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Integrated Geohazard Monitoring of At-risk Slopes and Historical Retaining structures

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Abstract

Over time, structures such as slopes and retaining walls are increasingly deteriorating, resulting in a risk of collapse. Factors such as climate change, human activities, societal development, rapid growth of cities, increasing population, and lack of finances to cover remediation works result in an increased risk of geological disasters.

With technological advances in the areas of low-cost sensors, optical topographic surveying, and BIM (Building Information Modelling), there is an opportunity to collect and process high-resolution temporal and spatial data which can be used to provide a detailed assessment of geological asset health. Such data can be used to target remediation works and reduce the risk of collapse.

In this paper, the use of wireless sensors to monitor slopes that are potentially at risk is assessed. A framework is developed to combine the acquired data with values obtained using drone surveys and terrestrial surveys within a BIM environment. The result is a real-time digital twin of the asset which serves as an early warning system. During the presentation, the ability of this BIM based digital twin system to identify areas of high risk of collapse will be demonstrated.

Keywords: Slope Stability, Structural Health Monitoring, Drone, Wireless Sensors, BIM

1. Introduction

Mass movement and landslides occur due to a multitude of factors such as rainfall, coastal erosion, and human interaction (Gariano and Guzzetti, 2016). The size of a landslide may appear small however its effect could be extensive resulting in loss of infrastructure, land, and even lives (Winter et al., 2016). Ireland is not a country considered to be impacted greatly by significant geohazard events however it is a country that experiences landslides of different magnitudes (Creighton et al., 2006).

Towns and cities built in locations exposed to adverse conditions are at increased risk of landslides (Jaedicke et al., 2014). One such example of this is Cobh, Co. Cork, Ireland. This town was built on the land of steep topography located overlooking Cork harbour. The geological strata that make up the terrain of the Cobh area are largely made up of three different sandstone strata: sandstone with mudstone and siltstone, narrow sandstone layer with sandstone bedding and minor mudstone and sandstone with sand and mudstone bedding down to the shore of the harbour. Its soil is primarily sandstone and so, due to the location and strata beneath the town, Cobh relies heavily on retaining walls for the preservation and safety of the town. Due to an increasing population and changing climates, the retaining walls of Cobh, as well as the soil slopes in the area, are gradually deteriorating and some such structures have collapsed (MWP, 2012). These collapses promoted preventative measures being carried out in high-risk areas in the past however these measures were extremely costly and difficult to carry out (O'Shea, 2016). Following the completion of these works, further high-risk structures were identified that require continuous monitoring and will require stabilizing measures to prevent significant deterioration.

Numerous methodologies are currently used for monitoring landslides on slopes, such as measuring tapes, extensometers, crack gauges, geometric levelling, terrestrial and area photogrammetry, inclinometers and Global Positioning Systems (GPS) are used. All provide optimal results and accuracy, e.g. from 0.5 mm for crack opening rulers to 0.2 mm in the case of geometric levelling.

Nevertheless, current methods for geo-structural surveillance require lengthy periods of analysis and monitoring of structures at risk of collapse. The time needed for adequate surveillance is lengthy whilst the technology used is expensive (Yadav et al., 2019). The cost of surveillance is high whilst the results are of low yield, given that these analyses only occur up to four times a year. In the interval between analyses, the damage that could occur may be dramatic whilst the repairs required for such change's damages may be extensive. Human life is always a risk if an at-risk structure is not adequately monitored, and intervention applied in time.

Therefore, current monitoring methods need to be expanded and developed to provide real-time and high-quality results on a continuous basis, so that adequate information on structures at risk is known to prevent further deterioration and loss. Novel technologies need to be applied to further improve monitoring methods in a way that is both faster and cheaper. The results of these analyses must be clear in their information and identify areas that require intervention at the optimal time.

