URBAN MODELING FROM LIDAR DATA IN AN INTEGRATED GIS ENVIRONMENT

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ABSTRACT

Lidar (Light Detection and Ranging) is a remote sensing technique utilizing laser technology. It has found applications in a wide variety of fields of study, including atmospheric science, bathymetric data collection, law enforcement and tele-communication. This article focuses on the application of Lidar data to feature extraction and 3D urban modeling. ArcView GIS package along other powerful image processing and 3D modeling extension modules is used for the study. Both interactive and automatic alternative methods are investigated and compared. Problems encountered are analyzed and possible solutions are proposed by fusing lidar data with other image data. Study shows that existing tools can be used to classify the lidar data, convert the results to 3D structured data. After an effective cleaning-up operation, a satisfactory 3-D modeling can be generated. The combination of interactive and automatic extractions demonstrates the most comprehensive and appealing results. Tests of built-up urban area at downtown Baltimore, MD are presented to support the analyses.

INTRODUCTION

Light Detection and Ranging (lidar) is a remote sensing technique utilizing laser technology. Rees (1999) defines the operation of lidar as "using a downward-pointing laser, transmitting very short pulses or a modulated signal in the optical or near infrared part of the electromagnetic spectrum. The backscattered radiation is detected and analyzed for time delay, amplitude or frequency, depending on the application." Lidar is therefore quite similar to radar, but utilizing shorter wavelengths. Other terms such as ladar, laser radar, laser fluoro-sensor and laser bathymeter are also used for various applications of this technology. Lidar techniques have been researched and utilized since the early 1960s, but seem to have become more prominent in the past few years. In fact, the first satellites carrying lidar sensors, Alissa, Balkan-1, and Balkan-2 are scheduled for launch beginning in 2002 (Rees, 1999). Lidar has found application in a wide variety of fields of study, including atmospheric science, bathymetric data collection, law enforcement, telecommunications and even steel production. This paper reports on using lidar data for feature extraction and 3D modeling in urban areas.

One of the earliest lidar applications was to study the atmosphere in 1963 by Fiocco and Smullin (Measures, 1984). One may encounter more references to atmospheric applications of lidar technology than other areas of study. Nevertheless, the use of lidar data for feature extraction and 3D modeling of urban areas has gained more attention in recent years. One key reason that the applications of lidar technology to terrain models and topographic mapping are increasing is its integration with Global Positioning System (GPS). A lidar system is often comprised of a laser scanner, a cooling system, a GPS receiver and an Inertial Navigation System (INS) (Airborne 1 Corporation 1999). The position and orientation of the aircraft or spacecraft are recorded at each transmission of the laser pulse. These measurements combined with the round-trip travel times of the laser pulses make it possible to obtain three-dimensional coordinates of each ground point that has reflected the lidar pulse. Another factor that booms the lidar applications in terrain science is its potential integration with rapidly improving and affordable Geographic Information System (GIS). Advantages of using lidar for topographic applications include the following: it allows rapid generation large-scale DTM (digital terrain model); is daylight independent; is relatively weather independent; and is extremely precise (3Di, LLC, 2000). Jelalian (1992) states that because lidar operates at much shorter wavelengths they are capable of higher accuracy and more precise resolution than microwave radar.

