A GRAPH-BASED APPROACH FOR HIGHER ORDER GIS TOPOLOGICAL ANALYSIS

J.-P. de Almeida [a, b,] *, J. G. Morley [a], I. J. Dowman [a]

[a] Dept. of Geomatic Engineering, University College London, Gower Street, LONDON WC1E 6BT, UK
(almeida, jmorley, idowman)@ge.ucl.ac.uk
http://www.ge.ucl.ac.uk/
[b] Section of Geomatic Engineering, Dept. of Mathematics, Faculty of Science and Technology, University of Coimbra,
Largo D. Dinis, Apartado 3008, 3001-454 COIMBRA, Portugal
http://www.mat.uc.pt/

KEY WORDS: LiDAR, Urban, GIS, Algorithms, Analysis, Interpretation, Understanding

ABSTRACT:

Retrieving structured information from an initial random collection of objects may be carried out by understanding the spatial arrangement between them, assuming no prior knowledge about those objects. As far as topology is concerned, contemporary desktop GIS packages do not generally support further analysis beyond adjacency. Thus, one of the original motivations of this work was to develop new ideas for scene analysis by building up a graph-based technique for better interpretation and understanding of spatial relationships between GIS vector-based objects beyond its first level of adjacency; the final aim is the performance of some kind of local feature organization into a more meaningful global scene by using graph theory. As the example scenario, a LiDAR data set is being used to test the technique that we plan to develop and implement. After the generation of the respective TIN, two different binary classifications were applied to the TIN facets (based on two different slope thresholds) and TIN facets have been aggregated into homogeneous polygons according to their slope characteristics. A graph-based clustering procedure inside these polygonal regions, by establishing a neighbourhood graph, followed by the delineation of cluster shapes and the derivation of cluster characteristics in order to obtain higher level geographic entities information (regarding sets of buildings, vegetation areas, and say, land-use parcels) is object of further work. The results we are expecting to obtain might be useful to support land-use mapping, image understanding or, generally speaking, to support clustering analysis and generalization processes.

1. INTRODUCTION AND MOTIVATION

Interpretation and analysis of spatial phenomena is a highly time consuming and laborious task in several fields of the Geomatics world. This is particularly true given the more accurate but also the larger and larger spatial data sets that are being acquired with the new technologies that are continuously being developed. That is why the automation of those tasks is especially needed in areas such as GIS amongst others (Anders *et al.*, 1999).

The aim of retrieving structured information, translated into more meaningful homogeneous regions (say, land-use parcels), from an initial unstructured data set may be achieved by identifying meaningful structures within the initial random collection of objects and by understanding the spatial arrangement between them, *i.e.*, by understanding the topological relationships between the identified structures.

1.1 Topology

Topology is a particularly important research area in the field of GIS for it is a central defining feature of a geographical information system. Generally speaking, as far as topological relationships between geographical entities are concerned, contemporary desktop GIS packages do not support further information beyond the first level of adjacency (Theobald, 2001). Therefore, one of the first motivations of the work described in this paper was also to develop new ideas for scene analysis by building up in a different way a technique for better understanding of topological relationships between GIS vector-based objects beyond the first level of adjacency.

1.2 Graph theory

Other initial interest was to investigate the possible use of *graph theory* for this purpose. This mathematical framework is said to be fairly powerful and elegant based only on a few basic extraordinarily simple principles (Temperley, 1981). Indeed, several authors (including Laurini and Thompson, 1992) maintain that this particular tool is extremely valuable and efficient in storing and describing the spatial structure of geographical entities and their spatial arrangement which, after stripping away their geometric properties, are seen in a GIS environment as points, lines or areas. Theobald (2001) adds that concepts of graph theory allow us to extend the standard notion of adjacency. To date, graph theory has been used in different applications in a wide range of fields to represent connections and relationships between spatial entities.

1.3 LiDAR data

In most of the applications developed so far, the starting situation is to some extent a meaningful data set in terms of the scene. We seek to explore and investigate whether it is possible to start at a level further back with an unattributed data set and, hence, we are assuming no prior knowledge of the spatial entities.
As the example scenario *LiDAR data* are being used to test the graph-based technique that we plan to develop and implement.

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* Corresponding author.

It is an unstructured data set without even providing any imagery of the surveyed area. Range data is a random collection of a considerable number of 3D points, with no pattern pre-defined, which are typically used for the generation of TINs which basically, in terms of GIS analysis, translate into what we define as a set of *first order connections* in vector domain, *i.e.*, spatial relationships between objects in direct contact. Using a graph-based approach, we are planning to build up networks of connectivity through these data sets that may allow the performance of what we call *higher order connections* analysis, *i.e.*, to investigate and understand the spatial relationships between objects within the context of the whole scene rather then within the context of their own neighbourhood.

