IMPROVEMENT OF AUTOMATIC DSM GENERATION OVER URBAN AREAS USING AIRBORNE LASER SCANNER DATA

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ABSTRACT

Airborne laser scanning has provided an efficient and accurate method of data acquisition for the determination of visible surface topography. The laser data can be quickly processed to provide coordinates of points on the visible surface with high spatial frequency and precision. This technology has benefits as compared to photogrammetric techniques, however there are limiting factors due to the laser data having no thematic information. The limitations may be overcome by utilizing aspects of both laser altimetry and photogrammetry in the surface determination process.
Research has been undertaken to accurately determine the visible surface in urban areas using airborne laser scanner data and digital aerial imagery. In this project, edges detected in the aerial images are used to refine the digital surface model (DSM) produced using data from an airborne laser scanner. The three dimensional edge information allows improvement of the laser DSM by providing accurate locations of surface discontinuities. Therefore the laser data and the edge information are merged to obtain the benefits of each data set, facilitating the generation of an accurate terrain model.
The approach has been tested over an urban site covering Ocean City, Maryland, USA. Laser data and aerial imagery, acquired on the same day, are available. Experiments were performed to test and refine the algorithm. This paper presents the data fusion approach, describes the data set and details the results of experimentation undertaken to investigate the validity of the approach.

1 INTRODUCTION

Digital surface models (DSMs) of urban areas are becoming widely used in an increasing number of applications, such as digital orthophoto production, three dimensional (3D) city modeling and 3D building reconstruction. Methods for generating surface models include using laser scanner data and using digital photogrammetric methods.

Airborne laser scanning is an efficient and accurate method of obtaining visible surface information with high spatial frequency. However these data provide only coordinates and have no thematic information. Terrain information, such as formlines or breaklines, is not available from the laser scanner data. The location of surface discontinuities may be estimated by methods such as planar segmentation (Schenk *et al.*, 1999), but accurate positions are not available (Vosselman, 1999). The spatial distribution of the laser data will affect the level of inaccuracy that is introduced due to the lack of terrain information. A high spatial distribution of data may well provide enough information to define the surface to the required accuracy, however if the spatial resolution of the data is low, extra information will be required to accurately define the surface.

Digital photogrammetry also provides a method of automatic DSM generation, however this process has limitations in accuracy due to image matching problems, which are caused by factors such as lack of image texture and foreshortening. An advantage of photogrammetric methods is that accurate locations of surface discontinuities can be obtained from aerial imagery. It is proposed to merge the accurate terrain information from the imagery with the laser scanner data, providing a more accurate data set than either of the two separate data sources. There are two phases to the proposed approach, surface matching and data fusion.

In the first phase, surfaces are created from each data source and accurately registered to the same coordinate system. Theoretically, the two surfaces should be on the same coordinate system, however experience shows that systematic errors introduce a misalignment between these two surfaces. This misalignment must be eliminated before data fusion may be performed accurately (Kraus and Pfeifer, 1998).

Several factors were considered when designing the matching algorithm, including the fact that no conjugate points occur in the data sets, and that the data sets may have different spatial frequencies. The transformation parameters are used to transform the laser data to the photogrammetric coordinate system, as the horizontal accuracy of the photogrammetric data set is more easily verified using ground control and visually identifiable points.

The second phase of the proposed approach combines information from each data source to obtain the optimal topographic surface. The photogrammetric data is utilized by extracting edges from the stereo imagery, and processing the edges using feature-based matching techniques. These edges are used to obtain accurate locations of the surface discontinuities in the urban scene. The edges are defined in three dimensions and are used as breaklines when merged with the laser data. The laser data is filtered to eliminate points that are close to the newly imported breaklines. This reduces the probability of erroneous points being included in the surface, as random errors in the laser data such as corner reflections will occur close to these areas. A new surface is generated using the merged data. This surface is expected to have a higher accuracy than either surface derived from the separate data sets.

The approach presented in this paper utilizes the beneficial properties of both photogrammetric data and laser data to produce an accurate DSM. Testing of the research approach has been undertaken using an urban site covering Ocean City, Maryland, USA. Laser data and aerial images, acquired on the same day by NASA and NGS respectively, are used. Preliminary experiments have been performed to test and refine the algorithm. This paper presents the surface registration and the data fusion components, describes the data set and details the results from the initial experimentation.

2 BACKGROUND INFORMATION

Digital surface models of urban areas may be created using different methods, such as digital photogrammetric processing or by using airborne laser scanner data. Each of these methods has benefits and limitations.

