Value added 3D modelling of Laser scanned and photogrammetric data.

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Abstract
Advances in both terrestrial laser scanning (TLS) hardware and photogrammetric solutions combined are creating increasingly more precise and rich 3D coloured data. In this article we show how Computer Graphics and Visualization techniques have played an important role in managing, modelling, and fusing data in an increasing myriad of applications such as environmental surveying, structure analysis, architecture and archaeology. Specifically we describe the typical modelling steps involved in the creation of a range of digital documents provided by the 3D digitization company Artescan to customers. In addition, we also address and discuss some limitations of existing software solutions and outline potential future research opportunities.

Keywords
laser scanning, photogrammetry, 3D modelling, CAD, orthophoto, virtual reality.

1. INTRODUCTION

Since the development of the first solid state ruby 'laser' (Light Amplification by the Stimulated Emission of Radiation) in the early 60s, progressive technological advances have allowed the widespread introduction of laser based surveying for engineering, construction, and environmental sciences [Large09].

While Light Detection And Ranging (LiDAR) allows for the rapid acquisition and creation of digital models of large surface areas of the Earth in Airborne Laser Scanning (ALS), terrestrial laser scanning enables the acquisition of local fine level details of structures such as faults in buildings. In this article we focus on the role of computer graphics and visualization in modelling procedures of terrestrial laser scanning data.

In section 2 we highlight the benefits of the use of 3D laser scanning technology in various applications and present considerations on data processing and management. In section 3 we provide an overview of the typical steps required in the modelling pipeline to create various types of digital documents, for instance topographical charts, 2D cross-section plans of buildings or 3D textured models. In section 4 we illustrate some of the digital documents produced for customers for their respective application areas. Finally in section 5 we outline desirable solutions that would help the modelling process.

2. BACKGROUND

In this section we focus on the following aspects:

- Mobility and safety benefits of laser scanning
- High data integrity
- Scanner operation
- New applications
- Data processing
- Data management

Mobility and safety benefits of laser scanning

Increasingly portable Laser scanning equipment have facilitated the task of model acquisition in for example topographical surveying and archaeology (Figure 1).

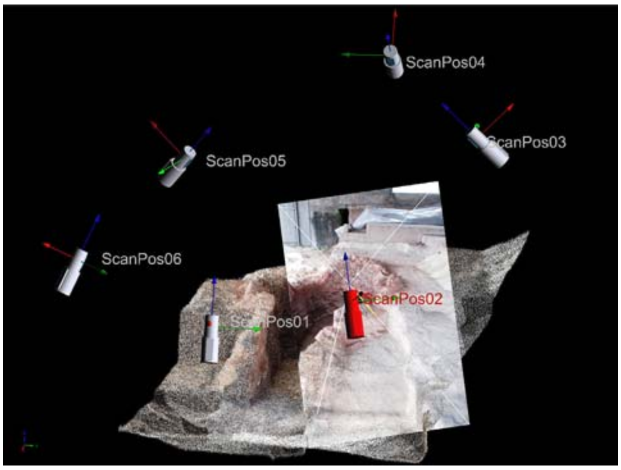


Figure 1: Point cloud rendering and photogrammetric image from one of the several laser scanner positions (in red) used for the digitization of the roman oven of the Quinta do Rouxinol, Seixal, Portugal.

As non-contact technologies, laser scanning and photogrammetry provide significant safety benefits for the operator when for example making measurements of hazardous sites such as a hydropower substation (Figure 2) or of sites with difficult access such as dams (Figure 3 and Figure 8). In addition class I laser scanners are totally harmless to humans, unlike higher level laser classes [IEC08] which require some precautionary logistics for a safe site acquisition.

Figure 2: Hydropower substation 3D surveying and modelling of the Cahora Bassa dam in Mozambique. Point clouds have been coloured by projecting the photogrammetrically processed acquired images.

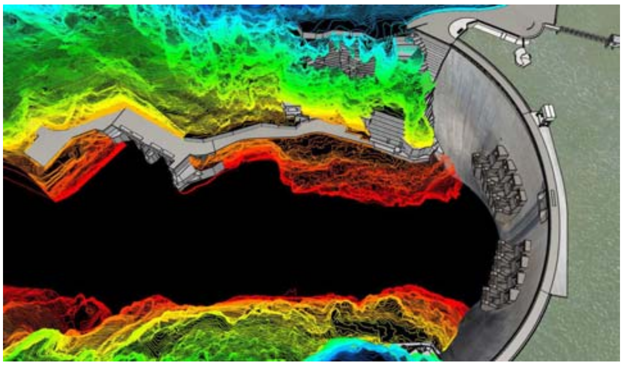


Figure 3: Contour lines extracted from point cloud data and structure analysis of the Cahora Bassa dam.

As an active sensor and unlike passive photographic cameras that capture the existing light, laser scanners analyse the reflected light from an emitted laser beam. This characteristic enables the acquisition of data in the absence of light, for instance in underground tunnels (Figure 6).

High data integrity

Another advantage of 3D laser scanning and modelling is the high data integrity associated with acquiring the full 3D model that enables individual 2D section analysis to be globally coherent, as shown in Figure 4 and Figure 5 with the 3D model of the Palácio de Monserrate, Sintra, Portugal.

Figure 4: Cross-section cut of the Monserrate 3D model.

By acquiring the full 3D model, many future surveys need only analyse a portion of the captured data, avoiding errors of individual surveys.

