URBAN 3D GIS FROM LIDAR AND DIGITAL ORTHOIMAGES

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ABSTRACT:

This paper presents a method, which integrates image knowledge and LiDAR point cloud data for urban DEM and DBM (digital building model) generation. The DBM is an Object-Oriented data structure, in which the building is considered as an building class, i.e. an entity of the class, in which the attributes of each building include roof types, coordinates of polygon of the roof, height, surfaces, parameters describing surface, and the LiDAR point array. Each polygon represents a roof of building. This data structure is flexible for adding other building attributes in future, such as texture information. Using image knowledge, we developed a new method of interpolating LiDAR raw data into grid DSM with considering the steep discontinuities of buildings. In this interpolation method, the LiDAR data points, which are located in polygon, first have to be determined, and then interpolation via planar equation is employed for grid DSM generation. The basic steps of our research are (1) Edge detection by digital image processing algorithms; (2) Completely extraction of the building roof edges by digital image processing and computer-human interactive operation; (3) Establishment of DBM; (4) generation of DEM by removing surface objects. Finally, we implement the above functions by MS VC++ programming. The outcome of urban 3D DSM, DEM and DBM is exported into urban database for future urban 3D GIS.

1. INTRODUCTION

There is an increasing need for urban three-dimensional (3D) model for various applications such as town planning, microclimate investigation, transmitter placement in telecommunication, noise simulation, heat and exhaust spreading in big cities, virtual city reality, etc. Traditionally, photogrammetry is an important tool to acquire the 3D data. During the past decade, digital photogrammetric methods for providing automatic digital surface model (DSM), or digital terrain model (DTM) generation have become widely used due to the efficiency and cost effectiveness of the production process. The performance of these systems is very good for smooth terrain at small to medium scale when using small and medium scale imagery. However, it decreases rapidly for complex scenes in dense urban areas using large-scale imagery. The degradation in the performance of photogrammetric processes is mainly due to the failures of image matching, which are primarily caused by, for example, occlusions, depth discontinuities, shadows, poor or repeated textures, poor image quality, foreshortening and motion artifacts, and the lack of model of man-made objects. To offset the effect of these problems, the extraction of buildings and DEM generation in urban areas is currently still done by human-guided interactive operations, such as stereo compilation from a screen. The whole process is both costly and time-consuming. Over the past years, a lot of researchers in the fields of photogrammetry and computer vision have been striving to develop a comprehensive, high success rate and reliable systems with either full automation or semi-automation to ease human-computer interactive operations. However, automatically extracting building information is still an essentially unsolved problem. A lot of efforts for overcoming the problems mentioned above still are needed.

In the current years, LiDAR (**Li**ght **D**etection **A**nd **R**anging) is widely applied in urban 3D data analysis. A variety of different methods have been proposed for this purpose, some of which can be found from Tao and Hu (2001). Baltsavias et al. (1995) discuss three different approaches for this purpose, namely using an edge operator, mathematical morphology, and height bins for detection of objects higher than the surrounding topographic surface. These main approaches are also used by other authors like Haala (1995), and Eckstein and Munkelt (1995). They analyzed the compactness of height bins, or used mathematical morphology (Eckstein et al., 1995; Hug, 1997). Hug (1997) applies mathematical morphology in order to obtain an initial segmentation, and the reflectance data are used to discern man-made objects from natural ones via a binary classification. Other building extraction methods include extraction of plannar patches, Some of which use height, slope and/or aspect images for segmentation (e.g., Morgan and Tempfli 2000; Haala et al., 1998; Morgan and Habib, 2001). In general, these methods can be grouped into two categories (Yoon, et al., 2002), classification approach and adjustment approach. The classification approach detects the ground points using certain operators designed based on mathematical morphology (Lindenberger, 1993; Vosselman, 2000) or terrain slope (Axelsson, 1999) or local elevation difference (Wang et al, 2001). Refined classification approach uses TIN (Triangulated Irregular Network) data structure (Axelsson, 2000; Vosselman and Mass, 2001) and iterative calculation (Axelsson, 2000; Sithole, 2001) to consider the discontinuity in the LiDAR data or terrain surface. The adjustment approach essentially uses a mathematical function to approximate the ground surface, which is determined in an iterative least adjustment process while outliers of non-ground points are detected and eliminated (Kraus and Pfeifer, 2001; 1998; Schickler and Thorpe, 2001). Despite a plenty of efforts have been made in urban 3D data analysis, difficulties still remain. The DEM generation from LiDAR data is not yet mature (Vosselman and Maas, 2001; Yoon et al., 2002). It has been realized, also by many other photogrammetrists, that methods based on single terrain characteristic or criterion can hardly obtain satisfactory results in all terrain types.

