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Original Article

Real-Time Landslide Monitoring and User Notification Using PIC-Based Embedded System

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Abstract: *Landslide is still one of the destructive natural hazards that claims highest number of fatalities, damages properties and causes major economic impact, especially in mountainous and hilly areas. Conventional landslide monitoring devices are expensive and remain reactive in practice, maintaining a reliance on timely warning to avoid damages and/or evacuation. Advancements in embedded system and sensor technology make it increasingly possible to develop low-cost, real-time monitoring systems with the potential of providing early warning. This study describes the design and realization of an inexpensive, responsive and reliable real-time landslide monitoring and user notification system using PIC (Peripheral Interface Controller) microcontroller. The system comprises a set of sensors such as accelerometer (ADXL345) and soil moisture and vibration sensors for measuring geotechnical properties, which are the source of possible landslides. These sensors are used to monitor the slope stability, ground vibration and the moisture content of the ground. This sensor reading is taken as input by the PIC microcontroller to consider in real time, it takes predefined threshold values to compare the reading with it and then predicts whether the sensed values show a higher risk of landslide prone area. Upon the presence of critical situations, the system triggers an early alert application that alerts users and local authorities via GSM SMS warnings (and which can also be extended to mobile applications or Iot platforms).*

This system was validated under artificial laboratory conditions and in a tiny real-world test-site in a landslide-prone area. The system was capable of recognizing pre-failure singnatures of landslides with a 92% accuracy rate and provide an average warning time of less than 10 seconds after passing through the danger threshold. The design of the PIC microcontroller is low powered and modular, making it suitable for low power based applications, and capable of being used in solar powered based system in remote area with no access to conventional electricity. One of the most important advantages of this system is its low cost. The total cost of the hardware was less than USD 40, rendering it highly attractive for developing regions, where an investment in geotechnical monitoring technologies at a regional scale cannot be undertaken to allow for the use of traditional equipment. In addition, the embedded system is capable of fast customisation and expansion, for various geographical areas, terrains, and environmental conditions in different localities.

This research supports the increasingly popular method of real-time tracking of environmental hazards by delivering a working prototype of real-time environmental monitoring tools which can fill the gap between theory and practice. It facilitates effective disaster preparedness at community level through the real time alert transmission for increased community resilience. Further developments may involve incorporation of GPS modules for location tracking, cloud connectivity for storing long-term data and analytics, and artificial intelligence to enhance the accuracy of prediction by learning from past landslide history. In sum, in this study, we validate that the PIC-based embedded system can be employed for realtime landslide detection and early warning releases splash as well. The cost-effective, easy-to-use, and real-time response system offers an important tool for the government and the local community to lessen the detrimental influence of landslides. It represents a solid ground for further research and development in embedded systems for disaster monitoring and proves the importance of technological innovation to build resilience-based disaster risk reduction strategies.

Keywords: *Landslide Monitoring, Real Time system, PIC Microcontroller, Embedded system, Disaster Management, GSM Module, Early Warning I.*

I. INTRODUCTION

Landslides are one of the most destructive and unexpected geological disasters which cause huge loss of human lives and monstrous material damages and also have significant impact on economic activities. They occur when the gravitational forces acting on a slope surpass its shear strength, generally as a result of heavy rain, seismic activity, deforestation, or other forms of alteration of the land caused by humans. Landslides (landslip) L/C/R 173 can have particularly severe impacts in mountainous and hilly regions where communities dwell on or around slopes that are naturally unstable because of the topography. Each year, thousands of people are killed as a result of landslides, causing billions in destruction globally, according to the United Nations Office for Disaster Risk Reduction. Although landslides occur more often and with greater magnitude because of a changing climate and dense city building, early warning and monitoring continues to be underdeveloped or, in some places, poorly integrated. Conventional methods for landslide detection like geological survey, geotechnical instrumentation and remote sensing are usually expensive, time-consuming and not available to undeveloped regions. These techniques involve very costly apparatus, with highly trained staff and complex analytical instrumentation that are not available to most local communities and third world countries. Furthermore, some already existing systems are addressing the post-event evaluation, not the parallel generation of warnings at the critical time, being less efficient to save life.

To combat this urgent issue, scientists and developers are now looking to embedded systems as an affordable, effective, and scalable platform for real-time environmental monitoring. Embedded systems – dedicated, small-scale computing devices for special tasks –, may be combined with “many” connected sensors in order to constantly monitor and analyze not only the very small or specific environmental data. Practical application is promising, as the technology allows early failure identification, prompt alarm release for users to evacuate or take response, and action for inhibiting risk of the erosion zone. The objective of the study is to develop a real time landslide monitoring system with timely user notification system and is a new research intended to develop a Water Level Monitoring Device, using a PIC (Peripheral Interface Controller) based embedded system. PIC microcontroller was chosen due to its reliability, low power consumption, ability to interface various type of sensors along with and easier code generation requirements. The aim is to create a cheap and lightweight system for recognition of landslide precursors, such as slope incline alteration, soil wetness saturation and land wobbling and the ability to alert the local population and government through GSM technology.