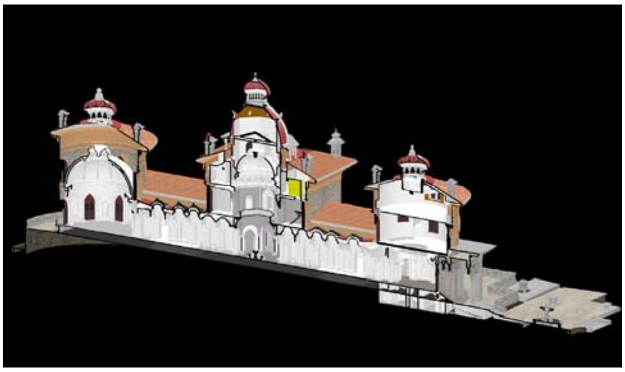


Figure 5: Longitudinal profile of the Monserrate 3D model.

These individual errors are typically due to the subjective nature of pinpointing the exact location of the features one wishes to measure. Specifically when using the optical scope of a *total station measurement device* in traditional surveying, there is a degree of freedom for the operator to choose the location of the measurement for a feature, whereas with laser scanning the decisions of placing a measurement follow a known sampling error.

Scanner operation

Laser scanners such as the Riegl Z360i (Figure 8) enable one to set the vertical and horizontal sampling intervals defined in angle increments of for example 1/100 of a degree within a vertical range of +/- 45° and a horizontal range of +/- 180°. The scanner thus provides points expressed in either polar coordinates with a range depth and intensity or Cartesian coordinates. The depth is typically calculated with the time of flight of the returned echo pulse. It is important to note that with this technology for a given angle pair only one point is captured, thus features such as foliage can hinder the acquisition of partially covered man built structures. New online waveform analysis laser scanners such as the Riegl VZ400 solve this problem by recording multiple echoes, thus providing multiple depth points for a given angle pair. The accuracy of the measurement is in the range of 3 to 5 mm.

Figure 6: Site reference frames: Scanner position local reference frames on surface and underground, with transformations for both for the project reference frame. Site survey of Caneiro do Rio Tinto, Portugal.

A digital camera can be mounted on top of scanner, enabling the automatic acquisition of images from each scan position. In addition the scanner can be coupled with a global navigation satellite system thus providing georeferenced scanned positions. This capability will be further discussed in section 3. The scanner thus provides local reference frames for the camera and laser scanner head for each scan position, a project reference frame and global reference frame (Figure 6).

New applications

With advances in technology more types of features can be acquired, and modelled. A typical laser scan captures features of interest and unintended features that can be studied in the future. This richness of data on the one hand opens up a range of new applications to study these acquired features of interest, on the other hand, extraneous features in the data foster research in algorithms to automatically remove them. In photogrammetry and remote sensing some of the challenges remain the same at different range scales and data sources (satellite imagery, aerial imagery and LiDAR, terrestrial laser scanning and close range photogrammetry). For example, the automatic segmentation and classification of features in the data such as roads, buildings, cars, people and vegetation. In laser scanning, both aerial and terrestrial, segmentation is considered as a means to organize points into homogeneous groups whereas classification is considered as a means to provide a class attribute for each segment in the context of a specific application [Pfeiffer07].

Data processing

Several commercial and open source solutions exist for geometric processing of large scanned data sets. It is beyond the scope of this article to make a detailed review of such systems. However, for a comprehensive list of available resources we refer the reader to [ISPRS09].

There is a large set of functions related with processing of laser scanner acquired data, and typically each solution is optimized for a particular goal or functionality. In the following items we describe processing functions focusing on open source examples.

Importing sets of point clouds and meshes, visualizing and manipulating them are basic functionalities, which are implemented in most of the related software. However considerations regarding whether a complete or partial model can be visualized during editing are made in the data management section.

Alignment tools normally use the well known iterative closest point (ICP) algorithm or as in the case of Scanalyze, one of it's variants [Rusinkiewicz01]. This system originated from Digital Michelangelo Project [Levoy00] and was designed for aligning and merging range data. An alternative mesh alignment approach for robust surface registration [Aiger08] is adopted in MeshLab, an open source editing software for meshes and also point clouds [Cignoni08].

Merging tools are also implemented in Scanalyze and Meshlab mentioned above. In the former automatic merging uses the VRIP [Curless96] algorithm, whereas the later uses Poisson surface reconstruction.

Surface reconstruction from point clouds [Amenta98] is followed by mesh *cleaning*, mesh *decimation* and mesh *smoothing*. Paraview [Ahrens05] is a system that relies on the VTK toolkit [Schroeder06] and offers a powerful set of filters to perform decimation, Delaunay triangulations, subdivision, smoothing and mesh fairing. While these algorithms take advantage of parallel processing and rendering, interactive editing relies only on discrete level of details of coarser volume representations. Alternatively Meshlab provides a wide set of powerful surface reconstructions approaches from point clouds. In the context of mesh decimation Scanalyze provides automatic model simplification using a quadric error approach [Garland97].

Mesh cleaning functionality enables one to create coherent meshes i.e. removing duplicate vertices and self-intersection or converting non-manifold representations and flipping inconsistent triangle orientations [Oliveira02]. In addition, if occluded areas (no point data) exist in the surveyed object, hole-filling techniques can be applied to repair the incomplete meshes. In Meshlab these functionalities are available through the Visualization and Computer Graphics library (VCGLib), which includes several mesh editing techniques. The Scanalyze system provides a set of mesh cleaning tools, one of which enables the completion of holes using a volumetric algorithm [Davis02].

