INTEGRATED REMOTE MONITORING FOR COASTAL GEOHAZARDS AND HERITAGE SITES

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ABSTRACT

In many regions of the world, coastal recession is a major issue. The coastal fringe represents a dynamic and complex setting, where numerous processes interact to shape the terrain. On certain coasts, these interactions can combine with local morphology to result in geohazards, such as slumps and mudflows. Such hazards can pose a major threat to human activities and areas rich in cultural heritage. There is a clear requirement for an effective monitoring strategy in order to assist those tasked with coastal management. However, traditional monitoring approaches tend to be spatially and temporally inadequate, and while significant research effort has concentrated on the application of more appropriate techniques, these are often unsuitable in isolation for monitoring of more complex morphology. This paper presents ongoing work on the development of an integrated, episodic monitoring strategy, primarily comprised of airborne and terrestrial laser scanning. In order to effectively integrate these datasets, software enabling weighted least squares surface matching has been developed. This gives the opportunity to register multi-source, multi-temporal datasets, allowing for change detection and analysis. Preliminary testing of this algorithm has been carried out on artificial datasets, and the results of these tests are presented and discussed. In addition, the development of a continuous GPS remote monitoring system is described, and the importance of historical datasets, and issues associated with this are discussed. The research is being applied to test sites on the North Yorkshire coast of eastern England, where geohazard features are commonplace.

INTRODUCTION

Background

Coastal recession is a naturally occurring, irreversible process, which has been ongoing for hundreds of thousands of years. Some coastlines are particularly vulnerable to this process due to their geological makeup, with soft cliff coasts being a case in point. Parts of eastern England for example can be particularly prone to instability. Recession here can take various forms, including landslides, rock falls, slumping, and various other mass wasting processes. These coastal geological hazards, or geohazards as they are commonly termed, can be unpredictable and dangerous, and can directly impact the rich human and cultural heritage often found in coastal regions. The ability to estimate future cliff position is therefore essential for effective coastal management and planning (Hall et al., 2002), and it is crucial that any such instability can be detected, monitored and mitigated where appropriate.

Geohazards are caused by a complex interaction of direct and indirect factors (Bray and Hooke, 1997), and monitoring offers the opportunity to progress understanding and prediction of how these features are likely to evolve over time. However, the coastal arena has traditionally been unreceptive to the application of surveying and monitoring techniques. This harsh environment is complicated by a number of factors. Tidal conditions make traditional surveying approaches difficult, and the terrain to be monitored can often be dangerous and inaccessible. Repeated surveys can pose a problem, as in this dynamic setting it can be near impossible to guarantee the integrity of control markers over time. Additionally, it is frequently necessary to capture large spatial extents, which can present a challenge in itself.

Traditional surveying approaches tend to be crude and spatially restricted (Morton et al., 1993; Hapke and Richmond, 2000), for example, by concentrating on repeated measurements of beach or cliff profiles by total station. Significant research effort has focused on the application of more suitable techniques, such as aerial photography, which has been utilised for coastal monitoring for some time (El-Ashry and Wanless, 1967; Thieler and Danforth, 1994; Smith and Waldram, 1996; Brown and Arbogast, 1999; Hapke and Richmond, 2000; Moore, 2000; Dornbusch et al., 2005). More recently, the potential of GPS has been examined (Morton et al., 1993; Mills et al., 2003), as has that of airborne laser scanning (Krabill et al., 2000; Adams and Chandler, 2002; Shrestha et al., 2005). However, while such techniques bring clear advantages to coastal surveying, none is without some significant drawback. For instance, while aerial photogrammetry allows for the rapid capture of large spatial extents and offers the benefits of a largely automated, well established workflow, there can be image matching problems due to poor texture in areas such as beaches (Buckley, 2003), or regions of deep shadow, as commonly associated with steep cliff faces. On the other hand, airborne laser scanning, as a direct sensing technique is unaffected by such issues, but does however lack the benefits of associated imagery (Ackermann, 1999).

This evidence points towards the needs for a more integrated approach, as suggested by a number of scientists (Ackermann, 1999; Schiewe, 2000; McIntosh and Krupnik, 2002), and this is the strategy which has been adopted in this research in attempt to produce a robust and effective monitoring solution.

