An efficient framework for spatiotemporal 4D monitoring and management of real property

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Key words: 3D reconstruction, 4D land information systems, Photogrammetry, CityGML, Change History Maps

SUMMARY

In recent years there is a clear tendency towards replacing traditional two-dimensional cadastral and land information systems with three-dimensional ones, because of the significant value introduced by the rich and detailed information residing within 3D models of real property. Considering the fact that real property is subject to frequent change (e.g. in terms of appearance, dimensions, function, use, etc.), the need arises for solutions that enable 4D management and monitoring of real estate assets (i.e. the three dimensions in the course of time). A serious impediment to the development and adoption of such 4D systems is the high amount of resources required (equipment, manual labour, expertise, time) which makes most approaches prohibitively expensive (both computationally and financially) and, ultimately, unrealistic. In this paper we present an ICT framework whose goal is to assist surveyors and other related experts to efficiently reconstruct, monitor and manage real property in four dimensions. The proposed framework is based on three main pillars: (i) 3D modeling of buildings based on sophisticated close range and airborne photogrammetry, a process that was applied in real world settings in the city of Calw in Germany, (ii) rich real property metadata inclusion using the CityGML open information model and (iii) Change History Maps, a concept that allows to exploit unchanged 3D information from past documentations and only focus on regions of change, so as to efficiently effect 4D monitoring of real property. The proposed framework is an endeavor to enable professionals involved in real property monitoring and management to reap the benefits of the progress of 3D modeling techniques as well as of the continuous improvement of open data models pertaining to urban development and real estate.

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1. INTRODUCTION

Three-dimensional land information systems present significant advantages over those that adhere to the conventional two-dimensional paradigm, since they encapsulate a far broader range of information regarding real property. They permit representing the spatial extent of ownership boundaries, as well as registering related property rights in all dimensions. Moreover, the information captured within 3D cadastral data models can be valuable in urban development, utility networks or transportation projects. 3D models of buildings and constructions can be created basically by photogrammetric techniques including airborne and close range photogrammetry. Those models can then be linked to 3D city information models such as CityGML so as to cover a vast range of metadata regarding a particular real estate asset.

Nevertheless, one of the most prominent characteristics of property, construction and land use is temporal variability. In the course of time existing buildings may undergo changes in their facades, roofs, height, use, etc.; also, new buildings are raised whereas existing buildings might be demolished or fundamentally renovated. All these changes have to be documented in a land information system, hence the need for a four-dimensional (4D) system arises. However, repeating the 3D modeling and information acquisition and capturing processes on a periodical (say, e.g., annual) basis is an unrealistic and practically impossible goal, because of the prohibitive amount of computational, financial and other resources (time, labour, expertise, equipment, etc.) needed. Therefore, a more efficient framework for 4D monitoring of real property is essential.

Existing literature mainly focuses on 3D modeling of buildings, while many of the proposed works often revolve around cultural landmarks reconstruction, although the techniques involved are applicable in a general context. Several methods have been proposed: image based methods that exploit photogrammetric aspects in creating high fidelity 3D maps (Hullo et al, 2009; Haala and Rothermel, 2012), photometric stereo that exploits light reflection properties for 3D modeling (Argyriou et al, 2014), real-time depth sensors, such as Kinect, to create cost-effective but of low fidelity RGBD images (Izadi et al, 2011), structured light technologies with the capability of simultaneously capturing 3D geometry and texture (Soile et al., 2013; Orghidan, 2014), and laser scanning for large scale automated 3D reconstruction (Valanis et al., 2009; Hai et al, 2013; Barone et al., 2012; Sitnik and Karaszewski, 2010). Each of these methods presents advantages and drawbacks. Automatic photogrammetric matching techniques present the advantage of creating high fidelity 3D point clouds, but the respective accuracy falls in cases of uniform texture images. Photometric stereo can be applied either for improving the results of image based matching or for reconstructing transparent surfaces, where conventional methods fail. Structured light 3D methods are suitable for high accuracy modeling, but present difficulties in scanning large scale development areas. Finally, 3D laser scanning alone presents the advantage of automation, but it fails in capturing textured point clouds and the cost of 3D modeling is high due to use of expensive terrestrial laser scanners. Recently there have been also published works on 4D cadaster and land information systems (Doner et al., 2008; van Oosterom et al., 2006; Doner et al., 2011; Doner and Biyik, 2013; Vučić et al., 2014; Seifert et al., 2015; Doulamis, Soile, et al., 2015).

In this paper we present an ICT framework to assist surveyors and other related experts to efficiently create a 4D land information system, based on photogrammetry, CityGML information model and Change History Maps, a concept that allows to exploit unchanged 3D information from past documentations and only focus on regions of change. A bird's eye view of the framework is given in Section 2, followed by the detailed description of its components: creating precise 3D models of real property using photogrammetry (Section 3), enriching these models with various kinds of metadata via CityGML (Section 4) and, as a last step, creating the 4D monitoring mechanism (Section 5). Finally, Section 6 concludes the paper.

2. OVERVIEW OF THE FRAMEWORK'S COMPONENTS

A schematic overview of the proposed framework is given in Figure 1. In the core of the proposed framework lies the 3D modeling mechanism. The approach followed is based on photogrammetry and involves many (often demanding) tasks, including acquisition of data from various sources (terrestrial laser scanning, close range and airborne imagery), photogrammetric image registration, geometric reconstruction and texture mapping. This sophisticated approach results in a precise 3D reconstruction of the modeled building, structure or larger area encompassing several buildings. The described approach has been applied in a real world scenario, namely 3D modeling of the Market Square of the city of Calw in Germany. In Section 3 we present the approach along with the obtained results.