In this study, we propose to combine LiDAR data and orthoimage data for urban 3D DBM, DSM and DTM generation. First, the image processing for edge detection is conducted from orthoimages; image interpretation is performed to recognize the building, tree, road, etc.; and then integrating the image knowledge into LiDAR point cloud for the 3D models of DSM, DBM and DTM. Finally, we realize these functions with Microsoft Visual C++. An urban 3D DEM, DBM and DSM are exported to urban database for future urban 3D GIS.

2. BUILDING DETECTION AND EXTRACTION

2.1 Edge Detection from Orthoimage

As described above, the building extraction based either images and LiDAR data cannot reach a satisfactory result. One of main causes is because of breaklines for urban building. It is thus very important to extract the breaklines of building before applying any interpolation technique because breaklines can be used to identify the sudden change in slope or elevation. Therefore, detecting breaklines will serve both interpolation and building extraction. In urban areas most of the breaklines represent parts of artificial objects such as building. In digital image, an breakline (edge) is a sharp discontinuity in grey-level profile. Thus, simplest edge detection method is to inspect the change of the digital number of each pixel in a neighboring region with the first derivative or the second derivative of the brightness. A lot of edge detection methods have been developed in the past decades in image processing community. However, the situation is complicated by the presence of noise, image resolution, object complexity, occlusion, shadow, etc. Our implementation of building edge detection is that the zero-cross edge detection operator is first employed, and then some post-processing, such as merging line segment into line, deleting isolated point and line segment are carried out. Finally, we developed an interface for extraction of complete edges of an object by human-computer interactive operation. These extracted edges of objects, associated with the horizontal coordinates are coded and saved in files in vector format for the future interpretation of objects (see Section 2.2).

2.2 Image Interpretation and Building Extraction

After the complete edges of buildings have been detected, the algorithms for extraction of the building geometrical parameters for interpretation of objects will be performed. The LiDAR data interpretation is based on the two facts: (1) The buildings are higher than the surrounding topographic surface; (2) The ability of the laser to penetrate vegetation, thus giving echo from several heights, makes it possible to distinguish between the two classes: man-made objects and vegetation. The extraction procedures are based on an implementation of the MDL (minimum description length) criterion for robust estimation (Rissanen, 1983; Axelsson, 1992). Thus, main steps are (1) linking the 2D complete image edges of building with 3D LiDAR data using horizontal coordinates; (2) determining the three dimensional building breaklines from image edges and exactly estimating the building boundary via integrating image edges and LiDAR; (3) interpreting the LiDAR data for buildings or vegetation using two facts and MDL. Internal breaklines can be determined by intersecting the adjacent planar facades within the building. It is known that the laser points are not selective, and they do not match building boundary. Therefore, one cannot determine the building boundary with only height data unless the density of LiDAR point cloud is like image grey representation. Figure 1 shows a portion of a building near its boundary. Some laser data points are located on the building while others are located on the terrain. The segments of LiDAR data therefore is from the image segments, which describe various building. Therefore, we have selected the geo-referenced images whose 2D geodetic coordinates are known. We can directly use the horizontal coordinates of the boundary edges to obtain each 3D building model. The building boundary in addition to the internal façade parameters and the internal 3D breaklines will be the results of the building extraction process. The topological relationships of building facades is described in the following section.