For this study, one of the methodologies used in this study was a laser scanner. The results provided were of very high quality. In the case study of the slope at Cobh, for an approximate length of 284 metres, it provided a point cloud made up of 7,374,899 million points, with an average distance between points of 0.025 and triangulation formed by 0.075. The scanning of the slope was repeated several times and with this, it was possible to create, by overlapping the point cloud, a single mesh of the model in which the practically millimetric movements suffered by the slope were represented. Likewise, the aerial topography carried out with the drone provided a point cloud through 22 photos obtained during the flight. Once the point cloud was processed with the Pix4DMapper software, the results were optimal and were subsequently used to create a mesh in which the triangulation was of a very similar precision to that obtained by the laser scanner.

Combining the use of novel technologies such as drones, sensors and BIM software, this research project aims to develop an early warning system. This early warning system aims to provide continuous data on at-risk structures monitored remotely. Following the deployment of laser scanners and drone software, object-oriented 3D models of the monitored structure will be created. Using sensors, it will be possible to monitor the behaviour of the slope or retaining wall surface and identify any movement. Combining the sensor data with the 3D object-oriented model, using Revit software, a BIM early warning structural health monitoring (SHM) system will be developed.

2. Data Collection Methodology

2.1 Identification and visual inspection of retaining walls and slopes

Identifying slopes and retaining structures suitable for a real-time SHM system was the first step in the project. Utilizing information provided by the Cork County Council from previous visual monitoring campaigns and works undertaken for slope improvements, a set of retaining walls and slopes at risk in the town of Cobh were selected. An order of priority for action was established for those retaining walls and slopes that were considered to be at the greatest risk. The table below lists the retaining walls and slopes subject to study in this research paper, as well as their location and nomenclature.

Table 1: Surveyed walls and soil slope.

Wall Name	Wall Number	Length	Structure Type	Damage Type
Laundry Hill	105	40.9 m	Masonry Wall	Cracks and crevices
Hillview Terrace	10	102.4 m	Masonry Wall	Cracks and crevices
Church Street	35	70.3 m	Masonry Wall	Cracks and crevices
Lower Road	72	182.8 m	Masonry Wall	-
Connolly Street	*16*	*284 m*	*Soil Slope*	*Partial surface landslide*
Saint Colman´s Cathedral Buttresses	-	72.2 m	Masonry Wall	-

The slope on Connolly Street is located to the east of the town in a busy location with commercial traffic and trucks as well as many residential properties surrounding the slope and it is adjacent to a busy fishing pier that is also used by the coastguard. Above the slope, which has been subject to previous landslides, is a two-lane asphalt road that is less than one meter from the slope with an old stone wall separating the two. South of the slope, is the water of Cork Harbour. Given the high risk of collapse of the slope and the state of the slope at the time of the visual inspection, it was decided to base the focus of the research project on the slope located on Connolly Street.

2.2 Topographic Data Collection

To create an accurate SHM BIM integrated system, accurate high-density surveys of the structures being monitored is required. Such surveys could be repeated and replicated as required whilst being quick in obtaining their result and coming at a low cost. Using laser scanners and UAV drones, the structures can be extensively surveyed providing imaging that can be processed into a 3D point cloud or mesh for the visual representation of the early warning system.

A Leica MS60 laser scanner was used for the topographic survey in this project, which provided a high-quality point cloud in less than an hour of work on the Connolly Street slope. The type of scan is based on a polygonal section, which is designed in the laser scanner's software. The number of points in the cloud depends on the level of quality required for the project. The higher the number of points, the higher the quality of the result, although this is slightly penalized by the working time.

The analysis of the data obtained from the Leica MS60 laser scanner was carried out in this research project using Leica Geosystems' Cyclone 3DR analysis software (Geosystems, 2022). This allowed the transformation of the obtained point cloud into an analytical BIM model.

Cyclone 3DR merges Jetstream technology, which enables centralized full-scale point cloud management with automated point cloud and model analysis. It is a simple workflow-based software, which adapts to different tools in the field of surveying, construction, and inspection. It simplifies tasks whereby it allows for the removal of data considered not relevant to the project from the point cloud or mesh. Finally, it allows full interoperability with the most common design formats, including IFC and Revit model files, as well as time-saving functions such as export to AutoCAD or sending to Hexagon Mine Plan.

