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An App for Visualisation of Avalanche Hazard

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Abstract

This project produces a functional mobile application to visualise potential avalanche hazards along popular winter mountaineering routes within a virtual 3D terrain reality, with a primary focus on Scottish mountains while providing excellent adaptability for other regions with appropriate data sources. Avalanche hazards were projected from a combination of professional avalanche forecasts and spatial analysis of mountain terrain models. Both the accuracy and the usability of the application were evaluated through various methods. The safety and ethical considerations on the application being put into real world use were also discussed.

Contents

1 Introduction

1.1 Overview of the project

The purpose of this project is to produce a functional mobile application to visualise potential avalanche hazards along popular winter mountaineering routes within a virtual 3D terrain reality, with a primary focus on Scottish mountains while providing excellent adaptability for other regions with appropriate data sources.

A model for projecting localised avalanche hazards based on carefully sourced and processed avalanche forecasts [1] and terrain model data [2] was produced by the project. The accuracy of the model has been evaluated against past avalanche records [3, pp. 143-151][4]. Usability and effectiveness of the application guiding the user away from hazardous locations were evaluated through experiments and test uses conducted with experienced mountaineers.

The project incorporated tools and techniques from various aspects of Computer Science, including software engineering, geographic information system (GIS) modelling, human-computer interaction, computer graphics and algorithms. Many of these tools and techniques are associated with current research in these areas.

1.2 Motivations behind the application

As a front-runner of digital avalanche forecasts, the Scottish Avalanche Information Service (SAIS) [1] have been providing frequent and reliable winter avalanche forecasts for decades in Scotland.

In addition to written observations on conditions of the snowpack and weather, a typical SAIS avalanche forecast also includes a compass ross, providing avalanche risk levels on the scale of 1 to 5 for slopes of different aspects above and below a transition threshold altitude, shown in Figure 1.1. However, while this compass rose provides a comprehensive overview on avalanche risks across the forecast region, it is not straightforward to interpret, as the user will need to work out the surface aspects and altitudes along their route, and mentally infer the risk levels of different locations along their route. This is a very complex task, and prone to errors as risk levels could vary sharply between neighbouring aspects and altitudes, as shown in Figure 1.1.

Therefore, the primary purpose of this project is to vastly simply this process, by generating a coloured image based on the altitude and surface aspects at each point (as determined by a terrain raster model), which is then laid on top of a computer-generated terrain model in the 3D terrain viewer. Hence the information supplied by the compass rose can be visualised in the most straightforward way, allowing the user to freely navigate the 3D model and observe the hazard levels at each location along their route. The avalanche hazard of the same area mapped in Figure 1.1 is visualised as shown in Figure 1.2.

In later stages of the project, we also seek to improve hazard representation through constructing a custom risk model based on information from the compass rose and terrain spatial data; and to improve the functionalities of the application by adding in features such as pathfinding.

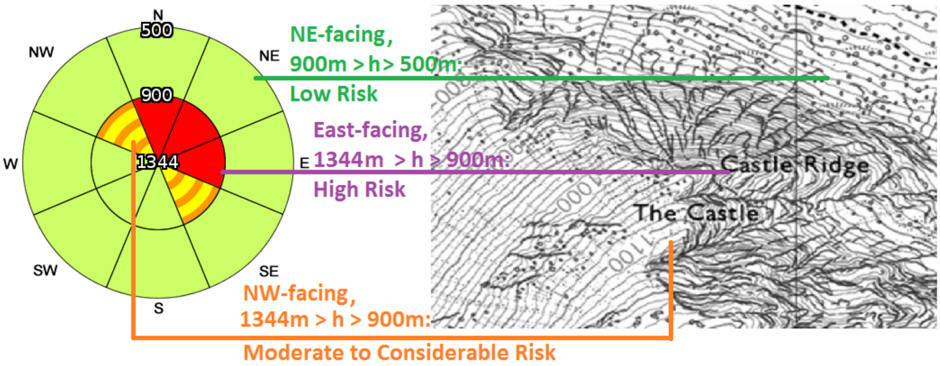

Figure 1.1: An example compass rose produced by the SAIS on January 6, 2016 for Lochaber (left), showing a steep transition of risk levels; and an example manual inference of risk levels based on the compass ross and contour lines near Ben Nevis, Lochaber (right). [5]