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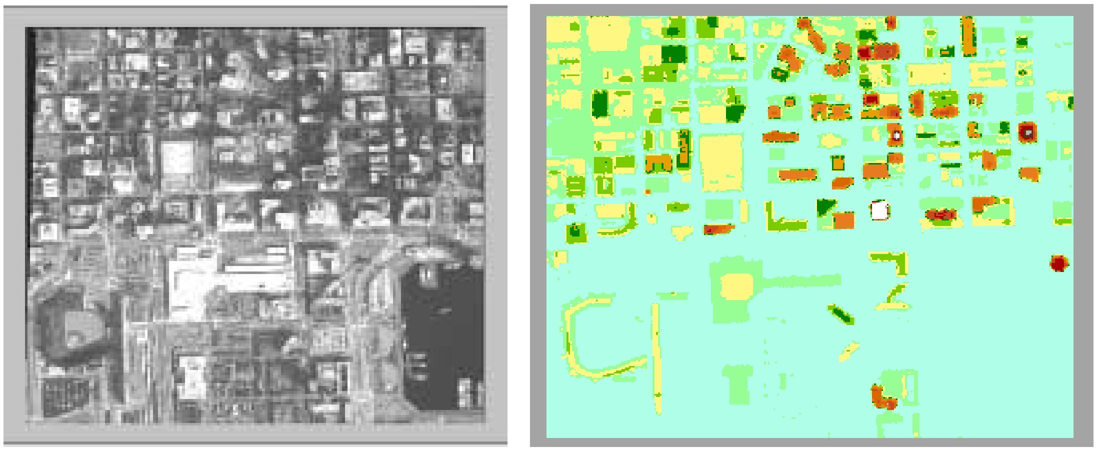
A number of articles have been published concerning research into the use of lidar data in terrain modeling from different perspectives. Taking the topic further are those that deal with visualization (Danahy, 1999) and virtual city models (Fritsch, 1999; Bhagawati, 2000). The field of planning has been identified as a major benefactor of the possibilities that arise from digital 3D building reconstruction. Danahy believes that for the planning field "digital visualization media provides the opportunity to overcome basic visual and spatial literacy differences between experts and clients." Among other interested parties is the telecommunication industry that uses information in 3D city models for the planning of locations of antennas (Brenner, 1999; Kirtner, 2000). The extraction of topographic features in the urban areas using lidar is obviously of great interest to mapping applications. The primary aim in the development of laser scanning was topographic mapping of forested terrain and other areas not suitable for aerial photography (Wever and Lindenberger, 1999). According to Kletzli and Peterson (1998), lidar data is "easily contoured for topographic applications and because each data point is geo-referenced the data is also easily merged with other feature or imagery sources." Hug (1997) states that laser scanners are especially in dense urban areas the best choice to obtain digital surface models. Haala and Brenner (1997) report on similar work that uses airborne lidar data for the generation of 3D city models. Kim et al (2000) provide a concise examination of using photogrammetric imagery and lidar data for obtaining DTM in urban areas. Förstner (1999) presents a thorough and informative discussion of the problems encountered in establishing the building models and their acquisition (feature extraction). He also discusses several extant acquisition systems and concludes that although fully automatic techniques are improving, up to the date of writing, they have not proven to be reliable enough to be used alone. A natural by-product or one step beyond of urban modeling is its photo-realistic visualization. Fritsch claims that the "overlay of laser scan data with digital aerial imagery delivers a first virtual 3D model." Förstner (1999) states that photogrammetry seems to be the only economic way to acquire truly 3D city data. This holds for the techniques of stereo compilation of imagery and the use of lidar data. Fritsch (1999) concludes his paper discussing the use of as many available data sources as possible to acquire a truly virtual city model through the data fusion process of ground plans, aerial photographs and laser scanning.

The objective of this research is to study the methodology and efficiency of urban modeling using lidar data within an integrated GIS environment. Lidar data, orthoimage and maps for Baltimore, MD downtown area are used for this study. In particular, the effort investigates both interactive and automated approaches for modeling buildings by using ArcView GIS and its extension modules. The difference and properties of those two approaches are studied. In addition, a database associated with the extracted buildings is created which contains the thematic information about building name and height. The created urban model and database can be viewed and queried within the GIS. The remaining of this article is organized as follows. Next section presents a brief overview on the data used for this study. After that, both interactive and automated approaches for extracting buildings from the lidar data are investigated and detail technique procedures are presented. Both building polygons and their three-dimensional views are demonstrated. Discussions are made on reducing the amount of interaction, classifying the lidar data, cleaning up automatically generated polygons, handling ambiguity due to the true 3D effect, and thematic information integration and its query are discussed. Addresses are also made on the differences and properties of those two approaches. The article concludes with future problems facing the automatic urban modeling and 3-D database creation from the lidar data and suggestions on potential solutions.