To have a complete documentation of real property, the aforementioned captured 3D model must be accompanied by all information that characterizes the building and its use, for example: function, usage, year of construction, roof type, height, number of floors above and below ground, address, rooms and furniture, proprietorial information, rights, obligations and building restrictions, like built-surface ratio, type of coverage, allowable building area and height. This is attained by employing the CityGML open data model in conjunction with an object-relational geospatial database, and linking the corresponding occurrence to the respective 3D model. The related description is provided in Section 4.

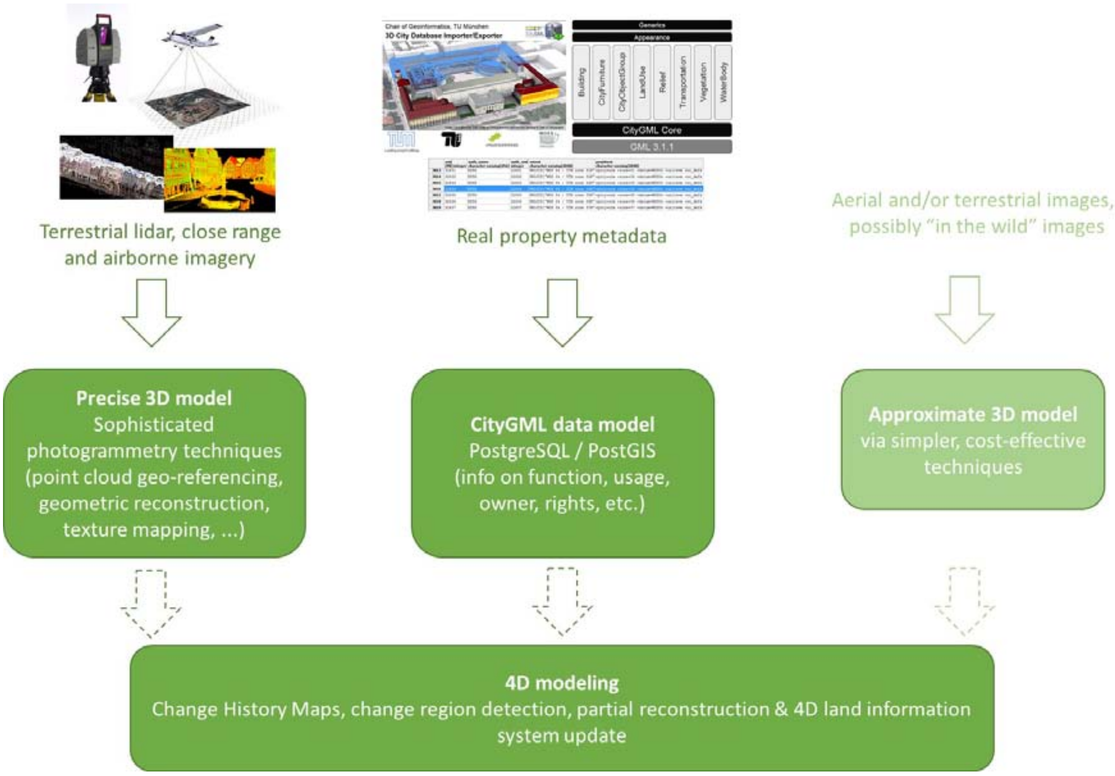

Figure 1. The framework's building blocks.

The aforementioned coupled 3D / CityGML model fully represents a building at a specific point in time. Since repeating the entire process for all buildings every time we need to update the 4D land information system is prohibitively expensive, the Change History Maps concept (described in Section 5) allows detecting those buildings (or parts thereof) that have undergone changes since their last precise documentation and repeat the sophisticated and resource demanding modeling process only for the minimum region required. This makes maintaining an updated 4D monitoring land information system a realistic goal and may yield a valuable outcome for surveyors, engineers, land developers, real estate agents, state registries and other types of stakeholders as well.

3. 3D MODELING OF REAL PROPERTY

Creating a precise 3D model of a building requires obtaining and combining a dense point cloud, texture mapping and geo-referencing information of the building under reconstruction effected via sophisticated laser scanning and photogrammetry techniques. In this Section we describe an approach developed and employed for the reconstruction of the historic Market Square of Calw, a historic medieval town in the northern part of the Black Forest in Germany; we employ this approach to reconstruct 3D photorealistic models of outdoors objects by means of automatically georeferenced High Definition Surveying (HDS) point clouds and still video images. The latter are used to both detect point features which are also found in the 3D HDS point cloud, and, to serve for photorealistic 3D models too.

3.1 Data acquisition, image registration and post-processing

Terrestrial LiDAR has always been popular due to its reliable measurement environment and efficiency. Terrestrial LiDAR includes many types of terrestrial laser scanner (TLS) systems that measure the time of flight (TOF) of the laser, and/or the phase shift of reflected continuous waves (CW). Static terrestrial LiDAR provides a precise measurement environment from which most 3D models can be generated, however the irregular circumstances on which the data is acquired sometimes prevent us from having a complete perspective of the buildings' facades (see Figure 2). These occlusions can be so severe as to force us to repeat the complete scanning of the place due to the complex involved registration process. Combining static LiDAR with other systems, such as close range and airborne photogrammetry, can offer a significant advantage. In addition, airborne images are required for point cloud acquisition of the roof landscapes which cannot be seen by a terrestrial laser scanner. An integrated GPS/INS system aboard is used for directly georeferencing the images, thus the local point cloud can be automatically georeferenced.