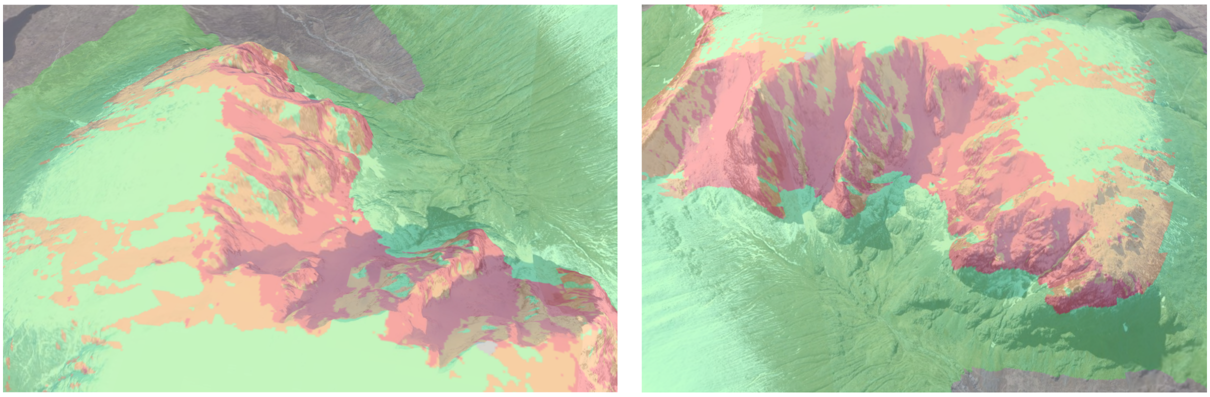

Figure 1.2: The avalanche hazard visualisation of the same area mapped in Figure 1.1, generated in the 3D terrain viewer by the initial stage product using the same avalanche forecast. The same slope is viewed from two different angles.

1.3 Stages of the project

The course of the project was divided into four development or evaluation stages, in order to effectively track and manage the workload. As the product from each stage is able to function independently of work done in later stages, unforeseen difficulties encountered in the research and development process can be effectively mitigated. The four stages are described as followed:

Stage 1 - Basic Functionalities: The aim of this stage was to select an appropriate application framework and libraries to produce a basic but functional application – a 3D terrain viewer with a hazard map overlay, the data for which would be derived solely from forecasts by the Scottish Avalanche Information Service [1]. The WebGL framework Cesium [6] was chosen as the foundation for front-end developments, while Python was chosen for developing the backend, and to interface other systems such as GIS processors with its vast range of interfacing libraries.

Stage 2 - Improved Spatial Analysis and Evaluation: This stage of the project extendes the data source for the hazard map overlay by performing surface fitting and spatial analysis on the terrain model data [2], in order to make the hazards more localised and to better reflect the hazard posed by unique terrain features such as concave slopes. MATLAB [7] was used to perform the computations for these purposes. Evaluations on the localised hazard map against avalanche records were also conducted at this stage, with a focus on the avalanche "blackspots" of Scottish mountains.

Stage 3 - Pathfinding and Risk Calculator: With a localised hazard map obtained in Stage 2, this stage was focused on developing a pathfinding tool for the front end application, allowing the user to plot a potential hiking path with a configurable avalanche risk level. Techniques such as A* path finding [8] were utilised to develop this functionality.