DATA DESCRIPTION

The data used in this study is graciously prepared and provided by EarthData at Maryland. It includes lidar height data and an orthoimage both covering the downtown area of Baltimore, Maryland. The lidar data and the orthoimage are preprocessed to UTM Zone 12 and NAVD88 orthometric height. Its post spacing is three (3) meters. The reported accuracy is 15 cm (vertical) and 25 cm (horizontal). As described above that data acquisition through multiple sensors is required for the creation of virtual worlds with real world contents, an orthophoto that is produced with this lidar data set is also provided for the study. Maps of the downtown areas from Internet are used to assist the acquisition of the thematic information for the database creation. Figure 1 below shows a reduced view of the orthoimage and the classified lidar data.

This project mainly uses ESRI's (Environmental Systems Research Institute) ArcView GIS 3.2 package and its extension modules, which seem to be the most suited for the research objective. All processes are completed in this single GIS package and its extension modules. Both interactive and automatic building extraction procedures are tried. The strength of ArcView GIS proves to be in the allowance for this integrated approach for urban modeling, when all its relevant functions are combined and used properly.



a. Orthoimage b. Classified lidar grid file

Figure 1. Test data for Baltimore downtow area

INTERACTIVE MODELING

Interactive feature extraction is performed in ArcView GIS by creating a new 3-D theme and populating it with "digitized" polygons. To digitize the shape of the buildings in the downtown area the following steps are followed. In ArcView GIS this procedure is more accurately called polygon interpolation and involves defining features with the cursor and a derivation of heights from the active grid theme. Both orthoimage and lidar data are used for the interactive extraction process. The orthophoto is used to trace the buildings while the height in the lidar data is assigned to the created polygons as the surface value. Buildings are far from uniform and therefore often need to be represented by a number of polygons. Higher precision may be achieved by creating many polygons per building to account for each portion of the building that may have a distinct height. As discussed by Ameri and Fritsch (2000), manual and interactive digitizing are laborious and one should seek for fully machine-based image interpretation systems. Yet it is recognized that this is a difficult task due to many factors including the enormous variation in the structure and shape of buildings, occlusion of building parts, the effect of shadows and small structures on the building roof. Besides, our experience shows that it is hard to be exact in the delineation of the polygons for many reasons. First, the nature and resolution of the cursor (a wide cross-hatch in our study) that appears when interpolating a polygon prevents a precision alignment of building boundaries. In addition, many of the encountered problems were due to the single-view nature of the orthophoto: only one photo of the scene is available, providing only one view of the structures from one direction. Shadows of the taller buildings fall across smaller buildings making discernment of building edges, shape and surface difficult. Zooming in on the scene is obviously helpful as an aid to more accurate interpolation of the building/polygon boundaries. The only limitation is that the entire building must be in view while digitizing, because the scene may not be paned during interpolation. Long or wide buildings must therefore be delimited at less detailed view. Another obstacle as Brenner (1999) identifies is that it is often not possible to recover information about building facades due to steep observation angles and occlusions.

The interactively interpolated buildings are shown in Figure 2 and 3. Figure 2 shows the building polygons interactively delineated and interpolated from the orthoimage. Its 3-D view is displayed in Figure 3 that takes the height information from the lidar data at corresponding locations when the polygons are delineated. In this way, the buildings are displayed in a three dimensional manner. As each building is delineated separately, the thematic information about the buildings can be easily included during this process. A serious problem in the interactively interpolated polygons is evident in the 3D view of that file as shown in Figure 3. The major flaw in the interactively extracted features is a gapping effect that occurs on the north/northwest sides of the buildings. As is shown in Figure 3, this hollowed-out effect is clearly noticeable, especially on the taller buildings. One can see buildings that one should not be able to see because they are located behind other buildings. Our initial analysis shows that this is likely caused by any slight mismatch between the orthophoto and the lidar data. Further analysis on this matter is given later.