Digital photogrammetric methods of automatic surface reconstruction have become widely used due to the efficiency and cost effectiveness of the production process, especially in open or flat areas, and when using small and medium scale imagery (Krzystek and Ackermann, 1995). However, most software packages perform poorly in areas with abrupt height differences, such as those occurring frequently in urban areas (Haala, 1999). The degradation in performance can be caused by failures of the image matching process (Axelsson, 1998). Such failures may be due to factors like lack of texture in the images (Haala, 1994), poor image quality, shadows in the images, occlusions, surface discontinuities (Haala *et al.*, 1997) and foreshortening. The problems occur when using digital photogrammetry in urban areas and result in inaccuracies in the DSM, which can be seen in the smoothing effect on surface discontinuities (Baltsavias, 1999; Haala, 1999; Toth and Grejner-Brzezinska, 1999).

One of the benefits of photogrammetry is that the imagery contains more information than just the position of pixels in the images. Gray-value changes in the images allow the identification and classification of objects, such as buildings or vegetation, and can be used to detect edges in the images, which often indicate the location of surface discontinuities (Baltsavias, 1999; Fradkin and Ethrog, 1997; Haala and Anders, 1997).

Laser scanning is recognized as an accurate data source for DSM generation in urban areas (Haala *et al.*, 1997). The spatial resolution of the data is dependent on several factors, such as flying height, flying speed and scanner frequency (Lemmens *et al.*, 1997). Characteristics and performance of laser data systems have been discussed by many researchers (Ackermann, 1999; Axelsson, 1998; Baltsavias, 1999; Fritsch, 1999; Hug and Wehr, 1997; Kilian *et al.*, 1996). Calibration methods and the errors that may occur in the data have also been investigated (Fritsch and Kilian, 1994; Huising and Gomes Pereira, 1998; Lemmens *et al.,* 1997). Data processing and filtering methods have been described by Axelsson (1999), Hug and Wehr (1997) and Kilian *et al.* (1996).

Laser data provides accurate points with high spatial frequency, however breaklines are not present in the data (Ackermann, 1999; Axelsson, 1999; Haala *et al.*, 1997; Kraus and Pfeifer, 1998), and therefore the position of surface discontinuities can only be estimated or calculated by methods such as segmentation of the range data (Haala *et al.*, 1997). To illustrate this point, Figure 1 presents an elevation image generated from laser data showing high-rise buildings. The edges of the buildings are not well defined, though a high spatial density of the laser data points is indicated by the 'ragged' nature of the edges, as also noted by Vosselman (1999).

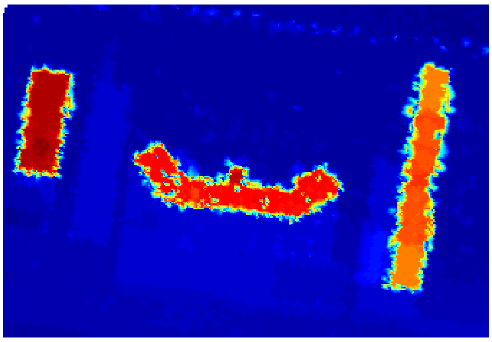

Figure 1. Plan view showing laser data.

Investigations and observations comparing DSMs produced from laser data and those derived from digital photogrammetric methods have been made in several research studies. In areas of the imagery lacking texture or contrast, the image matching might not provide accurate results whereas the accuracy of the laser is not affected (Baltsavias, 1999; Kraus and Pfeifer, 1998), however photogrammetric data have a higher planimetric accuracy than laser data (Baltsavias, 1999).

The complementary nature of the two data sources has been widely recognized and the approach of combining them has been suggested by researchers for several years (Fritsch and Kilian, 1994; Haala, 1994). This suggestion has been reiterated recently (Ackermann, 1999; Axelsson, 1999; Baltsavias, 1999; Csathó *et al.*, 1999; Fritsch, 1999; Haala, 1999; Haala and Anders, 1997; Toth and Grejner-Brzezinska, 1999; Vosselman 1999). The approach of using imagery to provide edge information has been highlighted by several researchers (Ackermann, 1999; Axelsson, 1998; Csathó *et al.*, 1999; Haala and Anders, 1997), and is the main concept of the approach undertaken in this research (McIntosh, *et al.*, 1999).