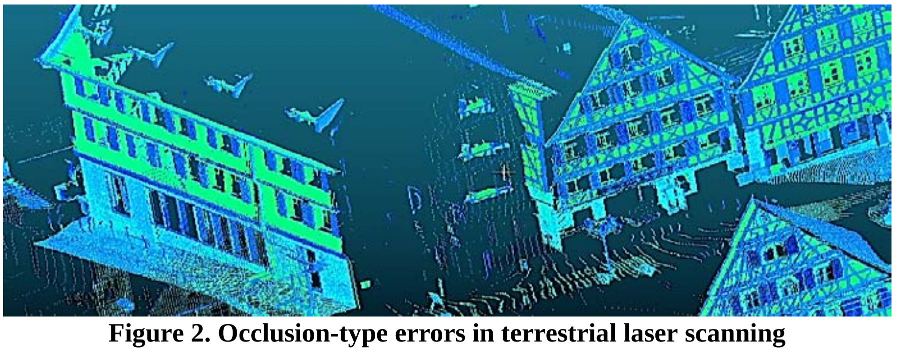

Figure 2. Occlusion-type errors in terrestrial laser scanning

3.1.1 Data Collection

Terrestrial laser scanning data: To begin with, point clouds can be collected using a laser scanner such as the Leica HDS3000 TLS. Figure 3 depicts the chosen buildings with their facades surrounding the square.

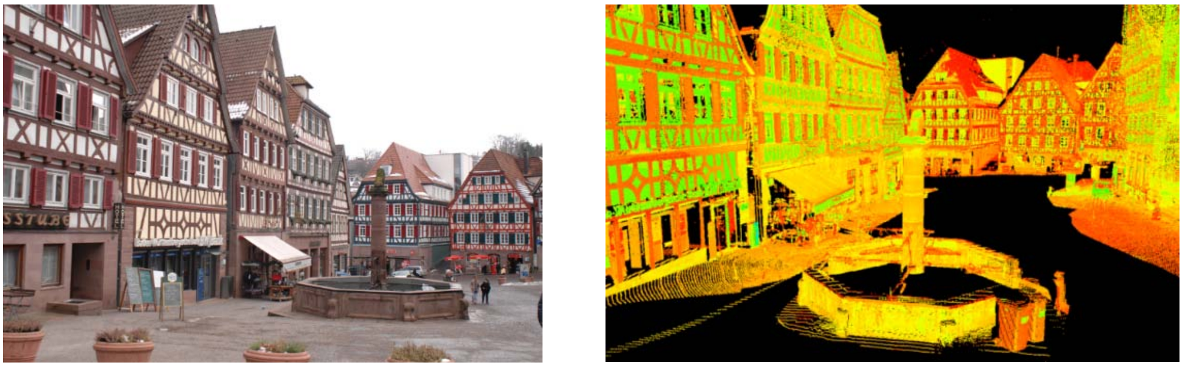

Figure 3. (a) Calw Market Square, Lower Part, (b) Point Cloud

Close range photogrammetric image data: Digital photogrammetric image data pertain to both close range and airborne photogrammetry. Regarding the former, the acquisition of digital images concerns the desired coverage of main facades, switching from higher to lower resolution perspectives following a technique called “One Panorama Each Step” (Figure 4). This method is a key strategy to optimally connect RGB low resolution laser images. Figure 5 shows the aforementioned sequence for reconstructing main facades in the model space. The images have to be taken with high overlap in each step, around 80% (Figure 5 right).