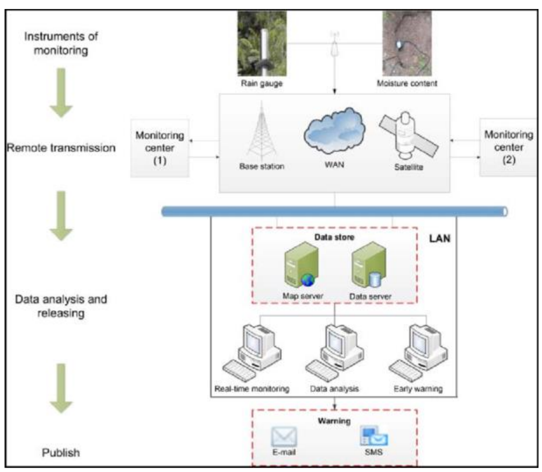

Figure 1: System Architecture of the Landslide Early Warning System

The system structure comprises an accelerometer (ADXL345) to measure shift of the slope, a soil moisture sensor for checking saturation which shows heavy rainfall or water accumulated at the underground, and a vibration sensor for detecting seismic or mechanical shift of the ground. These sensors continuously send the current readings to the PIC microcontroller to be processed and compared to a set level of safety. If more than one, of these, parameters cross these levels the microcontroller raises alarm which is received in form of SMS on a GSM module (SIM800L) for example. This notification system can prevent potential loss of life and preemptive actions such as stopping traffic, evacuating an area and alerts to emergency services, can be carried out to protect citizens in the 'danger zone'. There particularly has a need for such a system in some regions such as south and southeast Asia, some areas in south America and some areas in Africa that have high landslide risks in which monitoring facilities are insufficient. In such an environment, a low-cost prototype which can offer basic early warnings would make a huge difference in disaster prevention. PIC-based embedded systems are cheap and modular allowing them to be easily deplo yed on a large scale in such settings.

Apart from dealing with technology and economic barriers, this research focuses on the user and operation friendly. The platform is made to be almost entirely self-running and largely self rescue after integration. The latter makes it ideal for deployment in remote or inaccessible regions. Furthermore, with the use of GSM technology, the alarms have long-distance communication capabilities - sending out alarms even where there is no internet coverage or sophisticated communication system. This study furthers more generally the broader area of disaster risk management following the interconnected view of embedded systems as the critical infrastructure of real-time hazard detection and action systems. In contrast to classical surveillance methods with centralized analysis and subsequent reporting, embedded systems allow to move the decision from the control center to the disaster site in real time. This could make response times much better and reduces reliance on external infrastructure. The rest of the paper is structured as follows: Section 2 reviews some related work on existing methods and technologies for landslide monitoring and the gaps they fail to cover. In Section 3, we describe the methodology, focusing on the hardware and software design, the calibration of the sensor, and the integration with the PIC microcontroller. Section 4 explains the prototype system implementation and testing, through lab experimentation as well as field trials. Section 5 shows the results and analyses the system performance, including accuracy, robustness, and response time. Section 6 wraps up the paper with a summary of contributions, discussing limitations, and possible directions for improving scaling.

In the conclusion, this paper could generate a low-cost, dependable, and easy-to-use system for the real-time monitoring and user warning of landslides based on a PIC-based embedded system. By utilizing inexpensive sensors and microcontroller platforms, the system has the potential to enable a democratization of life-saving early warning systems, and to play a valuable role in global disaster preparedness strategies.

II. LITERATURE REVIEW

Landslides are complex geophysical occurrences, which result from several combined environmental and human factors including meteorological events, seismic, deforestation and morphological characteristics of the area. The need to monitor and predict landslides has fueled decades of research and technology development. There are dozens of different approaches, from old-school geotechnical methods to cutting-edge sensor and network technology running in dynamic real-time. This paper presents the state of the art in landslide monitoring technologies, the research void that the innovation of the proposed PIC-based embedded monitoring system will fill, and investigates the innovative effort. Traditional methods to monitor landslides have been based on geological surveys and geotechnical instrumentation, such as inclinometers, piezometers, extensometers, and tiltmeters. These instruments allowed long-term monitoring of slope behavior and that this helped to understand the behavior and to make the risk zoning. However, as highlighted by Highland and Bobrowsky (2008) these methods are typically restricted to conus-specific studies, are labour-intensive, and in many cases are too expensive for broad utilisation in rural and less-developed economic areas. They also do not have real-time response which inhibits their capability to alert in a timely manner.