Stage 4 - Usability Testing: The final stage of the project focus on the human-computer interaction aspects of the application. Experienced mountaineers were consulted and invited to test use the application and to provide feedback on usability as well as the effectiveness of the application guiding them away from avalanches that would have occurred in real use. Some improvements were made based on the feedbacks.

1.4 Considerations and statements on ethics

The application was designed as a tool to improve winter mountaineering safety, therefore evidently the foremost consideration on ethics is regarding the accuracy and robustness of avalanche hazards projected by the application. If a location with imminent avalanche threat is reported as safe by the application, a user relying on the guidance of this application could be placed in serious danger; conversely, if the application indicate avalanche warnings to users at a location where an avalanche is unlikely to occur, undue anxiety could be caused.

Due to the constraints placed on the lifecycle of this project, it is difficult to conduct an extensive peer review process to examine the accuracy of hazard projections. And while most open source libraries used during the development process are widely-used and have been well-tested, software errors may still occur and affect the safety assurance of the product. Furthermore, the lack of a known commercial or academic product with comparable functionalities eliminates the possibilities of cross-testing the software product.

As a result, while the application is functional and has shown promise during our own evaluations, it is not considered as a product ready for real-life use – a warning of which is displayed when a user accesses the application.

1.5 Structure of this report

A literature review is conducted in Chapter 2 over existing research and developments in the various aspects of Computer Science involved in this project. The procurement and processing of both avalanche forecast and topographical data used across all stages of the project are discussed in Chapter 3. Chapter 4 describes in detail the features and internal architectures of the application, as well as its development process. This is followed by Chapter 5, which describes the evaluation and testing conducted on the application as well as on the quality of its data. Finally, Chapter 6 concludes the report and discusses the potential uses and future developments of the application.

2 Literature Review

As an application designed to improve the usability of snow avalanche forecasts, it is necessary to first consider and evaluate past research and efforts made to understand and predict avalanches. While the term avalanche can be applied to various types of moving substances, such as rock and mud [9, p. 1], only snow avalanches are studied by this project.

2.1 Snow avalanches

Accumulated snow is usually not a stable structure – snow found in avalanches are usually 80% air, and the snow cover gradually deforms as environment temperature approaches the melting point of snow [10, p. 16]. This instability fundamentally allows frequent occurrence of avalanches.

Snow avalanches occur when large masses of snow or ice move rapidly down a mountainside or over a precipice, often triggered from the snow cover [9, p. 1]. Avalanches can either be triggered naturally due to combinations of certain geographical [9, p. 17] and meteorological [9, p. 23] conditions, or triggered by human activities nearby [11]. Often the latter is constructive to the former when an avalanche is triggered [10, p. 17][3, p .48].

McClung and Schaerer [10, p. 73] classified snow avalanches into two general types: loose snow avalanches, which usually involves surface snow and starts from a single area of the slope; and slab avalanches which are results of failures in the snow cover, featuring blocks of snow falling down the slope destructively. This classification is in agreement with most schemes, such as the avalanche classification by the UNESCO [12], which also diversifies the classification by types of originating zones, paths and deposition zones. The diversified classification has been further improved by recent researches [9].

Regardless of type and triggering source, avalanches are often deadly to human presence nearby, especially when travelling outside areas with built-up defense [9] (known as *backcountry*), as is often the case for mountaineers. During the 45 years leading up to 1999, a total of 440 fatalities from avalanche incidents were recorded in the United States [13]; while in the UK, avalanches in Scottish mountains alone claimed at least 73 lives during a similar time period [3].

With a prosperous winter sport industry bringing millions of people to mountain resorts every year[14], accurate forecasting of avalanches is becoming increasingly critical.

2.2 Avalanche forecasting

Avalanche forecasting is defined as predictions of current and future instability of snow in space and time relative to a given triggering level for avalanche initiation [15, p. 131]. When applied, the main concerns of such predictions are risks to humans or property.