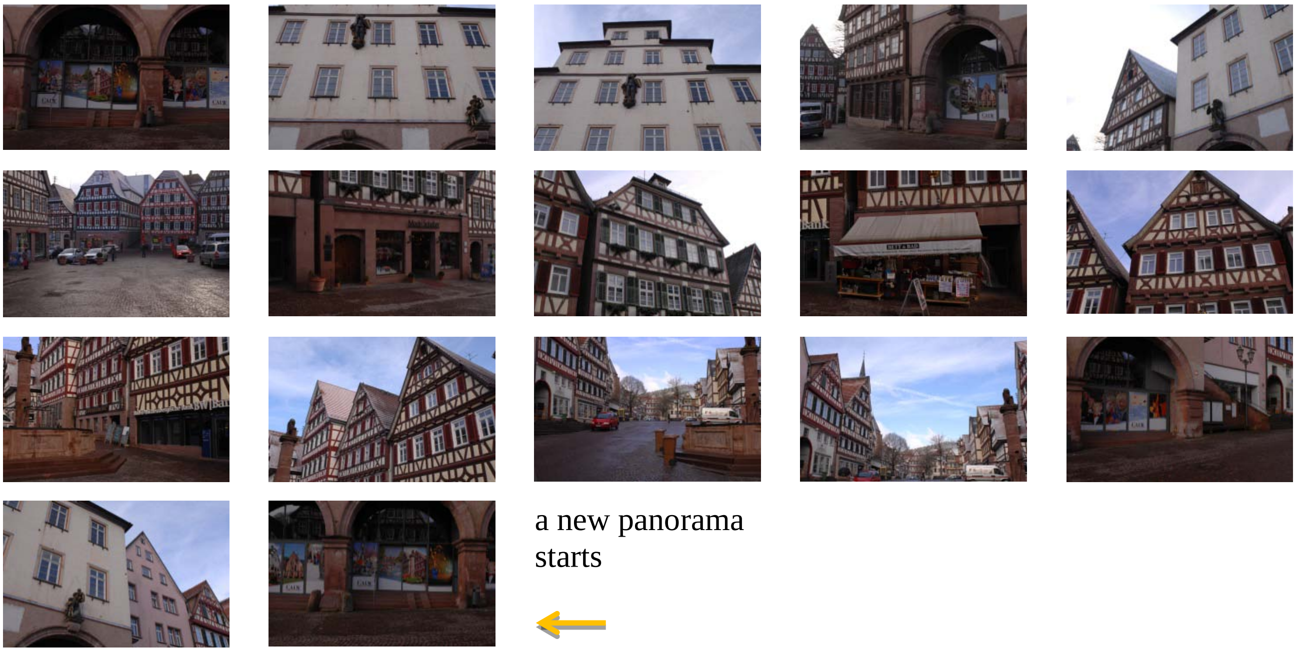

Figure 4. “One Panorama Each Step” Acquisition Strategy

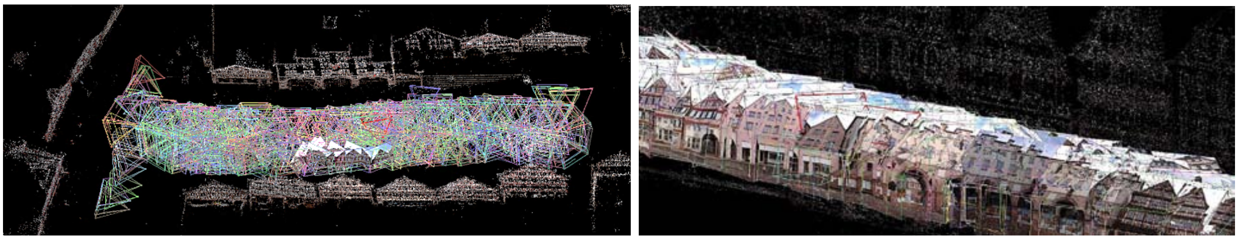

Figure 5. “One Panorama Each Step” Acquisition Strategy. Left: A Sequence. Right: 80% overlap in each step.

3.1.2 Registration of photogrammetric images and Dense Image Matching

The registration with regard to the laser point cloud into a local reference system (typically a laser station) can be performed automatically or semi-automatically.
The task of **automatic registration** is to assign corresponding points between the model and the object space. Automatic registration of digital images data into a local reference system is based on three main steps:

- Robust pairwise feature extraction and matching from all digital images and the generated laser RGB image

- Sparse 3D reconstruction of ties (model space) via Bundle Adjustment (Figure 6)
- Data transformation from model to object space after parameter estimation using detected control points from the previous two steps.

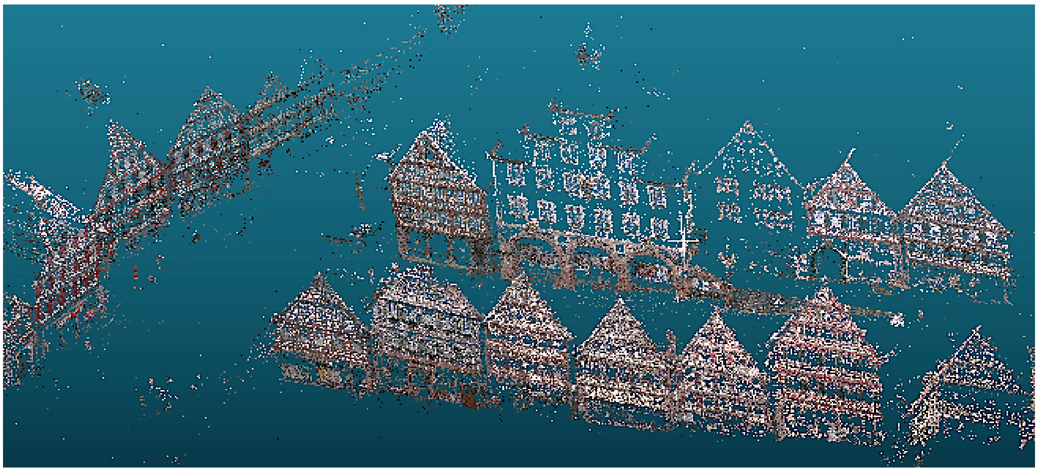

Figure 6. Sparse 3D Reconstruction of Main Facades in Model Space

The registration is visualized using a cloud to cloud distances scalar field, with the registered cloud as the reference. This method computes the distance from each laser point to its closest point from the registered cloud (Figure 7a). Figure 7b shows the main facades having the smallest distances as expected from a good alignment.

