3D - Laser Scanning: Integration of Point Cloud and CCD Camera Video Data for the Production of High Resolution and Precision RGB Textured Models: Archaeological Monuments Surveying Application in Ancient Ilida

Vaios BALIS, Spyros KARAMITSOS, Ioannis KOTSIS, Christos LIAPAKIS and Nikos SIMPAS, Greece

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SUMMARY

In this project, techniques of integration of 3D – Laser Scanning point cloud data and the video produced by the CCD camera are explored. This integration is employed to the production of high – accuracy and resolution RGB textured models and ortho - photo diagrams of archaeological monuments.

The "test site" for these techniques, is Ancient Ilida in Greece, which is origin of the Ancient Olympic Games, although it is often overlooked for the shake of Ancient Olympia. It was created in 9th century BC, but it bears significant multi temporal influences from more recent periods, including modifications which were made during the roman age, and even in the Paleo – Christian period. It was the place where the first Olympic Games were held, and was used by the athletes to train themselves for them.

This project mainly focuses on the computation of the relative geometry of the two sensors, the scanner and the CCD camera, the internal calibration of the camera itself and their utilization in the fusion of the video data and the mesh model resulting from the scanner's point cloud. The greatest majority of the problems and doubts are attributed to the non – measuring nature of the CCD camera, which was originally indented for qualitative only purposes (some kind of surveying video sketch). The issues raised by this fact are presented, solutions are proposed thorough evaluation of the result is presented and limitations are stated. The 3D laser scanning instrument used for this application is a Mensi GS200.

Additionally, specific issues hindering the RGB textured models production are explored, namely point cloud and video shadowing, lighting conditions differentiation during and between scans, RGB accuracy and resolution degradation due to blending of different scans.

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1. INTRODUCTION

The attribute of organizing city of ancient Olympic Games, classifies the Ilida in one from the more important and more interesting centers of Peloponnese. The city was discovered in the middle of Pinios River plains in a region that was occupied since the first hellenic era. It was created around 470 B.C. by the conjunction of various near rural municipalities, in order to constitute the capital of city - country of Ilia. It reached in particular prosperity at the roman era, when a big number of buildings and athletic installations were added. The first excavations in Ilida took place during the period 1910-14 from the Austrian Archaeological Institute of Athens. From 1960, the city with the wider region it was investigated systematically by the Greek Archaeological Company. The excavations revealed a particularly extensive city with abundance of buildings that is placed the period spanning the hellenistic and roman years.

During its prosperous period, one month before each Olympic Games were held, all the participating athletes were obliged to transit to Ilida, in order to workout under the supervision of the adjudicators in the gyms that existed to fulfill this need. The adjudicators who supervised the athletes to assure that the abided by the regulations emanated from Ilida, were elected for every Olympic Games holding and their education was held there Ilida and lasted ten months. Two days before the beginning of Games, athletes, critics and officials began in transition from Ilida to (Ancient) Olympia via Holly Road.

The objects to be surveyed (Figure 1) are the remains of a roman era building used for bathing. According to the archaeologists working in the site, the building was constructed with the materials from the remains of a building existing previously in the same position. The building comprises several rooms and an extensive hot air airway network.

Figure 1: View of the building remains to be surveyed

2. REFERENCE SYSTEMS INVOLVED IN 3D LASER SCANNING

In order for the complete process of the RGB color texturing of the mesh to be robustly comprehended, it is necessary to know the reference systems involved and the way of transiting from one to the other. It is not actually known if the processing software used for the particular work follows exactly the procedure described here, but we believe that it must not be applying a process far different than the one explained below:

The definitions of the reference systems involved in the 3D Laser Scanning follows:

- Individual point cloud local reference system: Its origin is the scanner's electro – optical center. The Y – axis is directed along the scanner's line of sight vector with an arbitrary horizontal angle (it may be the first horizontal angle or the approximate north by the reading of a built-in magnetic compass) with zero measured vertical angle. The Z – axis is the instrument's vertical axis (for the Mensi 3D laser scanning because of the absence of leveling it does not coincide with the true vertical or plump line). X - axis is selected to make the system right handed. Coordinates symbols expressed in this reference system are distinguished by the "L" superscript.
- Global point cloud reference system: It is the reference system to which target points from all point clouds refer to after the relative registration of the individual point clouds by the process described in the previous section. It is the individual point cloud local reference system described above, for an arbitrary point cloud, usually selected by the user (often called "reference scan"). Coordinates symbols expressed in this system bear the "G" superscript. Once all the other scans have been co registered to this reference scan, the often called "global scan" is created.
- "External" reference system: it is any reference system to which the 3D true RGB textured mesh, which is the final product has to be referenced. This could be any reference system: The national reference system or any geodetic reference system, a local reference system to which other nearby surveys have been performed as part of the same general project, or just a reference system whose Z-axis is vertical, something which most of the

times is required, and is needed specifically when working with the Mensi 3D laser scanning system, since it offers no leveling capability. Coordinates symbols in this system are recognizable by the “E” superscript.
- Image reference system: this is a two dimensional reference system. Its origin is placed in the geometrical center of the CCD camera image, and its x – axis is parallel to the pixel lines and y – axis parallel to the pixel columns. Coordinates expressed in this reference system are distinguished by the “I” superscript.

