An IoT Based Landslide Monitoring and Fuzzy Logic Driven Early Warning System

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ABSTRACT

The problem of landslides has been reported across the globe. Specifically, in Rwanda, the landslide problem has been witnessed in the western province of Rwanda for many years with a most recent event being reported in May 2021. When this happens it leads to losses due to destruction of properties and even sometimes death. Recently over 100 homes were damaged, 39 homes reportedly completely destroyed and 117 families were displaced as a result. However, there are no proper ways of alerting residence before such events occur so as to minimize the eventual impacts. Attempts have been made to come up with solutions but most of those are not applicable to the unique African setting due to connectivity, cost and power challenges. The emerging technologies of Internet of Things and Artificial Intelligence provide capabilities which can be exploited in coming up with improved solutions. This study therefore was aimed at designing and prototyping an IoT based landslide monitoring and early warning system. A qualitative research method was used to collect and analyze data during the system analysis phase. This system made up of an Arduino microcontroller unit (MCU), a soil moisture sensor, accelerometer sensor and a vibration Sensor. Based on the values collected by these sensors landslide prediction was done based on fuzzy logic on the microcontroller and appropriate warning alerts sent to the users via GPRS/GSM. The device is also fitted with a GPS module for tracking in case of landslides. The collected data is stored on the Thing Speak cloud platform for analytics and visualization. The implementation of the system will lead to a reduction in losses and deaths as a result of the earthquakes. The collected data can also be used for planning and further research by the government and other agencies.

Keywords: Landslide monitoring, IoT, Fuzzy Logic, Landslide warning.

1. INTRODUCTION

Landslides can be referred to as geological that cannot be easily predicted but lead to destruction of property and even deaths [1]. Landslides are the mostly common geological hazards during rainy seasons, which lead to deaths, destruction of property and huge financial losses not only in Rwanda but also in the rest of the world. It is estimated that over seventeen percent of fatalities that result from natural causes in the world are as a result of landslides. In Rwanda, especially in Nyabihu district, western province, there are the most frequent geological events resulting to deaths and, millions in damages to infrastructure yearly [2]. The frequency in the occurrences of landslides have been on the rise, a factor mainly attributed to the global changes in climate over the years. This has intern also resulted to an increase in the experienced damages and both loss of life and property. A step towards ensuring such problems are mitigated would be having a mechanism to monitor the real-time conditions in the field, predict the possibility of a landslide occurring and send early warning alerts to users so they can take precautionary measures.

In attempts to solve the problem of landslides, studies aimed at the prediction of landslides so as to reduce the effects of such occurrences have been conducted with notable progress. In [3] the increasing need for designing and developing frameworks that can help in monitoring alerting people when landslides occur is highlighted. The study added that an effective landslide and monitoring system should be able to; (i) collect real-time data form landslide prone areas and sense the soil movement and properties, (ii) send the collected data to a remote cloud platform, (iii) allow for a possibility to analyze the collected data in the cloud, (iv) alert people on the possibilities of landslides before they occur via mobile phone and applications.

In analytical study it is noted that, a number of technologies have been proposed and used for landslide monitoring [2]. These technologies include the following; geotechnical techniques, both ground and satellite based geodetic techniques. Over the recent years the application of new technologies such as geospatial and information technologies has improved the process of assessment of possibility of landslide hazards in a number of areas. Such technologies include geographical information systems (GIS) and remote sensing [4]. Most of these techniques are currently being used for landslide monitoring in the real world. However, several of these techniques are very expensive, it is not possible to deploy these techniques on a large-scale across many landslide locations, and they are not tailored for the African setting where there are connectivity and power challenges. For example, in the city of Portland, digital elevation maps (DEM) were proposed for landslide monitoring. The mapping cost of this method was between USD400 and USD600 per square mile [5]. This high cost of the system made it impossible for Portland to deploy this system. Similarly, other conventional methods for landslide monitoring like UAVs, satellite-based monitoring, ground based geodetic monitoring and geotechnical methods for monitoring landslides also suffer from cost problems [5]. The high cost of these conventional monitoring techniques calls for the need for alternative monitoring methods (e.g., using inexpensive materials, low-powered electronics, and MEMS-based sensors).