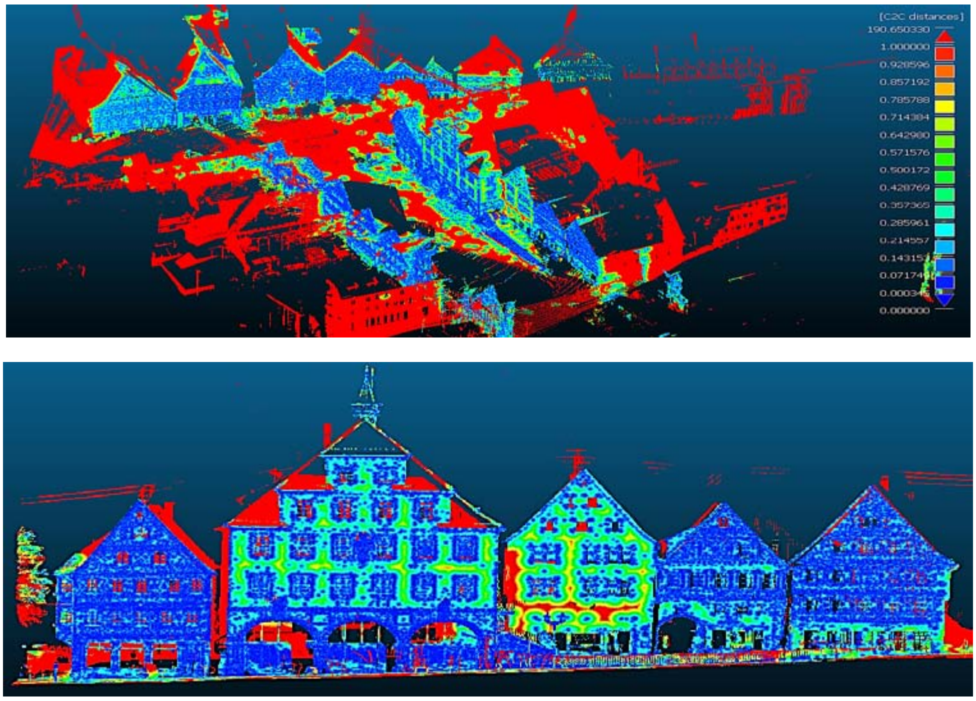

Figure 7. (a) Top: Cloud to cloud distances scalar field; (b) Bottom: Map of target areas

An efficient alternative to the presented automatic method is **semi-automatic** one, i.e. the **Iterative Closest Point** Algorithm (ICP), which requires the clouds to be already coarsely aligned to each other manually. The ICP algorithm then refines the registration by minimizing the distances between the corresponding point clouds.

The resulting Exterior Orientation and calibration parameters from the Bundle Adjustment are used for Dense Image Matching, based on the Semi-Global Matching strategy implemented in the SURE software (Rothermel et al., 2012). This step is necessary to register the dense imagery point cloud with the laser point cloud with the objective of correcting occlusions in the building facades (Figure 8).

Figure 8. Very dense 3D reconstruction using Absolute Oriented Images

3.1.3 Airborne Photographs and Georeferencing

Terrestrial Laser Scanning is fast and efficient and delivers point clouds of superior quality but suffers from occlusions, especially in inclined viewing directions. Close range photogrammetry covers panoramas and delivers very dense point clouds of excellent quality but suffers from lack of information for the roofs. Therefore, airborne imagery ideally complements the aforementioned two data sources. In the described developments a total of 6 images with 10cm ground sampling resolution (GSD) have been processed. With the already oriented aerial photographs georeferenced point clouds in Gauss-Krüger coordinates are obtained. A follow-up semi-automatic registration via the ICP algorithm is used for georeferencing all available point clouds (Figure 9).

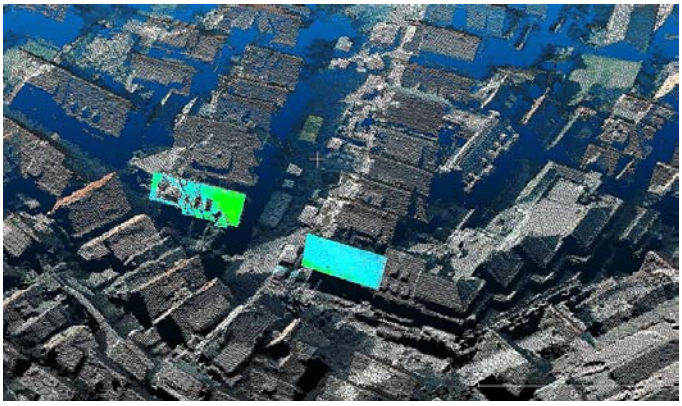

Figure 9. Automatic reconstruction of Point Clouds of the roof landscapes using airborne photographs. In green the types of region from the TLS Point Clouds for georeferencing via ICP

Finally, data acquisition and point cloud alignment are followed by a series of post-processing steps. Occlusions in the laser data can be corrected using close range photogrammetry and missing visual information from roofs is provided by the airborne data. Another post-processing step pertains to the enhancement of the color of the laser point cloud. The laser color might contrast with that from the digital camera system. In order to improve the definition of the cloud, we can project the TLS point cloud into the absolutely oriented close range imagery.

3.2 3D modeling of real property

Creating a photorealistic 3D model involves two main parts: geometric reconstruction and texture mapping.

Geometric reconstruction aims to fit standard surfaces to the point cloud. Basic geometric shapes are patches, cylinders, spheres, cones, elbows and line segments. In this project we use the software package Cyclone, from Leica Geosystems, to mainly fit patches and corners, as most of the reconstructed objects are facades. A patch can be used to reconstruct the walls while the corners are set at the point of intersection of corresponding planes.
A good cloud segmentation and a high level of model detail can speed up the process (Figure 10).

Figure 10. 3D Model of Calw Market Square.

Texture mapping concerns the image perspective, exposure time and occlusions in the camera field of view. The image perspective problem can be solved using the 8 parameters projective transformation, while occlusions are fixed manually via extraction and mapping. Corrections of perspective for texture mapping are performed using the Trimble Sketchup software (http://www.sketchup.com/). If the frontal view of an object is not appropriate or even available due to possible occlusions, a lateral view can free the image from the occlusion at an acceptable cost in texture mapping (perspective effect, see Figure 11). Finally, some results of the texture mapping process delivering photorealistic 3D models are given in Figure 12.