Aims and Objectives

The aim of the research is to further understanding of coastal geohazards, by developing a flexible and efficient monitoring strategy which will help to identify the linkages between the various processes influencing coastal recession, and driving the development of geohazards. This leads to the following objectives:

- to assess emerging geomatics technologies as potential solutions for improving the spatial and temporal resolution of monitoring strategies;
- to develop and implement software for the integration of multi-source datasets, and in doing so, build towards a more flexible and efficient monitoring strategy;
- to evaluate and refine the monitoring strategy through application to coastal test sites;
- to synthesise the integrated surface models with other relevant datasets, in a temporal GIS for enhanced analysis of change.

Test Sites

The monitoring strategy is being applied to test sites on the North Yorkshire coast of eastern England (Figure 1). Due to its geological composition, this coastline is generally prone to erosion, with ‘cliff instability, weathering and scouring of the cliff toe in most bays’ (Crosby, 1995). Much of this area forms part of the North Yorkshire and Cleveland Heritage Coast, a government-designated area, carefully managed in order to protect the unspoilt natural landscape. Sections of this coast are also designated Sites of Special Scientific Interest (SSSI), primarily due to their noteworthy geology, and as a consequence, are carefully managed in terms of land use and conservation. The coastal fringes of eastern England display evidence of their rich and complex past, and the physical remnants of this history provide a record of the evolution of the coast and the human legacy (Trow and Murphy, 2003). It is imperative for areas of human settlement and important heritage sites, that the risk of coastal recession can be accurately assessed. This allows the bodies responsible for their upkeep and preservation to plan a course of appropriate action, whether this be to allow some form of managed retreat, or to engage in full scale coastal defence engineering.

Filey Bay lies eleven kilometers south of the bustling seaside resort of Scarborough, and is the scene of the main monitoring activity. While erosion rates in this area are relatively low, areas prone to coastal landslips suffer from higher (up to 2m per year), more irregular, rates of retreat (Symonds Group, 1998). This site boasts a geology of soft cliffs, which are moderately steep, variable in profile, and rise to between 30 and 50 metres in height (Figure 2). The slopes are frequently interspersed with vegetation – typically rough grass, but shrubs and small trees are also found in places.

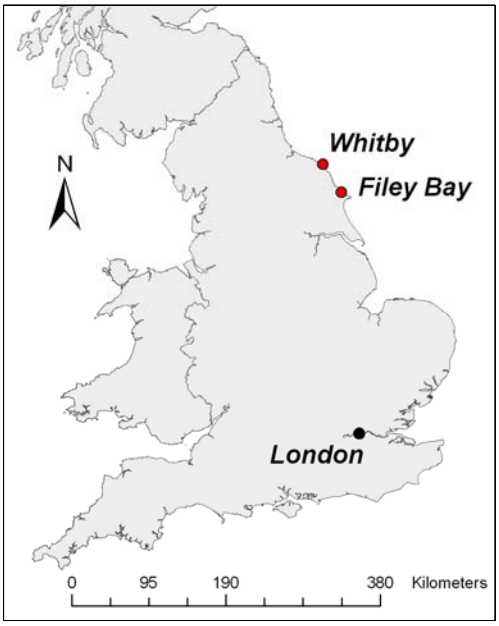

Figure 1. Overview map of England, showing study site locations.

The North Yorkshire coastline supports a rich heritage of human settlement, including important sites such as Whitby Abbey (Figure 2), originally founded in 657 AD, and particularly significant in terms of its cultural and religious history. This site draws many visitors each year, and is managed by English Heritage (EH), the public body responsible for all aspects of protecting and promoting England's historic environment. However, through the passage of time, the very existence of this site, like many others up and down the east coast, is being threatened by the relentless inward march of the sea. This ancient site of great historical value is comprised of near-vertical cliffs which are under threat from coastal retreat. The geology of weak rocks and glacial tills is prone to erosion not only through wave attack, but also because of the effects of groundwater seepage from within the cliffs (Clark and Guest, 1991). In recent years, cliff erosion has begun to encroach on areas of the site itself, and there is a pressing need for EH to understand the rate of retreat at this headland. This therefore provides the second test site for the research.

Despite being relatively well-contained geographically, these sites offer a variety of active geohazards. There also exists a range of historical erosion data for these locations, thus enabling more meaningful analysis of results obtained through this study.