3 PROPOSED DATA INTEGRATION APPROACH

The research presented in this paper utilizes information from laser scanner data and photogrammetric data to produce an accurate model of the visible surface. By merging the edge information and the laser data for surface generation, a DSM is produced that more closely represents the actual scene.

3.1 Surface Registration

The surface registration is undertaken to determine the transformation parameters between the laser surface and the photogrammetrically derived surface. Theoretically, the two data sets should be on the same coordinate system, however the systematic errors inherent in the laser data may introduce a misalignment between the two surfaces, which must be eliminated before data fusion may be performed accurately (Kraus and Pfeifer, 1998).

The transformation parameters are used to convert the laser data to the coordinate system of the photogrammetric data. The determined transformation parameters must be as accurate as possible to ensure no unnecessary degradation occurs in the accuracy of the surface generated from merging the data sets.

The algorithm was developed specifically for matching visible surface models of urban areas produced using different acquisition methods, and in particular, surfaces from airborne laser scanner data and surfaces automatically generated using photogrammetric data. The registration algorithm solves for three translation parameters, three rotation parameters and one scale factor. The surface points are not interpolated to a regular grid and there are no identifiable conjugate points in the surfaces. For more detailed information on the algorithm and the results of testing, the reader is referred to Schenk *et al.* (2000). Another approach for matching such surfaces is given by Habib and Schenk (1999).

3.2 Data Fusion

The data fusion component utilizes edges extracted from stereo imagery to obtain accurate locations of surface discontinuities. The edges are defined in three dimensions and are used as breaklines when merged with the transformed laser data. A new surface is generated using the merged data, which is expected to have a higher accuracy than the surface derived from either of the separate data sets. The conceptual approach formulated in this research proposes that the edges representing surface discontinuities are automatically derived as 3D line segments from the stereo imagery using edge extraction and feature matching techniques. Research has been undertaken into the extraction and matching of line segments, reconstruction of the matched line segments to 3D, classification of the laser data, incorporation of breaklines, and the creation of a triangulated irregular network (TIN) using constrained triangulation.

3.2.1 Edge Extraction. The edge pixels are detected in each image of the stereo pair of digital images. At present, the optimal zero-crossing operator (Sarkar and Boyer, 1991) is used for the detection of the edge pixels. The edge pixels are analyzed to find connected edge chains, and using these chains, straight line-segments are determined. Line segments are utilized as they adequately describe man-made objects and can be more accurately located than point features when using feature matching techniques (Fradkin and Ethrog, 1997). Also, each line segment is easily described using the start and end points of the segment and the gradient of the line.

The automatic extraction of edges has certain limitations that must be addressed. Using automatic extraction methods, not all surface discontinuities are detected due to factors such as lack of contrast in the imagery. There will be a number of incomplete or incorrect breaklines, and other breaklines, that do not represent surface discontinuities, will be detected. These particular breaklines will refer to visual edges in the images that are purely changes in gray value, such as line markings on roads. The effect of including these breaklines in the data fusion process is to be investigated, however it is not expected to be detrimental to the process.

3.2.2 Line Segment Matching. The segment matching approach used for this research was based on that of Schmid and Zisserman (1997), which employs the fundamental matrix (F matrix) to guide the matching process. Line segments are compared using the correlation coefficient for corresponding points between line segments. The two segments for which the highest average correlation coefficient is determined are taken to be the correctly matched line segments.

The search space is constrained using epipolar geometry and by determining the maximum disparity between the stereo pair of images. Therefore a parallelogram is defined using epipolar lines through the start and end points of the line segment, and using the width determined by the maximum disparity (Medioni and Nevatia, 1985). The line segments that occur in this search space are used in the process of determining the average correlation coefficients. The correlation window size was set to 15 pixels square, as suggested by Schmid and Zisserman (1997). The segment with the highest correlation coefficient is taken to be the matching segment. The length of the segments being matched was kept to over ten pixels, as shorter lines have greater uncertainty. Other constraints are a slope constraint, which was used only lightly as it had to take into account changes in viewing angle of the edges, and a uniqueness constraint, such that a segment in the second image could only be matched to one segment in the first image.

3.2.3 Line Segment Reconstruction. The 3D coordinates of the line segments are calculated using the interior and exterior orientation parameters of the aerial imagery. The end points of the overlapping section of the line segment are required in image coordinates from each of the stereo pair. As the line segment information is in pixel coordinates, an affine transformation is required to convert the information appropriately. The interior orientation of the imagery defines this affine transformation, and the rotation matrix and camera position are defined in the exterior orientation. The 3D coordinates of each endpoint of the line segment are calculated using this information. (See Kraus (1993) for equations.) The 3D coordinates are checked for gross errors using the range of elevations of the laser data and comparing these with the elevations of the reconstructed points to see that they are within a suitable range of these bounds.

