Selective 4D modelling framework for spatial-temporal Land Information Management System

Conference Paper *in* Proceedings of SPIE - The International Society for Optical Engineering · March 2015

DOI: 10.1117/12.2193464

Selective 4D modelling framework for spatial-temporal Land Information Management System

Anastasios Doulamis[a], Sofia Soile[a], Nikolaos Doulamis[a], Christina Chrisouli[b], Nikos Grammalidis[b], Kosmas Dimitropoulos[b], Charalambos Manesis[c], Chryssy Potsiou[a] and Charalabos Ioannidis[a]

[a]National Technical University of Athens, 9 Iroon Polytechniou St., Athens, Greece; [b]Information Technologies Institute, Centre for Research and Technology Hellas, Thessaloniki, Greece; [c]Geosystems Hellas, Athens, Greece

ABSTRACT

This paper introduces a predictive (selective) 4D modelling framework where only the spatial 3D differences are modelled at the forthcoming time instances, while regions of no significant spatial-temporal alterations remain intact. To accomplish this, initially spatial-temporal analysis is applied between 3D digital models captured at different time instances. So, the creation of dynamic change history maps is made. Change history maps indicate spatial probabilities of regions needed further 3D modelling at forthcoming instances. Thus, change history maps are good examples for a predictive assessment, that is, to localize surfaces within the objects where a high accuracy reconstruction process needs to be activated at the forthcoming time instances. The proposed 4D Land Information Management System (LIMS) is implemented using open interoperable standards based on the CityGML framework. CityGML allows the description of the semantic metadata information and the rights of the land resources. Visualization aspects are also supported to allow easy manipulation, interaction and representation of the 4D LIMS digital parcels and the respective semantic information. The open source 3DCityDB incorporating a PostgreSQL geo-database is used to manage and manipulate 3D data and their semantics. An application is made to detect the change through time of a 3D block of plots in an urban area of Athens, Greece. Starting with an accurate 3D model of the buildings in 1983, a change history map is created using automated dense image matching on aerial photos of 2010. For both time instances meshes are created and through their comparison the changes are detected.

Keywords: Land Information Management System, 4D modelling, Selective modelling, CityGML, Visualization

1. INTRODUCTION

Traditionally, the parcels of a land information management system (LIMS) are 2D spatial objects representing semantic and geometrical properties of the land resources. However, with the recent advances in the area of computer vision and photogrammetry, 3D geospatial information can be handled more efficiently emerging 3D-LIMS architectures. A 3D LIMS is capable of manipulating, storing, querying and analyzing 3D land properties, rights and spatial restrictions [1]. Recently several examples of 3D cadastral systems have been proposed in the literature [2], [3].

Also, several works and projects have been developed in the area of 3D modelling and reconstruction, especially for land information management. Thanks to the amazing success of systems like Google Earth (http://earth.google.com), online virtual globe viewers have become today a favoured means to access geospatial data [4]. The most popular European research initiative is the V-City project (http://vcity.diginext.fr/EN/index.html) where the purpose is to research, develop and validate an innovative system integrating the latest advances in Computer Vision, 3D modelling and Virtual Reality for the rapid and cost-effective reconstruction, visualization and exploitation of complete, large-scale and interactive urban environments. To achieve better realism, 3D maps have been very recently enhanced with video to create a sort of video augmented maps (http://www.bing.com/maps). With such approach, video clips are placed within a 3D environment to give the illusion of looking at the real world from its own point of view. While the displaying of very large data sets of satellite imagery, elevation maps and vector features has been the main research focus for a long time [5], [6], [7], researchers are now interested in more challenging areas such as the rendering of highly detailed oceans [8], forest, or cities [9].

There are several publications about 3D cadastre; however, so far there are no commercial 3D packages available, although some commercial companies like Bentley and ESRI working on developing 3D cadastral applications. Considerable research effort has been focused on 3D reconstruction algorithms like the ones in [10], [11], [12]. In particular, the work of [10] proposes an algorithm based on features found by Harris and Difference-of-Gaussians operators. These features are, first, matched across multiple images, yielding a sparse set of patches associated with salient image regions, then the initial matches are spread to nearby pixels leading to a dense set of patches and, finally, visibility constraints are applied to eliminate incorrect matches. A quantitative evaluation on the Middlebury benchmark shows that this method outperforms all others submitted by that time in terms of both accuracy and completeness [11], [12].

However, due to spatial-temporal alterations of the land resources and the respective rights, 3D LIMS architectures need to be extended towards a 4D representation, that is, 3D geometry plus time [13], [14]. Towards this direction, the European Union has been supporting a research initiative with the main purpose of developing tools and methods for an efficient 4D reconstruction [15], [16]. Four dimensional modelling allows for capturing the dynamic nature of land information. One of the main difficulties of the implementation of a 4D LIMS is the respective complexity arising from the fact that multiple independent 3D modelling processes are needed. Currently, 4D modelling is implemented by a simple aggregation of independent 3D digital models at different time instances. Although such an approach is appropriate for small scale application scenarios, it cannot be suitable for large-scale cases, like the ones encountered in land management. Continuous 3D capturing is an arduous and cost demanding process. For this reason, it is very difficult to create 4D land information management systems, since the respective effort and cost is exponentially increased. To make things worse, the complexity of the modern urban environment requires the ability to handle heterogeneous types of data -both on spatial and temporary levels- and the ability to process a mixture of existing and/or "in-plans" objects with different scales in a single system.