Figure 2. Study sites at Whitby Abbey Headland (left), and Filey Bay (middle and right).

METHODOLOGY

Continuous Monitoring

A key aspect of the research involves the development of an autonomous, dual frequency GPS system for continuous monitoring of geohazard activity. Although given sufficient epochs, episodic monitoring would allow for modeling of trends in the recession, permanent monitoring offers the benefits of continuous deformation analysis. Daily, seasonal and yearly signals can be identified, quantified, and their effects eliminated from the deformation time series. Additionally, the influence of site specific errors such as multipath and signal scatter are reduced (although not eliminated) by repeated, day to day observation patterns, and averaging over a 24-hour period. While this application of GPS may be new in the coastal context, there is evidence of its value in other, similar mass movement scenarios (Malet et al., 2002, Mora et al., 2003).

The system being developed here is based on a dual frequency GPS receiver, and core system elements include a capability for remote communication, and a renewable energy source. This will enable fully autonomous operation, with data being logged continuously, and transmitted to the university for automated processing in the *Bernese* scientific GPS processing software. A prototype system is shown in Figure 3. A system such as this offers the possibility for site-specific monitoring of areas identified as being particularly unstable, and could potentially act as a geohazard early-warning system.

Figure 3. GPS remote monitoring system prototype.

Episodic Monitoring

Continuous monitoring is of unquestionable value, but clearly there must also be a complementary mechanism to enable monitoring over wider coastal stretches. Geohazard activity can be sporadic and unpredictable, in both time and space, and the cost of an extensive network of remotely-operating, continuous monitoring stations would be prohibitive given present technological constraints. Therefore, episodic monitoring was chosen as the linchpin of the monitoring approach described in this paper. This allows for periodic examination of extensive coastal tracts, where areas of particular interest can either be periodically monitored on a more frequent basis, and in greater detail, or if the situation dictates, could be monitored continuously as described above. This offers a truly integrated approach, capable of responding over a range of scales.

In this study, airborne and terrestrial laser scanning were selected in order to evaluate the episodic monitoring component, and are being integrated though a surface matching approach to enable efficient terrain representation.

Airborne Laser Scanning (ALS). Also referred to in the literature as LiDAR, ALS offers fast remote capture of mass point cloud data, and as noted by Ackermann (1999), enables '… highly automated generation of digital terrain models (DTM) and surface models'. It is critical to acknowledge that recessional processes usually act over the entire coastal zone, with changes to one component directly or indirectly influencing the stability of others. Cliffed coastal areas such as those under study here, are typically composed of relatively flat expanses on the shore and cliff tops, and for full understanding of the recessional processes at work, it is vital that these areas be given equal weight in the monitoring programme. As an active sensor, ALS is highly suitable for this purpose, offering a regular, reliable representation of the terrain.

A successful application was made to the Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) in 2003 for ALS data acquisition of the three study sites described above. The ARSF instrument is an Optech ALTM 3033 scanner, and this was used to collect ALS range data in April 2005, and again in August 2005. Unfortunately, due to technical difficulties with the sensor, it was not possible for ALS to be acquired synchronous to the September 2004 epoch of field data collection. The datasets were flown at an altitude of around 1000m, resulting in a resolution of approximately one point per square metre, with very good coverage of the study sites. The raw observations were post-processed by the ARSF to produce *xyz* first and last pulse return data.

Terrestrial Laser Scanning (TLS). TLS was chosen for use in this study as it offers a suitable complement to ALS. Like ALS, TLS enables fast, remote capture of point cloud data, but in this case the data is collected from the ground. The importance of a terrestrial component is twofold. Firstly, while some elements of the cliff face may be captured from the air (i.e. by ALS), in many locations, more vertical slopes will be largely obscured, and can only be suitably acquired from a terrestrial perspective (Adams et al., 2003). Secondly, TLS offers the opportunity to focus efforts on particularly active areas of the cliff face; although not feasible to capture large spatial extents on the scale of ALS, it is possible to rapidly capture data of a relatively high accuracy and density – a feat certainly not realistically possible through traditional surveying techniques.