The advantage of using this software is the visualization of data and the easy interpretation of the results. A major point of analysis of the software is the possibility to superimpose two meshes and underline the points where the structure has undergone changes. These changes, such as cracks or fissures, allow being measured regardless of how small they may be. These are early indicators for early intervention. Finally, the result was a 3D object-oriented model that would serve as a basis for visualizing the movements of the sensors by means of a marker.

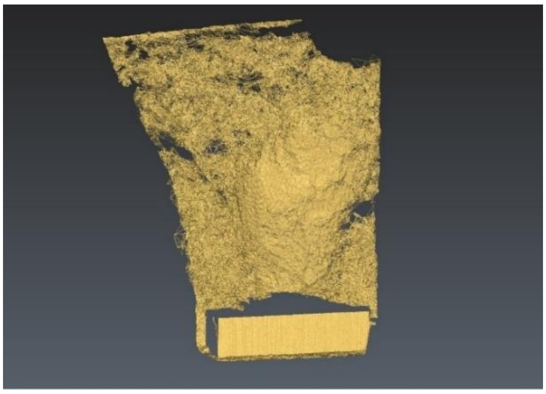

Figure 1: Point cloud resulting from the laser scan of the Connolly Street slope.

The second methodology used for the topographic data collection was a drone, in this case, the DJI Inspire 2 model. In order to achieve optimal results, three flights are made over the same area at different altitudes. The purpose of this is to provide the maximum level of detail of the infrastructure.

Through the use of the application Pix4DCapture, a drone flight was carried out over the Connolly Street slope. This is an application linked to the drone that allows the creation of a programmed flight map providing optimal points of photography with the flight settings being reproducible. The images generated through this software can then be transferred and processed for the development of a 3D point cloud.

The flights over the Connolly Street slope were carried out using the "double grid" option offered by the Pix4DCapture application software. The ‘double grid’ option consists of a grid placed over the surface to be flown, where the drone performs the flight and takes the necessary photographs according to the size of the surface. The drone flies along the grid lines in an orderly fashion. There are two superimposed grids in order to guarantee a complete flight from all perspectives to the chosen surface.

The result of the drone flight is a file containing the photographs taken during the task. The number of photographs varies depending on the size of the surface to be flown. The flight over the slope at Connolly Street involved a total of 22 photographs. The processing of the information resulting from the flight is carried out using Pix4DMapper software. This is a photogrammetry software that uses the images to generate a point cloud, digital surface and terrain models, orthomosaics, and textured models.

Finally, as the last method of data collection, wireless sensors were used. In recent years, sensor technology has evolved exponentially, leading to the implementation of sensors in structural health monitoring systems in all types of civil structures. There is a great diversity of sensor types, from wired to wireless sensors. One of the main advantages offered by the use of sensors in structural health systems is the collection of real-time data, which allows continuous monitoring of the infrastructures under study.

The main basis of structural health monitoring is the compilation of data, or measurements, that are required to be accurate and high quality in their results, and it is the sensors that are the protagonists in the process of data collection and measurement. They are designed to streamline the process and provide subject matter experts with an effective tool that will be essential in making decisions and ensuring safety.

A sensor network to monitor the slope movement was designed using accelerometers. The market offers a wide variety of accelerometers, all of which perform their functions perfectly, but for this project, it was initially decided to limit the study to one type of accelerometer and gyroscope model MPU 6050. Accelerometers were used for the monitoring of the slope in this research as they are more efficient and cost-effective in comparison to other sensors as well as the added benefit of ease of coding the sensor. The data extracted from accelerometers is easy to interpret and can be integrated into a 3-D orientated model easier when compared to other sensor types such as barometers.

The accelerometer is a sensor capable of measuring acceleration forces in single or multi-axis directions. An accelerometer itself has the ability to measure the orientation of a fixed platform relative to the earth's surface, while a gyroscope has the ability to measure gravity and linear motion. For this reason, the monitoring carried out on the Connolly Street slope was performed with accelerometers and gyroscopes, in order to measure the orientation through angular momentum (gyroscope) and the vibration that could be produced (accelerometer). This sensor network is non-intrusive and can be extended and applied to masonry walls and other structures requiring monitoring.