The fourth dimension – time – has been introduced more recently in these systems in order to enable users to "return to the past" and rediscover the same site as it existed several years, or even several centuries, ago. For instance, in such information systems one may investigate, visualize and figure out which was the arrangement of real estate properties and of the rights on them in the past; or one may visualize how an archaeological site looked when it was constructed. Such information can naturally be integrated within virtual globe viewers. Towards this dimension, the European Union supports the 4D-Ch World research initiative, with the purpose of creating an intelligent environment for dynamically creating 4D objects regarding land information systems from data acquiring from the Internet (4D reconstruction wild processing) [16]. The 4D-Ch World mainly focuses on the creation of 4D maps in the wild for personal use, meaning that unstructured Internet data will be exploited. The main limitation of 4D-Ch World, regarding its main research objectives, is that the 4D maps are created from Internet databases (e.g., Flickr) for personal use, and therefore, the precision of the 4D reconstruction is not yet appropriate for the case of land information management systems.

Another, drawback of the current international use of the fourth dimension is that it is limited to the display of different static configurations of geospatial datasets, which are not appropriate in case of land management, where the created 4D maps should be linked with additional spatio-temporal properties as well as semantic metadata necessary for city management applications.

It is argued that even the fourth dimension is not enough for the purpose of urban management, since such systems integrate various types of information, such as financial, architectural, topographical, cadastral, valuation, engineering, of quite different type and detail. For this reason, an additional dimension has been introduced for the case of land information management architecture; scale [17]. The advantage of a 5D multipurpose LIS architecture compared with a 4D one is that it yields a time-scale 3D model representation, as opposed to a time varying 3D modelling (using only the fourth dimension). Multi-scale is a well-known concept in the geo-information technology domain, but considering scale as an additional dimension of geodata, integrated with the other dimensions, is new.

To develop a cost effective scale-time evolved 3D modelling, tools that address the aforementioned difficulties and make 5D modelling a cost effective process are introduced. For this reason, a selective (predictive) multi-dimensional modelling framework is introduced in this paper. The research approach is able to identify regions of interest where 3D modelling takes place at the forthcoming time intervals. In particular, the algorithm detects spatial 3D differences and only regions that undergo significant alterations are 3D modelled, whereas regions of insignificant spatial-temporal changes remain intact. To accomplish this, spatial-temporal analysis is initially applied between 3D digital models captured at different time instances. So, dynamic change history maps are created. Change history maps indicate spatial probabilities of regions requiring further 3D modelling at forthcoming instances. Thus, change history maps are good examples for a predictive assessment, that is, to localize surfaces within the objects where a high fidelity reconstruction process is required at the forthcoming time intervals. The proposed 4D LIMS is implemented using the CityGML framework [18] format, so that the final product is interoperable and universal accessible across various platforms and networks. CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models. It is an application schema for the Geography Markup Language version 3.1.1 (GML3), the extendible international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC) and the ISO TC211. The aim of the development of CityGML is to reach a common definition of the basic entities, attributes, and relations of a 3D city model, allowing the reuse of the same data in different application fields. This is especially important with respect to the cost-effective sustainable maintenance of the proposed4D city models.

An important element of 3D visualization is Level-Of-Detail (LOD).The concept of LOD has been introduced to facilitate visualization of large scenes [19]. The idea is to represent spatial objects that are compatible with the pixel size of the screen, relative to the observer's distance. This permits the original geometric representation to be replaced with a new low-resolution representation. Low-resolution representations require less memory and processing time for rendering and hence speeding-up the visualization process. The different representation is used by the visualization system only if the object is far enough from the user. Closer objects are still represented in their full resolution and if a distant object gets closer (as a result of user navigation), the high-resolution representation is restored. Thus, a smooth transition between low and high levels of detail can be supported [20]. Regarding scale dimension, CityGML supports multiple representations in different LODs (Levels of Detail) simultaneously and generalisation relations between objects in different LODs. CityGML files can (but do not have to) contain multiple representations (and geometries) for each object in different LOD simultaneously. Generalisation relations allow the explicit representation of aggregated objects over different scales.

2. SELECTIVE 3D MODELLING

An innovative 4D modelling framework (3D geometry plus time) is proposed for improving the automation and cost-effectiveness of 3D capturing of land parcels and, at the same time, for provisioning new personalized tools and services to different actors (researchers, engineering, urban planners) involved. Figure 1 presents the overall concept of the proposed selective 3D modelling scheme.