1.4 An urban scene

Carrying out this sort of analysis in the context of an urban scene is particularly challenging given its relatively small component elements (such as, buildings, roads and intra-urban open spaces) and their generally complex spatial pattern. In fact, according to some authors (including Eyton, 1993, and Barr & Barnsley, 1996, both cited in Barnsley and Barr, 1997), the classification process of spatial information to produce land-cover maps (maps of *forms*) for urban areas can be considered fairly straight forward if we compare it with the process of deriving information from those maps on urban land-use (maps of *functions*). This is normally much more problematic namely because land-use is an abstract concept: an amalgam of economic, social and cultural factors defined in terms of *functions* rather than in physical *forms* (Barnsley and Barr, 1997).

2. DESIGNING THE GRAPH-BASED APPROACH

2.1 First order information retrieval

The LiDAR data set being used has got 3metre point spacing and it contains both ground points and objects points reflected from trees, buildings and other small objects above ground level. The data set refers to a surveyed area (1470x1530m^2) in Southwest London (Kew), including the Public Records Office and its neighbourhood, comprising a total of 169819 laser points (*vd.* Figure 1).

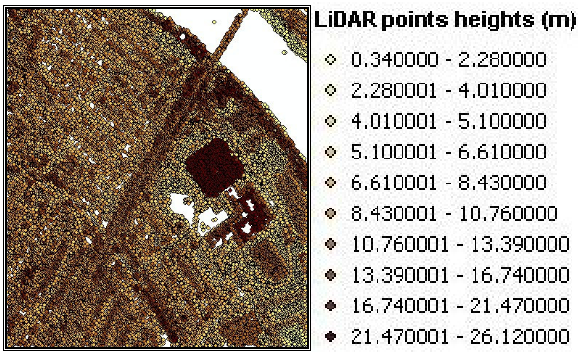

Figure 1. LiDAR data set being used
(Kew, Southwest London).

As explained, our starting situation is an unstructured data set of 3D points, meaningless in terms of urban scene. To start structuring information and make it more explicit, some topological information was brought in by establishing a triangulated irregular network (TIN) through the given data set (*vd.* Figure 2). In fact, the generation of the TIN was based upon the Delaunay triangulation which, given the fact that it is a maximal planar description of the given point set internal structure (Kirkpatrick and Radke, 1985), expresses proximities and neighbourhoods between the LiDAR points.

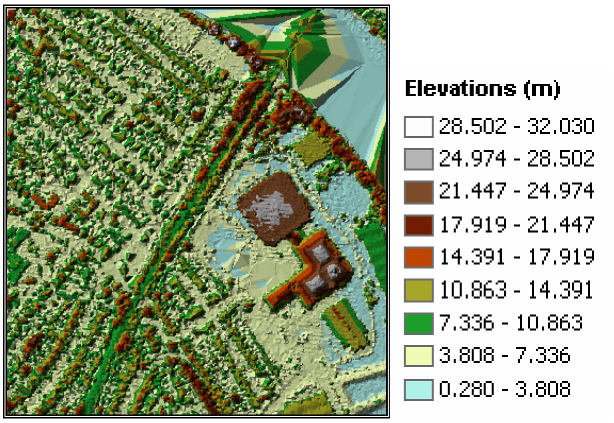

Figure 2. TIN generated from the LiDAR point set.

2.2 TIN facets classification

After the generation of a TIN from the cloud of LiDAR points, which translates a set of first order information, two different binary classifications (based on two different TIN facets slope threshold) were applied to the TIN facets: one uses 60° slope value; the other is an equal-interval classification using 45° slope value. With the first classification, polygons of steep facets (60°-90° slopes) were expected to outline buildings but, as we can see on the left hand side of Figure 3, building entities are not well defined. In order to obtain a better shape of these entities, the second classification was carried out and its results are shown on the right side of Figure 3.

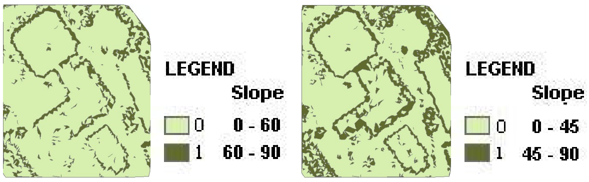

Figure 3. Two different classifications for the same area.
(60° *vs.* 45° degree slope thresholds).