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MEMS-based sensors and the associated monitoring systems have been used across a wide range of applications involving automotive, healthcare, defense, communication, agriculture, industries among others [5]. Different IoT frameworks provide guidelines that can be used to automate and control various application by the use of emerging smart sensing and actuation technologies. Such technologies have the potential of also being used for monitoring of landslides and have been exploited in some studies. IoT frameworks that can be used for landslide monitoring and sending early warning alerts have been designed and developed [6]. Such IoT frameworks include the processes of collecting data, transmitting the collected data, preprocessing the data, applying machine learning to gain knowledge from the data, use the results for making informed decision, and disseminating information via mobile phones and applications.

The use of MEMS based sensors has also attracted the interest of those who conduct research in areas relating to IoT and landslides. The use of such solutions provide an opportunity for the realization of low cost applications for monitoring of landslides. The use of MEMS based sensors for applications in the areas of landslide monitoring is still in its infancy stages of evolution. There is thus a need additional tests and applications based on such sensors that can be implemented in the real world for landslide monitoring. An evaluation of the capabilities of MEMS based sensors first in a lab based environment is an important step in designing and developing landslide monitoring system before deployment to the field. In this study an IoT and fuzzy driven system for landslide monitoring and early warning was designed and developed. The implementation of such a solution will not only help overcome the challenges of the existing solutions but also bring with it many benefits as are presented in the significance of the study section of this thesis.
The rest of the paper is organized as follows; the next section presents related works, the methodology is given in section III, section IV outlines the system design, the results are presented in section V and lastly a conclusion drawn and recommendations given.

2. LITERATURE REVIEW

In this section a review of related literature is presented. In the first section related works are presented and grouped in 3 categories; (i) Non IoT based solutions, (ii) IoT based solutions and (iii) Fuzzy logic driven solutions. The solutions are analyzed and the contributions to the field of study presented.

Related Works

Different solutions have been proposed and implemented over the years in an attempt to solve the landslide problem.

Non IoT based solutions: To begin with, in [7] an integrated landslide analysis process is proposed. In this strategy three main elements are considered: (i) landslide susceptibility using a remote sensing method for susceptible landslide location determination (ii) scaled-down landslide simulation experiments for sensor network validation for landslide monitoring, and (iii) on site sensor network deployment for enhanced landslide monitoring. Secondly [8] focused how to evaluate landslide susceptibility using physically based method and probabilistic approach, runout evaluation using dynamic model and volume based model, remote sensing techniques for landslide monitoring, in situ ground based monitoring techniques, and landslide early warning using physical and rainfall thresholds.

In [9] a new dynamic modeling system has been presented for monitoring and predicting storm-triggered landslides and the implications on the ecosystem. In the model, remotely sensed and conventional geologic and topographic data are injected, with the outputs being the diagnostics required for the assessment of the societal and physical impacts of landslides. In [10] an application of genetic algorithm and support vector machine (GA–SVM) method with parameter optimization in landslide displacement rate prediction is presented. This study was conducted in the southern eastern regions of china in a large-scale landslide in a hydro-electrical engineering area.

Such solutions do not monitor the real time parameters of the land and thus are not very accurate while at the same time they are not capable of ensuring the users get alerts within the shortest time possible.

IoT Based Solutions: In [11] a wireless sensor network (WSN) for real-time monitoring to detect landslides is used. In [12] a site-specific early warning and monitoring system for rainfall-induced landslides as developed. The proposed device consists of six sensor nodes and one rainfall station that continuously sense large amounts of data such as soil moisture, pore-water pressure (PWP), movement status, and rainfall. Abraham et al, in [13] developed an IoT-Based Geotechnical Monitoring of Unstable Slopes for Landslide Early Warning. To predict failure and provide early warning, a number of mechanical and electrical devices are used. Extensometers are used to measure the difference in soil mass between moving and stationary soil masses.

In [14] the active slopes in an area is monitored by the use of sensors for water volume contend and tilt micro electro mechanical systems (MEMS) based sensors. For communication between different sensors, a wireless communication module is used. A real time filed analysis was done so as to evaluate the applicability of the tilt based sensors by embedding the sensors in the soil to measure the angles of tilt and soil moisture content. For evaluation the data collected from the sensors was compared with those from observation and collected rainfall data. Explored in the study was the relationship between change in volumetric water content, rainfall, and tilt rate.

An end-to-end technological framework for data-driven IoT systems for landslide monitoring is introduced in [15]. The framework is made up of three main layers; the first tier is the data acquisition, the second is the data curation and lastly the data presentation.