Figure 2: Sensor deployment on Connolly St slope, Cobh.

Figure 3: Sensor deployment on Connolly St slope, Cobh.

2.3 SHM integration with BIM platform

Using the data collected through the sensors as well as the drone or laser scanner, this section explains how this information is integrated into BIM and how the information is treated and integrated into a single model. Thereby, through the sensor data, an early warning system will be created, which consists of a marker on a 3D object-oriented model of the slope, indicating any possible movement on the slope surface in real-time.

A state-of-the-art structural health management tool is thus designed, which helps to visualise in real-time the monitoring of the element under study. It also helps to reduce monitoring and maintenance costs by identifying early intervention requirements.

The purpose of this study was to highlight the versatility and usefulness of sensors in the process of developing an early warning system for geostructure damage and destruction. Following the coding and development of the sensor, it was applied in different manners to display its usefulness and relevance. To this end, the data capture methodology is structured in three different levels, based on the degree of movement. For the purpose of this research project, three levels of warning were used for ease of interpretation of the results. The traffic light system was implemented according to the degree of damage to clearly identify the slope surface changes. Depending on the accuracy of the diagnosis required, more levels could be incorporated into the early warning system to identify movements at different intervals.

Level 0 collects sensor data when the data indicates a static state. When the data collected is close to zero, the data would be categorized as level 0 data. Therefore, when the data is between 0.01 and 1.5 centimetres, it would be considered "practically static". This was the standard behaviour of the slope, where the data are considered to be of low relevance to the early warning system and display very few changes in the slope over time.

When the data received from the sensor ranged between the values of 1.5 and 3 centimetres, they were contained in Level 1 indicating an intermediate level of warning. A simulation of sensor movement was carried out to display the behaviour of the early warning system in the event of level 1 data as well as to assess the accuracy of the sensor in intermediate degrees of movement. The interval of 1.5 to 3 centimetres was used as this research project intended to identify early signs of slope surface movements instead of larger changes.

Level 2 data indicates extreme levels of sensor movement as is expected from events such as landslides. This data results from movements of greater than 3 centimetres. The sensor was again moved in an extreme movement with close surveillance of the data received showing its effect on the early warning system.

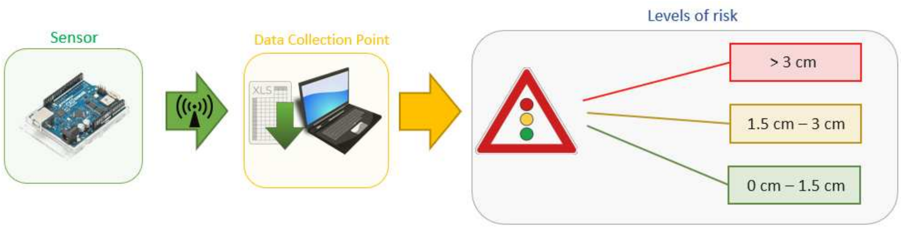

Figure 4: Overview of Sensor Data Collection and study levels.

2.4 Visualisation of sensor data in BIM

The information collected by the sensor is sent to a Google Sheet every 15 minutes, in order to visualize the information in real-time, the marker created in Dynamo must periodically read the code created. With this, it is possible to keep the Revit model continuously updated, without having to run Dynamo, as it will be done automatically every 15 seconds.

The design of the marker is based on providing, in Revit, the last position of the sensor in its three coordinate axes. In addition, limits will be established, which, linked to a colour scale, will facilitate the interpretation of the data. In this way, when the sensor exceeds the established limit on any of the coordinate axes, it will be displayed in red meaning extreme levels of movement. On the contrary, when the sensor remains static, the marker will remain green. In the case of a movement of intermediate magnitude, i.e. not exceeding the set limits, but still relevant, it is orange.