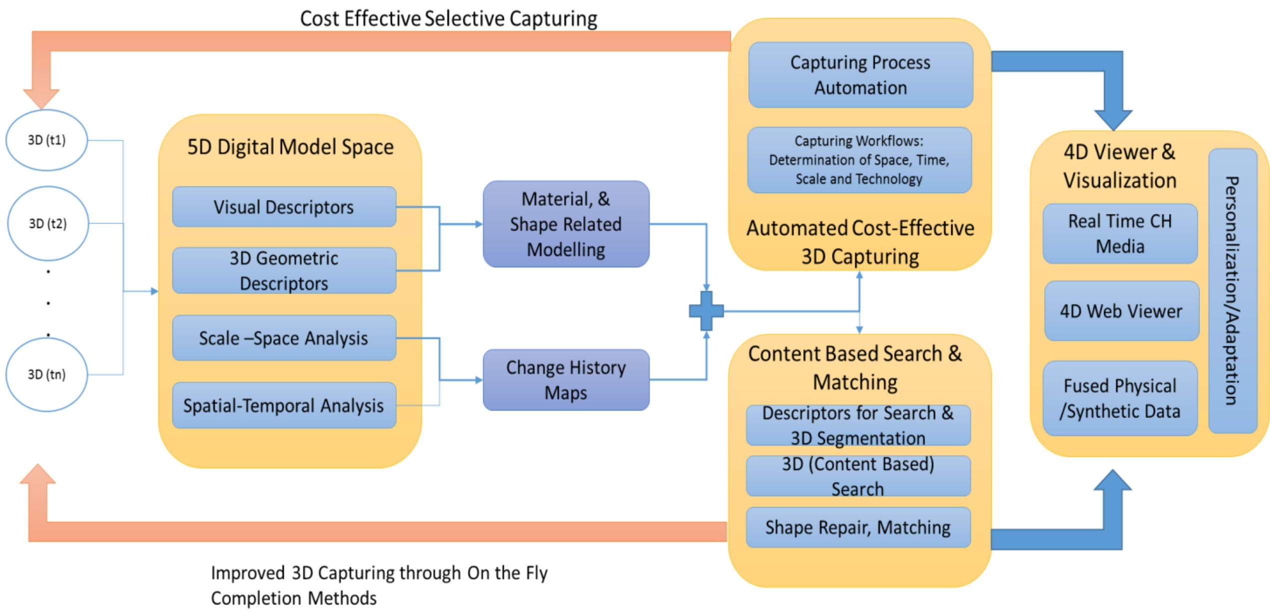

Figure 1. The proposed architecture for the selective (predictive) 3D modelling

Let us suppose that we have several 3D models obtained at different time instances t_1, t_2, …, t_n. The respective 3D models are denoted as $M_1^{3D}, M_2^{3D}, \ldots, M_n^{3D}$. These models have been generated independently one from another.

Therefore, it is clear that the respective computational and manual effort is exponentially increased. To address this difficulty, we introduce a selective (predictive) 3D modelling scheme; only regions that undergo a significant spatial-temporal change are 3D modelled at the next time instances. On the contrary, regions of insignificant change remain intact. For this reason, a spatial temporal analysis is initially applied on the 3D models to indicate the regions of changes. The results are change history maps that indicate the regions where spatial-temporal changes occurred. To reduce the computational time, scale-space analysis is adopted. Specifically the generated 3D models are hierarchically analysed using, for example, Gaussian pyramids and then change history maps are produced. This way, we are able to generate spatial-temporal differences of hierarchical scales.

Another dimension over which the spatial temporal changes are detected is through the exploitation of visual and geometric features extracted by the 3D models. In this way, the spatiotemporal differences are obtained not only from geometrically differences but also from semantic metadata. For example, in the case where the material of a building changes, although the geometric properties remain unchanged, a spatiotemporal interest region is identified.

The outcome of the spatial-temporal analysis is exploited for determining the most appropriate photogrammetric method for the next 3D modelling. Therefore, regions of insignificant changes can be captured with less precise 3D scanning methods, avoiding computational complexity. On the other hand, regions of significant changes are 3D scanned with precise methods, since no significant information is available from previous 3D modelling processes.

The results can be visualized into interoperable viewers, operating based on the CityGML framework. CityGML allows the description of additional semantic metadata information, such as the rights of the land resources. Visualization aspects are also supported to allow easy manipulation, interaction and representation of the 4D LIMS digital parcels and the respective semantic information.

3. CHANGE HISTORY MAPS

Change history maps (Figure 2) detect regions of interest in the 3D space by combining multiple instances of a 3D model $M_1^{3D}, M_2^{3D}, \ldots, M_n^{3D}$. This way, we can support the selective partial acquisition of a land parcel, which significantly accelerates the effort of 3D modelling especially in cases of time varying assets, like the ones encountered in outdoor urban environments. The change history map determines the regions that need to be reconstructed more precisely than others due to temporal changes.