In [16], A landslide monitoring system is proposed. The system is composed of autonomous sensing devices fitted with sensor suits that have been tailored to monitor landslides. Duty cycling s used to save energy with the sensing devices collecting data in defined intervals. For connectivity SigFox is used for transmitting data from the devices to the server

Such Internet of Things based solutions are a potential solution. They however, the solutions are mainly based on thresholds and thus reduces the effectiveness when it comes to changing dynamics in landslide hence the need for an intelligence based monitoring and prediction.

Fuzzy Logic driven solutions: A Fuzzy logic integration for landslide hazards mapping is proposed in [17]. They used a fuzzy logic integration approach to map landslide danger using multiple spatial data sets in this report, and they listed the areas that will be affected by potential landslides. Fuzzy inference networks combine some fuzzy memberships in series and others in parallel to combine different spatial data. In [18] a low-cost IoT system for communicating and predicting landslide danger is presented. The aim of the proposed system for landslide monitoring was to see how well it could quantify soil moisture and movement. Also investigated were the soil moisture and soil movement levels that were most likely to trigger landslides. A ramp was used to pack a soil trial from a mountain in the experiment.

In [19] A comparison of fuzzy logic approaches for landslide susceptibility mapping with GIS has been suggested. According to their study, there are multiple spatial data layers (i.e., parameters) that must be used for a landslide susceptibility assessment to determine the areas are at risk of sliding. It is crucial to identify parameters regulating the degree of susceptibility when using any model to assess landslide susceptibility. After each map class's fuzzy membership was allocated, the input layers were processed. The final production maps were created using fuzzy number, product, and gamma operators, as well as primary causal factors including lithology, land cover, slope aspect, and river of distance.

A study that aims to the process of finding out areas prone to landslides by applying fuzzy logic to the detection process is presented in [20]. The inputs to the fuzzy inference system in this solution are five namely; rainfall, moisture content from two different soil depths, land slope and vibration of the ground the output of the fuzzification process shows the vulnerability level of landslide area is very safe, relatively safe, relatively potential, potentially and very potential.

A landslide Early Warning System is proposed in [21]. In the study it is noted that some of the factors that contribute to landslides include but are not limited to; excessive soil water content, slope, and vibration. By the use of the growing technology of Internet of Things (IoT) such parameters can be measured using different sensors. A fuzzy based algorithm is then applied so as to predict the possibility of landslides.

The use of fuzzy logic is indeed an improvement to the threshold based solutions. Such studies show the potential of fuzzy logic in the prediction of landslides. The existing solutions are implemented in a cloud based architecture. Due to the connectivity and cost challenges in Africa, there is a need to implement such solutions without the need for constant connectivity as proposed in the thesis study.

Contributions: In this thesis study an IoT system for efficient landslide monitoring and early warning alerts designed and prototyped. The system consists of IoT based sensing devices, equipped with a tailored sensor suit for landslide monitoring, they were tested in a lab environment. The device is able to use fuzzy logic to predict possibilities of landslides in real-time without the need for internet connectivity. This also reduces in the power usage of the device and thus prolong its lifetime. Real time alerts are sent to the users via GPRS/GSM.

The system greatly improves to currently employed monitoring methods in terms of i) cost effectiveness due to reduced operating and capital expenses ii) scalability and ease of deployment iii) enabling the application of Artificial Intelligence without the need for connectivity; iii) high precision provision of data and granularity in near-real time; iv) agility and ease of use for the end-user (alerts sent directly to the user's mobile phones).

In contrast to the existing solutions, the proposed solution presented in this study constitutes a scalable, cost efficient solution with high reliability that is able to monitor real time soli parameters, report sensory data of very high precision in near-real time and in a continuous way, apply fuzzy logic on the embedded device and send real time alerts to the users' mobile phone. This performance is achieved by leveraging upon IoT technologies combined with fuzzy logic that is designed in a cloud environment and converted for embedded deployment. As such, this work nicely demonstrates the power of IoT and fuzzy logic not only in reducing the capital expenses and operation costs but also enabling the provision of novel services that previously were not feasible with the existing solutions.

3. METHODOLOGY

This section presents the tool and methods applied in the study. The first section presents the research design, followed by the data collection tools and a description of the study area. The system development method and the fuzzy logic tools are also presented.