A conventionally approach to avalanche forecasting involves extensive field observations and testings of the snow cover by experienced forecasters and mountain guides, cross-referencing of historic meteorological and avalanche records, and utilisation of statistical and information theory methods on data collected to reduce decision uncertainties, as summarised by LaChapelle [16] in 1980. This is still very similar to the approach the Scottish Avalanche Information Service (SAIS) use today [17, p. 5]. In this style of approach, final decisions on hazard levels are heavily reliant on the experience and judgement of the experienced forecasters. LaChapelle noted [16, p. 76] that while inaccuracies do occur in forecasters' decisions, complete failures are rare. McClung [10] further analysed the influence of human perceptions in avalanche forecasting, and gave a formalised decision-making process to eliminate biases and improve accuracy.

While human decision-making still plays a dominant role in forecasting avalanche hazard levels, computational models have been developed to improve data analysis and to provide supplementary opinions through machine learning methods, which are backed by a vast increase in accessible computing power, as McClung [18] explored as early as in 1994. Numerous models have since been developed, with computations performed on different types of data.

SNOWPACK, a snow profile comparison method was first published by Lehning *et al.* [19] in 2001. The method attempts to establish a numerical profile of snow cover conditions based on various measured properties of the cover, such as the size and type of snow grains, temperature and density of the environments. An agreement score could then be established by comparing the numerical profile with an observed profile in the field. If high agreement scores are reached by the experiments, the numerical profile becomes suitable for use in avalanche forecasts.

However, attempts to apply SNOWPACK in other regions with different snow conditions have identified weaknesses in the assumptions made by the model, which was originally developed for the Swiss Alps. A notable attempt was made by Hirashima *et al.* [20] from 2005 to 2006 in Tsunan, Japan. While numerical profiles computed were in reasonable agreement with the observed snow profiles in Tsunan, it was found that the stability index estimators embedded in the model was not suitable for the shear strength of Japanese snow, and an alternative method for calculating the index had to be adopted. This suggested that adaptation of *SNOWPACK* to a new region may require appropriate changes to the model based on local snow conditions.

While SNOWPACK was developed as a specialised method for analysis of snow covers, more generalised models such as the Nearest Neighbours (NN) method have also been developed. The NN model was initially developed by Buser [21] in 1983, which has since been supplemented by various studies, such as Purves *et al.* in 2003, and Singh and Ganju [22] [23] since 2004. The NN method applies a machine learning approach on historic avalanche and meteorological records, as well as on spatial data, to estimate the likelihood of an avalanche under the current conditions of a location. As the NN method has difficulties with high dimensional data, an alternative method based on Support Vector Machines (SVMs) have been proposed and developed [19] [24].

The most notable application of the NN method is by the SAIS. Avalanche forecasts from the SAIS that are partially dependent on the NN method achieved a weighted accuracy of between 71% and 82% on visible winter days between 1988 and 2002 [25, p. 351]. With up to 205 avalanches reported by mountaineers during the winter season of 2015-2016 [1] (as partly shown in Figure 2.1), the SAIS plays a very significant role in saving lives from avalanches. Data from SAIS forecasts would also be a critical component in data sourcing and hazard