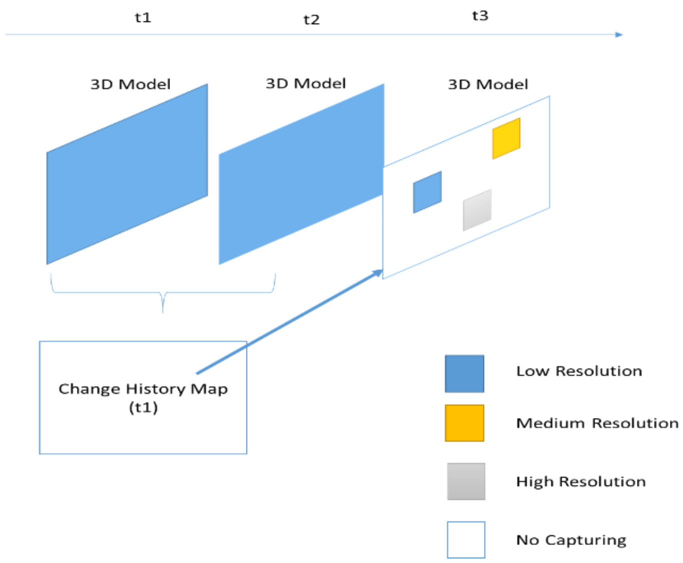

Figure 2. The research approach adopted as regards spatial-temporal analysis

3.1 Geometric History Changes

The first approach for creating the change history maps is through the geometric differences of the 3D models. A simple way is to apply a point by point difference. However, to address noise effects, we initially smooth the 3D models by the application of a Gaussian pyramid filter. Then, the change history maps are created directly from the filtered 3D models. Another important aspect is the appropriate alignment of the 3D models between two different time instances. For this reason, the ICP algorithm is applied between the two examined 3D models in order to align the point clouds of the two time instances. Figure 2 presents the concept of the geometric history maps. The spatial regions where a significant change is encountered are depicted as a rectangle. The three different colours indicate the resolution accuracy of the 3D modelling. This accuracy is directly proportional with the spatial changes obtained from the change history maps. The larger the changes, the bigger the resolution required for the 3D reconstruction.

3.2 Semantic History Changes

Another factor for determining the change history maps is through the metadata information embedded on the 3D models. Each building or a sub-cube within a building is represented by a set of metadata information. This information refers, for example, to financial, architectural, topographical, imagery, cadastral, valuation, engineering, ownership/use rights, etc. In case that the geometric properties of a building have not been changed but the semantic information connected with a part of this building has been changed, a change history map is also created. However, these regions do not imply a new 3D reconstruction process. It determines that the semantic metadata information has been updated.

3.3 Scaled History Maps

Another very important aspect in this research is the scale of representation. This is mainly due to the fact that the scale provides an interface so that the generated digital model to be distributed to various scenarios of users of quite different requirements. One main research aspect in this area is how to create multi-level scale resolutions from partial reconstructions. This is depicted in Figure 3. There is the initial highly accurate model and three digital models at three different time instances. The models are partially acquired using the change history map as derived from the spatial-temporal analysis (section 3.1). By exploiting this information the reconstruction of a multi-level resolution pyramid from the low to high resolution scales may be done.

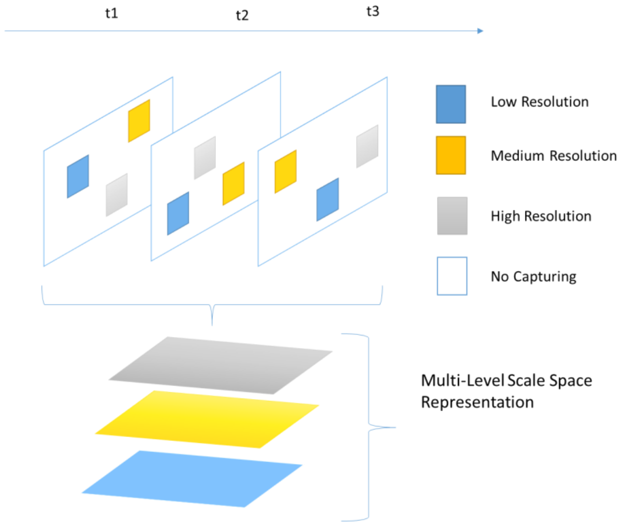

Figure 3. The research approach adopted as regards scale space representation.

The aforementioned approach is elaborated with an example. It is assumed that that a spatial region has been initially modelled with a high accuracy 3D capturing process and that this region goes through a spatial transformation in the following time period. A low resolution fully automated 3D modelling procedure takes place to identify the changes of the initial 3D model. In the case that changes are identified, the low accuracy model of the second time period is improved locally by enhancing the low resolution automatically captured 3D data to high accuracy representations.

4. DATABASE STORAGE AND 4D VISUALIZATION

Using the proposed approach, heterogeneous data associated with different time and scale information will be collected (analysed and semantically enriched), including multiple raster (e.g., terrestrial or aerial images) and vector files (e.g., shapefiles), as well as additional information from the Greek cadastre database. In order to be able to perform specific queries and visualizations using this information, it was decided to first transform them to an extended-CityGML format and semantically enrich them before storing them to a database. For this reason, all information is finally stored in a PostgreSQL/PostGIS database, which is open-source, cross-platform and suitable for handling spatial information. The storage includes both CityGML objects (representing the 3-D information/city models that will be constructed in the project) as well as additional metadata from the Greek cadastre that are linked to the corresponding CityGML objects (e.g. buildings). To this end, an open source software of 3DCityDB (www.3dcitydb.org) [19] will be used, which provides a geo-database, the relational schema, tools to import and export CityGML documents, and some additional tools.

Regarding the fourth-dimension (time), buildings that undergo changes between two consecutive time instants will be associated with two different IDs, while a single ID will be used if no change occurs. The additional time (START/END date) that will be added, as an external reference in the database will be used to encode changes in the time dimension. Future extensions making use of GML temporal objects could be examined, however their support is more suitable for future City GML versions (e.g., v3). For visualization of CityGML models that are produced by database queries, the viewers should support the following features: a) Controls allowing to interactively visualize different time instants and scales, b) Option to display (or highlight) the changes between two models (e.g., from two different time instants), c) Display of additional (descriptive, metadata, etc.) information (e.g., owner, rights)

Regarding the input data formats a number of visualization approaches are available. The first approach is direct visualization of the geometry of CityGML, however often this may not be very efficient. Some free user-friendly interfaces exist for visualizing CityGML models, including the Aristoteles3D viewer (http://www.geo-kiosk.net/explore-3dgeo/ Institute for Cartography and Geoinformation, University of Bonn) and others [19], [21]. Furthermore, QGIS (http://www2.qgis.org/en/site/), the popular open GIS tool, also supports reading and viewing GML files, although it offers limited support for visualization of CityGML objects and their semantic information.

