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5D Multi-Purpose Land Information System

C. Ioannidis[1], S. Verykokou[1], S. Soile[1], C. Potsiou[1]

[1]National Technical University of Athens, Greece

Abstract

The complexity of modern urban environments has led to the introduction of 3D Land Information Systems (LISs), which tend to replace traditional 2D LIS architectures for the purposes of urban planning and regeneration, land administration, real estate management and civil development. Both the need for 3D visualization of the geometry of buildings in various time instances through the years and the need for acquisition of 3D models in various levels of detail (LoDs), which not only fulfill the requirements of the various users but also they speed up the visualization process, are obvious. Thus, additional dimensions, that is, for time and scale, need to be supported by a modern LIS. This paper introduces a 5D modelling pipeline that may be adopted by a multi-purpose LIS for the selective creation of 3D models of an urban area in various time instances and at various LoDs, enriched with cadastral and other spatial data. The methodology is based on automatic change detection algorithms for spatial-temporal analysis of the spatial changes that took place in subsequent time periods, using image orientation, dense image matching and structure from motion algorithms; the procedure requires photogrammetric stereo plotting, implements procedural modelling and relies on the availability of overlapping aerial and terrestrial imagery, ground control points and cadastral information. Finally, an application based on the proposed methodology in an urban area in Greece is presented and the future work is discussed.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computational Geometry and Object Modeling]: Modeling Packages, I.3.6 [Methodology and Techniques]: Graphics data structures and data types, I.3.7 [Three-Dimensional Graphics and Realism]: Color, shading, shadowing, and texture.

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1. Introduction

Land Information Systems (LISs) have been used to employ a two-dimensional (2D) framework for cadastral and land use mapping. The increasing complexity of modern land use zoning has created the need for additional information about the elevation and therefore 3D LIS architectures have been introduced, making use of the latest topographic, photogrammetric and computer vision techniques for data collection. However, even the third dimension is not enough for urban management and regeneration purposes, due to the dynamic nature of land, which results in spatial-temporal alterations of both land resources and property rights. Thus, 3D LIS architectures are extended towards a 4D representation, handling time as the fourth dimension. Furthermore, the various users of a multi-purpose LIS need geo-data of various resolution/scales, e.g., for some applications very detailed data are required while for other ones, data of a low level of detail (LoD) work better. Thus, next to the spatial and temporal aspect of urban properties, the scale dimension needs to be handled in a multi-purpose LIS as well, named as the "fifth dimension".

Despite the fact that both time and scale have always played an important role in LISs, the temporal and scale aspect have been treated quite independently from the spatial one. In the last decade much research has been conducted on 4D cadastre and land administration, focusing on the spatial (3D) and temporal aspects of real property (e.g., [vOPS*06], [DTS*08], [DTS*11], [DB13], [VRM14], [SGR15], [DSD*15]). Additional research papers, such as [vOS10] and [SLM*12] focus on 5D modelling approaches and applications. Moreover, a few research projects on 5D modelling have been funded, such as the 5D geo-modelling (https://3d.bk.tudelft.nl/projects/geo5d), which aims at the integration of multi-dimensional characteristics of geographic data at a fundamental level of data modelling, and the 5DMuPLIS (http://www.5dmuplis.gr), aiming to develop an advanced 5D LIS for integrating and managing various types of information from governmental, regional and local databases at 3D spatial dimensions plus time and scale. Finally, the 5D SMART City^{TM} by Cityzenith (http://www.cityzenith.com/city.html) is a relevant open platform dedicated to make city data easier to access, analyze, use, share and monetize, by combining all 2D and 3D spatial information into a complete 3D model linked to several databases.

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One of the drawbacks of the current international adoption of four or five dimensions is the fact that such systems are generally limited to displaying various static configurations of geospatial data-sets, not linked with additional cadastral data, being inappropriate for land management projects. The purpose of this paper is the presentation of a modelling scheme that may be adopted by a 5D LIS for the selective creation of multi-scale 3D models in various time instances enriched with additional spatial-temporal properties, as well as urban, proprietary and cadastral data.