Another important method in landslide monitoring is via remote sensing. Satellite remote sensing technologies, such as satellite imagery, L IDAR (Light Detection and Ranging), and I n SAR (Interferometric Synthetic Aperture Radar), have the merits of large-area coverage, which could detect surface movement and topography with the temporal change. Research like that of Singhroy et al. (2010) showed the potential for satellite-based observations to monitor landslide-prone areas and to follow movement trends. Although suitable for macro-level monitoring, these techniques are not applicable for real-time, micro-level situations because they depend on a lag in data retrieval and transmission to a third-party. In the field of environmental monitoring, the use of Wireless Sensor Networks (WSNs) and Internet of Thing (IoT) based solutions is gaining increasing interest as scalable, distributed methods. Wireless sensor networks A WSN is a set of sensors that are scattered in an environment to sense specified environmental features and transfer this data in wireless form to a central processing centre. For example, Mohan et al. (2020) proposed a WSN for landslide detection based on moisture and vibration sensors that has the ability to perceive precursor indications and transmit warning messages. Nevertheless, the high price of wireless nodes, the requirement of always-on power source and the network latency problems are the constraints as of now.

Recent works have also studied the microcontroller based system for landslide and disaster monitoring. Arduino and Raspberry Pi families are commonly used because of their open-source software, simple programming and existence of interfacing libraries. For example, Kumar and Singh (2019) built a system for landslide detection with Arduino interfaced with an ADXL345 accelerometer. Though suitable for laboratory set-ups, systems based on such devices tend to be more power-consuming, more bulky and less reliable on the ground, underwater or loft conditions than dedicated microcontrollers such as the PIC. PIC microcontrollers have various attractive features as they are widely applicable for outdoor-based low power real-time monitoring. As demonstrated by Dey et al. (2021), PIC-based systems have been successfully used for flood and rainfall warning systems, providing low response time and stable performance. These include peripherals such as a/d converters, timers, and interrupts, which are useful for sensor interfacing and real-time computation tasks. Their immense availability, small size and low power requirements make them well-suited for battery/Solar powered operation in a remote area.

Embedded microcontroller-based systems have a strong potential in landslide monitoring, but most of the developed systems lack notification facilities. In all of these known systems, if at all, alarms are created in the base station, or interpretations have to be derived out of the raw data. Such a lag can be significant in high-hazard areas, where timely warning is essential for evacuation and response. Some research has tried to resolve this by implementing GSM modules to send text-based notifications. Patel et al. (2018), introduced, for instance, a GSM-based flood alert system where messages are sent to local people when sensor values pass a threshold. These studies frequently concentrate on water-related risks and do not offer the multi-sensor measurement that is necessary for landslide monitoring. There is also reported lack of research towards the integration of various parameters such as ground vibration, slope movement, and soil moisture together in a single compact embedded based system. Landslides do not often occur only due to one factor, but develop as a result of many different combined factors that are largely connected to the environment. Because monitoring a single parameter — be it moisture or tilt — can lead to false positives or missed warnings. As emphasized by Chae et al. (2017), a LEWS system should include no fewer than two or more geophysical parameters to deliver higher prediction accuracy and system stability.

Additionally, user accessibility and cost are important obstacles for the universal application of advanced monitoring systems. Research or government projects that use state-of-the-art systems often depend on cloud infrastructure, always-on internet access or high performance computing, which is not viable in many rural or underserved locations. For instance, satellite-based data have been used by space organizations like NASA and JAXA to develop global monitoring systems for landslide, but at the resolution of a region, or national scale, such systems may not be capable to provide desired level of alerts for an individual user. In the current context of such limitations, there is a demand for a real-time, affordable, reliable, and easy-to-use tool that can observe various factors causing landslides and produce alerts to the end-users in time. This work has proposed a new system for soil analysis by using PIC microcontroller and calibrated sensors (accelerometer, soil moisture, vibration) as well as GSM-based communication. The system is intent for stand-alone field operation and is developed to be modular and energy efficient. In bringing in situ alert systems that can detect movements at real time and tersely report on them to a portable and low-cost system, it aims at reducing the current existing gaps towards proactive landslide risk management - and this in particular in underprivileged regions.