A second approach is to first transform CityGML to a more efficient file format, for which viewers already exist and/or which can be displayed more easily. Most relevant open formats which are interoperable with CityGML and suitable for such an approach are a) KML/COLLADA and b) X3D (the successor of VRML). Both KML and X3D have support for time data/time stamps as well as for data animations. Therefore, suitable exporters of data in these formats can be developed, so that building changes in the time dimension and/or building changes can be properly visualized.

3DCityDB offers the export of CityGML files in the database to KML (https://developers.google.com/kml/documentation/kml_tut) and COLLADA file formats, which ensures the universal access across various platforms and networks. Moreover, Google supports the visualization of KML/COLLADA files in Google Earth and, thus, can be used as a user-friendly interface. Visualization of additional information, such as additional cadastral data from the database can be done using KML features, such as the “Placemark” feature, which is one of the most commonly used features in Google Earth and marks a location on the Earth's surface. The name, a custom icon as well as other labels or geometry elements can also be added to it.

Another option for achieving efficient visualization is by converting the CityGML data to X3D. X3D (http://www.web3d.org/standards) is a royalty-free open standard file format to represent and communicate 3D scenes and objects using XML. Then, a WebGL interface can be used for visualization of CityGML into any WebGL enabled browser (e.g. chrome, firefox, etc.) without need for any plugin. Similar work on visualization of OpenStreetMap data, as well as CityGML or X3D data, was performed using the OSM-W3DS provided by GIScience, Department of Geography, University of Heidelberg (http://xml3d.org/2012/09/openstreetmap-3d-viewer-and-tools/). This software was based on XML3D, a script library (http://xml3d.org/) based on WebGL and JavaScript which does not require a browser plugin. Additionally, first versions of a VRML/X3D to XML3D and a CityGML to XML3D converter have been released.

5. APPLICATION

The case study area is a region consisting of 10 urban blocks in the municipality of Kessariani (Figure 4-left), a suburb in the eastern part of Athens, Greece. The data used for the creation of the 3D models of the study area include two stereo pairs of analogue aerial images, at a scale of approx. 1:7000, taken in 1983 (Figure 4-middle) and in 2010 (Figure 4-right). Between these two periods significant changes have been detected on the buildings since this area was rapidly urbanised. Twelve ground control points are measured for this application; these are points that have remained unchanged in the greater region.

Figure 4. Municipality of Kessariani overlapped with the land parcels (left); the study area (marked with yellow line) in the aerial photos of 1983-1st instance (middle) and 2010-2nd instance (right)

The building outline, the roofs, the outline of other constructions, as well as mass points and lines defining the ground were stereo plotted using the 1983 (1st instance) stereoscopic model, in ImageStation Digital Photogrammetric Workstation. The next step is the creation of the 3D city model, at the level of detail of external volumes. For this purpose, a geo-database was created, with the buildings, the ground points and the lines as feature classes. TIN surfaces were constructed and were then converted in raster digital terrain models (DTMs), which were inserted in the geo-database. Finally, the buildings were extruded to the DTM. The outputs of the procedure are 3D polylines and shapefiles. Figure 5 shows the solid 3D buildings model of the study area.

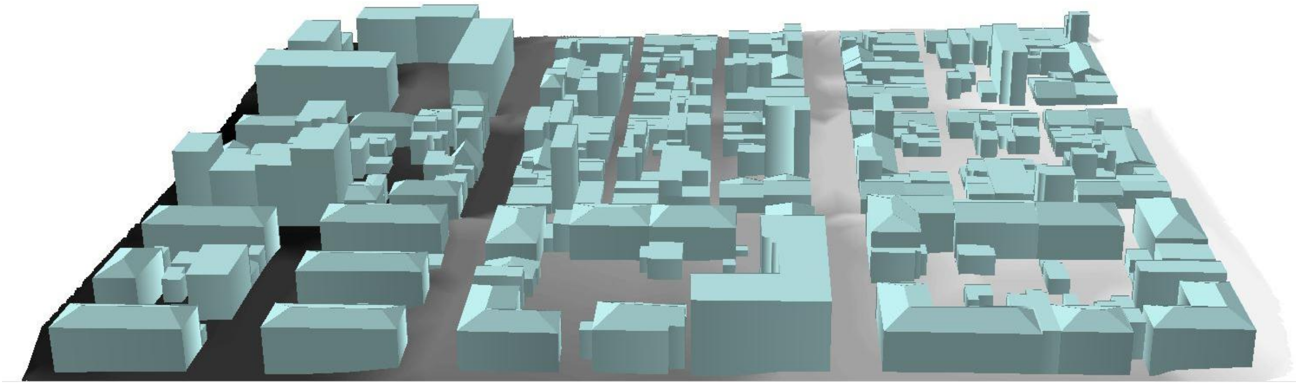

Figure 5. Accurate 3D model of the study area in the 1st time instance (1983)