Figure 11. Perspective effect in texture mapping

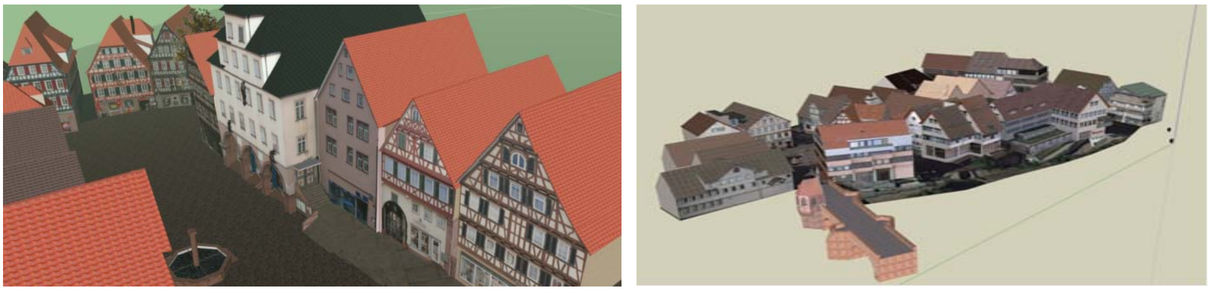

Figure 12. Calw Market Square buildings – Photorealistic 3D building models

4. CITYGML FOR REAL PROPERTY METADATA

To have a complete documentation of real property, the above described reconstructed 3D model must be accompanied by all information that characterizes the building and its use, including, e.g.: function, usage, year of construction, roof type, height, number of floors above and below ground, address, rooms and furniture, proprietorial information, rights, obligations and building restrictions, like built-surface ratio, type of coverage, allowable building area and height. To this end, we utilize a CityGML-based module. CityGML is an open data model for the storage and exchange of virtual 3D models of cities and landscapes. This standard is based on the Geography Markup Language 3 (GML3) schema (XML format) issued by the Open Geospatial Consortium (OGC) and ISO TC211. CityGML covers the geometrical, topological, semantic and appearance aspects of 3D city models. Furthermore, it differentiates between five consecutive Levels of Detail (LoD). All spatial objects can be represented by five different LoDs, from LoD0 to LoD4, ranging from simple shells to finely detailed models (Gröger et al., 2008).

A CityGML model is accompanied by an object-relational geospatial database (PostgreSQL w/ PostGIS 2.0 extension) and the schema of the database is structured in the format of the 3D City Database (3DCityDB). 3DCityDB is a geo database that allows for storage, management and representation of 3D city (CityGML) models of each LoD (Kolbe et al., 2009). This schema includes 60 tables, which are related to the Coordinate Reference System (CRS), the landscape, the buildings and the city objects of the study area. It's an extendable schema that also enables the inclusion of proprietorial information and building restrictions.

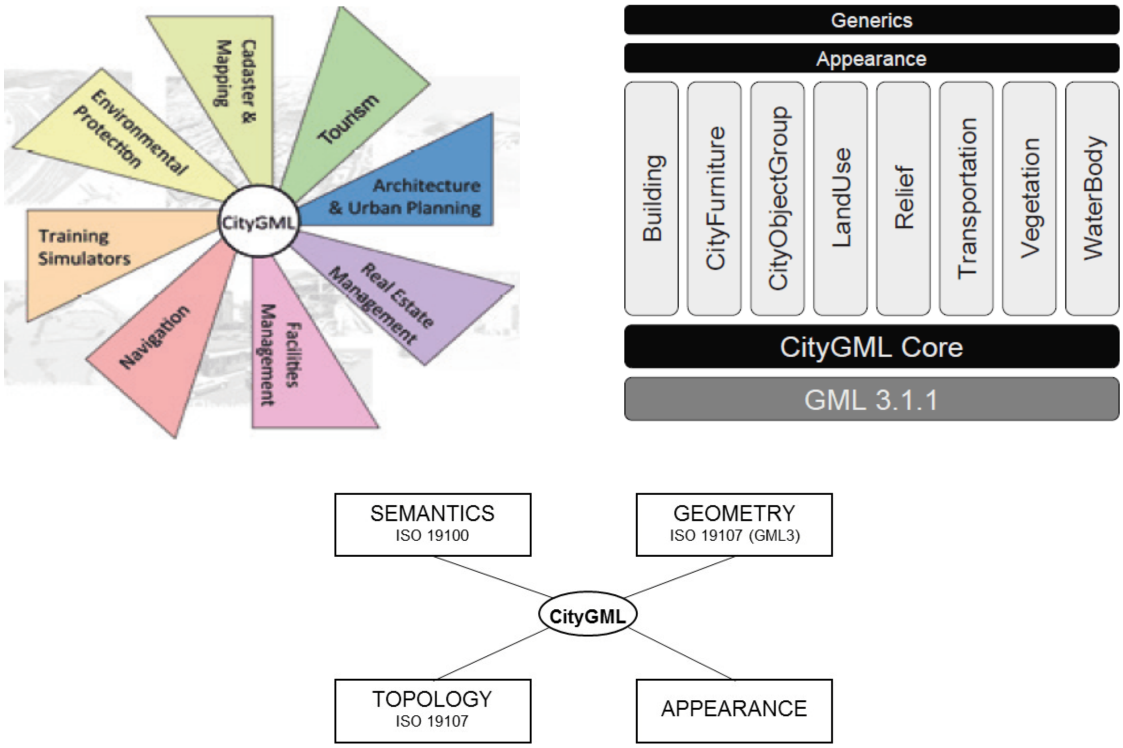

Figure 13. CityGML: (a) Related fields and applications, (b) Structure, (c) Aspects it encompasses