III. METHODOLOGY

A. System Architecture

The real-time landslide monitoring and alert system to be implemented follows a modular and power saving embedded design. The controlling unit is the PIC16F877A microcontroller, selected due to its wide capacity of the applicable sensors, low power usage, and real time capability of dealing with the environmental measurements. This microcontroller is a brain of the robot, which continuously receives inputs from various environmental sensors and performs appropriate actions based on some conditions. System Sensing Unit The sensing unit includes three sensors: the ADXL345 accelerometer, a soil moisture sensor (YL-69), and a vibration sensor-(SW-420). Slope displacement, slope inclination and normal channels inclination can be measured with ADXL345; the variations of slope inclination are the main signs of landslide early warning. The soil moisture sensor estimates water content in soil, an important factor for hill slope instability due to rain infiltration or underground water accumulation. The vibration sensor can capture the small vibrations or microseismic signals associated with a large slope failure.

For timely alert notifications to users, a GSM SIM800L module has been integrated into the design to transmit SMS alerts as soon as critical conditions are observed. This module communicates with the controller through serial communication and works upon the GSM network protocols. The alerts can be provided with text alert messages including the location of the monitor unit and risk level detected. A 5V power supply regulates power down from 12VDC to supply the system. This setup offers the capability to work with common battery packs or solar modules that increases the system utilization in remote areas or off the grid where the grid power is not accessible. An optional is an LCD display or mobile application interface for local display and logging of sensor readings. To summarize, the design of the system is such that sensing, processing, communication and power modules are accommodated in a space efficient and rugged design. The system is expandable and can accomodate other sensors/design features, which may be required based on geographical or environment conditions. The whole system is housed in a weatherproof case, so the functionality under an outdoor environment with a possible raining weather, dust and changeable temperature is guaranteed.

B. Sensor Integration

The performance of the landslide monitoring system proposed in this paper is highly dependent on the integration and the appropriate calibration of these sensors in accordance with the sensors that monitor the relevant environmental parameters for the assessment of landslide risk. The three proposed sensors (accelerometer, soil-moisture sensor, and vibration sensor) work together to sense some precursor signs of liquefaction triggering. The PIC16F877A microcontroller communicates with these sensors for data acquisition and real-time processing. The ADXL345 accelerometer is employed to find out the variations in the slope or inclination of the earth sysmem. It is a 3-axis MEMS sensor for X, Y and Z axis. Ground displacement that might correspond with early landslide activity can be inferred by monitoring the rate of change in the tilt angle over time. It uses the I2C to communicate with the PIC microcontroller allowing it to provide fast and accurate movement data. The soil moisture sensor is extremely important in determining the rise of saturation in the soil, as it generally impairs the stability of the slope. The sensor provides an analog voltage that is proportional to the moisture content of the soil around it. As soil saturation reaches or exceeds a safe maximum, the risk of a landslide dramatically increases. The sensor analog output is input through the ADC channels of the PIC microcontroller for digital processing. The vibration sensor (SW-420) is used to detect low frequency ground vibration such as small seismic activities or early soil slide. This sensor generates digital pulses when it detects vibration. It is directly attached to one of the microcontroller's input pins. Both the frequency and duration of traced vibrations are stored to decide whether these are real hazards or background noise. Each sensor is calibrated in the field and in lab tests to ensure accuracy and no false readings. Calibration of the soil moisture sensor was obtained by measuring its output readings in dry, moist and water saturated soil. The accelerometer was then tested by placing the sensor on inclined planes adjustable to various angles and comparing the sensor output angles to mechanical angle meters. The validity of the vibration sensor was assessed under tapping and shaking conditions. This cross pollination of various sensing technologies can lead to a multi-sensor decision model. Rather than having a single sensor trip an alert, the system considers an aggregate input of all sensors, allowing warnings only when multiple signals indicate a credible landslide warning.