Figure 2. Interactively interpolated polygons

Figure 3. 3D view of Figure 2

Only the buildings that completely fall within the limits of the orthophoto are interpolated. This resulted in there being less information (fewer features) in the interactive model than the automated model (see next section). It appears that the lidar height data extends slightly beyond the limits of the orthophoto. There are 355 polygons in the downtown buildings in Figure 2. Each polygon that makes up a feature was assigned an identification number (Polygon ID). For the buildings whose names are not known, the ID ranges from 0 to 10. The buildings are assigned an ID sequentially and after 10 is reached, the sequence repeats. The named buildings have an ID ranging from 11 to 23. This building attribute table is then edited to add a field for building names, which are identified from maps of downtown Baltimore.

AUTOMATED MODELING

The automated approach for building modeling in ArcView GIS is essentially a procedure of raster-to-vector conversion, in particular, a conversion from the lidar grid data to shapefile, from which a 3D building model can then be generated and displayed. A grid file of the lidar data is color-coded by height as shown in Figure 1. Noting that the Inner Harbor is in the southeast corner of the study area, it is evident that the underlying terrain is relatively flat. There is a rise in elevation as one proceeds northwestward. This is advantageous for distinguishing the building heights from the terrain surface. Any number of classes may be chosen for the gird data within ArcView. The figure shows the data (ranging from –1 to 163 meters) divided into 15 classes with a properly chosen colormap.

Fully automated procedures are used to create shapefiles (both 2D and 3D) from the gird data. The various available automated analysis steps and resulting outputs in ArcView GIS are provided in Table 1. The shapefile directly generated from the grid file is shown in Figure 4 and contain 50,088 shapes (polygons). If the end result is to have a 3D display for visualization purpose, the resultant 3D view shown in Figure 5 looks reasonably good. One can even further manipulate the view for the perspectives from different directions and conduct limited query. However, for the purpose of a searchable 3D model and database, this result contains an overwhelming number of polygons to manipulate. Although this shapefile approximates the building shapes, it is far too crowded at the edges of the buildings to be of much benefit for feature extraction and modeling. The selection of a single building for query purpose is almost impossible in practice, since thus converted shapefile is not fully and correctly structured. One object (such as a building) or its primitives (such as faces of the building) may correspond to many small polygons in the shapefile, which essentially are redundant for determining the building shape and structure. Therefore, steps to simplify the results are necessary.

Table 1. Automated 3D Functions in ArcView GIS

Procedure	Sequence of Steps
2D Shapefile	[Select Theme(grid)]-Theme-Convert to Shapefile
3D Shapefile	[Select Theme(.shp)]-Theme- Convert to 3D Shapefile
Contour	[Select Theme(grid)]-Surface-Create Contours
Slope	[Select Theme]-Surface-Derive Slope
TIN	[Select Theme(grid)]-Theme-Convert Grid to TIN