Having created a new empty database in PostgreSQL/PostGIS, this database is then connected to the 3DCityDB package in order to get structured according to the 3DCityDB/CityGML schema and define the CRS (e.g. for Athens, Greece: SRID = 32634, WGS84/UTM zone 34N). A database report is then generated. The report contains the entities of the database and the number of elements for each entity, which for empty databases is expectedly zero. The existing 3D model is also connected to the structured database within the 3DCityDB. Subsequently, the database is populated with the appropriate spatial data, like the geometrical envelope and the topological relations, of all the objects' parts of the connected 3D city model and the aforementioned data types that are related to the buildings' function, usage, year of construction or demolition, roof type, height, storeys above and below ground, address, rooms and furniture, proprietorial information, like owner, rights, obligations and building restrictions, like built-surface ratio, type of coverage, allowable building area and height, as well as information about the land use, the vegetation and waterbodies, other city objects and their surfaces and textures. Then, the updated database is connected again to the 3DCityDB. In this stage, the database report, which is generated again, shows certain entities with non-zero elements. Prior to the exportation of the final files, certain parameters are defined in the 3DCityDB package, with regard to the appearance of the buildings and the other city objects (Kunde et al., 2013).

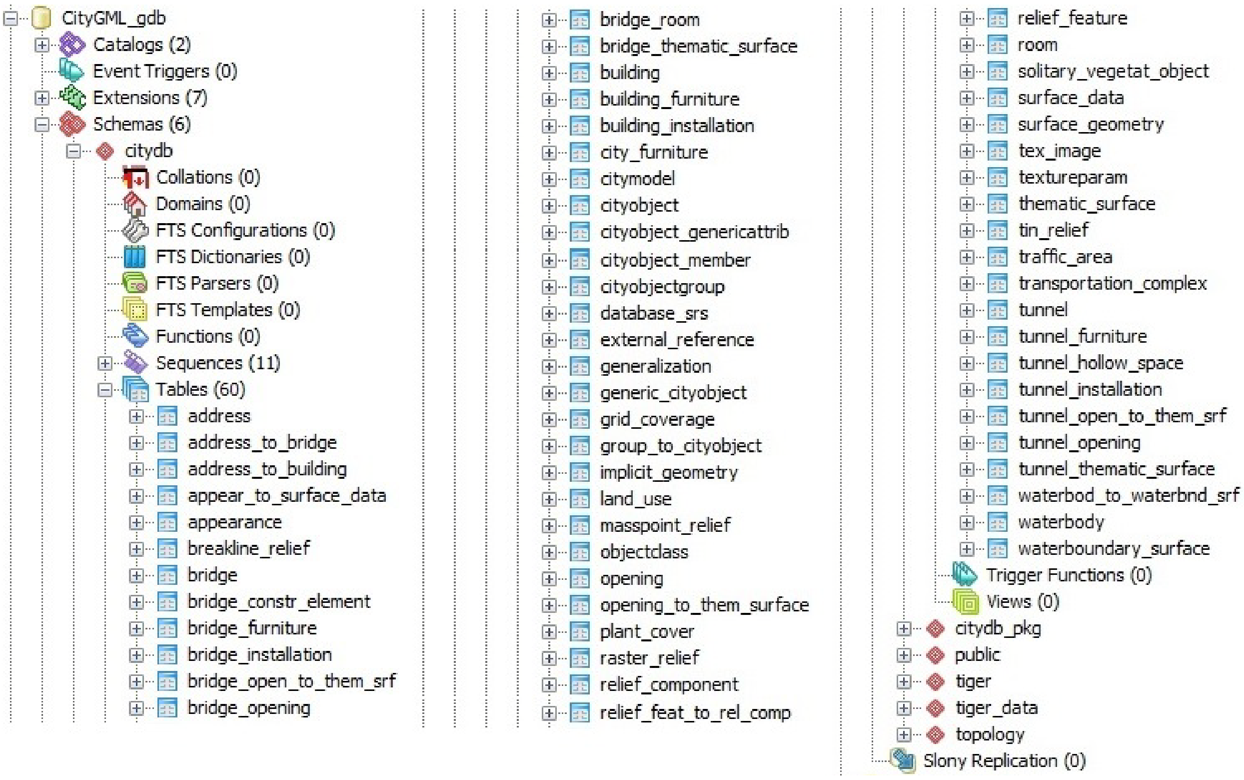

Figure 14. 3DCityDB schema of the database

The final files that are exported by 3DCityDB are a CityGML file in GML3 format, which includes spatial and descriptive data from the database and KML/COLLADA files that allow for visualization in Google Earth environment. KML/COLLADA files are also enriched with information by the relational database and visualize all the objects of the 3D city model in several types: their footprint on the ground, their volume, the analytical geometry of their surfaces and the different colors per type of surface, their surfaces' textures. It is possible for a user, upon a selection of a visualized building or a city object in Google Earth, to appear a pop-up balloon next to it with some information about it from the database. This procedure facilitates engineers who operate within the urban planning, the land management, registry and other relevant fields, offering data organization. It also supports SQL and thus allows for analysis tasks, complex queries on the database, data and schema validation and spatial data management and mining through the PostGIS extension. Finally, each GML3 file is associated through a unique identifier with a distinct building whose 3D model has been acquired by the process described in Section 3.