3.2.4 Filtering Laser Data. For an accurate description of the surface discontinuities in an urban area, it is important to detect the roofline of buildings and also the ground surface near that roofline. The laser data is used as an indication as to whether the automatically detected breaklines are rooflines or ground surface breaklines. The area surrounding each roofline is investigated to determine if there is a corresponding ground breakline. If only the roofline is detected, the surface discontinuity will not be accurately delineated. In this case, a breakline is added to define the ground surface.

The laser data is classified as either ground points, vegetation or building points. The laser points nearest the breakline are used as an indication as to whether it is associated with a building. As this research is for urban areas, certain assumptions are made which allow a simplified approach to the classification of the laser data. It is assumed that the terrain is generally flat and that the vegetation will cover smaller areas than the buildings. This approach is adequate for the present research, however a more sophisticated classification approach will be implemented in the future, such as those described by Axelsson (1999) and Schenk *et al.* (1999).

The initial filtering of the laser data determines the ground points from other higher points. In this research, the area being investigated will either be over flat terrain or the area will be small enough to be able to discount affects of a gradual slope, therefore the ground points are below a certain elevation. The higher points are either vegetation points or building points, or extraneous points such as those on power lines that are not of interest in this research.

The classification approach used to determine which points are vegetation and which are building points depends on the spatial frequency of the data. In high frequency data, the spatial distribution of the data may be used in the classification process, however with lower resolution data it is more difficult to incorporate this information. Vegetation has a random spatial distribution, whereas building points have a planar distribution, as shown in Figure 2. As the information being used in this research has a low spatial resolution, an assumption is made that vegetation will be isolated points or groups of isolated points, whereas buildings cover a larger area.

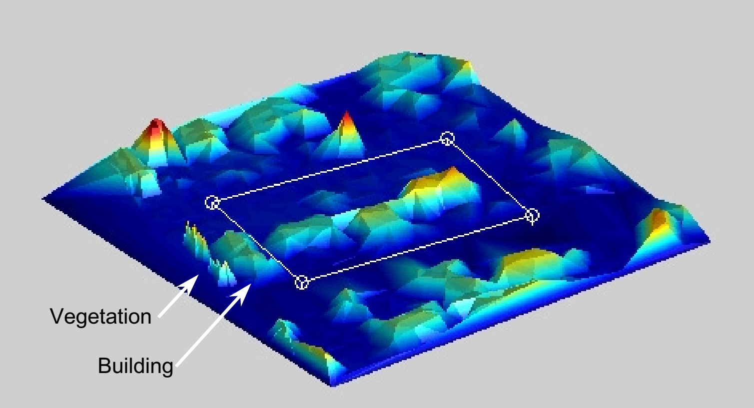

Figure 2. Laser data showing vegetation, buildings and the area used for experimentation.

3.2.5 Surface Discontinuities. The most important edges to be detected are the discontinuities between the roof and the ground. These areas are important to the accurate representation of the visible surface, as they contain dramatic changes in elevation. Where a roofline has been detected which has no corresponding ground surface breakline, a new breakline is added to accurately describe the visible surface.

The breakline representing the roof will be projected vertically onto the ground surface to produce a new breakline, thus describing the surface at ground level as well as roof height. The location of the new breakline must be slightly offset outward from the roofline, as the triangulation process being used does not allow points to exist with the same horizontal location, as would be the case for a vertical plane. The elevation of the ground surface at the location of the added breakline must be determined. It is proposed that the laser data in the areas surrounding the breakline be searched. The new breakline will be generated and assigned the elevation of the ground points in that area.

3.2.6 TIN Generation. The laser points that occur on the breaklines are eliminated, again due to the triangulation process not accepting points with identical horizontal locations. The triangulation process is used to generate a TIN that utilizes the laser data points and constrains the triangles to follow the breaklines. The inclusion of the elevation information to the triangulation provides the digital surface model produced by combining the laser data and the photogrammetric data.

4 EXPERIMENTATION AND RESULTS

The initial testing was carried out using a data set over Ocean City, Maryland, USA, which includes digital stereo imagery and laser data. The data set covers different types of areas, including residential areas, flat terrain, beach front, dunes, canals and high-rise buildings. Only a small portion of a residential area has been used for the initial testing of the algorithm. For detailed information regarding the test site, see Csathó *et al.* (1998).