For the creation of the change history map the application of a fully automated procedure for the creation of the 3D model of the 2nd instance (2010) is needed, so that it will be fast and low cost even if it is of low accuracy. The use of the Dense Image Matching is chosen, which is a Computer Vision technique that can generate a dense Digital Surface Model (DSM) of an area or object relied on feature-based matching (FBM) algorithms is chosen [22]. In the stereo matching methods, a reference and a matching image are required. Dense Image Matching is an image pixel-wise matching process which can find homologies for the total number of pixels of the reference image. The final product is a dense DSM or else a disparity map and a 3D point cloud at resolution in the order of the ground sampling distance (GSD) of the input imagery. The performance of the Dense Stereo Matching depends on many parameters as no general solution to the correspondence problem exists due to ambiguous matches [23]. A variety of constraints (epipolar geometry, left-right consistency, etc) and assumptions (e.g., image brightness constancy and surface smoothness) are applied to achieve accurate and reliable results. Stereo algorithms in Dense Image Matching generally perform four steps [24]:

- matching cost computation; it is a similarity measure of the intensity or colour values for corresponding pixels
- cost aggregation; it is based on the assumption that neighbouring pixels in a support region around each pixel share the same disparity; thus, an aggregation of initial pixel-wise matching costs from the previous step is carried out
- disparity computation; the optimal disparity value is selected for each image pixel; the computation of disparity can be performed with a Local, a Global or a Semi-Global algorithm

- disparity refinement; this step aims to eliminate and recover inaccurate and invalid disparity values at the disparity map. Disparity map may contain outliers due to low texture, noise, and holes which correspond to invalid disparity values by the left-right consistency check.

The eATE (enhanced Automatic Terrain Extraction) dense image matching module of Erdas Imagine 2015 was used to extract an initial georeferenced dense point cloud of the study area using the scanned aerial images of the 2nd instance (2010). The eATE module implements a pixel-by-pixel correlation for high density output terrain products. It is based upon user defined region strategies and parameters that control and guide the terrain processing. Concerning the tuning of the parameters, all pyramids of the using imagery were used in the correlation process to increase the efficiency of the stereo matching algorithm. The matching cost method of Normalized Cross Correlation (NCC) with a 3x3 window size as well as a radiometry threshold in order to force correlation on points in low contrast image areas were used. Also, disparity refinement thresholds were used to refine the correlation and to provide improved sub-pixel results. Finally, a blunder check process of left-right consistency constraint was carried out.

The point cloud of the study area and the surrounding region colored by the elevation and RGB coding are depicted in Figure 6-left; the corresponding mesh-surface of the area is illustrated in Figure 6-right. The point clouds were stored in the LASer (LAS) format. The building' outlines are not accurately shaped with sharp edges; however this is not crucial for the success of the procedure as we only aim to detect the general boundaries of the changes.

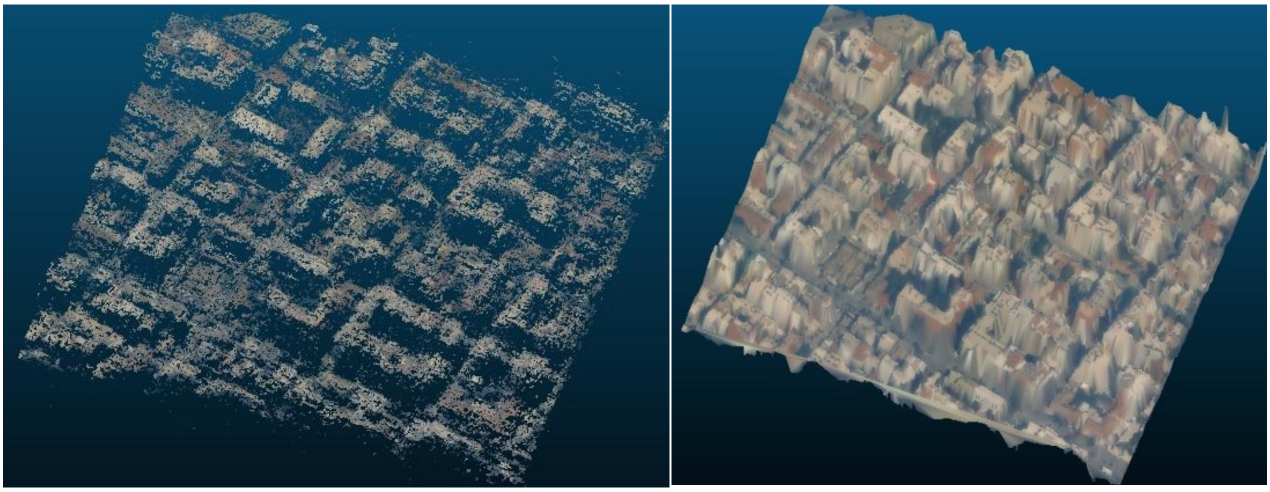

Figure 6. 3D model of the study area in the 2nd time instance (2010) as a result of the dense image matching technique