Research Design

A qualitative research design was used in the study. With the qualitative research method, the participants accounts of perception, meaning and experiences are elicited. Descriptive data is presented based on the participants own written or spoken words. This method is non statistical, the participants are selected purposively and are small in number. A qualitative research design is the best option for research where little is understood about the area of focus. The qualitative research design helped to provide an in-depth data and information about landslides in the Nabihu District, western province on Rwanda.

Data Collection

Data Collection Instruments: The main instruments used for data collection were observation guides, interview guides and a document analysis guide. These tools were selected based on the nature of data that was to be collected, the objectives of the study and research contains of time and other resources. In this study, the researchers were interested in getting information on landslides in the western province of Rwanda.

Data Collection Procedure: The researcher sent written request for appointment to conduct research to the district disaster management officer in Nyabihu district, Rwanda. Follow up telephone calls were made before the scheduled visits.

We choose to use in-depth interviews to collect data from the disaster management staff in charge of handling issues related to landslides. For the interview guide, open ended questions were used. This offered the researcher a chance to ask follow up questions and additional explanations about landslides in the district. The researcher also visited different locations is in the district and observed the landscapes, effects of landslide and the soil types.

Statistical Treatment of Data: After the collection process the data from the interviews and observation were transcribed then grouped accordingly. The researcher developed themes in relation to the objectives of the study. Thematic analysis and content analysis was used in analyzing the collected data and making inferences by a systematic and objective identification of characteristics of responses.

System Development

The Software prototyping approach was selected as the software development method for the development of an IoT bases system for monitoring landslide and sending warning alerts. The selection of this model was guided by the need to understand the need of the users and come up with system requirements at an early stage. In addition, it was possible to get user feedbacks enabling the researcher to understand what is expected form the solution.

Fuzzy Logic

MATLAB fuzzy logic tool box was used to develop the prediction model using logic rules implemented in a fuzzy inference system. This model was later converted to an Arduino compatible model for implementation on an embedded device. A total of three inputs were given to the designed fuzzy inference system with one output expected.

4. SYSTEM ANALYSIS AND DESIGN

This section presents the analysis and design of the landslide monitoring and early warning system. The system architecture, system level design and system requirements are presented.

System Architecture

Sensors will be deployed in the field to collect real-time data. After acquisition of data from the embedded part, the system through an intelligent fuzzy based logic system on the microcontroller will perform processing and give an output showing the probability of a landslide in a scale of zero to one. The collected data will also be transmitted to a ThingsSpeak platform for storage and future analysis. The system end-users/actors include local authorities, local population, MIDIMAR and police.

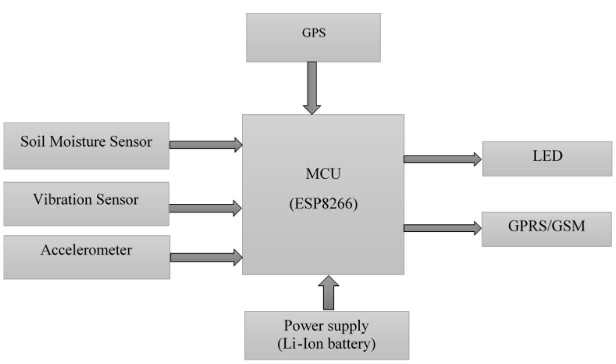

Fig. 1. Embedded system block diagram

Figure 1 shows the embedded system block diagram. The embedded system consists of a Soil moisture sensor for detecting capacitive soil moisture, vibration sensor for detecting land vibrations, accelerometer to detect land acceleration and gyroscope, and GPS (Global Positioning System) which is used to locate the position of the monitoring device. The input values will be fed into a MCU for data processing and sent to the cloud via GSM communication module for storage. An LED will show the status of prediction output

Fuzzy logic Design

The Mamdani method of the fuzzy inference engine was used. This method operates in four main systematic steps; The first step involves the Fuzzification of the inputs, this is followed by evaluation of the rules, there after the rule outputs are aggregated and lastly defuzzification is done and outputs given.

So as to get more accurate results the variables were tuned appropriately during the model design. The three inputs to the FIS were the soil moisture sensor readings, vibration sensor reading and the accelerometer sensor readings with the output being the probability of a landslide happening. For inputs triangular and trapezoidal membership functions were used with the triangular membership function also being used for the outputs. Figure 2 show the inputs and outputs for the FIS.