2. The 5D modelling framework

The contribution of this paper is the description of a complete processing chain for the creation of 3D models of buildings at different epochs and levels of abstraction, enriched with appropriate data. The proposed 5D modelling framework (Figure 1) relies on the selective 3D modelling in various time instances and at various LoDs, by implementing automatic spatial-temporal analysis in order to reduce the time and cost of the modelling process [DSD*15]. The input data consist of overlapping aerial images from various time instances, ground control points, terrestrial images of the building façades and cadastral data.

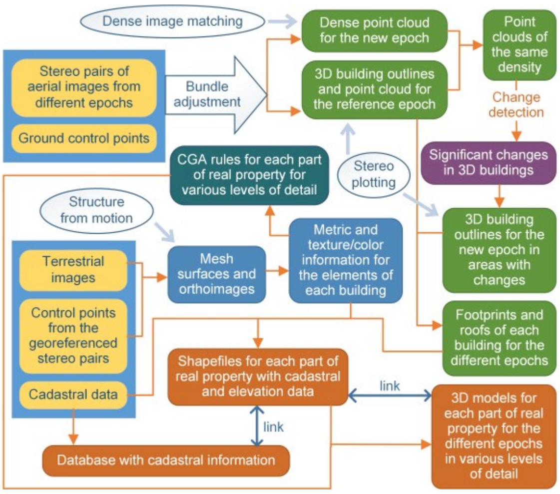

Figure 1: *The 5D modelling scheme.*

Accurate 3D models are generated through photogrammetric analysis of aerial and terrestrial imagery via a procedural modelling approach. As far as the fourth dimension is concerned, 3D models of two different time periods are created in the areas where a spatial alteration is detected through automated change detection algorithms. The fifth dimension is introduced via the creation of models of various epochs that correspond to different LoDs. The concept of LoD not only facilitates and accelerates the efficient visualization of large scenes, via the display of the model at the appropriate resolution depending on how far or close it is from the user's point of view, but also it provides models of different scales according to the requirements of the various users of the multi-purpose LIS. In this paper, the differentiation of LoDs proposed by CityGML is used; specifically, three levels of detail LoD1, LoD2 and LoD3 are implemented. LoD1 comprises prismatic objects with flat roofs; a building in LoD2 has information about the roof structures and balconies as well as the surfaces; LoD3 denotes architectural models with further detailed wall and roof structures, balconies, bays and projections and high-resolution textures are mapped onto these structures [Ogc12] (Figure 2).

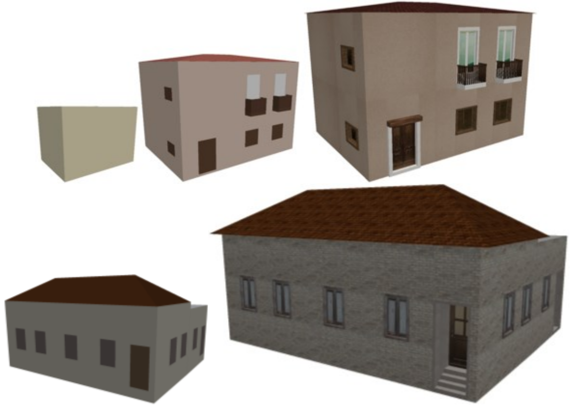

Figure 2: *Top: 3D models of a building in LoD1 (left), LoD2 (middle) and LoD3 (right). Bottom: 3D models in LoD2 (left) and LoD3 (right).*

2.1 Spatial-temporal analysis

The first step is the camera exterior orientation estimation of every aerial image through bundle adjustment with self-calibration in cases of unknown camera interior orientation parameters. Subsequently, building outlines, roofs, mass points defining the ground and points on the top of man-made constructions are stereo plotted using the georeferenced stereo models of the reference epoch. Dense image matching is applied on the stereo models of the forthcoming time instances for the automatic generation of 3D point clouds for the new epochs. The point clouds vary significantly in terms of density, due to the different methodologies (i.e., manual and automated techniques) applied for their generation; thus, they are transformed into meshes and new point clouds of the same density are then created. The application of a smoothing filter (e.g., Laplace) on the automatically generated meshes of the new time instances is usually required for the elimination of local outliers due to mismatches from the dense image matching process.

Spatial-temporal analysis is accomplished through the automatic detection of significant changes in the point clouds. Specifically, the distance between each point in the reference point cloud and its nearest point in the new point cloud is computed. In order to detect significant 3D changes, a distance threshold of 3.5 m, associated with the height of a typical floor, and a threshold of 2.5 m above ground, to ignore cases of differences in vegetation, cars, etc., are implemented. In this way, change maps are obtained, indicating regions that require further 3D modelling at new time instances.

