the period extender and another three-channel acceleration signals if an analog output accelerometer is used. The design requires a converter with at least six input channels. Velocity and acceleration signals need to be sampled, if possible, simultaneously. The analysis of seismic signals promotes the oversampling of each channel. Therefore, the ADC should be chosen to have a sampling rate much higher than 1.2 kSPS. The function of the low-cost processor varies with the application. For remote nodes that use an external computing device for data analysis, the processor is a data logger that stores and packs the seismic data of all channels to the standard format and sends them to the computing device via a data interface. The instrument's location data may either be extracted from a GPS module or manually set during installation. For the time data, the low-cost DSP can use either its internal RTC peripheral or via NTP through the data interface. In the following parts, we are going to mention a couple of circuits for MEMS and Geophone interface circuits, and period expansion circuits with ADC.

B. MEMS accelerometer, geophone interface circuit with ADC

The output signal from sensors can be very small, these voltages can usually not be recorded with any recording device directly and must first be amplified, and filtered. The circuit diagram, which is shown in Fig.11 describes the interface circuit for the geophone sensor. It consists of four blocks; a low pass filter (LPF), an amplifier circuit, then another LPF circuit, and a period extension circuit. First LPF is used to filter signals outside the frequency range of interest of the geophone. The amplifier circuit provides high gain amplification for geophone signal to be sampled at high resolution.

The second LPF is used to filter any noise and ensure a smooth decay for LPF. A period extension circuit is used to extend the working frequency range of the geophone till it reaches 0.1 HZ. There are many geophone interface circuits introduced by many authors, only interface circuits introduced by authors in [18] [19] will be presented in Fig.12 and Fig.13.

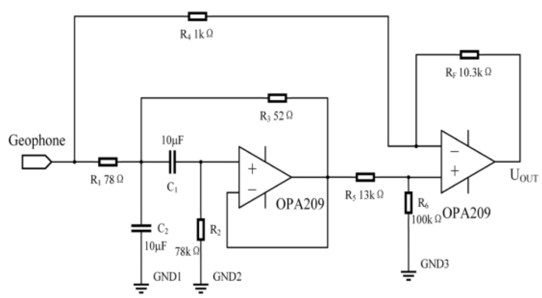


Fig.12. low pass filter and amplifier circuit for geophone

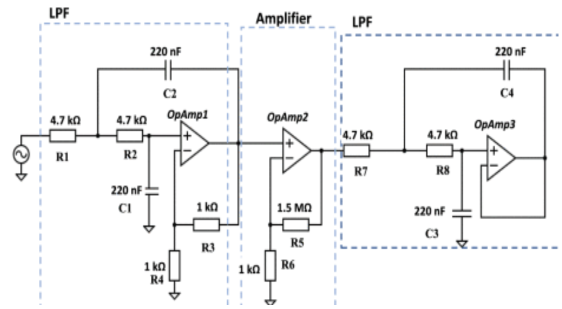
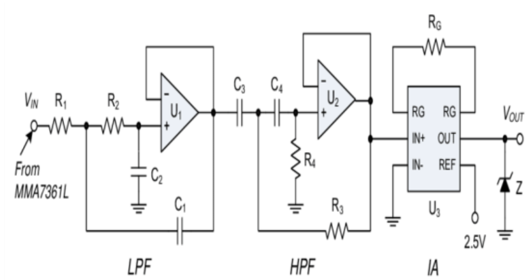


Fig.13. Geophone period expansion circuit

The circuit diagram, which is shown in Fig.14 describes the interface circuit for the MEMS accelerometer sensor. It consists of three blocks; a low pass filter (LPF), and high pass filter (HPF), and an amplifier circuit. The function of LPF is to reduce high-frequency noise, whereas HPF is to remove static voltage (DC) caused by the static acceleration of the accelerometer. There are many MEMS accelerometer interface circuits introduced by many authors, but only interface circuits introduced by authors in [20] are Introduced in Fig.15.



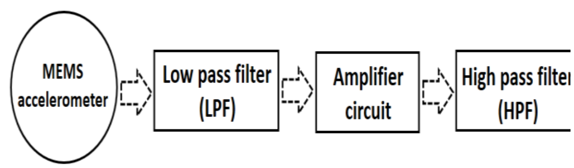


Fig.15. MEMS accelerometer interface circuit, LPF, HPF, and amplifier

Fig.14. MEMS accelerometer interface circuit diagram.