5. CHANGE HISTORY MAPS: AN EFFICIENT APPROACH TO 4D MONITORING

Ideally, being able to produce 3D modeling results of real property for different time periods would lead to a consistent 4D "reconstruction". However, this is very difficult to attain because creating a 3D model, let alone a precise one, requires a large amount of resources (equipment, man effort, time, etc.) making the process an expensive (both computationally and financially), arduous and practically impossible task. To address these limitations, a concept is proposed that transforms the time and resource demanding process of 4D modeling into a cost-effective framework able to be implemented in large scale scenarios (Doulamis et al., 2015). The approach is based on exploiting information of 3D reconstruction from previous time instances.

Change history maps detect regions of interest in the 3D space by combining multiple instances of a 3D model. This way, we can support the selective partial acquisition of a real estate asset, which significantly accelerates the effort of 3D modeling. The change history map determines the regions that need to be reconstructed more precisely than others due to temporal changes.

The first approach for creating 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, 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 15 presents the concept of the geometric change history maps. The spatial regions where a significant change is encountered are depicted as gray-colored cubes.

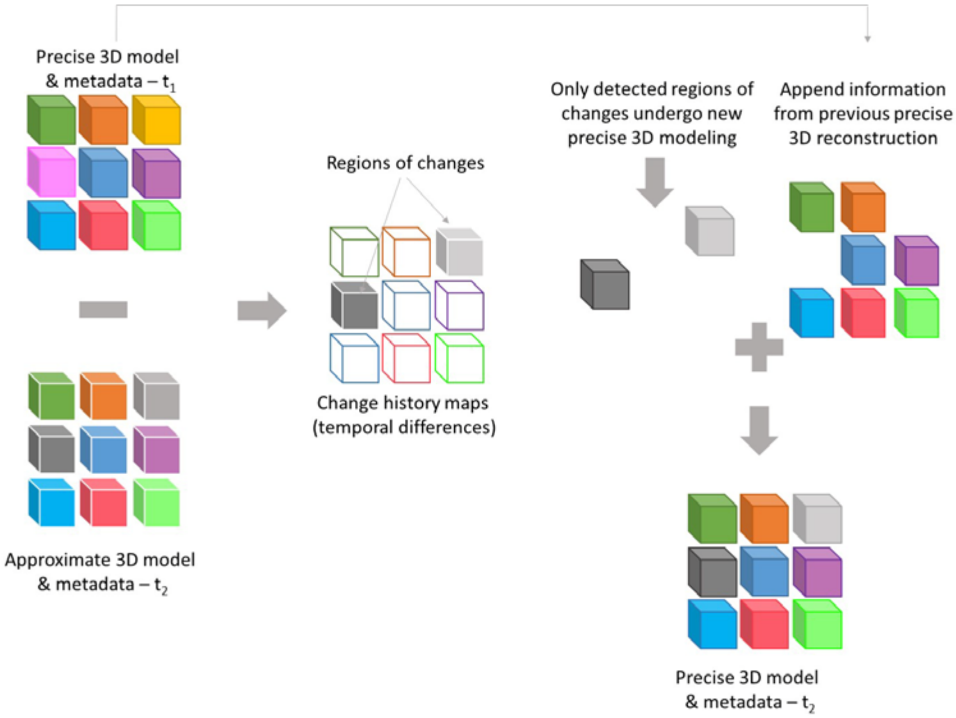

Figure 15. The proposed 4D modeling approach based on change history maps and partial reconstruction.

Another factor for determining the change history maps is through the CityGML metadata information accompanying the 3D models, as described in Section 4. In case that the geometric properties of a part of the real property asset have not been changed but the semantic information connected with a part of the resource has, a change history map is also created. However, this does not imply a new 3D reconstruction process is required, but instead specifies that the semantic metadata information has been updated.

The concept can be further explained via a use case. Let's assume that a spatial region in a real estate asset under discussion has been initially modelled with a high accuracy 3D capturing process (such as the one described in Section 3) and that this region goes through a spatial transformation in the following time period. A low resolution 3D modeling procedure (e.g. based on aerial/terrestrial images or even "in the wild" images available in online collections) takes place to identify the changes of the initial 3D model. If changes are identified, the low accuracy model of the later time period is improved locally by enhancing the low resolution automatically captured 3D data to high accuracy representations. What's more, in cases where significant changes are detected, this process will highlight the specific regions for which the process of data acquisition, processing and 3D modeling has to be repeated, instead of having to perform the entire project for the full scale of the modeled site. This approach therefore makes 4D modeling a more realistic process by significantly reducing the computational (and other) costs involved, while retaining the quality of the reconstruction.

6. CONCLUSION

Real property monitoring and management can reap significant benefits by the progress of 3D modeling techniques as well as the continuous improvement of open data models pertaining to urban development and real estate. Despite the clear need for 4D cadastral and land information systems that will be capable of capturing the changes buildings undergo in the course of time, the periodic repetition of sophisticated 3D reconstruction and metadata collection processes is prohibitively expensive (both computationally and financially) and, ultimately, unrealistic. In this paper, we proposed a framework that leverages 3D information from previous photogrammetry-based modeling instances to create 3D models of real property for new time points focusing only on those cases and regions where changes have occurred. The proposed efficient framework is enabled by the Change History Maps concept which also covers potential changes in semantic metadata of real property, as documented in PostgreSQL databases using the CityGML model. We think that the presented approach can provide significant added value in the increasingly popular research field of 4D land information systems and real property photorealistic reconstruction.

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