Only regions which have undergone a significant change are modelled at new time instances, whereas regions of insignificant changes remain intact. Thus, 3D building outlines in areas where a significant change has occurred at a new time instance are acquired through manual stereo plotting using the georeferenced stereo models.

2.2 Extraction of metric, textural and color information

The building outlines suffice for the creation of 3D models in LoD1; however, textural or color and metric information for the elements of every building is essential for 3D modelling in higher levels of detail (LoD2, LoD3). This kind of information may be obtained through an automated Structure from Motion (SfM) procedure, using terrestrial images of the building façades as well as control points measured in the stereo models of the aerial imagery, for the 3D reconstruction of the sides of every urban block. The results of this process (point clouds, mesh surfaces and orthoimages) are used for the extraction of information about the height of floors, the dimensions of doors, windows, balconies and other architectural and construction details. However, in the case of an old building which has been replaced by a new one, terrestrial images may not be available. In this case, metric and textural or color information may be extracted using old data-sets of oblique aerial images, if available, or information about the architecture of the specific era or even by oral descriptions for the state of buildings by previous owners.

2.3 Creation of footprints enriched with metadata

The generation of footprints for the internal areas of the buildings of the reference epoch and the buildings which have changed is the next step. Firstly, the editing of the 3D outlines, acquired through photogrammetric plotting, is an essential step in order to ensure that there are neither overlaps or gaps among adjacent building polygons, nor open polylines instead of building polygons. Building footprints are generated using the horizontal positions of the stereo plotted outlines of the building roofs and the appropriate ground elevation, acquired from the digital terrain model (DTM) of the region of interest, which is created using the ground points extracted via photogrammetric plotting.

The creation of the footprints of the component parts of buildings (apartments, common used areas, parking slots, etc.) is accomplished using cadastral information in combination with floor height measurements extracted from the orthoimages, as well as using the building footprints and the outlines of roofs. The orthoimages and the mesh surfaces also serve as a guideline in case of missing cadastral data. In order to store other attributes of each part of a real property as well, except for their location and shape, the interoperable shapefile format is used. In this way, each part of a real property is assigned various attributes, to wit, elevation, floor height, identifier of the relative cadastral vertical and horizontal property where applicable, description of the type of the cadastral property, identifier of the floor, percentage of ownership regarding the parcel, type of usage, identifier of the parcel along with a unique identifier of the specific part of the real property, etc. All the structures of a parcel are stored in a single shapefile.

An external database with cadastral information, is also created. It includes identifiers and categories of the persons (e.g., physical, legal, notary), identifiers of the documents from which rights are born (e.g., contract, court order), dates when documents were created, identifiers of the rights (e.g., ownership, easement), percentages of ownership on parcel and/or on horizontal or vertical properties, denominators of these percentages, dates when rights started to exist, etc. This database is connected with the records of the shapefiles using some common fields. In this way, every part of a real property is connected with all the available metadata.

2.4 Three dimensional modelling in various LoDs and time instances

The 3D model of each part of a building is created through procedural modelling. According to this approach, 3D content is generated using a set of rules, that is, computer code, which is applied to initial shapes (footprints of constructions stored in shapefiles in our case) to iteratively generate and refine a design by creating more details. CGA (Computer Generated Architecture) shape grammar, as introduced by [MWH*06], may be used for this purpose. The rules defined by a CGA grammar system enable the procedural creation of complex 3D models of buildings by firstly producing a crude volumetric model, then structuring each façade and finally adding details for doors, windows, balconies, etc., in the target level of detail. Important advantages of this approach are the rapid creation and updating of 3D models, in comparison with traditional modelling techniques, and the representation of different scales, through the introduction of various LoDs of the 3D content.

The rules are created using metric information, color and texture for the elements of each building and are applied to the footprint of each part of a real property (apartment, common area, storage area, etc.). In this way, 3D models of various LoDs and time instances are created and exported in suitable format, readable by the corresponding LIS.