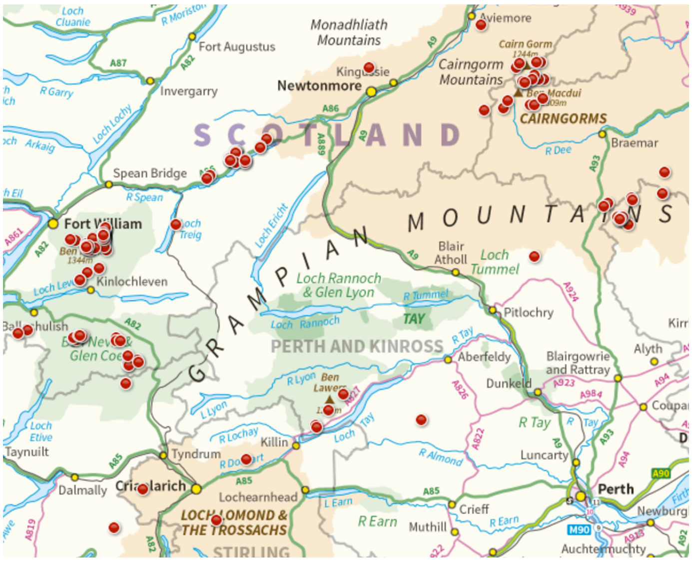

Figure 2.1: User-reported avalanches in the Cairngorms and the Glencoe regions during winter sports season of 2015-2016, generated by the SAIS.[4]

modelling during this project, and is directly used to derive the hazard map overlay in **Stage 1** of the project.

In addition to analysis of snow and terrain conditions and past avalanche records, studies of vegetations in mountainous areas can also provide important information on recurrence of avalanches. Christophe *et al.* [26] developed a model based on observation of tree-rings. As avalanches affect the growth of trees and other vegetations on the mountain slopes, growth condition of trees would provide useful insight into the magnitude and frequency of past avalanches in the area. One downside of the model is its unsuitableness for direct use in forecasting temporal avalanches, as the formation of general vegetation conditions require a long period of time. However, for the purpose of this project this model could potentially be used for establishing a static risk level for each point in the terrain, which is to be included in the overall risk model.

2.3 Modelling and visualisation of avalanche hazard in GIS

In order to effective store large amounts of geographical data for computing hazard map overlays for the project, a geographic information system (GIS) [27] is the most suitable method of organising avalanche hazard data.

While a majority of implemented avalanche forecasting methods – such as those discussed in Section 2.2 – provide generalised risk levels with respect to unique sets of environmental conditions, these generalised risk levels cannot be easily converted into localised hazards in a GIS, as these forecasting methods only operate on smaller subsets of parameters contributing to an avalanche. To evaluate the avalanche hazard of a specific location (e.g. Red Ben in Ben Nevis, Lochaber), it is necessary to develop a systematic method of calculating risk for each point in the region, taking into account as many hazard parameters as possible. Computations of per-point risk will allow the generation of the improved hazard map used in **Stage 2** of the project.

According to Bühler *et al.* [28], parameters influencing avalanche hazards can generally be placed in one of the three categories: (a) terrain topography features at each point in the modelled area; (b) meteorological data of the general area; and (c) characteristics of the snow cover in the area.

Terrain topography features, such as aspect and slope [29, pp. 17-18], convexity and concavity [30, p. 267], and roughness [31, p. 12] can be computed directly from a terrain height-map raster. For the main area of study in this project – Scotland, the government-owned Ordnance Survey has mapped the entire terrain of the British Isles (excluding Republic of Ireland) into a raster with resolution of 5 meters [32]. The data is updated frequently, and has a root-mean-square error of 2.5 meters in mountainous area, which is sufficient for the need of this project. As terrain features outside urban areas are not subject to frequent change, once the aforementioned terrain features are computed, they do not need to be re-computed until the source terrain data updates.

Meteorological and snow profile data, on the other hand, are largely dependent on the current and recent weather conditions in the forecasting regions. Commonly examined parameters by past researches include temperature change, snow accumulation [33], humidity[34], and wind direction [35]; as well as snow profile parameters such as snow grain size and density (as analysed in the SNOWPACK model [19]). However, as most past researches relied on weather forecasts in the regions in which they were conducted, not all parameters they used are available in Scotland. Fortunately, each SAIS avalanche forecast is also accompanied by a snow profile, containing measured meteorological and snow conditions observed during the field work of that forecast [36].

A number of efforts have been made to produce GIS models of avalanche hazards based on some or all of the aforementioned hazard parameters.