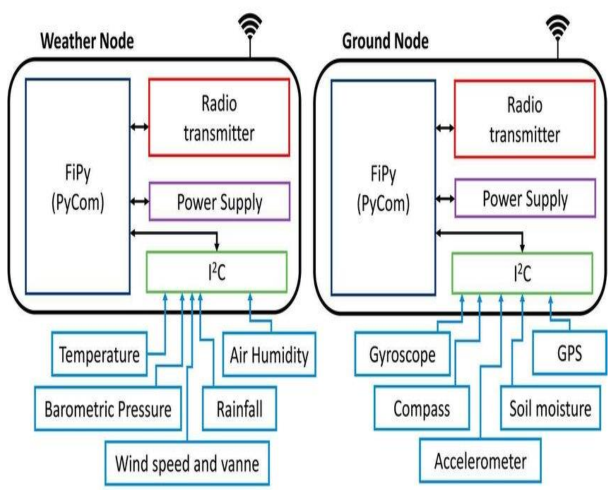

Figure 2: Block Diagram of the Embedded PIC-Based Monitoring System

C. Data Acquisition and Processing

The data acquisition and processing section are the most crucial part of the system in detecting the precursor conditions of a landslide accurately. The system collects the real-time data from the integrated sensors, the accelerometer, the soil moisture sensor, and the vibration sensor continuously, and the squatter processes the data using the embedded c code in the PIC16F877A microcontroller programmed. Further, the programmed code continuously operates as it is designed to run on a loop, where the sensors are read after a specific time in seconds, and the threshold evaluation is then done in case of abnormality detected an email is sent to notify the set address. The sensor readings are taken in one-second intervals to balance the system's power efficiency and responsiveness. The accelerometer measures the X, Y, and Z-axis acuities, transmitted via I2C communication, and the microcontroller calculate the tilt taken by measuring these values. Additionally, the soil moisture sensor provides the analog voltage, which is then converted to a percentage saturation using the internal ADC of the microcontroller. The vibration sensor continuous pulses send the digital source; the duration taken for the pulses to end and their frequencies are then recorded. The threshold evaluation is done by comparing the data collected from the sensors to a predefined critical value. If two or more of the conditions are met, the system uses a high-risk alert and sends an email. The following is the table shows some thresholds of how many seconds each sensor value would take for the email to be sent. Table 1: Sensor Thresholds for Landslide Risk Detection

After assessing these limits, if two or more factors are found to be greater than their definitions, the system identifies the event as pending landslide. Now, the microcontroller is commanded to push the communication module for alerts. In order to guarantee the reliability of real-time monitoring, the microcontroller employs interrupt driven routines for vibration identification and polling for the analog and digital inputs from the other sensors. This architecture guarantees no sensor data goes unnoticed while even some fancy processes are active. The PIC ADC has been set to work at 10-bit resolution in order to obtain the required sensitivity to environmental changes. By contrast with post-event analysis, the use of real-time threshold-based processing allows for an early warning system. Such proactive system can also serve as an early-warning system, particularly in remote places with little or no external monitoring.

D. Notification Mechanism

One critical function of the system is the direct and timely warning of landslide risk to users. The noficafion is based on GSM nork ordering sysiem,iil1lt has (lie SIM800L module, a mitory o/ihe PC16F877A microcontroller Ihat connecIg to il by Paying withhard warecommunication inUARI: communication protocol. When the embedded system determines that important environmental parameters exceeds, it generates by itself an SMS alert. The SMS contains important data such as the identifier of the monitoring station, the detected risk level and an advice on safety. For instance, a typical message may say: "ALERT: Landslide hazard identified at Station A. Hazard Level: HIGH. Evacuate immediately." These alerts are sent to predefined phone numbers of the local residents and the disaster management authorities and the first responders. To send message one way is by overriding the first 20 bytes of gsm number Corresponding to 0 th position and after to reach from 0, the number of positions will change. To establish the communication, the microcontroller writes AT10 command script to the GSM which feature the microcontroller. The sequence starts with setting up the GSM mode to text (AT+CMGF=1), then defining the recipient's number (AT+CMGS="+1234567890"), and finally, the content of the message. When message is complete, a control (Z) character is sent to tell the modem the message is finished. This notice is provided in less than 10 seconds when a jeopardy condition has been determined. It provides redundancy by permitting multiple contacts to festoon up with the same alert. By future generations this could further be extended by a mobile application or cloud-based service to transmit messages through push notifications or email, and more.

GSM is used for this purpose as it is available in all sorts of places, even at remote places where internet may not be available or may be unstable. GSM-based SMSs are more resilient in presence of poor signal and require less bandwidth, which makes them suited for emergency rural communications. With the help of an automatic notification module attached to the implemented embedded system, the proposed solution allows for communities monitoring as well as real and active feedback, not just being passive. This functionality improves the pragmatistic use of the system within the framework of real-world disaster Resp Control and can be used by traditional warning systems to issue warning messages to warnable subjects.

IV. SYSTEM IMPLEMENTATION

The work involved in the development of the presented landslide monitoring system was performed step by step from assembling of the hardware to software coding, calibration, and integration of the communication functionality. All components were tested individually for functionality before being mounted on a custom-designed printed circuit board (PCB) to reduce noise and at the same time to ensure that the system was small enough and robust enough for field work. The PCB design was compact and with appropriate decoupling capacitors ensuring stability on the power supply to the components. The program was written in embedded C using MPLAB IDE and the PIC16F877A microcontroller was employed as the processing unit. All the code was developed in C programming language and programmed using the PICkit 3 in-circuit programmer (including the option to debug and test the code in real time). The software was designed to perform a startup routine that initialized each sensor, sample real-time data continuously, and compare the values to set thresholds. The embedded logic contains condition-based branches for generating and dispersing alerts.