2.5 Data enrichment of the 5D models

An important aspect is the connection of the 3D models with the appropriate attributes stored in the corresponding record of a shapefile and therefore with the cadastral information stored in the external database. This connection is accomplished through the assignment of the appropriate name to every 3D model. Specifically, the name of a model has the following format: “ID_LoDi_TIME”. Via the fields ID and TIME, the model is connected with the appropriate record of a shapefile of a specific time instance, in order to access the available data. LoDi differentiates the level of detail for which the model is created. Thus, for every part of a real property, n · m models are created, where n indicates the target levels of detail (3 LoDs in our case) and m is the number of times a significant change has occurred in the real property throughout the years. The search for the field ID is limited to the records of only one shapefile because of its name.

3. Case Study

The study area consists of 9 urban blocks in the municipality of Kessariani, in the eastern part of Athens, Greece. The 3D reconstruction in three LoDs takes place in two different time instances (1983 and 2010). The initial data consist of a stereo pair of analog greyscale aerial images at a scale of 1:7000 taken in 1983 and a stereo pair of analog color aerial images at a scale of 1:6000 taken in 2010, both with known interior orientation.

The relative orientation of each pair of images was performed. The positions of the ground points that had to be measured were determined through stereoscopic observation in the resulting stereo models of both pairs, in order to be clearly visible in both of them. The existence of these points so far was checked using the free software Google Earth. Intergraph ImageStation software suite was used for the above mentioned procedures. 14 points well distributed in the overlapping areas of the stereo pairs were collected in the field via RTK GPS measurements and were referenced to the Greek Geodetic Reference System (GGRS87).

The exterior orientation of the four images was calculated via bundle block adjustment, which resulted in RMS errors of 0.27 m, 0.18 m and 0.08 m in X, Y and Z respectively. The final stereoscopic models of the overlapping areas of the 1983 and 2010 stereo pairs with a correct scale, orientation and position in GGRS87 permitted high-precision 3D measurements in the region of interest through manual photogrammetric stereo plotting. The building outlines, the roofs, the outline of other constructions, mass points and lines defining the ground as well as points on the uppermost part of buildings were stereo plotted using the 1983 stereoscopic model (Figure 3, left). The aerial triangulation of the images and the stereo plotting were conducted using ImageStation.

The manually collected point cloud for the epoch of 1983 with a density of approximately 1 m is illustrated in Figure 4, left. A TIN surface was constructed, using the ground points and lines and was then converted in raster DTM using Esri’s ArcGIS platform. The automatically generated point cloud via dense image matching was acquired using the eATE (enhanced Automatic Terrain Extraction) module of ERDAS IMAGINE Photogrammetry and has a density of about 0.5 m (Figure 4, right). The final point clouds, with a density greater than 0.5 m, of an urban block in the region of interest are illustrated in Figure 5.

Figure 3: *Stereo plotting of the study area using the 1983 and the 2010 stereo pair.*

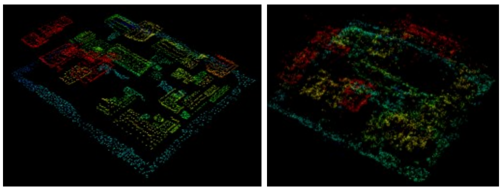

Figure 4: *Initial point clouds for the region of interest for the epoch of 1983 (left) and 2010 (right).*

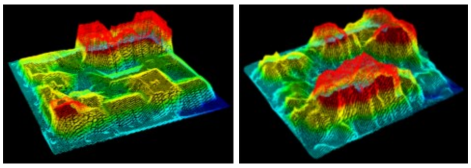

Figure 5: *Final point clouds of an urban block in 1983 (left) and 2010 (right) respectively.*

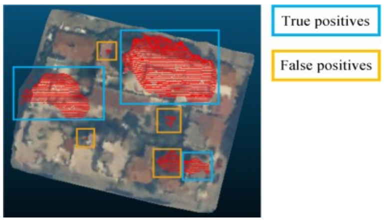

Figure 6: *Point cloud of an urban block illustrating the changes (colored in red) superimposed on the mesh of 2010.*

The change detection process was conducted using the open source software CloudCompare and leaded to satisfactory results. Except for the true positive changes between the two point clouds, some false positive changes were also observed in areas with high and dense vegetation as well as in remaining blobs of outliers (Figure 6). False positive changes were detected by optical observation. The stereo plotting of areas with changes was accomplished in ImageStation (Figure 3, right) using the stereo model of 2010. Figure 7 shows the differences in buildings that took place in the period 1983 - 2010 in 3D view.