In addition, and in order to explain the geometric relations between these reference system which will follow, the introduction of two more intermediate reference systems is required:
- The CCD camera reference system.
- The scanner reference system.

Actually these two reference systems serve the purpose of establishing the geometric relation of the 3D laser scanner and the on – board CCD camera sensor.

These systems are defined as follows:
- The Scanner reference system origin is the optical centre of the scanner measuring head. The Y – axis is the scanner measuring head’s optical axis; positive direction is the scanner’s look direction (extending outwards to the target objects). The X – axis is the axis of vertical rotation of the measuring head; positive direction selected such as to make the system right handed. The Z – axis is simply perpendicular to the plane defined by the X and Y axis; positive direction selected to make the system right handed, that is directed from the scanner’s optical centre to its top. This scanner – specific reference system as defined above is fixed with respect to the scanner measuring head, which means that physical points of the scanner measuring head structure have constant coordinates contrary to the target objects of the surrounding, whose coordinates change with respect to that reference frame as the scanner head rotates to perform its scan task. Additionally, it is worth noticing that to the above reference system definition, it was assumed that the axis of vertical rotation contains the optical centre of the measuring head. This is the case in the 3D laser scanners, as it is in almost all the surveying instruments. The scanner’s reference system and coordinates expressed in that system will be symbolized as X^{SCN}, Y^{SCN}, Z^{SCN}.
- The CCD camera reference system origin is the optical centre of the camera. The Y – axis is the optical centre of the CCD camera; positive direction is the camera’s look direction (extending outwards to the target objects). The X – axis is parallel to the axis of vertical rotation of the scanner measuring head; positive direction selected such as to make the system right handed. The Z – axis is simply perpendicular to the plane defined by the X and Y axis; positive direction selected to make the system right handed, that is directed from the camera’s optical center to its top. In complete accordance to the scanner’s reference system, camera – specific reference system as defined above fixed with respect to the camera, which means that physical points of the camera structure have constant coor-

dinates contrary to the target objects of the surrounding, whose coordinates change with respect to that reference frame as the camera rotates. The CCD camera's reference system and coordinates expressed in that system will be symbolized as X^{CCD}, Y^{CCD}, Z^{CCD}.

The geometrical relations of these last two auxiliary reference systems need to be presented first:
The CCD camera is rigidly attached to the scanner measuring head. With respect to the scanner, it has no kinematics degrees of freedom. Therefore, the camera rotates horizontally and vertically exactly to the amount the scanner does. Consequently, the two reference systems relative geometry (or transformation from one to the other) parameters, expressed in one of these systems remain constant, i.e. independent from the rotation or translation of the measuring head.

The CCD camera mounted on the 3D laser scanning system, is physically offset with respect to the 3D laser scanner measuring head. This is a fact which can be anticipated, since it would be technically impossible to create a 3D laser scanner and a CCD camera hybrid sensor with the same optical centers. Consequently, one 3D translation must be introduced to establish the two sensors relative geometry: $DX^{SCN\text{-}CCD}$, $DY^{SCN\text{-}CCD}$, $DZ^{SCN\text{-}CCD}$

The constructor of the system is expected to have taken care to keep the optical axis of the CCD camera parallel to the one of the laser scanner measuring head, in order to ensure at least roughly parallel lines of sight for both sensors. However, and in cases when the CCD imagery is to be used for quantitative purposes (such as true RGB colour texturing of the 3D models), precision is the main requirement. In these cases, the parallel optical axis assumption for the two sensors can not be considered valid: The construction angular deviations between the two sensors become non – trivial, and ignoring them could lead to fatal results for the confidence and accuracy of the true colour RGB texturing. Consequently, one 3D rotation must be introduced to establish the two sensors relative geometry: $r_X^{SCN\text{-}CCD}$, $r_Y^{SCN\text{-}CCD}$, $r_Z^{SCN\text{-}CCD}$. The above mentioned six transformation parameters are quantities that need to be determined by means of a least squares – based calibration process. This process is often referred to in the 3D laser scanning as "external calibration". The 3D laser scanning system constructors usually provide the external calibration parameters to the user. They also usually provide software and guidelines to the users in order to enable them to perform the calibration themselves. It is strongly recommended to perform this external calibration process habitually, and whenever there is concern about a possible disturbance to the structural integrity of the instrument.