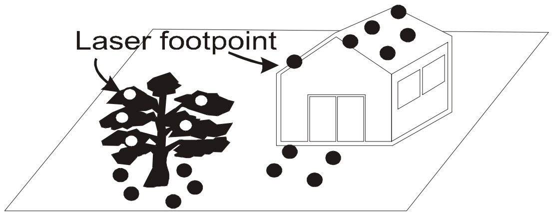

Figure 1. LiDAR footpoints on building and vegetation

3. DIGITAL BUILDING MODEL (DBM)

In our research, an object-oriented data structure has been developed for description of digital building model (DBM). During the development of this model, we mainly think of making best use of the data sets for better creating DBM for buildings, for instance the roof, which we have obtained from the geo-referenced image, which provides the information of roof, and the LiDAR data, which provide information of the height of building. In this model, each building is an object of the building class, i.e. an entity of the class. One building object consists of the attributes of the Building ID, roof type ID, and the series of the roof surfaces. Each surface in the surfaces series of a building object is also considered an object. The surface's class is comprised of the surface boundary, the LiDAR footpoints within the surface and planar equation parameters describing the surface by fitting LiDAR footpoints. The boundary is composed of a set of points. The advantages of this model is its flexibility for expanding for future use, e.g. to add other building attributes such as, wall surfaces, texture etc (see Figure 2). We implement this data structure with Microsoft Visual C++ 6.0 as follows:

```
typedef struct{
        double dx;
        double dy;
        double dElevation;
} LiDARPoint;

class CBuilding : public CObject
{
protected:
        unsigned m_nBID;    // Building ID
```

```
        unsigned m_nRoofType; //Roof Type ID
public:
        CTypedPtrList<CObList, CSurface*> m_surfaceList; //Surfaces series in one building
…….
…….
…….
};

class CSurface : public Cobject
{
public:
        //Planar equation parameters
        double m_dP1;
        double m_dP2;
        double m_dP3;

public:
        CArray<CPoint, CPoint>  m_ptEdgeArray;
        // Point array on behalf of the surface boundary
                CArray<LiDARPoint, LiDARPoint> m_ptLiDARArrayIn;   // Series of LiDAR points within the footprint of the surface
        ………….
        …………
        ………….
        };
```

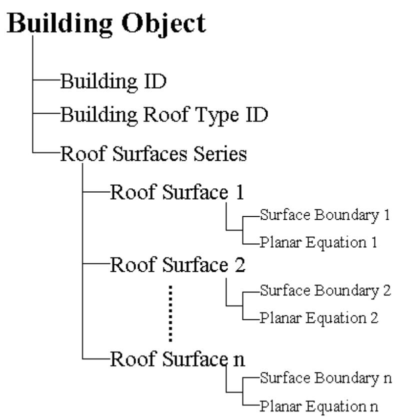

Figure 2. Object-oriented digital building model

4. CREATION OF DIGITAL SURFACE MODEL (DSM)

4.1 Establish the Relationship between Images and Lidar Point Cloud Data

The orthoimages are stored as raster data, while the LiDAR point cloud is scanned along track. The linkage of the two data sets is implemented by the horizontal coordinates. Thus, we have to determine which LiDAR footpoints are inside of boundary of building. We use filling algorithm, whose steps are (a rectangle is taken a sample):

- The determination of 4 corner coordinates:

For a given building, the coordinates of 4 corner points can be obtained from image edges: (see Figure 3)

Corner 1: (X_1, Y_1)

Corner 2: (X_2, Y_2)

Corner 3: (X_3, Y_3)

Corner 4: (X_4, Y_4)

- The determination of straight line equation for each side of rectangle by 4 corner coordinates. The equation is expressed by:

$$AX + BY + C = 0$$

- The determination of the LiDAR footpoints are inside or outside by filling algorithm. This algorithm is illustrated in Figure 3.