The research was designed around a monitoring strategy with a repeat interval of approximately 6 months. Consequently, fieldwork was carried out at the Filey Bay test site in late September 2004, repeated in April 2005, and again in August 2005. These surveys primarily involved TLS capture at four locations along the bay, as shown in Figure 4. At each of these locations, cliff profiles were also measured by total station in order to validate the TLS datasets. Three of these sites had already been the focus of an earlier coastal monitoring research project carried out at the University of Newcastle (Buckley, 2003) and as such, a five year record of change on the cliff profiles at these locations already existed. The terrestrial scanning was carried out using a Cyrax 2500 scanner (September 2004, August 2005), a Riegl LPM-i800HA scanner (April 2005), and a Leica HDS3000 scanner (August 2005). These scanners offer various advantages and disadvantages, and it was an interesting exercise to evaluate their contrasting characteristics under such demanding conditions. The Riegl scanner proved particularly advantageous for this particular application, as its longer range (800 metres) enabled all scanning to be carried out from the beach. This was particularly useful for the survey of the SPT test site, an extensive cliff failure at the southern end of Filey Bay, which is relatively active.

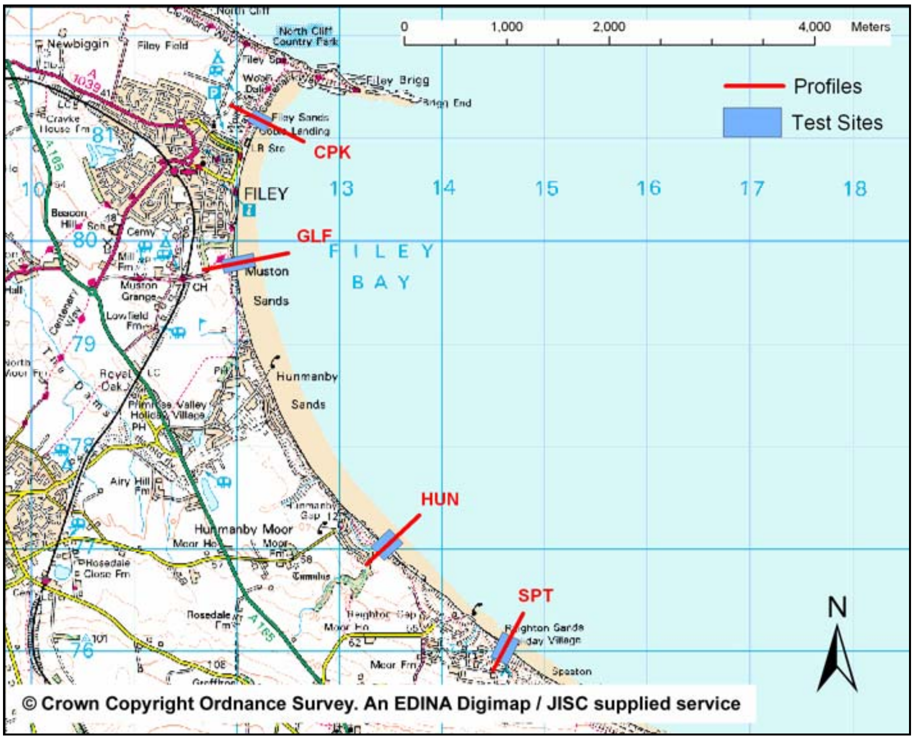

Figure 4. Map of Filey Bay test sites.

Historical Aerial Photography. In a study such as this, analysis of change over a period of five or even ten years is generally insufficient to be able to draw any meaningful conclusions relating to coastal recession rates or trends. For this reason, it was decided to use archival aerial photography in order to examine change over a longer historical timescale, and enable contemporary observations to be placed in context. Aerial photographs are commonly used for monitoring of coastal erosion (Moore, 2000). While aerial photography alone may not be sufficient for effective monitoring, it does provide the most accessible record of landscape change over the last fifty years or so, and is useful for describing general patterns of change.

Epochs of photography dating back to 1966 were acquired for the test sites (Table 1), and these datasets are being incorporated in the monitoring strategy through surface matching, as described below, in order to highlight areas of significant change over time.