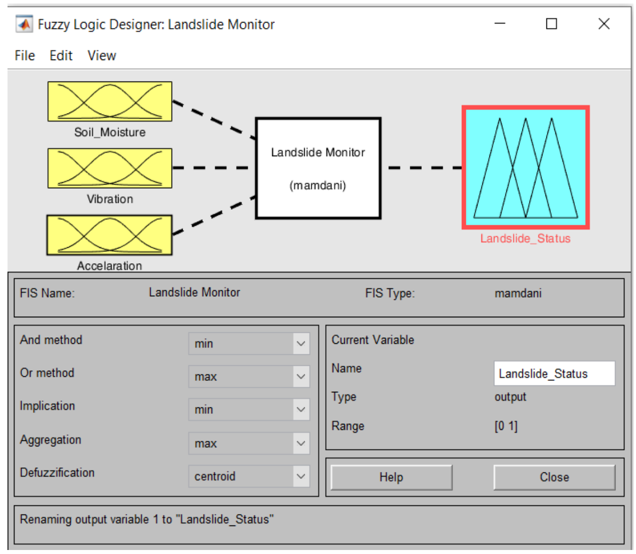

Fig. 2: FIS inputs and Outputs

Membership Functions

The membership functions were each designed based on the expected measuring ranges for the inputs and the probability of landslide ranges. Different types of membership functions were used for the inputs and outputs. For the soil moisture and acceleration sensors, triangular membership function was used, while for the accelerometer a trapezoidal membership function was used with the triangular membership function being used for the landslide status output. The soil moisture sensor had three membership functions (Wet, Average, Dry), the accelerometer reading had two membership functions (No vibration and vibration detected), the accelerometer also had three membership functions. and the landslide status output had 3 membership functions (No landslide, landslide warning, and landslide in progress).

Fuzzy Rules

A total of nineteen rules were created. This rules defined the inputs and the expected outputs under each rules.

Conversion to Embedded fuzzy

After the design and creation of the rules. The code was analyzed and converted to an Arduino code the was tested on an Arduino device.

5. EXPERIMENTAL RESULTS AND ANALYSIS

In this section the results for the solution are presented, the results from the FIS are first given and discussed, this is followed by the results from the prototype. A discussion on the objectives and an analysis of the system performance are also presented.

Data Collection Results

The qualitative data collected through interviews were grouped into themes so as to gain a better understanding of the area and the problems of landslides in western province Rwanda;

Characteristics of the Area: The slope level was reported to be between 45%-60%, the soil type was mainly loam and clay. The areas with clay soils were more prone to cases of landslides. This data can inform the selection of installation points for the system.

Available Data: It was reported that there are no existing data in relation to vibration, soil moisture or land acceleration in Rwanda. This supports the need for our proposed solution that can be implemented not just to help mitigate the problem but also in collection of data for future studies and for decision making.

Landslide management and control: There are no existing systems in place that can monitor and send early warning alerts to minimize the effects of landslides. The reported causes of landslides included high slopes, soil type and improper use of land. However, some control measures that have been put in place include building of terraces to minimize soil erosions, tree planting, Agroforestry and harvesting of rain waters. This also supports the need for our solution.

FIS Results

The surface viewer shows in figure 3 gives a plot of the results under different conditions. When the soil is dry and no vibrations are detected the probability is a landslide is lowest as opposed to when the soil is moist and both vibrations and accelerations have been recorded by the sensing device

FIS performance in Arduino

After the design of the FIS it was tested in MATLAB, it was converted to an Arduino compatible code and tested on the embedded microcontroller. A comparison was done and it was noted that the results of the probability of a landslide occurring is the same in the Arduino and in MATLAB. This proves that the use of an embedded fuzzy logic system does not affect the working of a FIS.