The above procedure is then repeated for each building.

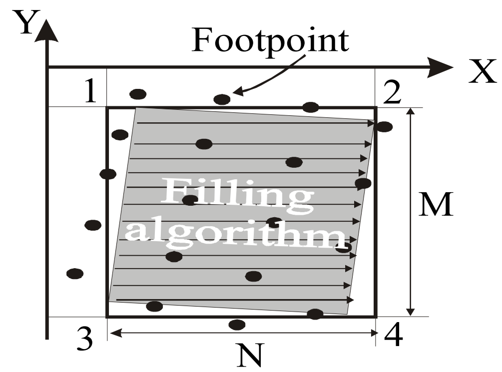

Figure 3. The determination of inside footpoints in a building using filling algorithm

4.2 Interpolation algorithm via Planar Equation

After we obtained a complete extraction of roofs' surfaces, we have obtained the LiDAR point within the footprint of the surfaces and store them into an array in a surface object of a building, whose procedure was described in Section 4.1. Now, each building object has its LiDAR point data, associated with boundary information. There are many interpolation methods. However, these methods calculate the unknown elevation by using the close known neighbors, like IDW (Inverse Distance Weight) and give them different weight on the basis of the distance between them and the unknown points. We here suggest a innovate method for LiDAR data interpolation. The basic principle is to fit the surface of building using planar equation from the surface boundary, and LiDAR footpoints within boundary we already obtained. The planar equation and the surface boundary can be more accurate and efficient as the model of the roofs' surfaces than LiDAR data array within the boundary. The planar equation is like the following:

$$AX+BY+CZ=1 \qquad (1)$$

Where A, B, and C are unknown parameters, X, Y and Z are coordinates of LiDAR data. Actually, only three LiDAR points can determine the planar equation (surface of building). However, usually, at least three laser footpoints are measured in each surface. Least square method is thus employed to calculate the parameters of the planar equation as follow.

$$\begin{bmatrix} X_1, Y_1, Z_1 \\ X_2, Y_2, Z_2 \\ \cdots\cdots\cdots \\ X_m, Y_m, Z_m \end{bmatrix} \times \begin{Bmatrix} A \\ B \\ C \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ \cdots \\ 1 \end{Bmatrix} \quad (2)$$

where *m* is the number of LiDAR point in a surface.

5. CREATION OF DIGITAL TERRAIN MODEL (DTM)

LiDAR data presents two aspects: ground and buildings. Thus, the data could be segmented into two types of regions corresponding, on one hand, to a surface linked to the ground, and, on the other hand, to a surface linked to surface objects. Therefore, we have to separate the surface objects from the ground surface data processing above, which leads to the generation of both the digital terrain model (DTM) and the digital surface objects. Digital building model has been generated above, and the DTM can be generated by removing the surface objects such as building. The steps are

(1) based on the extracted boundary of building in image processing, we can get the horizontal coordinates of these boundary point.
(2) seeking for corresponding LiDAR footpoints according to horizontal coordinates.
(3) removing those LiDAR footpoints whose horizontal coordinates are same the one of building boundary.
(4) Interpolating DTM via Inverse Distance Weight (IDW) method.

6. EXPERIMENTS

6.1 Data Sets

Virginia Department of Transportation, contracting to Woolpert LLC at Richmond, Virginia, provided us a 5 strip raw LiDAR data and original images, as well as orthophoto. The project area extended from the west side of Wytheville east approximately 14 miles with a north-south extent of approximately 4.5 miles centered on Wytheville.