Table 1. Summary of historical photography acquired for the test sites

Site	Year of capture	Scale	Source
Filey Bay	1967	1:10,000	Ordnance Survey
Filey Bay	1980	1:7,800	Ordnance Survey
Filey Bay	2000	1:22,000	Univ. of Newcastle
Whitby	1966	1:7,500	Ordnance Survey
Whitby	1986	1:5,300	Ordnance Survey
Whitby	1994	1:1,600	English Heritage

Background to Surface Matching. Least squares based surface matching plays a key role in this research by permitting the integration of terrestrial and airborne datasets, and in the process, enabling detection of coastal change. The least squares matching technique allows a poorly-controlled floating surface to be matched to a well-controlled reference surface. This match is based on the 3D conformal coordinate transformation, which enables conversion from one three dimensional coordinate system to another, by means of three rotations (ω, φ, κ), three translations (Tx, Ty, Tz), and a scale factor (s) (Wolf and Dewitt, 2000). Surface matching is of great use in situations where it may not be possible to identify the requisite control points from both datasets in order to perform this transformation by conventional means. This is a situation encountered in coastal surveying, where the dynamic environment and lack of accessible, hard detail can make traditional registration approaches difficult and costly. In least squares based surface matching, each point on one surface can be considered to provide control information, and in this manner, the algorithm utilises conjugate surface patches, by attempting to minimize the vertical distance between a point on the floating surface, and a corresponding surface patch on the reference surface (Mills et al., 2003). In standard least squares fashion, the procedure attempts to minimize these differences globally across the surfaces, iterating and updating the transformation parameters until some convergence criterion is achieved. The post-match least squares residuals highlight areas of difference, which in the case of matched multi-temporal surfaces could represent changes due to geohazard activity. This software was developed as part of an earlier coastal monitoring research project at the University of Newcastle, and is described more fully in Mills et al. (2003, 2005).

Dataset Integration. With airborne and terrestrial laser scanning datasets being harmonised to create an effective episodic monitoring strategy, there are some important factors which must be considered. Although both datasets are the product of laser scanning, and thus similar in many ways, there are some noteable distinctions:

- there will be differences in point structure due to differing scanning mechanisms;
- spatial resolutions are likely to differ;
- as a result of the alternative control methods employed, accuracies will vary between the datasets;
- differing surface representations may exist (e.g. due to the effects of data filtering, ALS first pulse return or last pulse return, sensor look angle, etc.).

For this reason, it was clear that the surface matching software must be further developed to accommodate these factors. As previously suggested, surface matching is useful for a number of reasons. In the case of this research, TLS is proving to be the more accurate of the datasets, and as such, the ALS is being matched (registered) to this terrestrial surface. In addition, surface matching also allows for detection and removal of any discrepancies which may exist between overlapping ALS strips (Maas, 2002).

Vegetation is a factor which can often complicate measurement of the true terrain surface. On soft cliffs such as those under consideration at the Filey Bay test site, vegetation is a common feature, as illustrated in Figure 2. Through standard off-the-shelf processing software, this element can be filtered out to some extent, but it can be difficult to determine just how faithful to reality the portrayal of the resultant 'ground' surface really is, as this is largely dependant on the extent to which the sensor has penetrated the vegetation. This, in turn, is governed by a range of factors, including incidence angle, scanning resolution, and vegetation structure. If two surfaces, measured at different times, and potentially acquired through different techniques, are to be surface matched successfully, then elements such as vegetation are important considerations. If the surfaces were acquired at different times in the vegetation growth cycle, then this is one possible source of difference which will be immediately introduced, with the potential to complicate the pattern of post-match residuals and lead to erroneous identification of geological instability. This leads to two primary conclusions; firstly, where possible, the effects of any such complicating features should be eliminated from the matching process, and secondly, it is desirable to introduce knowledge of influential surface characteristics, including vegetation, into the post-match analysis process.

If we have a situation as described above, where concentrated areas of real surface change, further complicated by the presence of vegetation exist, then it may be prudent to consider elimination of such contaminating observations from the datasets through some form of weighting scheme. The inclusion of a weight matrix is a standard extension to least squares, and is widely used in order to reduce the influence of less reliable observations (Draper and Smith, 1981). This basically allows a weight to be assigned to each observation in the dataset, enabling the influence of individual observations to be controlled. It was decided therefore to examine the effects of weighted surface matching through some simple tests, as described in the Results section below. For a full description of the mathematical theory of least squares, including the weight matrix, refer to Cross (1983).