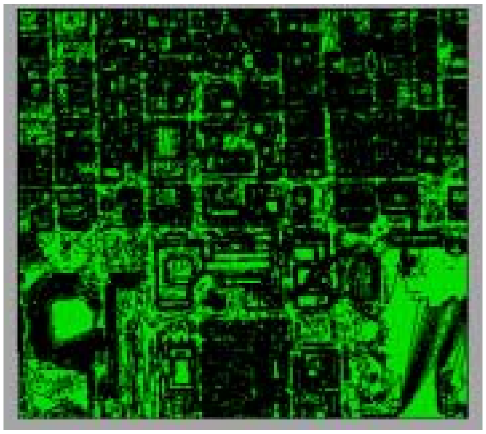


Figure 4. Automated shapefile

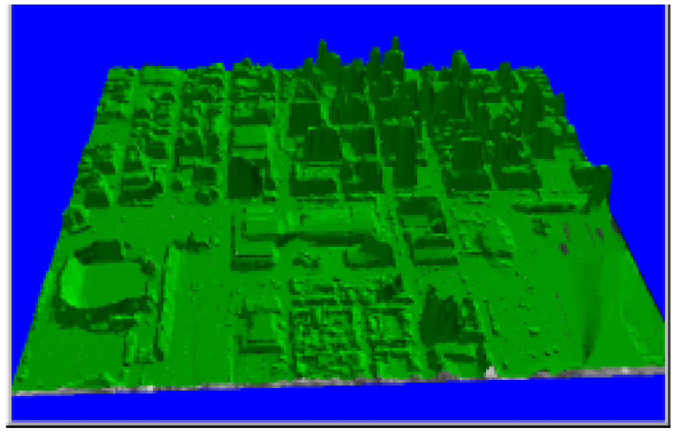


Figure 5. 3D view of Figure 4

Further analysis of the 3D model generated from the 3D shapefile will be presented later. It may be observed that there is a noticeable rise in the southeast (lower right) corner of the downtown block (in the water). My knowledge on the subject cannot explain this anomaly (height greater than the water surface), but Fowler (2000) and Maune et al (2000) inform us that a lidar system designed for topographic scanning, as we are considering here, will have different requirements than one designed for bathymetric surveys. Therefore any lidar returns in the water will not be comparable to the returns over land. Therefore, this paper will not seek to delve into this problem. Other possibilities for 3D model generation include creating contours from the LIDAR data, deriving the slope and generating a TIN (Triangulated Irregular Network). For the buildings we are seeking to model, TIN is not a justifiable option. Other automated feature extraction options were tried, but my initial efforts concentrated on the interactive approach, as described in the following section.

The effort towards reducing the number of polygons and their simplification in the automated created shapefiles turns out to be successful. It is prudent to generalize the heights of the features by reclassifying (not just for display purpose) the lidar data into 15 classes, as is usually displayed in ArcView (obviously, any reasonable number of classes may be chosen). Each class is approximately 10 meters in range. After the reclassification, the reclassified gird data is cleaned to smooth the boundary of the classes and eliminate small spots which are caused by noises in the lidar data and don't contribute to the structure of the buildings. As is shown is Figure 6, the resultant cleaned classified grid data is shaped even closer and more realistic to the true shape of the buildings. Therefore, the 3D view of Figure 7, though greatly generalized, presents a better and realistic view than Figure 5, which is derived from the original non-classified lidar data.

A vectorization is implemented to the cleaned classified lidar grid. The resultant shapefile is shown in Figure 8.

Figure 6. Cleaned classified lidar grid

Figure 7. 3D view of Figure 6

Comparing to the original shapefile in Figure 4, Figure 8 contains only 3,663 generalized polygons – a reduction of 46,425 polygons (92.7%). This new shapefile is created automatically, which turns out to be closer to the appearance of the real buildings. Figure 9 gives a 3D view of this cleaned shapefile. Comparing to the shapefiles obtained from interactive tracing of the orthoimage in Figure 2, it can be seen that the automated generated shapefile of Figure 8 has the majority of buildings correctly represented. Great resemblance is found between the buildings in these two shapefiles. Only detail differences may occur mainly at the edges and boarders of buildings due to the generalization involved in the reclassification and clean-up operations. Therefore, this automatic approach implemented and described above can practically reach the equivalently good extraction and modeling outcomes as the interactive approach. In addition, the automatic approach does not need the orthoimage to interactively trace building boundaries and therefore can intrinsically avoid any potential effect caused by the mismatch between the lidar data and the orthoimage. It provides a fast, easy and effective way for urban feature extraction, modeling and visualization.