Mesh texturing functions are available in some solutions (e.g. Paraview), other solutions only support the visualization of the previously textured meshes (e.g. Meshlab) while some solutions do not support textures (e.g. Scanalyze).

Data management

Software supplied with Laser scanner systems such as Riegl's RiSCANPRO, typically manage the different data files associated with a survey project, provide editing and modelling functions and have a degree of visualization support. This software follows an external memory management paradigm similar to that of [Cignoni03] where pointers to files residing in secondary memory are loaded and unloaded to and from main memory in turn by the user and operations such as triangulation and stitching together of meshes is performed to create a larger combined model.

Several point-based rendering tools exist for interactive visualization of whole out-of-core point cloud datasets, (e.g. QSplat[Rusinkiewicz00], XGRT[Wand07a]). In addition [Wand07b] enables editing operations on parts of the model whilst viewing at the same time the whole model using a multi-resolution rendering of out-of-core hierarchical point sets. In contrast, for huge out-of-core triangulated meshes, existing visualization solutions provide little or no editing capabilities whilst viewing the full model. Namely level-of-detail techniques are applied to a finished model before the model can be visualized. Borgeat et. al [Borgeat05] divide a textured scanned model into smaller surface area parts, and create discrete LoDs for each part, during visualization discrete LoD are switched with geomorphing to avoid popping artefacts. Gobbeti et. al [Gobbeti05] enable the interactive visualization of complex isosurfaces, CAD and scanned models by dividing a scene into voxels and pre-compute shaders that enable one to model the original appearance of the geometry in each voxel, at run-time far away voxels are splat and triangles in close by voxels are rendered normally.

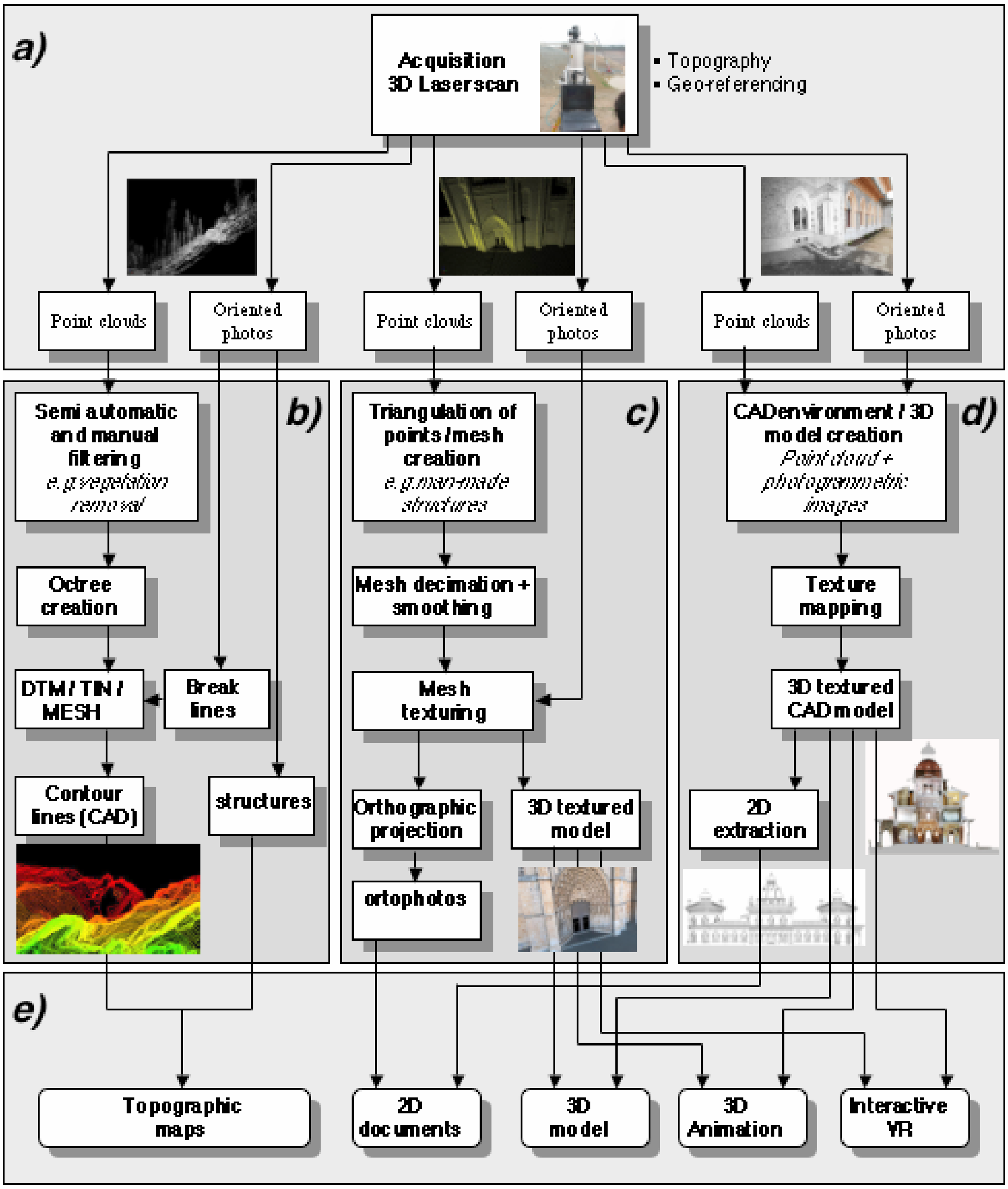


Figure 7: Overview of digital document creation process, starting with acquisition 7-a; main modelling pipelines 7-b, 7-c, 7-d and resulting digital documents 7-e.