RESULTS

Field Data Processing

After each epoch of field data collection at the Filey Bay test site, the TLS data was processed, and registered to a global reference frame through GPS control data collected at the time of fieldwork. Processing of the 2004 TLS data highlighted some important issues. Firstly, there were some minor registration discrepancies between overlapping scan positions, most likely due to high winds having affected the stability of scan control targets (illustrated in Figure 5) between time of scanning and time of total station control observations. This problem was overcome by application of the surface matching software. Secondly, as discussed above, when the TLS data was compared to the total station profiles, it became apparent that although overall agreement was good, on parts of the cliffs where vegetation was dense, discrepancies were greater, despite the fact that the TLS data had already been filtered to remove vegetation.

Preliminary inspection of the first epoch of ALS data indicates a high quality dataset, with excellent coverage of the study sites. Once all ALS data is received from the ARSF, work will concentrate on integration of these datasets with the TLS, and historical photography.

Figure 5. TLS control target.

Processing of Archival Aerial Photography

The historical photography detailed in Table 1 was acquired and photogrammetrically processed in order to extract DEMs of the test sites. This process was far from straightforward given that much of this photography was relatively old, of varying quality, and lacking camera calibration information. However, it was possible to extract useable terrain models. As yet, it has not been possible to carry out a quality assessment of these datasets, but it is expected that despite the uncertainty over metric quality, this information will still remain a key component of the monitoring strategy, by allowing more general, long-term erosion trends to be established.

Weighted Surface Matching Testing

With the acquisition of the historical datasets, and the collection and preparation of the field data in progress, it was necessary to give greater consideration to the performance of the weighted surface matching software, which is fundamental to fusing the surfaces and enabling multi-temporal change detection. Therefore, the weighted surface matching algorithm was tested on a synthetic dataset in order to examine its behaviour under idealistic conditions. The test surfaces were based on a sine function, and each surface comprised 2500 points distributed in a regular grid pattern, as shown in Figure 6 below.

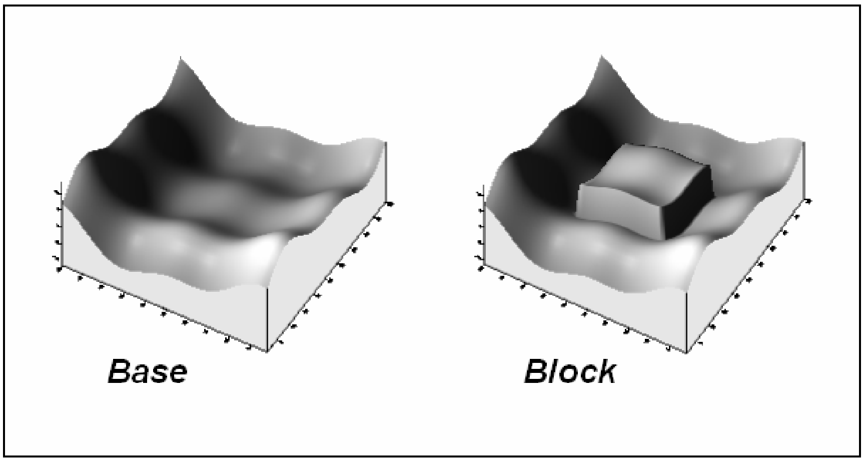

Figure 6. Illustration of artificial test surfaces.

In these tests, *Base* provided the fixed reference surface. The *Block* surface was initially a replication of *Base*, and an 'outlier' feature was then introduced into this, by incrementing the central area by + 10 units (dimensionless) in the *z* direction, creating a block effect. Following this, two tests were devised (referred to here as A and B), with the *Block* surface transformed by the two sets of parameters detailed in Table 2. As these transformations are known, it was possible to assess the quality of the final match through comparison of the matched position of each point to the original position of that point (prior to the induced transformation). This is described through 'mismatch' statistics, a technique recommended by Pâquet (2003), which may provide a more reliable means of measuring the success of the match than examination of the recovered transformation parameters alone.