Grêt-Regamey and Straub [40] utilised a Bayesian network to study the relation between snow accumulation and flow model of avalanches, and visualised risks of avalanche impacts in an area with the trained network [41]. A more comprehensive risk model was used by Cappabianca *et al.* [37] to produce a similar visualisation, as shown in Figure 2.2 (top-left).

However, neither of the two studies above considered the full topography features of the triggering zones (e.g. lacking convexity and terrain roughness), some of which significantly affect the probability of release, as shown by Ghinoi and Chung [42]. Bühler *et al.* [28] devised a considerably accurate release zone identification algorithm based on terrain topography features alone, as visualised in Figure 2.2 (top-right).

More recent researches have also included meteorological analysis in the risk model. A notable example is by Veitinger *et al.* [39] in 2016: in addition to topography features such as slope and roughness, wind sheltering effects of terrain was computed based on the direction of wind, and included in the fuzzy logic computations of per-point risk. The algorithm's visualisation of avalanche release risk on a slope where a real avalanche took place is shown in Figure 2.2 (bottom-right). While evaluations showed that little accuracy improvement was achieved in the general case due to potential mapping errors, the algorithm was more accurate than its predecessor in locating frequent avalanche release areas.

Most hazard map visualisations of the aforementioned studies are in 2D only and are static once computed, providing no interactive capabilities. To our knowledge, only Pistocchi and Notarnicola [38] constructed a static 3D model with an avalanche risk overlay, as shown in Figure 2.2 (bottom-left), similar to the 3D model constructed in this project. For practical field use, capabilities of displaying additional image layers and map features "on the fly", as well as the ability to observe from different angles and distances will be very helpful to users.