3. MODELLING PIPELINE

In this section we describe the modelling steps involved in the creation of the examples highlighted in the previous sections and the creation of the digital documents presented in section 4. Figure 7 provides an overview of the digital document creation process. Namely the modelling consists of:

- Acquisition of point clouds and oriented photos.
- Modelling pipeline *b*.
- Modelling pipeline *c*.
- Modelling pipeline *d*.

We note that several digital documents use only a small subset of modelling steps, and that Figure 7 only depicts the main modelling pipelines currently used in Artescan.

Acquisition of point clouds and oriented photos

The data acquisition process is of extreme importance, as it will affect the overall quality and accuracy of the final results.

An important aspect to be considered is the coverage of the object under study. To obtain a whole coverage, the data must be acquired from different stations and attitudes. When choosing the positions for placing the laser scanner (scanpositions) it is important to ensure that there is some overlap between successive scans to facilitate the process of registration, which is described later in this section, and avoid occlusion of areas.

With systems such as the one shown in Figure 8 the data acquired from each scanposition will consist of a point cloud (normally with millions of points) with XYZ plus intensity (I) information for each point, as well as digital photographs with recorded orientation parameters (oriented photos) as can be seen in Figure 9.

Figure 8: Data acquisition of the Alto Ceira dam, Portugal with a Riegl Z360i coupled with a Nikon D100.

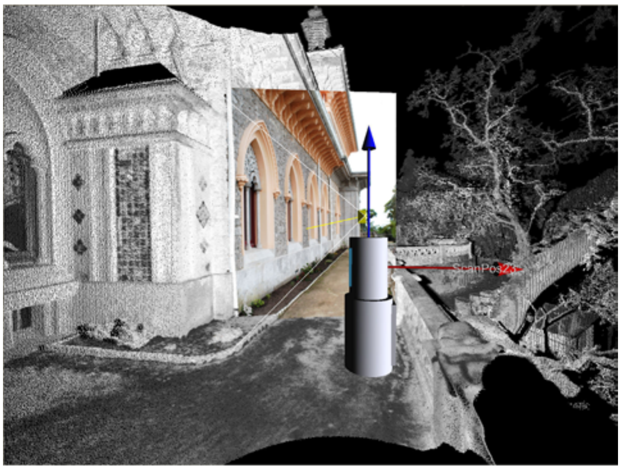


Figure 9: Point cloud and oriented photo of Monserrate exterior.

Another important aspect to be considered is how data acquired from different scanpositions and local reference frames is transformed onto a single common coordinate system of the project. In this context this transformation is known as registration or relative orientation. Namely for each scanposition, point cloud coordinates and orientation parameters of the acquired photographs are expressed in the particular instrumental system of coordinates of the scanner at that position and orientation. Hence it is essential to transform the data from these different scanpositions onto a single common coordinate system. For this purpose different registration methodologies can be adopted.

With indirect registering, surface-matching techniques can be applied as long as a good overlap between different point clouds exists with geometrically well defined objects in the overlapping areas. Higher precision can be accomplished using a different technique where correspondences between data sets are established by common 3D points, denominated as tie points. The first step using this method is to distribute a set of tie points materialized by retro-reflectors around the area of the object under study, with planimetric and altimetric variation. These retro-reflectors will be surveyed in the laser scanner acquisition process and automatically detected by the acquisition software. As the instrumental coordinates for each scanposition is well defined, if two scanpositions capture the same set of retro-reflectors (normally 6 to 12) it is possible to infer the correct 3D transformation matrix that registers one instrumental coordinate system to the other. As in photogrammetry tie points are used to put together two datasets (two point clouds instead of two images) but if geo-referencing is needed we will need to know the coordinates of some of the tie points in a meaningful coordinate system. These tie points are referred to as control points. In the TLS scenario some retro-reflectors can be measured with the use of conventional topographic methods (using a total station or global navigation satellite system, GNSS) in a meaningful coordinate system (e.g. WGS84 or a national datum).

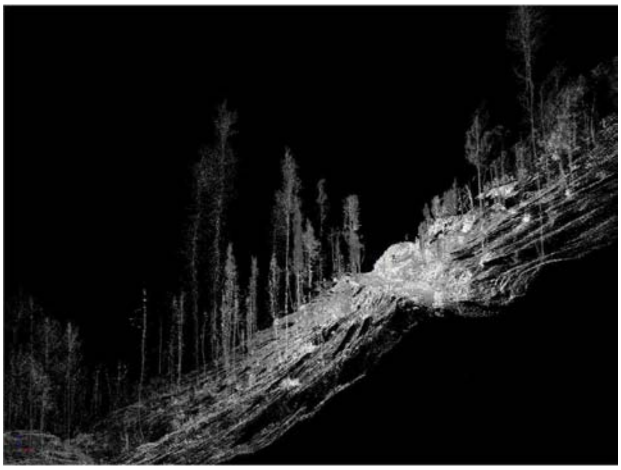
With the direct geo-referencing approach the position and attitude of the device is calculated by other sensors such as the ones incorporated in INS (inertial system) and

GNSS systems integrated and calibrated with the laser scanner (for example in a kinematic survey scenario).