C. ***Real-time data acquisition and processing***

to run the hardware of the built GMMU, we need to build several libraries to process, store, and transmit seismic data in real time to a data center. RB-DAS is a multiprocessing, real-time data collection, and processor software package developed by the PRO-MATE authors [3]. The authors developed a set of operational modules that function in parallel and exchange data with each other via shared data memory. Upon initial power-up, a module receives a series of setup messages. It then continues to execute certain data processing tasks and shares a collection of data processing products with other modules. The modules developed for building the RB-DAS were restricted to the PRO-MATE hardware; we will talk about the general modules in the following section that developers may want to take into account when creating their operating modules to run their own GMMU.

D. ***Sequential Vs parallel computing***

sequential and multiprocessing computing are major techniques used to develop data acquisition and analysis software. In the sequential software technique, it runs each module of the software once at a time, so the system's response time is extended, which may result in the loss of some digital data from the digital seismic sensor because the system has not finished responding to the previous data. Sequential software is suitable for low-frequency or lower sampling rate seismic data acquisition systems or in cases where the GMMU records seismic events only and drops continuous data, so it is not a problem if any data gets lost during the processing of the detected seismic event. The design of parallel data acquisition software where consists of a group of modules "immersed" in a message -transmission "medium" (Rings) as shown in Fig.16. each module does a specific function and shares data products with other modules through a communication medium.Modules communicate by broadcasting and receiving different signals. Using parallel computing speeds up system response times, and ensures that no data is lost. Parallel computing is suitable for GMMUS where it uses a high sampling rate and records data continuously.

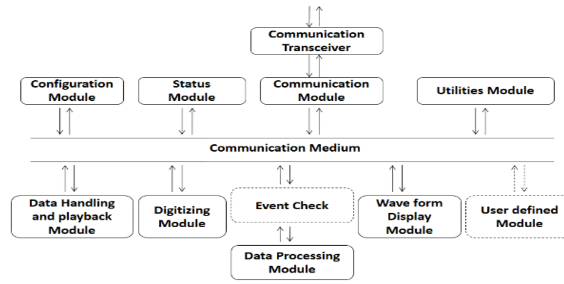


Fig.16 parallel computing modularity idea

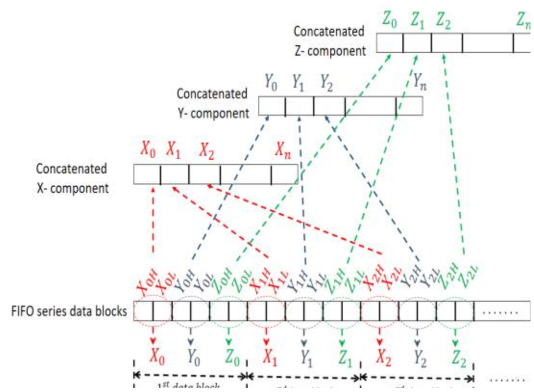


Fig.17. digital data separation and concatenation

E. ***Digitizing module***

Using the I2C data exchange and communication protocol, the digitizer module connects with the digital sensor to collect real-time digital data from the ADC. For each of the three channels, the ADC stores digital data as serial data in a First-in First-out (FIFO) register. The digital data in the FIFO register is arranged serially, as illustrated in Fig17, with each pair of bytes representing a single sample of each component. The data lists for each component are formed by the separation and concatenation operations carried out by the digitizer module.

F. ***Event Detection/ processing module***

The seismic events should be detected and retrieved to process the seismic data. As seen in Fig. 18, the event detection module sets a user-configurable 10-second time window before calculating the STA/LTA ratio. The event detection module then generates an event alarm when the STA/LTA ratio rises above the predetermined threshold. A series of operations are carried out by event processing to determine the PGA, PGV, and PGD for the detected event.