THEMATIC DATA INCLUSION AND QUERY

Figure 8. Cleaned shapefile

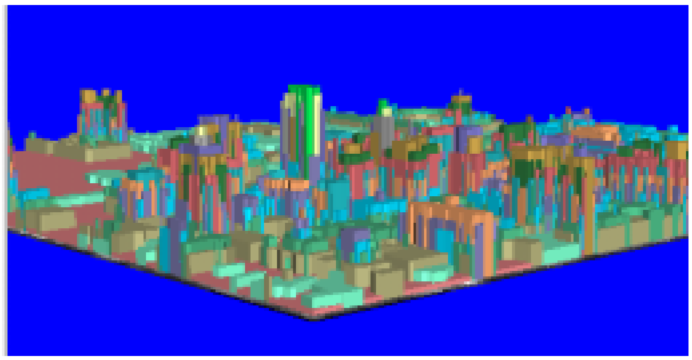


Figure 9. 3D view of Figure 8

The inclusion of thematic information is desired for each building so that it will be possible to query the 3-D view. This will allow a user to select a building and obtain its query results, such as building's name, height and usage. This information is associated to each polygon in the view. Since one building may be composed of many polygons, all of them need to be assigned with pertinent thematic data. The more information known about the buildings, the better the thematic attributes a query can provide with. Our study shows that the thematic information can be conveniently associated to a view when the buildings are extracted interactively. The automatically generated shapefile usually has too many detail, small and incomplete polygons to be associated with thematic information, except the building height which is automatically associated during the process. Figure 10 and 11 below show a list of buildings and a query result. It should be noticed that a query on the automated 3D view yields only building height information. However, an intersection of the interactively created theme with the automatically created theme will obtain the information contained in both themes. Therefore, a query on the intersected theme responds with attribute information from both themes that are joined in the intersection process.

Downtown Buildings

Polygon Id	Building Name
16	Baltimore Arena
11	Baltimore Convention Center
11	Baltimore Convention Center
11	Baltimore Convention Center
11	Baltimore Convention Center
11	Baltimore Convention Center
18	Charles Center
18	Charles Center
18	Charles Center
18	Charles Center
15	Federal Building
15	Federal Building
15	Federal Building
13	Harborplace
13	Harborplace
13	Harborplace
13	Harborplace
21	Hyatt Regency
21	Hyatt Regency

Figure 10. List of buildings

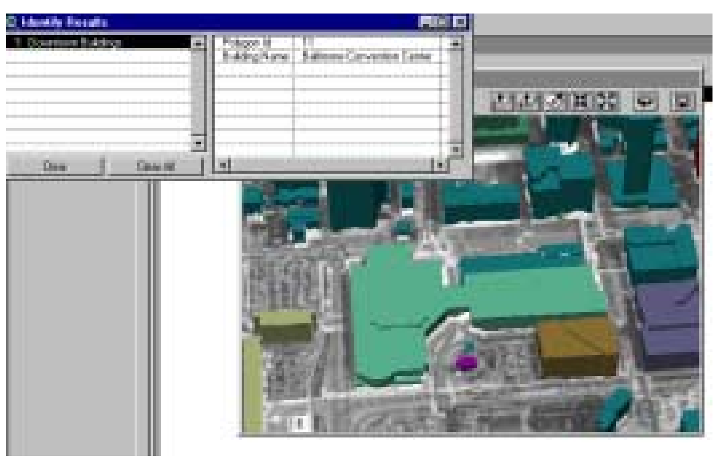
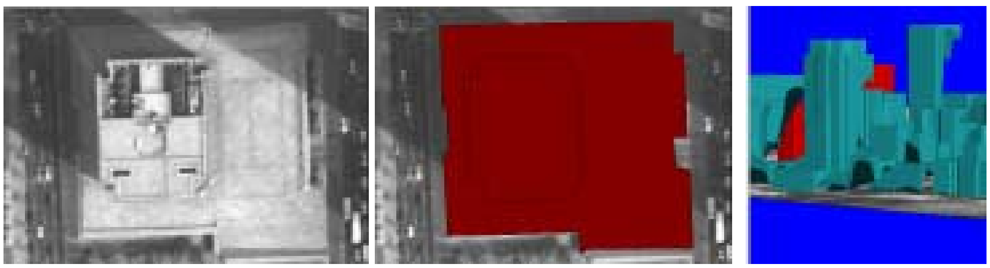