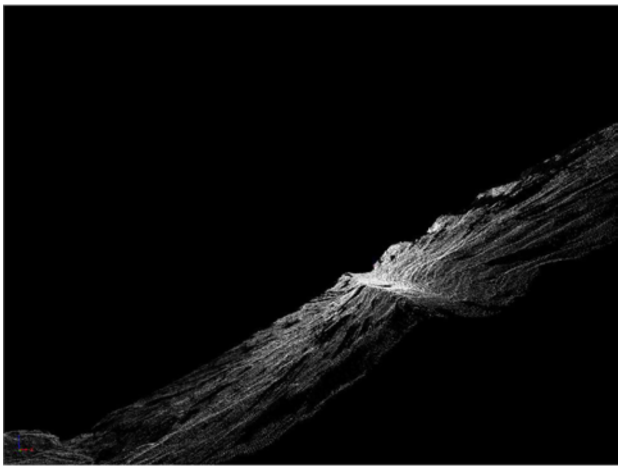
A rapid survey approach can be accomplished with a stop and go methodology using a combined method of registration. In this method an approximated value for the position and orientation of each scanposition is directly acquired using a GNSS system coupled to the TLS (position) and compass (orientation). These values are then improved using multi-station adjustment that will iteratively adjust these position and orientation matrices to already registered positions with the control points approach described earlier. In this way the accuracy of the measurements will not be affected by the potentially less accurate GNSS position measurement.

Modelling pipeline b

As mentioned previously some applications using LiDAR and TLS face similar challenges in the context of classifying or eliminating all together undesired features in the data. Laser data from both aerial and terrestrial platforms acquire the so-called digital surface model (DSM), which means that all objects present in the scene will be surveyed. As described previously, after the segmentation of the data has been performed, a classification procedure which is application dependent is applied. For instance in a forest inventory application single tree parameters, such as tree-specifies, tree height, diameter at breast height (DBH) or the height of crown base are the typical parameters to be measured [Thies04]. However, for most topographical purposes what is required is the digital terrain model (DTM) instead, which represents only the surface of the earth without the canopy. For this end, unwanted objects such as vegetation, cars or people must be removed by typically a combination of automatic and manual techniques. On one hand irregular x y z data from LiDAR can be easily approximated in 2.5 D and stored in an image representation suitable for image processing and feature extraction. On the other hand irregular x y z points from TLS can be spatially binned into an octree or grid structure. TLS produces real 3D data that allows access to areas that are typically occluded in a 2.5 representation, thus the filtering and segmentation algorithms used are inherently different. In general, algorithms for removing or classifying features, unfortunately typically require considerable manual supervision and editing to ensure good quality results. In the context of pipeline b, terrestrial laser scanning is used to create 2D and 3D topographic maps. In the case of natural environments, the original data undergoes a semi-automatic filtering process based on robust local surface fitting and outlier detection. Figure 10-a) shows an example of unfiltered data with vegetation and Figure 10-b) shows the data after filtering.



a)



b)

Figure 10: Vegetation filtering of a valley in Góis, Portugal. a) Acquired point cloud before filtering; b) Filtered point cloud.

Once the data has been filtered, the point clouds are spatially organized into an octree (Figure 12-a). Oriented photos are then used to manually generate vector features in a CAD environment.

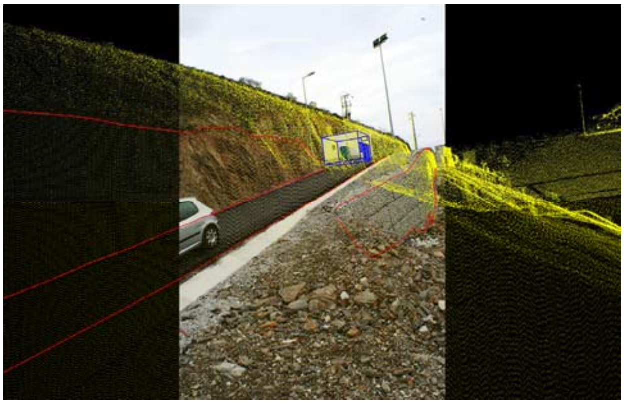
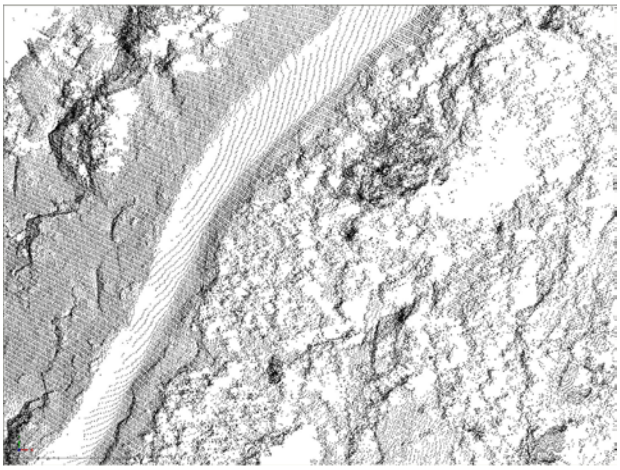
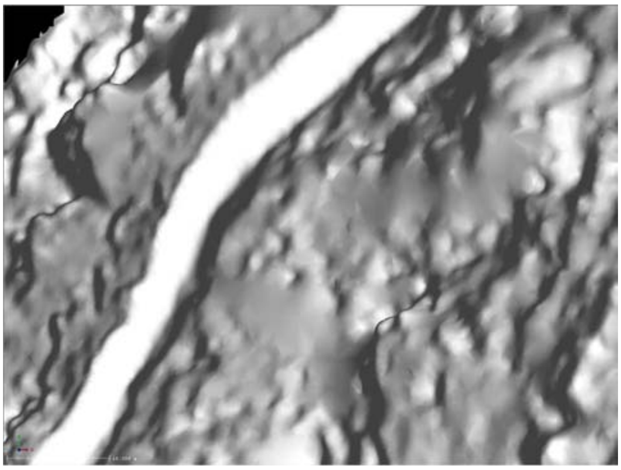


Figure 11: Manually defined break lines in red, and structures in blue superimposed on oriented photo of Olgas dam, Portugal.