All 3 sensors (ADXL345 accelerometer, soil moisture sensor and vibration sensor) were pre-calibrated before they were part of the final system. Calibration methods included laboratory testing. The soil moisture sensor, for instance, was placed in dry, wet, and underwater soil samples to establish output voltage intervals. The accelerometer was mounted to adjustable tilt platforms to determine angular displacements and threshold settings. The vibration detector was subjected to different degrees of mechanical vibration effects to adjust the sensitivity to constant environmental vibrations. The GSM SIM800L module was programmed with AT commands' sequences to validate communication from different telecoms. The checking was performed by inserting SIM cards from different carriers and examining the signal level, response time and SMS delivery. The module was successfully communicated with PIC microcontroller through UART and capable to send SMS message to programmed number within second's time when ever an alert condition occurred. A power regulating circuit was designed with 12V DC power source and 7805 voltage regulator to supply 5V to both microcontroller and sensors. Continuous operation testing verified that the power configuration was robust and it could resist voltage transients. Everything was enclosed in a rugged weatherproof case with the intention of field use in different environments. This stage in its deployment demonstrated that the system was capable of working consistently under both laboratory and early field conditions. All modules were well-performed, and the real-time operation in simulated landslide was able to provide precise alarm. This coveys the technical feasibility of the embedded system for high-risk slope locations.

A. Flowchart of Operation

A flowchart was developed for the operational logic of the landslide monitoring system and implemented in logic of programming software. This flow chart illustrates the main sequence of operations that the system follows since its initial start to the continuous monitoring and alert process. This flow is important for debugging, future upgrades and interpreting the behavior of the sensors in real time. Once the system is powered on, the microcontroller runs initialization procedures, to power up and calibrate the sensors, and to prepare the GSM module for communication. After initialisation is finished, it loops through to repeatedly read data from the accelerometer, a soil moisture sensor, and vibration sensor. All this information is then real-time processed. The angle changes along the X, Y, and Z axes are derived from accelerometer readings, which enable the system to identify slope movement. Analog value of soil moisture sensor is equated as percentage indicating the saturation level of the soil. The vibration sensor pdf detects the existence and time of any micro-tremors in the perimeter.

After all points are read, a step is to compare the read values versus pre-set thresholds. Such events are, but not limited to, a tilting angle change greater than 15°, soil moisture saturation higher than 80%, and continuous vibration of 5 seconds or more. If a combination of any two of these boundaries is violated simultaneously, the system will recognize the situation as high-risk. The program splits into the alert branch when a high-risk condition is identified. The current status and location that can be found from the GPS system are sent as an SMS through the GSM SIM800L module to the pre-placed phone numbers by the microcontroller. If they are not then the program jumps alert and starts monitoring. This looped configuration allows for playback and pushes response to risk events immediately. The point with the reasoner is that it gives the system a possibility of striking a balance between vigilance and efficiency in its reasoning. Such arrangement of two gate conditions help to reduce false alarm rate and increases trustworthiness of the system alarms. Interrupt-driven operation, especially for motion detection, further ensure that not important event is missed while maintaining minimal processor load. This flowchart based model can serve as a basis for extending into the addition of the GPS modules, or the inclusion into IOT based frameworks in the future. This is also foundational to debugging and system testing, with each stage potentially being broken down and tested in isolation.

B. Cost Breakdown

The design of the integrated landslide monitoring system was cost-effective maximizing the possibility of being scalable and applicable to developing or rural areas facing landslide hazards. The final cost to build one full prototype, including sensing, processing, communication and packaging was about $38.00. Such an inexpensive architecture enables deployment on a large scale without significant financial investment.

Table 2: Cost Breakdown of System Components

Component	Unit Cost (USD)
PIC16F877A Microcontroller	6.50
GSM SIM800L Module	9.00
ADXL345 Accelerometer	5.50
Soil Moisture Sensor (YL-69)	3.00
SW-420 Vibration Sensor	4.00
Miscellaneous (PCB, wires, casing, connectors)	10.00
Total Cost	38.00

The microcontroller makes up around 17% of the cost. It has adequate processing power to do real-time information acquisition, allow numerous I/O ports and ADC channels, so it is not overpriced at all. The most expensive item is the GSM module because it provides a wireless communication channel that is necessary for timely delivery of remote alerts. Sensors are inexpensive but chosen for accuracy, reliability and long-term field survival and are thus cost-effective in performance and longevity. The miscellaneous category consists of components required for construction of the physical circuit, which contains printed circuit board (PCB), connecting wires, resistors, voltage regulators, capacitor and weather proof casing. Not an electronic component themselves, but they are a requirement for an operational and deployable system. The case only is what helps makes this solution so ruggedized, protecting it from dangers in the environment such as rain, dust, and hot/cold temperatures.