As the range data available constitutes a very large data set, two case studies were chosen amongst the total LiDAR data set: one of which includes the Public Records Office and its surrounding area, corresponding to a relatively simple urban scene (it is the one showed in Figure 3); the other one corresponds to a much more complex scene given the higher density of small size urban features, buildings and trees.

To start with, the two binary classifications obtained for the simple urban scene (Public Records Office and its surrounding area) were compared and contrasted.

All the operations described above for the TIN facets classification and the respective generation of polygonal regions (through critical lines) were performed in ArcGIS environment.

2.3 Graph construction

Towards the establishment of a network of connectivity within the given data set and the generated TIN, this approach identifies graph nodes as each one of the polygons aggregated from TIN triangles.

To build up a graph of adjacencies it was necessary to access polygon and respective arc attributes to retrieve polygon adjacencies which, as we are using an ArcGIS environment, implied a combination of information spread basically over two lists: polygon component arcs list (information referring to area definition) and the arc adjacent polygons list (information referring to *connectivity* of arcs and *contiguity* of polygons).

Figures 4 and 5 show the graphs obtained for the different classifications carried out, using 60° and 45° slope thresholds respectively.

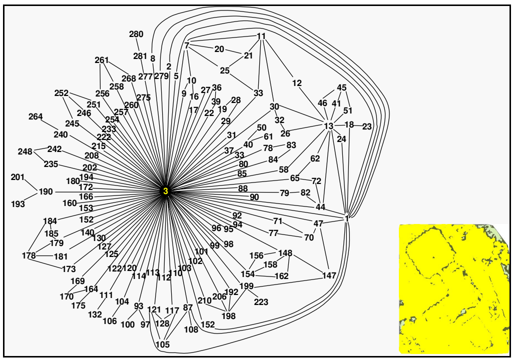

Figure 4. Respective graph of adjacencies for the Public Records Office area (60° slope threshold).

Graphs obtained are planar graphs as they can be drawn on the plane without any crossing edges and such that no two end-nodes coincide. According to one of the graph theory theorems (save the obvious exception of graphs containing loops or multiple edges), planar simple graphs (like those obtained) can always be drawn in such a way that all its edges are represented by straight lines, as was proved in 1936 by Wagner (Wilson, 1996). Thus, graph in Figure 4 was redrawn in that way.

In order to carry out the task of redrawing the graph using only straight lines, a slightly different arrangement of its nodes had to be considered and therefore the planimetric location of some of them actually changed. Nevertheless, their relative position to each other is absolutely the same (in other words, their topological relations were preserved) and hence the graph obtained is essentially the same as well, though with a slightly different configuration. More precisely, we shall say that the two graphs are isomorphic.

We did not accomplish the same task for the graph in Figure 5 as it is too complex. In addition to this, the reason for the straight lines drawing was just an attempt to point out an extremely important fact for us since we are interested in studying and analyzing topological relations between the spatial objects: although the planimetric location of some of the graph nodes changed, their relative position to each other was preserved. And that is what topology is all about, about the invariant properties of a map under deformation (Laurini and Thompson, 1992). This fact makes definitely clear the effectiveness of graphs in storing topological information of a given scene.

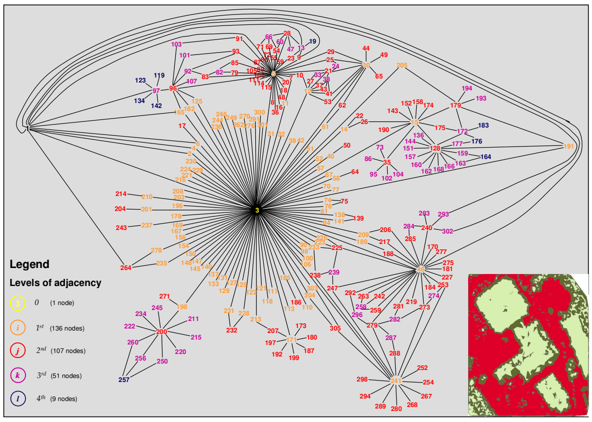

Figure 5. Respective graph of adjacencies for the Public Records Office area (45° slope threshold) and its different levels of adjacencies.

In Figure 5 different levels of adjacency are represented. Polygon *3* (highlighted on the right hand side of Figure 5) is the largest and the most connected *flat* one and therefore the one used as the *Useful External Border* (*vd.* Nardinocchi *et al.*'s definition for the *UEB*, 2003) with which the graph construction was started. Thus, assuming that polygon *3* is, in fact, the *ground* polygon, those levels of adjacency can also be seen as different levels of containment.