Examples of such features can be seen in Figure 11, where terrain discontinuity lines, also referred as break lines (shown in red in Figure 11) are used to create a digital terrain model (Figure 12-b), in pipeline b the DTM is represented with a triangulated irregular network (TIN). Finally the DTM can be used to compute contour lines (Figure 12-c).



a)



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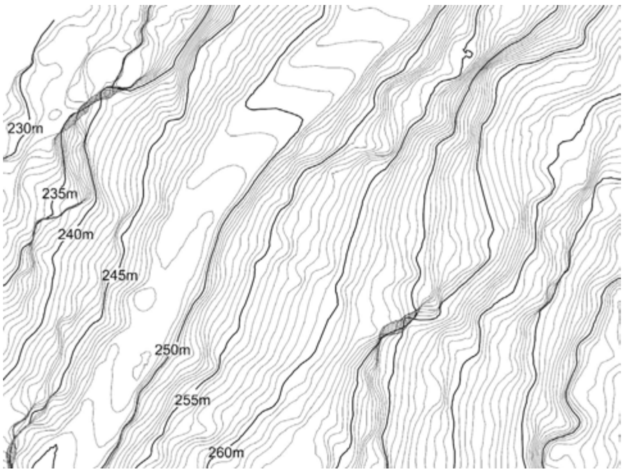


c)

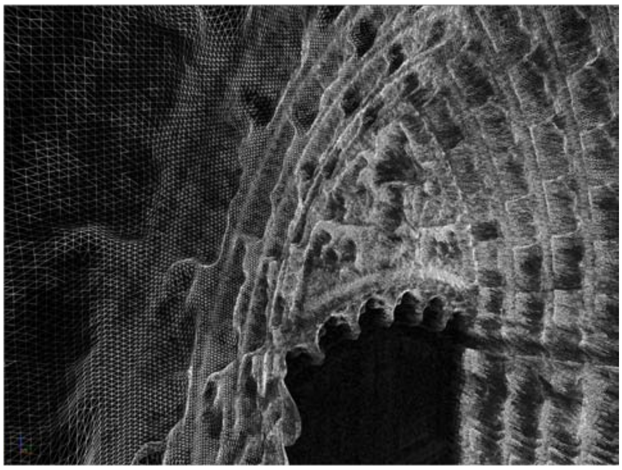
Figure 12: Topographic map creation from Vale do Tamega, Portugal. a) Terrain point cloud spatially indexed in an octree; b) Digital terrain model; c) contour lines.

In surveys containing man made structures such as buildings, these can also be manually generated on the ori ented photos (shown in blue in Figure 11), and incorporated in a topographic map.

Modelling pipeline c

In this section we describe the main modelling steps required to generate orthophotos of for example a scanned building, and how to create a 3D textured mesh model.

a)



b)

c)

Figure 13: 3D texture model creation from an architectural survey of the Mosteiro da Batalha, Portugal. a) Acquired point cloud; b) Triangulated mesh; c) 3D textured mesh.

The first step is to triangulate portions of a point cloud (Figure 13-a) using for example a Voronoi triangulation algorithm. The resolution of the triangulated result will typically include noise and exceed the required modelling resolution. To address these factors, decimation and smoothing are applied (Figure 13-b). Examples of smoothing options available are Laplacian smoothing and Taubin et. al's robust filter technique [Taubin96].

Finally oriented photos can be used to colour the point cloud, or texturize the triangulated mesh (Figure 13-c). Although orthoimages have existed for more than half a century as a cartographic document obtained from aerial photography, only recently have they had more wide spread use in architectural surveying.

Unlike conventional photos orthoimages have metric qualities that are specially useful in a range of surveying and modelling applications. Namely when orthoimages are imported into a CAD environment, they can be used to model and register for example architectural elements in need of restoration, pathologies in structures or can be used to guide the vectorization of intricate architectural structure details and facade features. Orthoimages thus provide many benefits over traditional surveying methods with their reliability and their ease in semantic and positional integration with other survey data.

Orthophotos are created by orthographic projection of the textured model onto a desired plane (Figure 14 shows an orthophoto produced with the textured mesh of the model in Figure 13).

Figure 14: Orthophoto creation from the architectural survey depicted on Figure 13.

Finally to produce a complete 3D textured mesh model of a large survey, several intermediate modelling files are typically produced, with mesh merging and hole filling steps.