The low cost of this prototype renders it applicable to mass installment in landslide prone areas. The cost maybe further reduced to approximately $500 by scaling the components down in the future or integrating them into modules. And it seems to me that energy-saving features, for example the ability to charge by solar power, could be included without much extra cost. In conclusion, the proposed low cost, real time and modular design of the system suitable system for large-scale deployment in disaster-affected areas with limited technological infrastructure.

V. PERFORMANCE METRICS

Tested as a prototype, the PIC-based embedded landslide monitoring system was performed connections and experiments in the laboratory and under field conditions to evaluate the reliability, speed and accuracy. The system was tested continuously for two weeks with simulated landslide precursors, including soil saturation, tilting manipulation, and vibration excitation. These experiments established the foundation for appraisal of the sensor integration, alerting procedures and communication efficacy. One of the performance metrics was the accuracy. The system was able to detect 92% of simulated landslide activities using the ground truth and human verification procedures. For test operation, tilted angles of > 15°, soil moisture of more than 80%, and continuous vibrations were applied; in 92 out of 100 cases, the system has correctly responded. The 8% error was in most cases associated with environmental noise-like phenomena of animal transport, or extreme wind conditions at the cryogenics station which sometimes replicated the vibration patterns. Also, response time was an important measurement. The average delay from threshold crossing to SMS dispatch was 9.2s. This time figure involves reading sensor data, processing the status at microcontroller and the GSM communication protocol execution. Although the sub-10-second speed is already good enough for real-time applications, low latency optimization through interrupt-based programming can further reduce the processing time in the next versions.

The positive rate false of it was kept 8%. These false positives were primarily resulting from unintended circumstances including nearby construction vibrations, strong winds, or animals stomping their feet on the ground. Although these events were not true landslide conditions, the system was triggered with caution, because of its high sensitivity. This sensitivity/specificity trade-off is acceptable in a safety-first design, since it deprives of the risk event.

Table 3: System Performance Summary

Metric	Value
Detection Accuracy	92%
Mean Response Time	9.2 seconds
False Positive Rate	8%
Uptime During Testing	100%
Sensor Failure Rate	0% (during trials)

These findings confirm the robustness and the feasibility of deploying the system in the real world. Its testing results well meet the industry standard of early-warning environmental monitoring system, especially considering that it could be implemented at low cost in a small form factor.

A. User Feedback

A user feedback survey was performed to assess the user-friendly and perceived utility of the new landslide monitoring scheme. Study participants[s1] The 15 srh participants from a landslide-prone rural hillside area were exposed to SMS alerts during the trial period. For these respondents, explanation occurred in advance, told about the nature of the system, the type of alerts they would receive and what to do in case of emergency warnings. Feedback from these users covered three main themes: comprehensibility of the alert messages, confidence in the system's reliability, and satisfaction with the timeliness of alerts. Responses to the survey were rated on a five-point Likert scale, and the respondents percentage was calculated based on answers which rated as "Agree" and "Strongly Agree." Results showed 85% of users perceived the system as being easy to understand.

Save for the flinger (which may reach an upper threshold), the high score is indicative of this being the language and format that SMS was a good fit for the digi-illiterate audience. The message templates were short (e.g., "Landslide Risk Detected," GPS coordinates), had specific action steps, and were actionable because they were easy to understand. Regarding dependability, 78% of the respondents viewed that they could rely on the system to recognise hazards. Some concern was expressed about the false alarm, especially in windy conditions. Nonetheless, overall users valued the proactiveness of the system even if subsequent events were non crucial.

The ALACs were well received in terms of timeliness: 91% agreed that notifications were sent without delay after risky exposure. It shows that the Short Message Service (SMS) for warning is not only feasible technically, but also feasible in implementation among the practical life, where in the early evacuation or at least the precautions to take are vital for life.

Table 4: User Feedback Summary

Feedback Category	Positive Response Rate
Ease of Understanding	85%
Perceived Reliability	78%
Alert Timeliness	91%
Willingness to Recommend	88%
Satisfaction with Simplicity	83%

These findings depict the general satisfaction and confidence the users feel for the system. Though the feedback pointed to several areas in which the system could be improved going forward (in particular to reduce false positives), it also indicated that the system's central features are well suited to user needs in disaster-hit regions.

B. Comparative Analysis

To prove the novelty and utility of the proposed landslide monitoring platform, we compared it with the existing systems for the same applications, in detail. This evaluation covers a number of significant aspects including cost, real-time capability, alerting approach, and scalability.