3. DISCUSSION

By observing different paths within the generated graphs, namely by trying to understand the geographical meaning of sequences of different levels of adjacency, and containment, between nodes (which represent polygonal regions generated from the original TIN facets) along graph paths, we concluded that different types of analyses will be possible to retrieve further geographical information. For instance, we may say that the polygon represented by the node in the tail of a graph path (representing the highest level of adjacency) is a candidate to be either a "hole" on the ground or "something" on the top of an urban entity, say, a building.

To give an example of what kind of scene analysis might be possible to carry out once the whole process is automated, let us try to understand the meaning of a graph path in terms of urban scene, and for that, let us consider for instance the one highlighted in Figure 6 (a detail of the bottom left-hand corner of Figure 5).

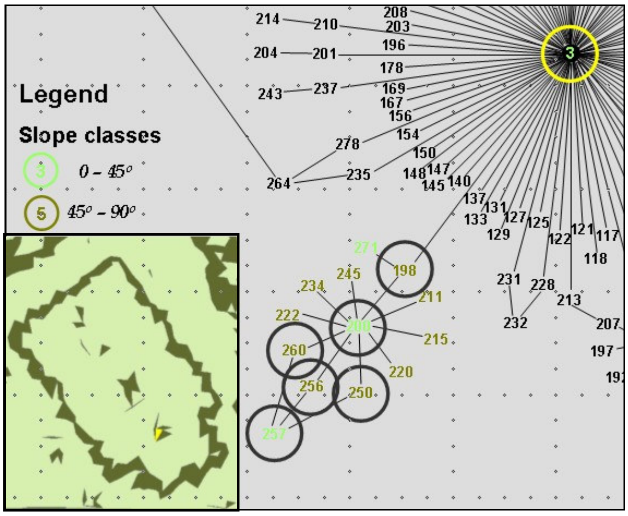

Figure 6. An example of the meaning within the context of the urban scene that may be inferred from a graph path.

Let us go through the given path starting from polygon *3*, the useful external border. On the first level of adjacency the *steep* polygon *198* is found which is contained by the previous one. This, in turn, contains *flat* polygon *200* on the second level of adjacency. Polygon *200* contains several others and, in particular, contains *steep* polygons *250*, *256*, *260* which all together contain *flat* polygon *257* belonging to the fourth and last level of adjacency. In terms of urban scene, the meaning of this sequence of spatial relations of adjacency and containment is the existence of a building (pictured on the bottom left-hand side of Figure 6) whose boundary is almost shaped by the *rectangular* dark green polygon displayed

4. CONCLUSIONS

The first steps towards the development of a graph-based scene analysis technique have been presented in this paper. A neighbourhood graph was generated within the initial unstructured data set to bring in topological information. This task was accomplished by generating a TIN based on the Delaunay triangulation. Two classes of polygonal regions were generated gathering *flat* and *steep* TIN facets respectively.

Now that those polygonal regions were generated, the next step is the automated generation of graphs (considering the polygon centroids as its nodes) which has not been fully implemented yet and is currently being explored. Subject to our further work is the subsequent aggregation of those nodes into identified meaningful structures; these, in turn, should be clustered into homogenous regions; after the delineation of cluster shapes an analysis process will have to be carried out (either by pattern recognition or interpretation procedures). The aim of the final cluster shapes analysis is the retrieval of higher level information, *e.g.*, sets of buildings, vegetation areas, and say, land-use parcels.

The results we are expecting to obtain might be useful to support land-use mapping, image understanding or, generally speaking, to support clustering analysis and generalization processes.

REFERENCES

Anders, K.-H.; Sester, M.; Fritsch, D. (1999), Analysis of settlement structures by graph-based clustering. *Semantische Modellierung, SMATI 99*, 41-49. Munich (Germany).

Barnsley, M.J.; Barr, S.L. (1997), Distinguishing urban land-use categories in fine spatial resolution land-cover data using a graph-based, structural pattern recognition system. *Comput., Environ. And Urban Systems*, Vol. 21, No. 3/4: 209-225. Elsevier Science Ltd.

Barr, S.L., Barnsley, M.J. (1996), Inferring urban land-use from satellite sensor images using kernel-based spatial reclassification. *Photogrammetric Engineering and Remote Sensing*, No. 62: 949-958.

Barr, S.L., Barnsley, M.J. (1997), A region-based, graph-theoretic data model for the inference of second-order thematic information from remotely-sensed images. *International Journal of Geographical Information Science*, Vol. 11, No. 6: 555-576. Taylor & Francis Ltd.