Figure 11. 3D query result

FURTHER ANALYSES

The gap effect

It was noticed that in the interpolated polygon views it appears that many building walls are not complete as is shown in Figure 3 above. This effect does not occur in the automated 3D shapefile. As has been mentioned, in the interpolation process the orthophoto is selected for tracing the building polygons. This is a rather reasonable choice as the LIDAR data does not define the building boundaries clearly enough for this purpose. Though seemingly the best choice, it is a source of the gap effect. While interactively interpolating, the polygons drawn may not capture all the height information for the feature if there is some mismatch in the position of the photo and the height source. The planimetric locations of the polygons are traced from the orthophoto while their heights are assigned from the lidar data. Therefore, any mis-registration of those two data sets may possibly cause a building polygon being assigned an elevation from a wrong place. Therefore, a precision merge or registration of different data source remains a problem that needs to be worked on.



a. Orthoimage   b. Traced polygon   c. 3D View

Figure 12. Gap effect in interactive modeling

Intersection

As is stated by Haala and Brenner (1997), in order to obtain a 3D city model, the buildings must be separated from the terrain surface. An intersection operation is carried out for this purpose. This operation creates a file that is simply the lidar height data for the area covered by the interactively interpolated polygons. Figure 13 shows the 3D view color-coded by buildings after the intersection operation. The intersection tool is useful for separating a feature extraction task into separate layers. In this way, the building polygons have been isolated from the general terrain. Nevertheless, the underlying terrain is still influential because the base of each building is not located at the same height. The intersection operation only comes into play when an interactive building polygon file has been created.

Figure 13. 3D view after intersection of interactive and automated modeling

Comparison of two methods

In working towards a more automated approach, it seems useful to compare the two building files generated interactively (Figure 2) and automatically (Figure 8) to see how much of interactive extraction may be reduced by automation. Clearly, automation can handle many of the shorter and more regularly shaped buildings. Yet, structures only a few stories high are not feasible for automation. This may be noticed in the lower central portion of the scene, where there are some row-houses. It is hard to distinguish the very low structures from the terrain. In comparing these two shapefiles, it would appear that many of the buildings are well defined enough by the automated procedure with little or no interactive input. It is approximate that above 40% of the buildings are extracted sufficiently by the automated procedure. Additional buildings can be added with minimal interactive assistance.

The automated building polygons are also often less satisfied when the buildings are so close to one another. It is difficult to distinguish one building from another in this case. Therefore, it points to the conclusion that less dense areas are better suitable for automated feature extraction.

A comparison of the generated 3D views shows that the shapes of some building tops are quite differently represented. However, without additional information, it is hard to precisely distinguish which model is more correct. Densely spaced groups of buildings show the difficulties of distinguishing the features for both interactive and automated extraction. It is difficult to discern whether the how many buildings there are, if they are connected, or simply share walls. All this suggests that additional data from other sources are needed and will benefit the analyst for modeling and analysis. For an 3D database, thematic information about the buildings are collected based on other available information and associated to every building polygon.

CONCLUSIONS

This study shows that building modeling and visualization using lidar data in an integrated GIS environment is more effective and efficient than expected. An automated approach based on classification of lidar data can produce a rather realistic modeling for the buildings and majority of them are correctly shaped and presented. The interactive approach based on tracing orthoimage and association to lidar data can provide a more realistic view. The gap effect may occur to buildings in the interactive approach due to the possible mis-registration of those two data sources. An intersection of interactively collected buildings with classified lidar data can separate the buildings from the terrain background.

The use of lidar data for feature extraction and 3D urban modeling seems to have much promise for the future. The utility of interactive feature extraction was proven once again and automated procedures showed much promise for reducing the labor of interactive feature extraction. ArcView GIS, with its increasing suite of advanced extensions, allows many users a great deal of computing power for feature extraction and 3D modeling. Many questions remain unanswered and will hopefully provide plenty of material for future endeavors.

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