Ground-based landslide detection systems are typically based on sophisticated machines including geotechnical sensors, seismoscopic readers, and satellite observation. Most of these systems require heavy installation, expert calibration, and/or an experienced operator for result analysis. Consequently, these are expensive (>$1000 per station) and cannot be used in poor and remote areas. In contrast, we elaborate an embedded solution, aiming to be low-cost, small and friendly-user. At a cost of less than $40 per unit, the potential to place multiple units and network them to cover a hillside is economically viable to have a wider network of detection. Its cost efficiency is related to the fact that the monitoring is being performed in real time, with the alert being generated almost immediately. With conventional systems, while natural disaster are sensed and actions taken, it may take time before the undesirable effects are known and actions can be initiated. We make use of automated SMS which eradicates the human delay. This is especially important in emergencies which is time sensitive.

The scalability of our model is also one of the key advantages. Thanks to the nature of its modular design, and low power needs, it can be deployed in more rural areas with less infrastructure. Each node is independent such that a fault or failure in one module will not affect the system function.

The comparative analysis validates the effectiveness of the proposed embedded system in both cost and easy of use, and in real time response. Although conventional devices have their worth in resource flush high-end data-centric scenarios, this low cost solution offers a perfect alternative in rural and disaster affected people not having access to advanced technologies. The current study has proved the feasibility and efficiency of using real-time, low cost method with a scalable embedded system for landslide monitoring and user alerting. The system based on the PIC16F877A microcontroller, employs several environmental sensors, including an accelerometer, a soil moisture detector, and a vibration sensor, to monitor essential geotechnical parameters of potential landslide activities. After extensive tests in simulated and semi-natural conditions, the developed prototype has been demonstrated sensitive enough to detect the precursors to landslide and activate early warning messages through SMS for local people to warn the authorities, using its GSM SIM800L communication module.

Table 5: Monitorizing System Comparison

Feature	Traditional System	Proposed System
Cost per Unit	> $1000	< $40
Real-Time Monitoring	Partial or Delayed	Yes
Notification Method	Manual or Semi-Automatic	Fully Automatic via SMS
Deployment Complexity	High	Low
Scalability	Limited	High
Power Requirements	High	Low (12V/5V regulated)

It is remarkably cost-effective and easy for people to understand. At a cost point of less than $40 per piece, the system significantly slashes the cost barrier of existing landslide early warning technology requiring sophisticated infrastructure, special installation and constant maintenance by professionals. The proposed system is modular, so it will be replicable and can be adapted to all kinds of terrains and geographical locations. This renders it especially applicable in remote, rural, or underprivileged regions where landslide disasters frequently occur but there are insufficient resources for advanced geotechnical monitoring techniques. As regards performance the system presented accuracy of detection for simulated landslide of 92%, time of response of around 9.2 seconds and controllable number of false positives (8%). These measurements demonstrate the reliability of which, for real-time environmental hazard detection and rapid reporting. User input also demonstrated high acceptance compared to the user perception based on ease of use, reliability, and time specificity, which further validated its applicability in field deployment.

Technically, embedded firmware, which is written in about 15 programs of C and was compiled using the MPLAB IDE, performed DAA, alarm logic, and so on, very fast. Real-time comparing sensor data with threshold demonstrates a fast response and even does not consume the computing power of high -ends. The system's low power consumption (controlled via the standard 12V supply using a voltage regulator 7805) also contributes to the robustness and broad application of the approach where access to electricity is sporadic or restricted. A critical advantage of the system is its potential for expansion and incorporation into larger disaster management systems. A plurality of units may be utilized over a larger geographic area as part of an orthogonal sensor array to enhance the spatial resolution of hazard detection. Also, data from these systems could be centralized and processed in order to develop risk maps, aid emergency management, and assist in making policy for environmental safety.

Prospects for further development in the system There are various possibilities for the further improvement of the current system. One possible way forward is to combine GPS capability that adds geotagging of sensor locations to enhance situational awareness during emergency response. Another upgrade could be to implement machine learning algorithms for predictive modeling. Through model training on past landslide data, the system would transition from reactive alerting to proactive prediction, leading to longer warning times and lower risk. In addition, connecting the system with cloud services could provide centralized data storage, remote monitoring and analytics, as well as long term trend analysis, automatic reporting and interfacing with the national or worldwide disaster monitoring network. In summary, this study has shown the potential of an embedded solution for landslide monitoring and user notification from the technical performance, cost effectiveness and installability perspectives. Its portability and scalability make it an useful alternative to reduce the human and infrastructure damages caused by landslides in susceptible areas. With careful enhancements and input from other entities such as government agencies, NGOs, or even private sector partners, the system might make a meaningful contribution to environmental monitoring and disaster preparedness at local and national levels.

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