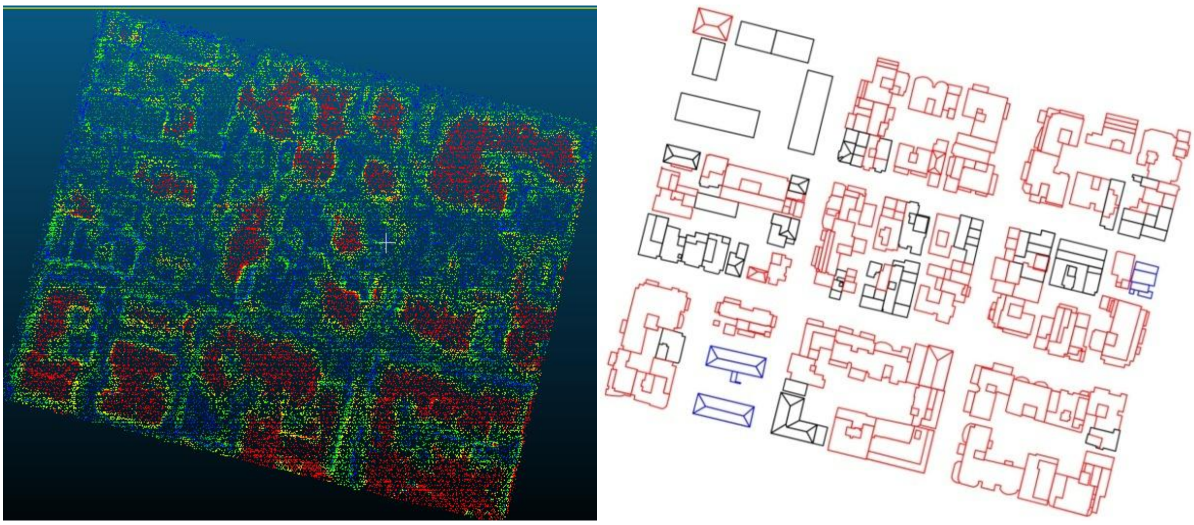

Figure 7. Map illustrating the changes that took place between the two instances in the study area. Left: Coloured point cloud according to the detected height differences; Right: Drawing of the differences as they are derived from the visual control.

In the following a comparison of the geo-databases that have the 3D models of the two instances is made. The two point clouds vary significantly in terms of density, therefore they are transformed into meshes. For the mesh of 2010 the application of a Laplace filter with smoothing factor 0.20 is implemented. Finally, the two meshes are transformed into point clouds of the same density, approximately 0.30 cm, and using a comparison test the areas with changes are located, with a threshold of 4 m so that changes like a new floor can be detected. Figure 7-left shows the result, illustrating the changes detected between the two instances (change history map); the red colored points depict the areas with constructions which have changed in the period between the two instances. Figure 7-right shows a drawing with an accurate representation of the buildings, as it is derived from the comparison of the detailed photogrammetric maps of the two time periods; black buildings are those without any changes, red are the buildings which have changed in the period between the two instances and blue are the buildings which have been demolished and not being replaced. It is obvious that the change history map shows sufficiently well the areas where a new and accurate 3D model should be made, as well as the areas without any changes where no action is needed. Figure 8 shows the final accurate 3D model of the study area, which was completed by local photogrammetric recording of the buildings in the changed areas.

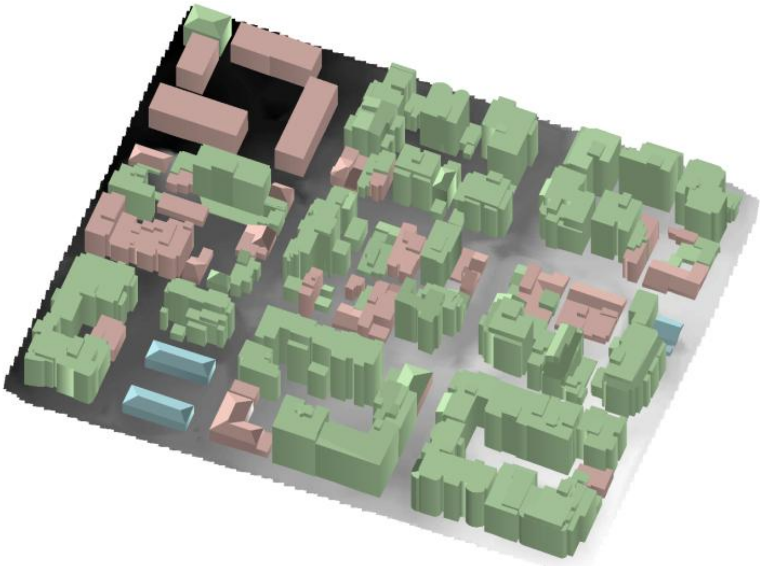

Figure 8. Accurate 3D model of the study area; buildings are coloured according to the period of their construction

6. CONCLUSIONS

The development of a 4D Land Information Management System, which shows the development of a 3D model of an area through time, may have multiple uses and applications. A significant negative factor is the cost of the creation of accurate 3D models in various time instances. The application of the proposed selective (predictive) 4D modelling framework may improve automation and cost-effectiveness of 3D capturing of land parcels and constructions, since only the spatial 3D differences are modelled at the forthcoming time instances, while regions of no significant spatial-temporal alterations remain intact. The use of dense image matching techniques gave satisfactory results according to the accuracy requirements of the procedure. The open source 3DCityDB geo-database incorporating with PostgreSQL seems appropriate to manage and manipulate 3D data and their semantics. The proposed implementation of the CityGML framework allows the description of the semantic metadata information and visualization aspects for easy manipulation and representation of the 4D LIMS.

ACKNOWLEDGEMENTS

This research was conducted in the framework of the research project “5 Dimensional Multi-Purpose Land Information System” (5DMuPLIS). For the Greek side 5DMuPLIS project is co-funded by the EU (European Regional Development Fund/ERDF) and the General Secretariat for Research and Technology (GSRT) under the framework of the Operational Programme "Competitiveness and Entrepreneurship", "Greece-Israel Bilateral R&T Cooperation 2013-2015".