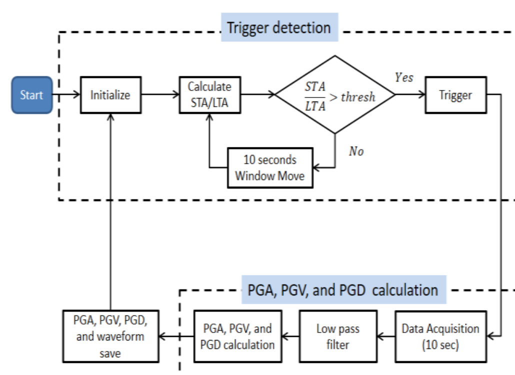


Fig.18 The event detection and processing model

G. ***Data handling, playback, and utility modules***

Real-time data collected by the GMMU, detected earthquakes, earthquake processing data production, sensor response files, and device state-of-health are stored in a large SD card for further analysis and device monitoring using the data handling, playback, and utility modules. One MiniSeed file containing 24 hours of continuous data may require a lot of post-processing tools due to its length, or the 24-hour continuous data file may be divided into groups of files that are all the same length (file length = 24 hours/number of files), requiring less post-processing software. There is no need to preserve continuous data when storage is restricted and noise should be removed. Seismic data that has been detected is stored in separate files that can be saved in any standard seismic data format, including MiniSeed, ASCII, SAC, or another user-selected format. Separate PDF files contain a report about the data products used for event processing. When it comes to file-saving techniques, the hierarchical file system is recommended. Network Name (NET), Station Name (STN), Channel Name (CH), and event origin time (year, month, day, hour, minute, seconds, and milliseconds) are examples of site parameters and event detection time that can be used to name files in a clear and meaningful manner. Time-stamped digital data should be saved in very long ring buffers so that users can access and convert it using built-in data conversion tools to any other seismic data format.

H. ***Configuration module***

The configuration module exchanges configuration messages with the operating modules and obtains configuration settings from GMMU users via a graphical user interface (GUI). The configuration module wakes up all operational modules by sending a configuration alert message, and then it begins to communicate configuration messages with them as fresh user configurations become available.

3- APPLICATION ZONE

The following wide areas of application can be distinguished: earthquake observation and seismological study, seismic surveys and imaging, and vibration monitoring of structures and structural assessment.

A. Earthquake observation and seismological study

The GMMU-based seismic stations can be installed in relatively noisy sites such as urban areas or even inside buildings, over time, some GMMU developed until they become well-established structures extending both at the urban scale and country scale. The use of GMMU-based networks for more specific seismological applications (i.e., localization, magnitude estimation, etc.) is conversely not robust at present, mainly because the data accuracy requested for such tasks is certainly higher. GMMU stations could contribute to temporary network tightening in case of a seismic crisis when a fast monitoring enhancement around the epicentral area is desirable, also with the help of local citizens. Moreover, in the cases when a certain degree of redundancy is required, then a mixed traditional- GMMU network could represent a proper solution in terms of cost–benefit ratio.

B. Seismic Surveys and Imaging

Another field of application of GMMU is seismic surveying and imaging both for deep (i.e., oil and gas exploration) and shallow (e.g., near-surface geophysics) investigation; fundamentally. the GMMU sensors might be preferable because of their reduced dimension and weight, being easier to handle, and also better in long-term endurance. In this field, either commercial products or specifically designed devices can be used. Moreover, the use of GMMUs can indirectly improve the quality of seismic imaging: a huge array of sensors (hundreds to thousands) can be deployed at the same time with contained cost and acceptable quality, resulting in high-resolution geophysical models.

C. Vibration Monitoring and Damage Assessment of Structures

Structural Health Monitoring is a fundamental tool to integrate and support conservation strategies of infrastructures and to preserve their strategic function (i.e., security, management, organization). Buildings and any infrastructure in general, are built to stand for ordinary and extreme events. The stress factors acting on the structures can be due to natural or anthropogenic factors: seismic events, atmospheric agents (wind, thermal cycles), vibration due to traffic flow, and applied loads. They all contribute to lowering the resistance properties (corrosion, alteration, etc.).

CONCLUSION

Over the past ten years, there has been a growing demand for low-cost ground motion monitoring units for the development of new seismic monitoring networks. Many network operators also supported the deployment of real-time, low-cost, high-density networks. Therefore, the proposal of developing a road map as a fundamental step to assist developers and operators of seismic networks in creating low-cost ground motion monitoring devices was an aspect of the study issue. We tried to answer the research question by providing basic building blocks that provide basic knowledge about seismic backgrounds such as earthquakes, and earthquake parameters; seismic instruments and electronic backgrounds such as MEMS accelerometer, geophone, choosing the right sensor, Op-Amps and filters, ADCs, processing boards, and data communication boards and protocols; general diagram for building low-cost ground motion monitoring units such as geophone and accelerometer interface circuit; basic operating modules to run the hardware such as digitizing module, trigger and analysis module, data handling modules, and configuration module. The authors' experience developing their low-cost PRO-MATE ground motion monitoring equipment formed the basis for our perspective on the proposed road map, and we made all attempts to include every important detail. The roadmap isn't perfect; depending on what they want to build, some developers may discover something they overlooked, and others might find material that isn't needed. By filling a small research gap, we believe that this article will benefit everyone by saving their research time.

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Disclosure

The author reports no conflicts of interest in this work.

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