LiDAR Data

The LiDAR data were obtained by using an Optech 1210 LiDAR system in September 2000. The LiDAR data have accuracy (on hard surfaces) of 2.0-feet at least and point sampling density is sufficient to provide an average post spacing of 7.3-feet in the raw DSM. It was provided in raw text format. The LiDAR parameters used for this project are as follows:

- Aircraft Speed: 202 ft/s
- Flying Height: 4500ft above ground level
- Scanner Field of View (half angle): ±16 degrees
- Scan Frequency: 14Hz
- Swath Width: 2581ft (1806 ft with a 30% sidelap)
- Pulse Repetition Rate: 10KHz
- Sampling density: average 7.3ft

Aerial Image Data

To aid planimetric compilation, quality control of the LiDAR data, the analog black-and-white aerial photography was acquired along east-west flight lines over the project area on September 19, 2000 at a scale of 1:1000. Woolpert camera number 5099 was used. Kodak 2405 file was used with a 525-nm filter and 153.087 focal length. A total of 96 exposures were acquired over 4 equal length flight lines. Aerial photo has a pixel resolution of 2.0-feet, and the orthophoto was produced using fully differential rectification techniques and the LiDAR DTM. All the elevation data were referenced to NAVD88 datum; and horizontal data were referenced to NAD83/93 Virginia State Plane Coordinate system. The city of Wytheville, Virginia, lies in the west part of the data coverage. As the availability of data and its precision, we selected the data of southern part of the city for our study.

6.2 System Development

We developed a system of semi-automation urban 3D model generation from LADAR data and image data under Microsoft Visual C++ platform. The system consists of

(1) New/open a project: This module opens an existing or new project.
(2) LiDAR data check: This module is to check the systematic error of LiDAR via various methods, such as overlay LiDAR data onto georeferenced image, ground control points checks, etc.
(3) Data input (image and LiDAR): this module contain data input, data format conversion (e.g, for raw image to bmp image, tiff image format, etc)
(4) Image processing and interactive edit: This module contains image filtering, enhancement, edge detection, line feature and area detection and description, image interpretation, interactive operation, etc.
(5) Topology generation of building and DBM generation: This module is to implement the functions of topologic description of building and of digital building model generation using object-oriented data structure.
(6) Urban DSM and DTM generation: Generating high-accuracy DSM by applying the surface equation; some conventional interpolation method, such as IDW are available. The DTM is generated by removing surface objects.

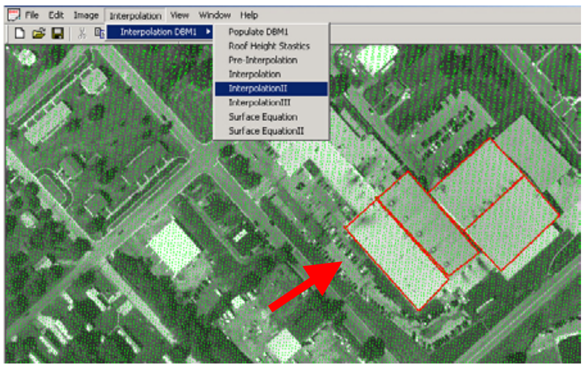

Figure 4. The semi-automatic urban 3D model generation (the green points are LiDAR point cloud; the grey image is aerial images; and the red lines are the detected edges of building.)

By this software, a group of experimental results are list in Figure 6 through Figure 11. Figure 6 is the result of automatic detection of building edge, and Figure 7 is detected buildings after human-computer interactive operation. Figure 9 is the digital surface model from our algorithm. In order to compare the interpolation accuracy of our method with other interpolation methods, we selected the Inverse Distance Weight (IDW) method and Spline, whose results are shown in Figure 8 and Figure 9. As we can see, the two interpretation methods can not reach high accuracy. The building edges are not very clear. It appears that there are dim slopes to the ground. Also, the roofs' surfaces are rough, but the most of real roofs' surfaces are planar. Obviously, our interpolation result is much better than IDW and Spline. The edges and the roof surfaces are clearer. Figure 11 is digital building model. The most important is that each building is an object in our program, it is better for future analysis.