The laser data have been transformed to the coordinate system of the photogrammetric data using the parameters determined by the process of surface registration. The two data sets are therefore on the same coordinate system and represent the same surface. Laser points in the new data set are eliminated if they occur within close proximity to the breaklines. The breaklines and the laser data are then merged to create a new data set.

4.1 Surface Generation and Registration

The transformation parameters were determined using the developed registration algorithm. Rooflines were measured analytically to produce planes, and these planes were used with the laser points in the registration process, thus providing a result that was not dependent on automatic DEM generation techniques. The transformation parameters between the surfaces were in the order of one to two decimeters. Further details are provided in Schenk *et al.* (2000).

4.2 Data Fusion

Edge pixels were extracted from a stereopair of aerial images using the optimal zero-crossing operator (Sarkar and Boyer, 1991). Figure 3 shows the edge pixels as an overlay on the aerial image. The area depicted is the region used for the experimentation discussed in this paper.

The segmentation of the edge pixels creates straight line segments. Only segments longer than ten pixels were used in the segment matching process. The segments in the left and right images were searched to find corresponding segments. The segments shown in Figure 4 are those that were found to have a matching segment in the second image.

The line segments were reconstructed to three dimensions using the information available from the interior and exterior orientations of the aerial imagery. A plan view of the reconstructed line segments is shown in Figure 5. As a comparison, breaklines associated with the buildings were measured manually and are shown in Figure 6. Future research will investigate using multiple images to provide higher accuracy line matching, as presented by Schmid and Zisserman (1997) and Baillard *et al.*, (1999). The inclusion of this approach will depend on the availability of multiple images over the area of interest.

The laser data have been classified according to elevation, and are shown in Figure 7. The manually measured breaklines were included in this figure to illustrate the effectiveness of the classification procedure for this data set. The surface created using only the laser points is shown in Figure 8. This serves as a comparison for the surfaces created using the combined data sources.

The surface generated using the laser data and the manually measured breaklines is shown in Figure 9. This is the representation of the visible surface that the research attempts to achieve automatically. Figure 10 shows the surface generated using the laser data and the automatically extracted breaklines, with breaklines added at ground height. A visual comparison of Figures 8 and 10 shows the improvement achieved by including the automatically derived breaklines with the laser data when determining the visible surface model over the urban area.

Figure 3. Aerial image and detected edge pixels.

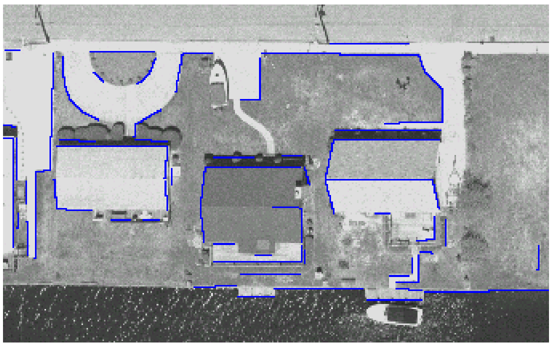

Figure 4. Matched line segments.

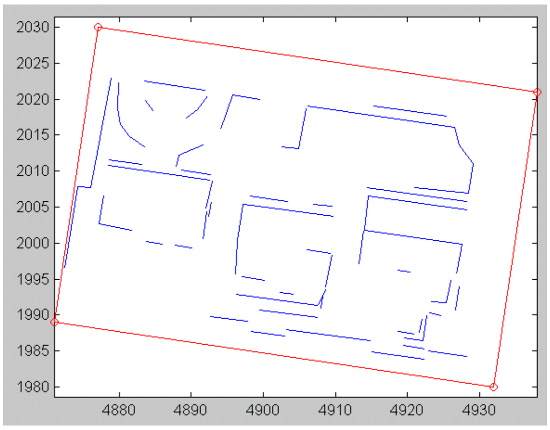

Figure 5. Reconstructed line segments.