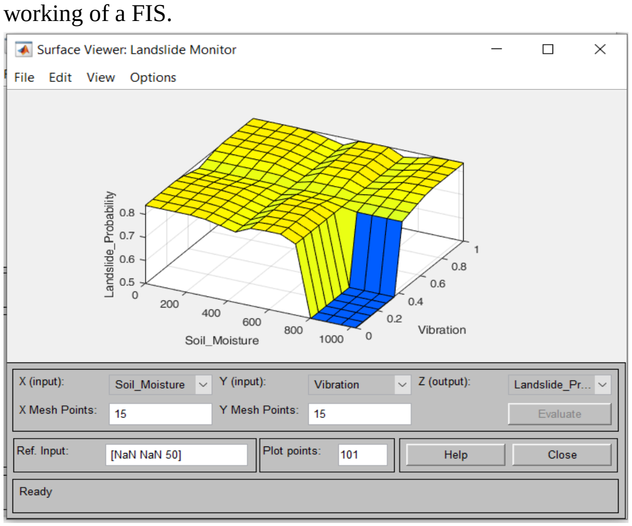

Fig. 3: Surface viewer for the FIS results

System Prototype

The system was developed and tested in a lab environment. Figure 4. shows the working prototype and different connected components.

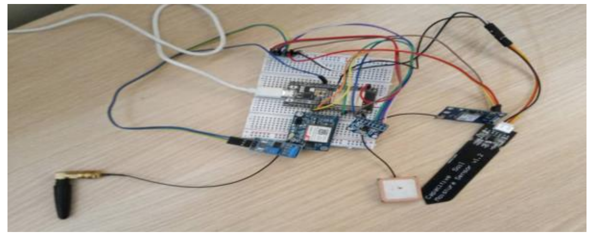

Fig. 4. System prototype

The results show that the application of a fuzzy based model on an Arduino. The prediction was done on the Arduino and the users were notified appropriately where necessary. This is indeed a proof that upon deployment the system will help minimize the effects of landslides in Rwanda

From the prototype the working of all sensors were tested and they were able to collect the needed data that formed inputs to the FIS.

Data collected from the prototype were sent to the cloud from time to time for storage and visualization. Disaster management officers are thus able to view and show the status of the monitored region.

Comparison with existing solution

So as to evaluate the advantages of our solution over existing solution a comparison was done with the reviewed solutions.

Table 1: Comparison with existing solution

Solution	IoT based Solution	Warning Alerts ability	Fuzzy Based	Require Data Connectivity
Integrated landslide analysis	no	no	no	no
Physical based method	no	no	no	no
GA-SVM	no	no	no	yes
WSN real time monitoring	yes	no	no	yes
Geotechnical monitoring	yes	yes	no	yes
MEMS System	yes	no	no	yes
IoT Framework	yes	no	no	yes
Landslide monitoring system	yes	no	no	yes
Landslide mapping	no	no	yes	no
IoT system	yes	no	yes	yes
Fuzzy system	yes	no	yes	yes
Landslide warning	yes	yes	yes	yes
Our solution	yes	yes	yes	no

From the analysis our solution performs better than all reviewed solutions in the following ways;

1) Our solution applies the use of latest cheap and affordable MEMS technology to monitor landslides as opposed to some solutions that do not use IoT technologies.
2) Our system is integrated with an early warning module which is an additional functionality as compared to most of the solutions.
3) Our solution also applies the use of fuzzy inferences system for better prediction of landslide an improvement to other IoT solutions
4) As compared to all other reviewed solutions it only our solution that applies fuzzy on the embedded system and therefore no need for cloud connectivity. This makes our prototype appropriate for the African market where connectivity and energy are challenges. This also helps reduce on operation costs as well.

5. CONCLUSION AND RECOMMENDATION

Landslides are a problem in different parts of the globe. In Rwanda, the western region is more prone to landslides due to the physical characteristics of the area, type of soil and high amounts of rainfall. However, there are no system in pace for collecting data, monitoring and for sending early warning alerts hence the need for the proposed solution.

In this study we; (i) successfully designed and implemented a fuzzy logic inference engine for prediction of landslide. The FIS was implemented on an embedded device which is an improvement to existing solutions that are based on the cloud. A comparison of the results show that the performance of the FIS does not change when optimized for implementation on an Arduino (ii) successfully designed and prototyped and IoT based landslide monitoring system and a fuzzy based early warning system. If implemented this solution will help in minimizing the effects of landslides.

We recommend the implementation of the solution so that further testing may also be conducted to improve on performance.
Future works will involve field implementation of the solution and further testing with industrial grade sensors.uniformity of appearance for the Proceedings, your paper should conform to the following specifications. If your paper deviates significantly from these specifications, the printer may not be able to include your paper in the Proceedings.

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