Figure 5. Original image

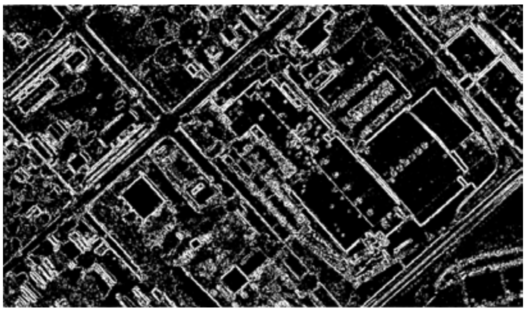

Figure 6. Automatic edge detection of building

Figure 7. Edge detection by human-computer interaction operation (Red line in color image)

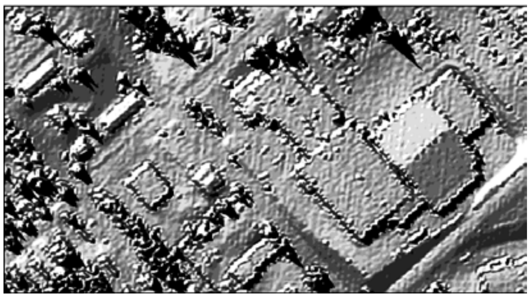

Figure 8. The result of raw LiDAR data interpolation by IDW.

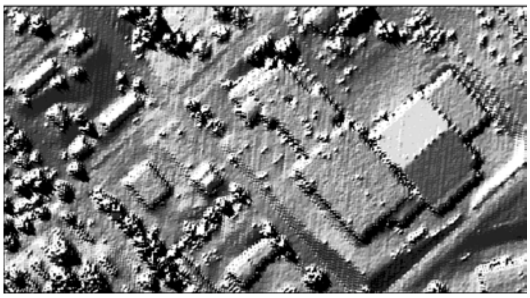

Figure 9. The result of original LiDAR data interpolation by spline

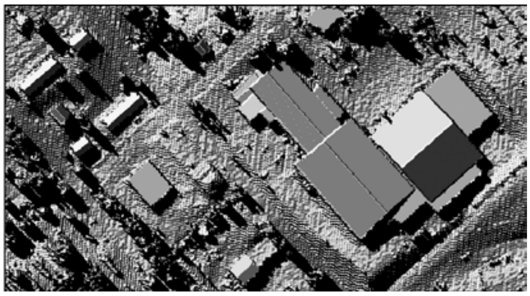

Figure 10. The result of raw LiDAR data interpolation by our software.

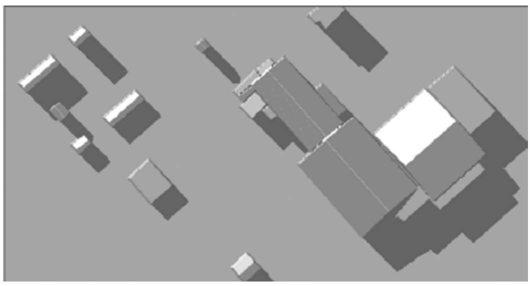

Figure 11. The urban digital building model.

7. CONCLUSION

In this paper, we presented the generation of urban 3D model, including 3D DSM, DBM and DTM via integrating image knowledge and LiDAR. A human-computer interactive operation is developed for image knowledge acquisition. The main contributions of this paper are to develop a high-accuracy interpolation method for DBM/DTM/DSM generation and to develop an object-oriented building model. In this model, we defined the roof types and surface LiDAR footpoints, etc. as objects. To the roof surfaces, the model consisted of roof surface's boundary and their planar equations, which is from the combined processing of the LiDAR and orthoimage data. For planar equation for each roof surface, we firstly extract the LiDAR point data lying within it by their spatial relationship, and calculate the planar equations' parameters with these LiDAR points by least square method. We use the planar equation to calculate the girds' value within the roofs. The experiment shows the better results of DSM, DBM and DTM with our method has been reached.

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