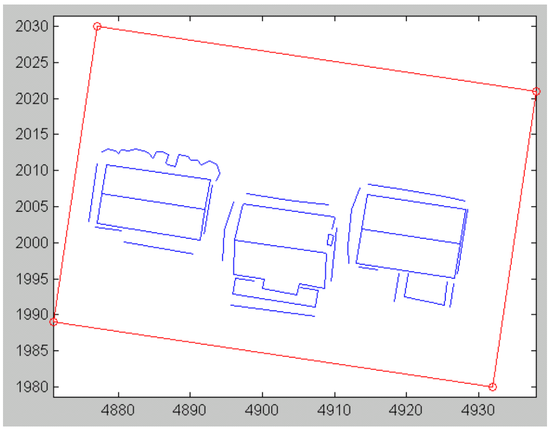

Figure 6. Manually measured breaklines.

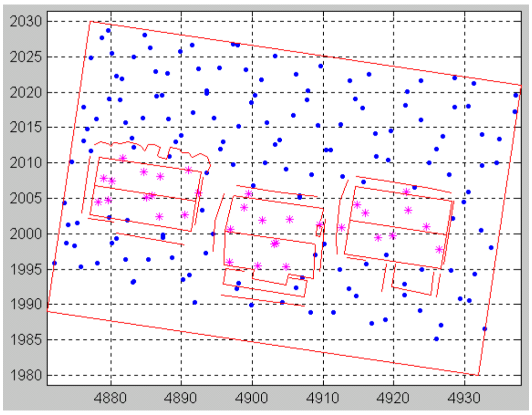

Figure 7. Classified laser points.

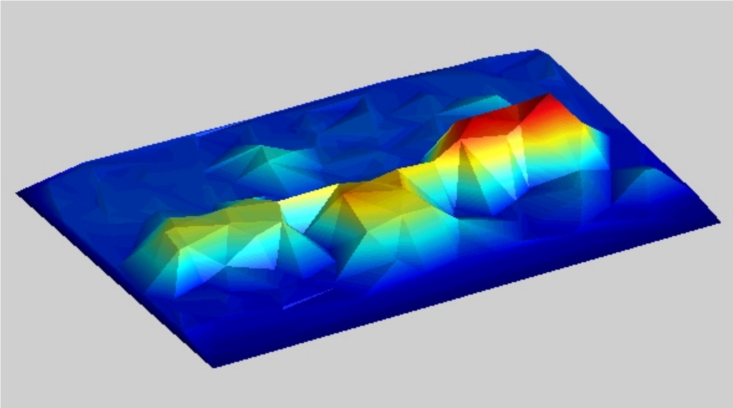

Figure 8. Surface derived from laser points.

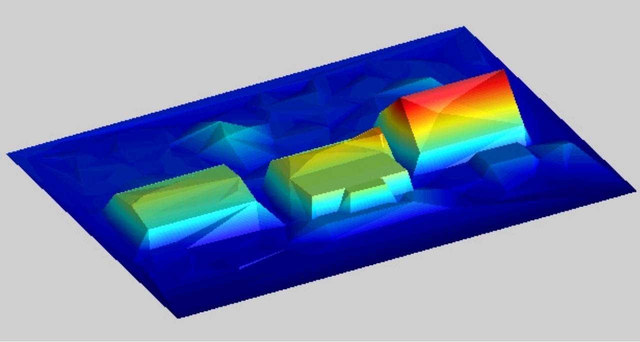

Figure 9. Surface from laser and manually measured breaklines.

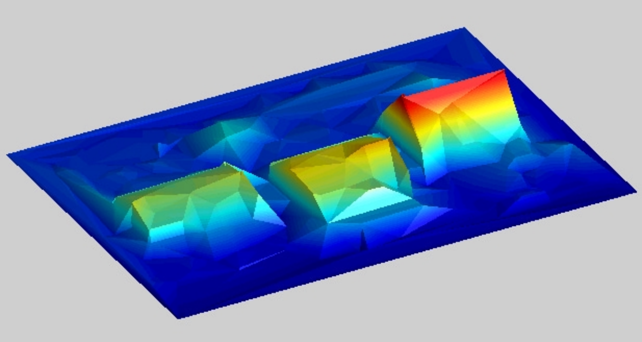

Figure 10. Surface from laser and automatically generated breaklines with added ground breaklines.

5 SUMMARY

This paper describes the development of a general scheme for the integration of laser and photogrammetric data. This scheme includes the development of a surface registration algorithm and a data fusion algorithm. Initial testing of the integration algorithm has been carried out using data over Ocean City, Maryland, USA. The testing has shown that the visible surface is more accurately represented using the combined data than when using either data set separately. Further research is required into the optimization of the 3D reconstruction of the surface discontinuities. The information obtained from this process determines the improvement that will be gained from the merging of the laser data and the photogrammetric data.

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