3. Results

Different methodologies employed in the study provided a wide range of results. By collecting data via laser and drone, point clouds were obtained, which provided the study with knowledge of the structural state of each of the elements under study, as well as a clear definition of their geometry. In addition, the point clouds were subsequently used as the basis for the creation of a mesh, which would represent the possible movements of the sensors. The integration of all the data in BIM helped to generate a single model with all the information obtained. Moreover, the results obtained from the topography and the sensors were the basis for the creation of an early warning system, which indicated the responses of the sensor located on the slope to different levels that were simulated.

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3.2 Topographic survey results

A total of three drone flights were carried out for the inspection of the Connolly Street slope. Each of the flights was done using different flight parameters such as different speeds, heights, and surface dimensions. These varying parameters were used to establish which flight generated the highest-quality images.

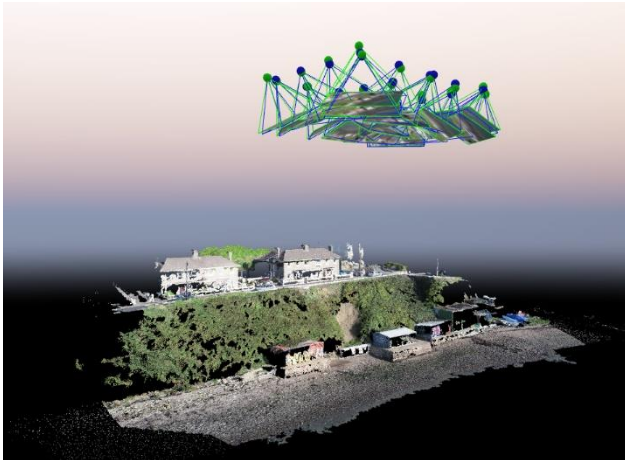

Figure 5: Point Cloud resulting from drone flight over Connolly St Slope, Cobh.

The results of the three flights were an average of 20 aerial photographs of the slope. The image processing through the Pix4DMapper software provided a 3D point cloud which was derived from the overlapping photographs, resulting in the reconstruction of the slope in the original colours.

From the single drone flight, the resulting point cloud has various levels of detail at various points. The drone flight centred on the soil slope itself and did not focus on the area surrounding the slope and so the resulting point cloud has black holes surrounding the slope. The single drone flight was considered sufficient as the level of detail from the soil slope images were adequate for the generation of the point cloud. When the point cloud was further processed by Revit, the apparent black holes were eliminated.

3.3 Integrated BIM base SHM tool

The integration of results in BIM was carried out in the same way as the sensor results were obtained, i.e. the information source for the programming code was Google Sheet data sheets obtained for each level of study. In this way, it was possible to verify the response of the marker to different values at different study levels.

The marker designed always showed a colour scale that varied from green, which was assigned to the smallest value in the sample, to red, which corresponds to the highest value in the data sample. For this project, it was decided to leave the numerical value of the sample on the marker in order to be able to see how big the movement of the marker was.

Here it is shown how, through the movements experienced by the sensor located on the slope, the results in centimetres of these movements are received and how, according to the alert levels established in the design code of the marker in Dynamo, the marker indicates to which alert levels they belong, by numerically displaying the movements in the marker as well as the colour range to which the movement corresponds.

	A	B	C	D	E
1	Time	X	Y	Z	C
2	11:34:03	0.17343	0.03874	0.17354	3
3	11:49:14	1.38685	1.37430	0.27356	3
4	12:05:11	2.53975	1.97643	1.38756	3
5	12:20:32	1.86887	1.37330	1.36378	3
6	12:36:01	3.98630	3.26157	3.87563	3
7	12:51:27	3.18634	3.14230	0.32773	3
8	13:06:45	2.39863	2.37673	2.47864	3
9	13:21:08	0.98367	0.65430	0.23723	3
10	13:36:42	0.29862	0.16342	1.38753	3
11	13:52:42	4.87662	2.76748	3.32786	3
12	14:07:56	3.98643	3.06476	4.05623	3

Figure 6: Googlesheet spreadsheet; Level 1.