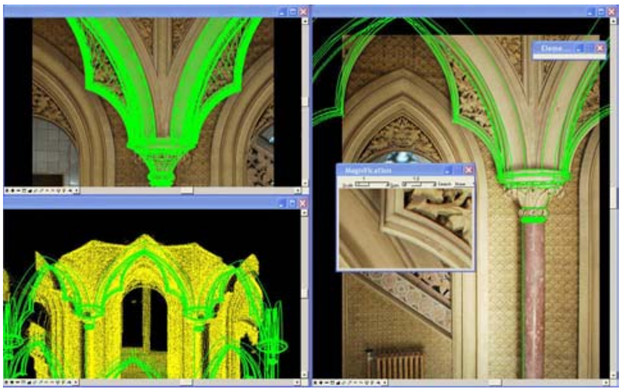
Modelling pipeline d

For architectural or engineering structure surveys it is of great importance that the data acquired from the object under study to be detailed, accurate and precise as discussed earlier and thus the use of laser scanner technology is desirable. On these application areas the representation of the collected information is most useful when hierarchy and structure is added incrementally during the modelling. For instance the use of layers of information allows the user to visualize different features of interest more clearly, by not rendering other layers. If on one hand the approach described in pipeline c, the creation of triangulated meshes from point clouds accomplish a faithful representation of intricate surfaces, on the other hand Computer Aided Design (CAD) enables a more straightforward hierarchization and structuring of the information in a 3D model for analysis purposes. Instead of having just geometry in "triangle soups", layers and relation information complement the geometric data.

The surveyed object can be modelled by combining point cloud data with photogrammetrically oriented photos acquired in the field, in a CAD environment and using its vectorization tools (Figure 15). This procedure, using a single image and the digital surface model (in the form of a point cloud) is known as monoplotting [Luhmann08]. A layer structure is adopted for the classification of features such as window, door, column, etc.

This kind of modelling approach has some subjectivity in the choice of level of detail. Hence the client's requirements are analyzed before setting the most adequate level of detail of the representation. Figure 15-b) depicts the vectorization of a higher level of detail than that of Figure 15-a).

a)



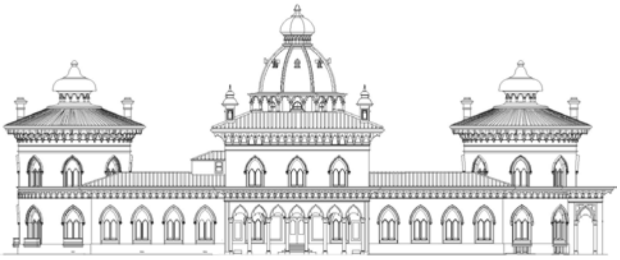
b)

Figure 15: 3D CAD model creation of the Palácio de Monserrate. a) Manual 3D modelling of vector primitives using both superimposed photogrammetrically oriented images (right) and point cloud data (bottom left); b) Finer detail modelling of intricate architectural features.

After the 3D model has been built, texture mapping techniques are used to enhance its visual appearance, thus generating a photorealistic model (Figure 16).

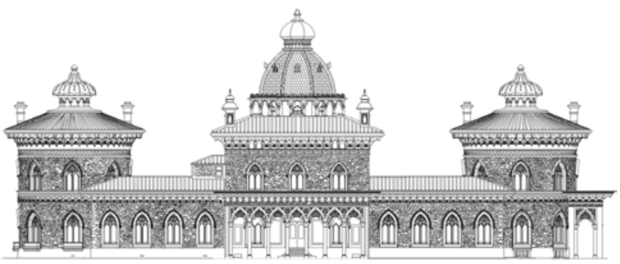
Figure 16: Exterior of the created 3D textured CAD model.

The 3D model in this stage can be used for the generation of virtual products that will be discussed in section 4. It can also be used for the extraction of coherent profiles and cross-sections thus creating high integrity 2D documents (Figure 4 and 5). In Figure 17 (a to c) the process of producing a complete 2D architectural document is depicted [Oliveira09]. The constructive vector lines are generated from automatic extraction of 2D vector data from the 3D model (Figure 17-a). This drawing is superimposed in a CAD environment onto an orthophoto from the same view (Figure 17-b) thus assisting the manual vectorization of additional decorative details (Figure17-c).



a)

b)



c)

Figure 17: Production of 2D architectural documents (Palácio de Monserrate). a) 2D vector data extracted from 3D model; b) Corresponding orthophoto; c) Added 2D vector detail of rock, tiles and masonry features.

4. DIGITAL DOCUMENTS

In the previous section, the modelling steps to produce several kinds of digital documents were described. In this section we provide a brief overview of the types of digital documents that can be created.

2D Topographic maps, resulting from pipeline b) were shown in Figure 12-c, and are ideal for printing; however 3D topographic maps that are visualized in digital platforms are increasingly gaining popularity. The use of 3D data from TLS for generating DTMs allows for new approaches to solve several problems in engineering, such as the problem of monitoring surface deformation. Specifically DTMs from the same geographical area but from different moments in time, epochs, can be generated and compared for the purpose of spatially continuous surface monitoring (Figure 18, right). On the other hand 3D visualization of a mesh (Figure 18, left) can show phenomena that would not be easily recognized with conventional engineering documents, and in some instances not even whilst present on site [Boavida09].

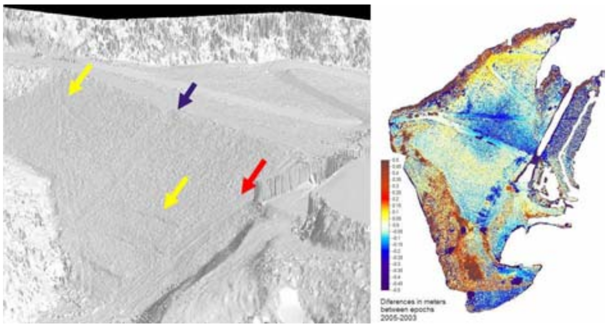


Figure 18: Monitoring of earth dam surface deformation (Lapão dam, Portugal). left) 3D visualization; right) Colour ramp of differences in meters between epochs.