Table 2. Initial transformations applied to *Block* surface. Distance units are dimensionless

Test	Initial Transformation						
	ω°	*φ*°	*κ*°	*Tx*	*Ty*	*Tz*	*s*
A	0.000000	0.000000	0.000000	0.500	0.500	0.500	1.000000
B	2.000000	2.000000	2.000000	2.000	2.000	2.000	1.000000

The aim of this experiment was to examine the effect of weights applied to areas of the surface. Individual weights can range between 0 and 1, with a weighting of 0 effectively eliminating that observation from the adjustment, while a weighting of 1 allows the observation to behave normally, as in non-weighted least squares. Values between 0 and 1 are of course possible, and useful. The testing was carried out by applying increasingly large weightings in steps of 0.1 to the central block feature, while all other areas of the surface were assigned weights of 1 to allow normal behaviour. *Block* was then matched to *Base* for each of these weighting variations.

Results of Test A are shown in Table 3. For reference, the results of an unweighted match (i.e. standard least squares) are also included to illustrate the impact of the block feature. This shows that the software was unable to converge under these conditions. As would be expected, the correct parameters were recovered most successfully where the block area was weighted out completely (0). This is confirmed by mismatch values of 0.000. As the influence of the block increases through increased weighting, the match becomes less successful, as reflected through the increasing mismatch statistics. Finally, with the block weighted at 0.6, the software was unable to reconcile the two surfaces, and from this point on, the tests failed to converge.

Table 3. Results of matching *Block* to *Base* using Test A parameters

Weight*	Matched Parameters at 1σ level							Mismatch	
	ω°	*φ*°	*κ*°	*Tx*	*Ty*	*Tz*	*s*	Mean	σ
none	No Convergence								
0.0	0.000000 ± 0.545269	0.000000 ± 0.545269	0.000000 ± 0.446136	-0.500 ± 0.295	-0.500 ± 0.407	-0.500 ± 0.309	1.000000 ± 0.008324	0.000	0.000
0.1	-0.498447 ± 0.500997	0.493454 ± 0.421656	0.043833 ± 0.378348	-0.252 ± 0.274	-0.208 ± 0.373	-0.410 ± 0.286	0.981552 ± 0.007414	0.612	0.218
0.2	-0.991197 ± 0.494587	0.904647 ± 0.390036	0.115129 ± 0.359262	-0.009 ± 0.260	0.048 ± 0.357	-0.331 ± 0.271	0.964399 ± 0.007232	1.173	0.417
0.3	-1.215178 ± 0.492054	1.411959 ± 0.376110	0.133643 ± 0.357004	0.280 ± 0.250	0.648 ± 0.376	-0.351 ± 0.260	0.942591 ± 0.007403	1.789	0.590
0.4	-1.342006 ± 0.479258	1.600510 ± 0.361834	0.130481 ± 0.347118	0.446 ± 0.241	0.972 ± 0.361	-0.436 ± 0.251	0.930124 ± 0.007097	2.162	0.680
0.5	-1.359184 ± 0.507723	2.175121 ± 0.347738	0.164932 ± 0.350126	0.878 ± 0.241	1.894 ± 0.393	-0.502 ± 0.247	0.901183 ± 0.007535	2.881	0.895
0.6→0.9	No Convergence								

*Weight refers to weighting applied to block area. All other areas were given weightings of 1.

N.B. Parameters generally negative as they are the values required to transform *Block* back to *Base*. Distance units are dimensionless.

While the initial transformations applied in Test A were fairly mild, involving only translations, Test B provided a slightly more demanding examination of the software, as the surfaces would initially have been in poorer alignment (refer to Table 2). Table 4 shows the results of these tests. The testing was repeated as before, and yet again, a weighting of 0 for the block allowed very good recovery of the initial parameters. For weightings of 0.1 and 0.2, the software performed in a similar manner to Test A, and actually produced slightly improved matches, as can be seen from the mismatch statistics for these cases. However, for weightings of 0.3 and greater, the procedure failed to converge. Gruen and Akca (2005) note that where poor initial approximations exist for the unknowns, some of the parameters, particularly the scale factor, are prone to converge to the wrong solution, and it was suspected that this may be the case here. Preliminary repeat tests were therefore carried out, with the scale factor held fixed, and this alteration yielded significantly improved mismatch statistics. In addition, indications were that the software was better able to cope with increased weightings for the block area.