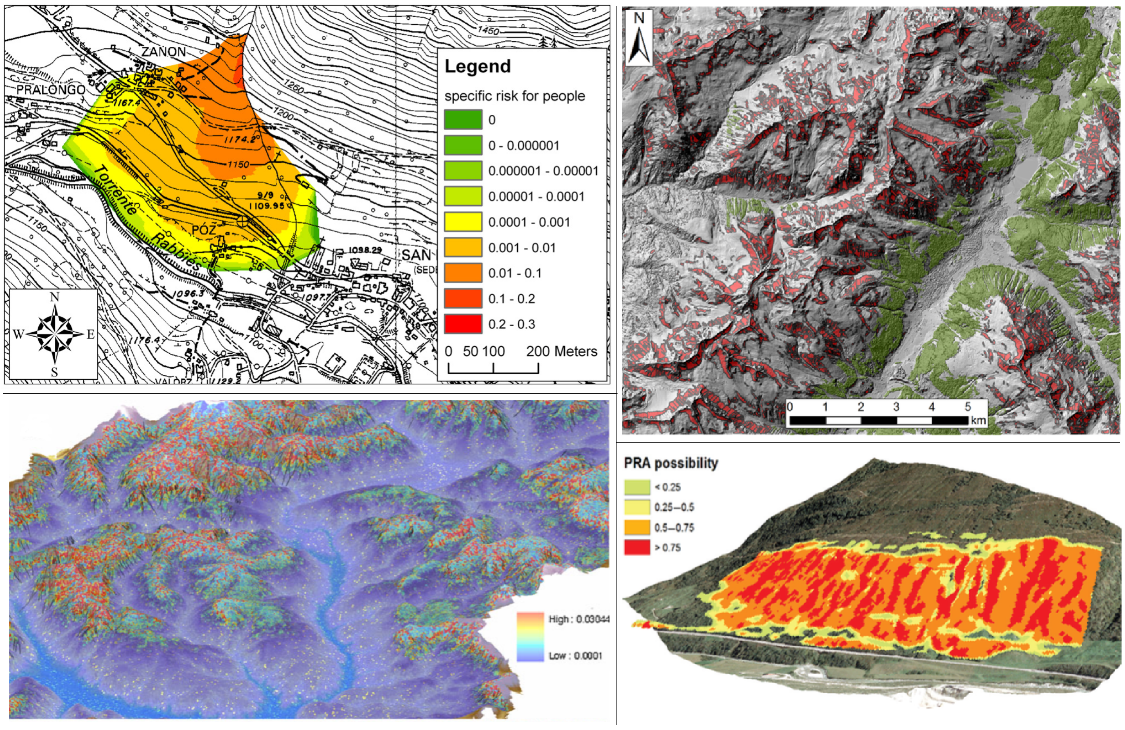

Figure 2.2: Hazard maps produced by prior efforts in visualising avalanche hazards: flow model and snow profile analysis by Cappabianca *et al.* (top-left) [37]; data-driven analysis by Pistocchi and Notarnicola (bottom-left) [38]; terrain topography analysis by Bühler *et al.* (top-right) [28]; and terrain topography and wind shelter analysis by Veitinger *et al.* (bottom-right) [39].

2.4 Colour representation of risks

While a realistic imagery of the surface can be produced in the 3D viewer by covering the artificial surface with corresponding aerial photographs, an appropriate colour representation scheme needs to be chosen for the hazard map overlay, which visualises the risk level at each point in the terrain model. Considerations need to be made regarding the choice of the colouring scheme, as well as in what form the colours are displayed. While all colouring schemes should have an unique representation for each distinct level of risk, how well an average user of the application perceives the colouring scheme is a usability issue. The two main colouring schemes proposed by existing researches and some attempts of applying them will be discussed in this section.

2.4.1 Saturation-based colouring

This is the simplest colour representation scheme. A single colour determined by a hue value is chosen, and in the context of visualising hazards the colour of choice is often red [43] [44]. The saturation of this colour at different points in the visualisation would vary, dependent on the level of risk at that point. As summarised by Cheong *et al.* [44, Ch. 2], there have been conflicting conclusions from researches on the effectiveness of saturation-based risk visualisations, when compared with visualisations using other schemes. Experiments also conducted by Cheong *et al.* showed that the accuracy of user decisions under this scheme is good while multitasking, but otherwise not as good.

While the subject of risk mapped by the visualisation of Cheong *et al.* is wildfire hazard, a known visualisation of avalanche hazard under this saturation-based scheme was by Bühler *et al.* [28] as discussed in Section 2.3, although no human-computer interaction (HCI) evaluation was conducted. This scheme is also used by Spachinger *et al.* [45] for flood risks.

2.4.2 Hue-based colouring

This colour representation scheme is similar to the saturation-based scheme, but uses different hues of colours (e.g. yellow and red) for different levels of risk in the visualisation. The European Avalanche Hazard Scale [9, pp. 93-94] – also used by the SAIS in the UK – applies such a hue-based scheme, as shown in Figure 2.3. This scheme is also used in visualisation of avalanche hazards by most studies discussed in Section 2.3, as shown in Figure 2.2.

Low Risk	Moderate Risk	Considerable Risk	High Risk	Very High Risk

Figure 2.3: Colouring scheme reconstructed from the European Avalanche Hazard Scale, used by the SAIS [46].

However, some studies have considered the hue-based scheme used in Figure 2.3 to be less effective, most notably by Conger [47], which found that using green to represent low risk deviates from the common perception of green being a safe-indicating colour, which is not always the case in avalanche forecasting. Orange was also found to be inappropriate in association with a risk, and more difficult to print cartographically [47, Ch. 4.2]. Therefore Conger has suggested that the risk scale should be rescaled into four, in order to abolish the use of orange.

HCI evaluations conducted by Cheong *et al.* [44, Ch. 5] concluded that while a hue-based scheme is often most preferred by users, its user decision accuracy is not the best among different colour representation schemes.