REFERENCES

[1] Stoter, J. E. and Oosterom,P., [3D cadastre in an international context: legal, organizational, and technological aspects], Taylor and Francis (2010).

[2] Mekawy, M., Paasch, J. and Paulsson J., “Integration of 3D Cadastre, 3D Property Formation and BIM in Sweden,” Proc. 4th International Workshop on 3D Cadastres, Dubai, United Arab Emirates (2014).

[3] Felus, Y., Barzani, S., Caine, A., Blumkine, N. and van Oosterom, "Steps towards 3D cadastre and ISO 19152 (LADM) in Israel," Proc. 4th International Workshop on 3D Cadastres, Dubai, United Arab Emirates, 391-409 (2014).

[4] Butler, D.,“Virtual globes: the web-wide world,” Nature 439(7078), 776-778 (2006).

[5] Losasso, F. and Hoppe, H.,“Geometry clipmaps: terrain rendering using nested regular grids,” Proc. SIGGRAPH '04 (2004).

[6] Gobbetti, E., Marton, F., Cignoni, P., di Benedetto, M. and Ganovelli, F., “C-BDAM - Compressed Batched Dynamic Adaptive Meshes for Terrain,” Computer Graphics Forum 25(3) (2006).

[7] Dick, C., Krüger, J. and Westermann, R.,“GPU Ray-Casting for Scalable Terrain Rendering,” Proc. Eurographics, 43-50 (2009).

[8] Bruneton, E., Neyret, F. and Holzschuch, N., “Real-time Realistic Ocean Lighting using Seamless Transitions from Geometry to BRDF,” Computer Graphics Forum 29 (2), 487-496 (2010),

[9] Himmelstein, J., Balet, O., Ganovelli, F., Gobbetti, E., Specht, M., de la Rivière, J.B., Mueller, P., Engels, C., Van Gool, L. and Cavazzini, A., “The V-City Project: towards rapid and cost-effective reconstruction, visualization and exploitation of complete, large-scale and interactive urban environments,” Proc. VAST 2011 - The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (2011).

[10] Furukawa, Y. and Ponce, J., “Accurate, dense, and robust multi-view stereopsis,” IEEE Transactions on Pattern Analysis and Machine Intelligence 32(8) (2010).

[11] Seitz, S. M., Curless, B., Diebel, J., Scharstein, D. and Szeliski, R., “Multi-View Stereo Evaluation,”<http://vision.middlebury.edu/mview/> (2010).

[12] Kazhdan, M., Bolitho, M. and Hoppe, H., “Poisson Surface Reconstruction,” Proc. Eurographics Symposium on Geometry Processing, 10 p. (2006).

[13] Doulamis, A., Doulamis, N., Ioannides, M., Weinlinger, G., Makantasis, K., Protopapadakis, E., Sasntos, P., Julien, M., and Peter, M., "4D reconstruction of the past," Proc. SPIE 1st International Conference on Remote Sensing and Geoinformation of Environment (2013).

[14] Hadjiprocopis, A., Ioannides, M., Wenzel, K., Rothermel, M., Johnsons, P. S., Fritsch, D., Doulamis, A., Protopapadakis, E., Kyriakaki, G., Makantasis, K., Weinlinger, G., Klein, M., Fellner, D., Stork, A. and Santos P., “4D reconstruction of the past: the image retrieval and 3D model construction pipeline”, Proc. SPIE 2nd International Conference on Remote Sensing and Geoinformation of the Environment (2014).

[15] European Union, 4D CH WORD <http://www.4d-ch-world.eu/>

[16] Makantasis, K., Doulamis, A., Doulamis, N. and IoannidesM., “In the wild image retrieval and clustering for 3D cultural heritage landmarks reconstruction,” Multimedia Tools and Applications, August 2014 (2014).

[17] van Oosterom, P. and Stoter, J., “5D data modeling: full integration of 2D/3D space, time and scale dimensions,” Lecture Notes in Computer Science, vol. 6292, 310-324 (2010).

[18] O. G. Consortium, [OpenGIS® City Geography Markup Language (CityGML) Encoding Standard], Eds: Gröger G., Kolbe T., Czerwinski A., Nagel C. (2008).

[19] Clark , J.H., “Hierarchical geometric models for visible surface algorithms," Communications of the ACM 19(10), 547-554 (1976).

[20] van Oosterom, P., Zlatanova, S. and Penninga, F., [Advances in 3D geoinformation systems]. Springer (2008).

[21] Iñaki, I., Izkara, J. L and Delgado, F. J., "From point cloud to web 3D through CityGML," Proc. of 18th international conference on Virtual systems and multimedia (VSMM) (2012).

[22] Nebiker, S., Lack, N. and Deuber, M., “Building Change Detection from Historical Aerial Photographs Using Dense Image Matching and Object-Based Image Analysis,” Remote Sensing., vol. 6, 8310-8336 (2014).

[23] Brown, M., Burschka, D. and Hager, G., “Advances in Computational Stereo,” IEEE Transactions on Pattern Analysis and Machine Intelligence 25(8), 993-1008 (2003).

[24] Scharstein, D. and Szeliski, R., “A taxonomy and evaluation of dense two-frame stereo correspondence algorithms,” International Journal of Computer Vision 47(1), 7-42 (2002).