Table 4. Results of matching *Block* to *Base* using Test B parameters

Weight*	Matched Parameters at 1σ level							Mismatch	
	ω°	φ°	κ°	*Tx*	*Ty*	*Tz*	*s*	Mean	σ
none	No Convergence								
0.0	-2.069719 ± 0.560667	-1.927727 ± 0.480974	-2.069756 ± 0.422061	-2.002 ± 0.319	-2.000 ± 0.440	-1.998 ± 0.350	1.000000 ± 0.008446	0.000	0.000
0.1	-2.537418 ± 0.495768	-1.437790 ± 0.421896	-2.011104 ± 0.377899	-1.741 ± 0.283	-1.684 ± 0.391	-1.868 ± 0.302	0.981607 ± 0.007411	0.608	0.213
0.2	-2.999292 ± 0.487859	-1.031067 ± 0.390831	-1.929133 ± 0.358643	-1.483 ± 0.269	-1.406 ± 0.375	-1.754 ± 0.286	0.964530 ± 0.007234	1.165	0.407
0.3→0.9	No Convergence								

*Weight refers to weighting applied to block area. All other areas were given weightings of 1.

DISCUSSION

Data collection and analysis reaffirmed the importance of adopting an integrated monitoring strategy, as it was clear that no one technique alone could possibly be adequate for such a varied and demanding environment. In this project, ALS data is proving essential for overcoming occlusions in the TLS datasets, and for supplying a wider overview of the landscape. While TLS can provide a highly detailed and valuable surface representation, this is only really practical for small pockets of geohazard activity.

The continuous monitoring element is still under development, with the dual-frequency GPS receiver currently undergoing rigorous quality testing under a controlled environment on the university campus. This should help to confirm the potential of this system for site-specific geohazard monitoring, which is a key element of the integrated monitoring strategy. These observations will be processed, analysed and presented at a later date.

Development of the surface matching software towards a more refined means of surface integration has shown interesting preliminary results, through testing of weighted surface matching of artificial surfaces. These tests highlighted the impact of an extreme discrepancy in the matching surface, and enabled examination of weighted matching. The results have provided an improved understanding of the effect of different levels of weights, and underlined the potential viability of this as a mechanism for reducing the effects of outliers in the datasets. Future work will concentrate on refining and automating the weighting aspect, before testing on real field datasets, and moving towards fusion of surfaces originating from ALS, TLS and historical photography. In addition, locked away in this data is further information which can be extracted and put to use in the analysis process. A DEM can provide information on slope steepness and aspect, and in this case, point density. Furthermore, where raw laser scanning datasets are concerned, non-ground points can be retained, and used to extract information on vegetation characteristics. Together, this information can be used alongside the post-match residuals, in a multi-temporal GIS, in order to better understand the patterns of residuals, and make informed judgements on geohazard activity.

With the research largely focussed on the soft-cliff environment of Filey Bay, it is desirable that the strategy be tested under a different geological setting, and this is where the second test site, Whitby Abbey Headland comes into play. TLS and ALS data will be collected at this site in April 2006, and the episodic monitoring, including the contribution from historical datasets will be examined in order to evaluate the transferability of this integrated monitoring approach.

CONCLUSION

This paper has presented an integrated approach to the challenge of monitoring coastal geohazards on soft-cliff coastlines. Initial results have been presented and discussed. The integration of airborne and terrestrial laser scanning shows promise in providing an effective means of episodic coastal monitoring, and allows some of the difficulties associated with the use of individual techniques alone, to be overcome. Archival aerial photography is being used to establish a historical baseline for coastal change, and some of the issues surrounding this technique have been described. The ability of any monitoring strategy to focus on priority locations is important, and where particularly active geohazards exist in sensitive areas, this is critical. A dual frequency GPS unit has therefore been developed and is being tested for continuous monitoring of such sites.

The research described in this paper is not driven by the exploration of the combination of these *particular* remote monitoring techniques, however successful they may prove to be in this instance. The cornerstone of this strategy is the integrated episodic-continuous approach, and the associated development of software for fusing multi-sensor, multi-temporal datasets in order to enable adaptable and efficient coastal monitoring. With this in mind, it is anticipated that the resultant approach should be applicable to a range of coastal environments, as well as alternative terrain monitoring applications.

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