Bunn, A.G.; Urban, D.L.; Keitt, T.H. (2000), Landscape connectivity: A conservation application of graph theory. *Journal of Environmental Management*, no.59, 265-275. Academic Press (USA).

Edelsbrunner, H.; Kirkpatrick, D.G.; Seidel, R. (1983), On the shape of a set of points in the plane. *of IEEE Transactions on Information Theory*, Vol.29, no.4: 551-559.

Eyton, J.R. (1993), Urban land-use classification and modelling using cover-type frequencies. *Applied Geography*, Vol. 13: 111-121.

Forberg, A.; Raheja, J.L. (2002), Generalization of 3D settlement structures on scale-space and structures recognition. Work Report, Institut für Photogrammetrie und Fenerkundung (Universität der Bundeswehr München), Lehrstuhl für Kartographie (Technische Universität München), Munich (Germany).

Gibbons, A. (1989), *Algorithmic Graph Theory*. Cambridge University Press, Cambridge (UK).

Gross, J.; Yellen, J. (1999), *Graph Theory and Its Applications*. CRC Press, Boca Ratón (Florida, USA).

Kirkpatrick, D.G.; Radke, J.D. (1985), A framework for computational morphology. *Computational Geometry* (TOUSSAINT, G.T., ed.), 217-248. North- Holland, Amsterdam (The Netherlands).

Laurini, R.; Thompson, D. (1992), *Fundamentals of Spatial Information, 5*. Academic Press, London (UK).

Nardinocchi, C., Gianfranco, F., Zingaretti, P. (2003), Classification and filtering of laser data. ISPRS Workshop on *3D reconstruction from airborne laser scanner and InSAR data*. Dresden (Germany).

Radke, J.D. (1982), *Pattern Recognition in Circuit Networks*, PhD thesis, Department of Geography, University of British Columbia (USA).

Rigaux, J., Scholl, M., Voisard, A. (2002), *Spatial Databases with Applications to GIS*, Chapter 8. Morgan Kaufmann, San Francisco (USA).

Schalkoff, R. J. (1992), *Pattern Recognition: Statistical, Structural and Neural Approaches*. John Wiley, New York (USA).

Sedgewick, R. (1988), *Algorithms* (2nd ed.). Addison-Wesley, Reading (MA, USA).

Steel, A.M.; Barnsley, M.J.; Barr, S.L. (2003), Inferring urban land use through analysis of the spatial composition of buildings identified in LiDAR and multispectral image data. *Remotely-Sensed Cities* (MESEV, T.V., ed.). Taylor & Francis Ltd., London (UK).

Temperley, H. (1981), *Graph Theory and Applications*. Ellis Horwood Ltd., Chichester (UK).

Theobald, D.M. (2001), Topology revisited: representing spatial relations. *International Journal of Geographical Information Science*, Vol. 15, No. 8: 689-705. Taylor & Francis Ltd.

Toussaint, G.T. (1980a), The relative neighbourhood graph of a finite planar set. *Pattern Recognition*, Vol.12, No.4: 261-268. Pergamon Press Ltd.

Toussaint, G.T., (1980b), Pattern recognition and geometrical complexity. Proceedings of *V International Conference on Pattern Recognition*: 1324-1347. Miami (USA).

Urquhart, R. (1982), Graph theoretical clustering based on limited neighbourhood sets. *Pattern Recognition*, Vol.15, No.3: 173-187. Pergamon Press Ltd.

Wilson, R. (1996), *Introduction to Graph Theory* (4th ed.). Longman, Harlow (UK).

Zeng, Yu; Zhang, J.; Wang, G.; Lin, Z. (2002), Urban land-use classification using integrated airborne laser scanning data and high resolution multi-spectral satellite imagery. *Pecora15/Land Satellite Information IV/ISPRS Commission I/FIEOS 2002Conference* proceedings. Denver (Colorado, USA).

ACKNOWLEDGEMENTS

Faculdade de Ciências e Tecnologia da Universidade de Coimbra (Faculty of Science and Technology of the University of Coimbra, Portugal) and *Fundação para a Ciência e Tecnologia* (the Portuguese Foundation for Science and Technology, scholarship SFRH/BD/9909/2002), which financially support this research project. The University College London Graduate School has also funded the participation in ISPRS XXth Conference-Istanbul 2004.

An acknowledgement is also due to Dr. João Coutinho-Rodrigues (Department of Civil Engineering, Faculty of Science and Technology, University of Coimbra), J-P de Almeida's PhD co-supervisor at the University of Coimbra.