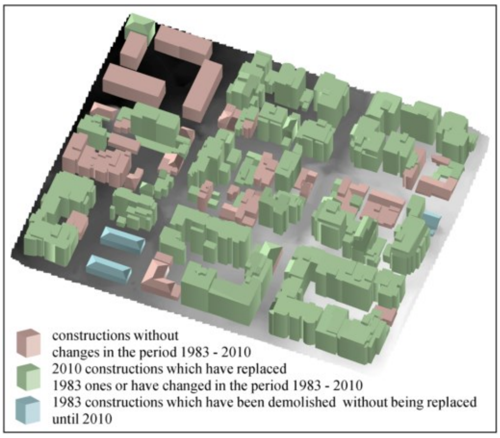

Figure 7: *3D view of the buildings of the region of interest superimposed on the DTM, illustrating the changes that took place in the period 1983 - 2010.*

A large number of terrestrial imagery (120 images) covering all the sides of one of the urban blocks was obtained. Agisoft PhotoScan software was used for the creation of dense 3D point clouds, meshes and orthoimages for the building façades (Figure 8).

Figure 8: *Point cloud (left) and orthoimages (middle and right) of some buildings in the region of interest.*

The shapefiles which contain the footprints of the inner parts of buildings (apartments, garage places, etc.) as well as cadastral and elevation data and the external database were created based on information that was collected from the Greek Cadastre. Cadastral information in this area was available only after 2004. Thus, as far as 1983 structures are concerned, many speculations were made based on the exterior design in order to digitize the inner areas of buildings and enrich them with appropriate data, using Esri's ArcGIS tools. The database was created using Microsoft Access.

The 3D models of the study area in Kessariani were created in three levels of details (LoD1, LoD2, LoD3) using CGA shape grammar and the footprints of each part of real property. Esri CityEngine software was used, because it implements procedural modelling for the creation of 3D content, reads CGA rule files as well as a variety of geo-spatial and vector data, such as shapefiles, and exports 3D models in suitable formats. The task of 3D modelling in LoD2 and LoD3 was the most time consuming one, requiring about 0.5 to 3 hours per apartment, depending on its complexity. The final 3D models were saved in KML/COLLADA format in order to be inserted in Google Earth. Figure 9, top illustrates the 1983 3D models of the buildings of an urban block of Kessariani at LoD2 superimposed on the textured DTM of the region. Details of the 3D models of 1983 at LoD3 are illustrated in Figure 9, middle and bottom. Figure 10, top illustrates the 3D models of the same urban block of 2010 at LoD3. Finally, details of the 3D models of 2010 at LoD3 are illustrated in Figure 10, middle and bottom.

Figure 9: *Top: 3D buildings of an urban block of Kessariani of 1983 at LoD2, superimposed on the DTM. Middle and Bottom: Details of the 3D models of 1983 at LoD3.*

4. Conclusions

In this paper, a 5D modelling framework for the acquisition of accurate 3D models of buildings in various LoDs and time instances, enriched with appropriate data and metadata, for use in a multi-purpose LIS, is proposed. Furthermore, an application in an urban area in Greece, which uses the proposed pipeline, is presented. The fact that the proposed methodology does not entail a fully automated procedure is due to the high accuracy required for the modelling of buildings for the purposes of land management and urban land readjustment. Any fully automated procedures tested in the region of interest resulted in less accurate 3D models with quite a few gaps.

Currently, an add-on for Google Earth, which displays for every user a selected 3D model of all the relative attributes and metadata, produces answers to spatial, cadastral, proprietary and urban queries and automatically determines which LoD of a 3D model has to be displayed, supporting a smooth transition between low and high levels of detail, is under development. This add-on will serve as a 5D multi-purpose LIS based on an open platform and will use the proposed methodology to capture 5D models. In this way, a complete display of past, current and future instances of a specific region will be provided.

In conclusion, the proposed methodology is suitable for various types of applications, including 3D cadastre, land administration, urban planning, land management, civil development, real estate valuation, real estate management and rural and urban settlement upgrading.

Figure 10: *Top: 3D buildings of an urban block of Kessariani of 2010 at LoD3, superimposed on the DTM. Middle and Bottom: Details of the 3D models of 2010 at LoD3.*

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