The values chosen for the time 12:05:11, ranged from 1.38 in the Z-coordinate to a maximum value of 2.53 in the X-coordinate.

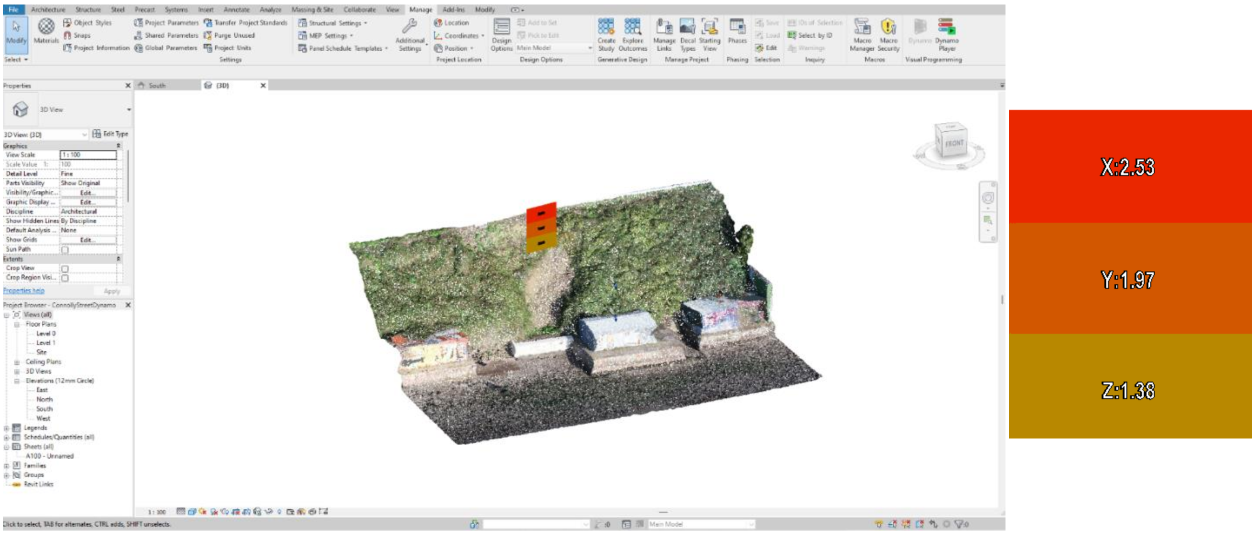

Figure 7: Marker visualization for Level 1 and Colours range.

For these values, the marker flagged the X-coordinate value as a potential hazard result, since it is the closest value to the set limit of 3.

Using this system, the exact risk for landslide or slope collapse cannot be determined due to the contribution of a number of factors, such as vegetation, weather, vibrations. This system, however, does alert the user to the degree of movement on the surface which would be an indication of the level of change. Through this interpretation, the user would be able to deduce the slopes or retaining walls that are deteriorating quickest, being more likely to collapse and require the earliest intervention.

4. Conclusions

The fundamental goal of the research was to find a way to monitor geological structures at high risk of collapse and to integrate the results into a BIM SHM system.

The main conclusion from the study presented in the subsections below are:

- Both UAV and Laser scanner can provide high-resolution low-cost data for building a BIM SHM System, however UAVs are more suitable for Geohazard monitoring.
- Non-intrusive low-cost wireless sensors can be used to monitor a range of at-risk structures, but each system requires site specific calibration and setup.
- A BIM base SHM system is capable of monitoring geohazards in real-time and can provide an early warning system for at-risk structures.
- This SHM system utilises industry standard BIM software and provides high resolution datasets that can be used to improve mitigation and remediation strategies. The script developed for the purpose of

developing an SHM system on Dynamo is opensource, therefore further work could be carried out to translate this opensource data to the .IFC format in order to enable it to be used across platforms in BIM. Furthermore, Arduino sensors are low cost and opensource coding is easily applied to their use further promoting the application of this SHM system to other platforms. Google sheet is a free platform that is suitable for small projects however this could be upgraded to a database type model such as the Azure database for multi-model systems.

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