In Figure 19, we show the use of orthophotos for assisted visual inspection of concrete pathologies in a concrete wall dam [Boavida09]. This orthophoto was produced with pipeline c.

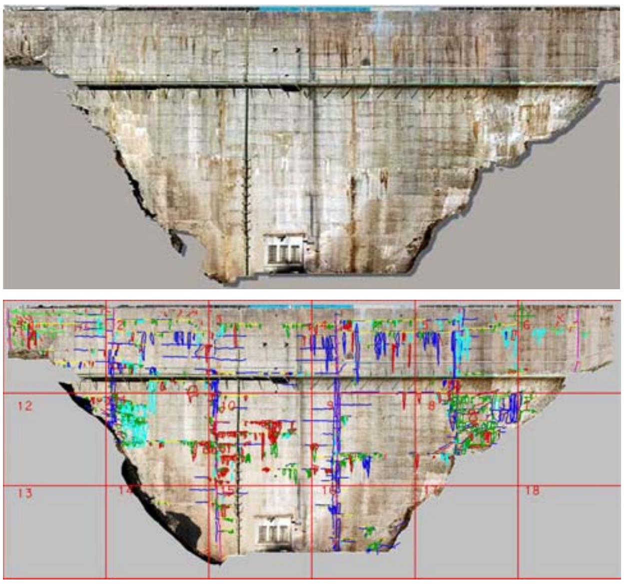


Figure 19: Pathology monitoring of concrete wall dam (Alto Ceira dam, Portugal) top: Orthophoto; bottom: vectorized CAD features drawn over orthophoto.

Some digital documents can be the result of parts of more than one pipeline. For example, the vectorized street facade 2D digital document on Figure 20 was created using modelling steps from pipeline b and d. Namely structures were manually vectorized using oriented photos and point clouds.

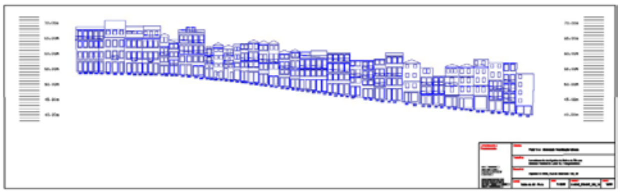


Figure 20: Architectural document of street facade survey of Bairro da Sé, Porto, Portugal.

Figure 21 shows the result of pipeline d, where the 3D CAD model was complemented with relatively simpler geometry and exported to a KML format, that can be visualized in Google Earth.

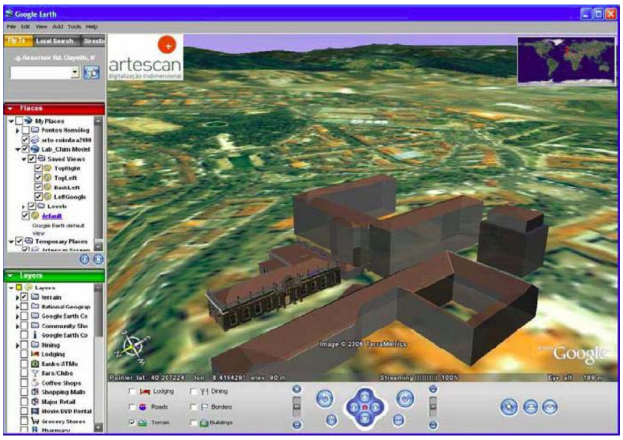


Figure 21: Google Earth, KML 3D model from laser scan on lower left (Laboratório Chimico, Coimbra, Portugal).

3D models resulting from pipelines c) and d), can be also exported to the 3D PDF format that can be easily visualized in adobe reader. This platform enables the easy sharing of information that has the additional benefit of being encrypted. Furthermore the 3PDF enables the visualization of layered information. Figure 22 shows the viewer in action with a 3D archaeology model.

Figure 22: 3D PDF of the resulting textured model of the survey of a roman oven. (Quinta do Rouxinol, Seixal, PT).

The 3D textured models produced with pipeline c) and d) can be used in interactive virtual reality applications. Immersive experiences can be generated in virtual environments where the user can interact and analyse the modelled information. Animations can be created to simulate events (e.g. the water filling of a dam) or to create a predefined tour around the object of interest, as shown in the still frame in Figure 23.

Figure 23: Still frame from an animation sequence (Palácio de Monserrate).

5. FUTURE WORK

In this section we point out areas that would further improve modelling tasks, in terms of reducing costs and time.

Modelling of large surveys can be a lengthy process, where several intermediate modelling files with different versions are created to produce a final model. Alike digital photographs, the explosion in the number of files created warrant different search and indexing techniques. Specifically it would be desireable to have tools that help asset management, for example establishing possibly through static renderings which files map to which survey areas with alpha blending. In addition, as mentioned in section 2, most LoD algorithms for interative visualization of whole triangle meshes are based on the precomputation of the final model, however intermediate modelling files can also have a considerable size and the time for LoD pre-computation of several inherently temporary versions of meshes might not be tolerable by the user.

It would be desireable to have more robust segmentation and classifcation algorithms where less manual intervention would be required.

Finally it would desireable to have better integration of CAD primitives and triangulated meshes.

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