Other variations of applying hue-based colouring include an attempt by Gavaldà and Moner [48] to represent mountaineering route hazards with red-yellow-green traffic signals; as well as a method developed by Saito *et al.* [49], using two tones of hue to represent hazard at each level, which in this case is unsuitable for the steep transitions of risk frequently occurring in avalanche hazard maps [49, Ch. 5.1]. Conger [47, Ch. 5.2] also suggested a method of partially filling hazard areas with triangles that are coloured according to the colouring scheme. This however would be difficult to implement in practice, due to the size variations of neighbouring points with the same risk level.

2.5 Cost-based terrain pathfinding

Based on computations of per-point risk in **Stage 2** of the project, **Stage 3** focuses on implementing the extended functionality of terrain pathfinding, which will involve adapting existing pathfinding algorithms for use under the complicated conditions of backcountry terrain.

As according to Moore *et al.* [50, pp. 4-5], the terrain height-map raster from Ordnance Survey, as discussed in 2.3 is essentially a square-grid network model of the real terrain. The network model was constructed from sampling the real elevation data at a resolution of 5 meters, which minimises the risk of missing abrupt changes in elevation. Pathfinding can then be conducted on the model. The most widely implemented algorithm for this purpose is the A*

Search Algorithm [51], utilising heuristic analysis to guide a graph search based on Dijkstra's Algorithm [52].

A* is most widely implemented in the development of pathfinder artificial intelligences in computer games [8]. Since its introduction, a significant number of studies have been conducted to improve the performance of A* search, including iterative-deepening A* (IDA) [53] which requires less memory at runtime; hierarchical path-finding A* (HPA) [54], which utilises hierarchical abstraction on large data grids to produce a near-optimal solution at very high performance; and *navigational mesh* (NavMesh) [55], which minimises the structure representation of data to reduce memory use and computation time.

When adapting A* or its aforementioned variants for computing a path in the terrain and taking into account the avalanche risk level at each point in the terrain raster, both the distance and the risk levels need to considered by the heuristic function of A*. Due to the nature of the uneven terrain, the proper walking distances between points can be estimated by Naismith's Rule and its variants [56]. To represent the points as a data structure, Yap [57] has suggested using a tiled hex grid to organise neighbouring points for optimisation of performance, which then be analysed with a hierarchical search algorithm such as HPA [54].

2.6 Usability aspects of the application

As the front-end application built with Cesium is designed to be used both on a mobile device with touchscreen and on a desktop computer with a mouse, best practises of design from existing HCI research on both types of user interfaces need to be considered, as well as the principles for a system that would potentially be used in the field rather than in office.

Nielson and Olsen [58] proposed a formal method of manipulating the view of a 3D object (such as the virtual terrain globe in this application) with a 2D interface. This allows translations, rotations and scalings of the object to be performed by a single 2D event device, such as a mouse. In practise, methods of interactions have been mapped to specific combinations of actions of the mouse wheel and mouse keys [59, pp. 195-197]. However, not all users find mouse interactions straightforward when navigating a 3D scene, and their satisfaction of the mouse interface largely depends on their proficiency with the mouse, as demonstrated by Dubois *et al.* [60]. The default mouse interaction designs of Cesium is similar to that of Google Earth as evaluated by Dubois *et al.*, although specific overrides can be programmed [6].

On modern mobile devices, touchscreen is often the only interface available for the user to interact with the application. With mouse clicks replaced by touch interactions [59, p. 191], manipulations of the 3D object in the viewer are often less straightforward, as studied by Ku and Chen [61], which provided some recommendations on designing touchscreen-based interactions of a 3D object viewer. Touchscreen interaction designs of Cesium largely conform to these recommendations in practise.

For an application that could be used in the field under time and user attention constraints, a study by Pascoe *et al.* [62] shows that the application should have context awareness and utilise interaction designs which minimise distraction to the user. Another study by Albinsson and Zhai [63] explored methods to improve the precision of touchscreen interactions under rough inputs from human fingers.

3 Procurement and Processing of Data

4 Description of the Application

5 Evaluation and Testing of the Application

6 Conclusions

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