The relations between the first three defined reference systems are presented below:
Individual point cloud local to Global point cloud reference system conversion (co – registration to reference scan): Generally, this is a six – parameter transformation. Three of these parameters form the position difference $D\vec{R}_{L\rightarrow G}$ between the scanner's electro optical center as stationed for the individual scan point cloud and the origin of the global point cloud reference system which may be the position of the scanner's electro optical center stationed for an individual scan point cloud arbitrarily selected by the user of the processing software ("reference scan"). The other three parameters are rotations, one, r_Z, is the azimuth difference of the Y axis of the two reference systems and the need for the other two stem from the instrument's lack of leveling ability (which is the case in the Mensi GS200) - $r^{L\rightarrow G}{}_X, r^{L\rightarrow G}{}_Y$ difference of the deflections from true plump line between the Z – axis of the two systems. Based on this explanation, this transformation is finally given by the relation below:

$$\vec{R}^G = D\vec{R}^{L\rightarrow G} + M^{L\rightarrow G}(r^{L\rightarrow G}{}_X, r^{L\rightarrow G}{}_Y, r^{L\rightarrow G}{}_Z)\vec{R}^L$$

The provision of a leveling ability in a 3D laser scanning system (such is the case with Callidus), eliminates the need for the two rotations $r^{L\rightarrow G}{}_X, r^{L\rightarrow G}{}_Y$, since the instrument's vertical axis coincides with the plump line of the region. The previous equation becomes:

$$\vec{R}^G = D\vec{R}^{L\rightarrow G} + M^{L\rightarrow G}(r^{L\rightarrow G}{}_Z)\vec{R}^L$$

The determination of the six parameters for this transformation is possible by scanning sufficient number of common targets. The scanning of each target provides three observation equations, one horizontal angle, one vertical angle and one slant distance. Therefore, at least two commonly visible targets are required for the calculation of the relative geometry between two scans, although it is strongly recommended to use at least three common targets, to enable blunder detection and avoidance, error estimation and increased accuracy in the registration by implementation of least squares adjustment.

Global point cloud to External reference system (absolute registration or georeferencing): Generally, this is also a six – parameter transformation. Three of these parameters form the position $\vec{R}_0^E$ of the origin of the global point cloud reference system, which may be the scanner's electro optical center position stationed for an individual scan point cloud arbitrarily selected by the user of the processing software (reference scan). The other three parameters are rotations, one "r_Z", is the azimuth of the Y axis of the global scan reference system and the need for the other two stems from the instrument's lack of leveling ability (which is the case in the Mensi GS200) – "r_X, r_Y" are the angle expressing the deflection from true plump line of the Z – axis of the global reference system. If the external system is a map projection, provision must be made for a scale factor, symbolized as "λ". Based on this explanation, this transformation is finally given by the relation below:

$$\vec{R}^E = \vec{R}^E + \lambda M^{G\rightarrow E}(r^{G\rightarrow E}{}_X, r^{G\rightarrow E}{}_Y, r^{G\rightarrow E}{}_Z)\vec{R}^G$$

The provision of a leveling ability in a 3D laser scanning system, eliminates the need for the two rotations $r^{G \to E}{}_X$, $r^{G \to E}{}_Y$, since the instrument's vertical axis coincides with the plump line of the region. The previous equation becomes:

$$\vec{R}^E = \vec{R}^E + \lambda M^{G\to E}(r^{G\to E}{}_Z)\vec{R}^G$$

The determination of the parameters of the absolute registration is possible by scanning sufficient number of targets whose position is known in the external reference system. The scanning of each target provides three observation equations, one horizontal angle, one vertical angle and one slant range. Therefore, at least two (or three if the external reference system is a map projection) known position targets are required for the calculation of the registration of the global scan, although as before, it is strongly recommended to use at least three common targets, to enable blunder detection and avoidance, error estimation and increased accuracy in the registration by implementation of least squares adjustment.

Global Point Cloud to CCD sensor image coordinates: This is 3D to 2D system transformation. It provides the 2D video image coordinates of a specific point in the 3D space. This transformation is achieved by the well – known in Photogrammetry colinearity condition equations. In photogrammetry these equations stem from the perspective (central) nature of the projection of the objects in space on the film or CCD array surface, no matter whether the image acquirement has been done with airborne, space or terrestrial sensors. The image coordinates are functions of the following parameters:

$$x^i_A = f(x^i_0, z^i_0, X^G_A, Y^G_A, Z^G_A, X^G_0, Y^G_0, Z^G_0, \omega_A, \varphi_A, \kappa_A, c)$$
$$y^i_A = g(x^i_0, z^i_0, X^G_A, Y^G_A, Z^G_A, X^G_0, Y^G_0, Z^G_0, \omega_A, \varphi_A, \kappa_A, c)$$

where:

x^i_A, y^i_A	CCD camera image coordinates of a point A	
X^G_A, Y^G_A, Z^G_A	Global scan coordinates of point A	
X^G_0, Y^G_0, Z^G_0	Position of CCD camera optical center in global scan coordinates	External Orientation Parameters
ω_A, φ_A, κ_A	Rotation angles ω_A, φ_A, κ_A about X, Y, Z axis respectively	
c	CCD camera focal length	Internal Orientation Parameters
x^i_0, y^i_0	Image coordinates of the camera principal point	

The internal orientation elements are quantities that need to be determined by means of appropriate camera calibration processes used extensively in photogrammetry. The 3D laser scanning system constructors usually provide the interior orientation elements. They usually also alternatively provide software, guidelines and calibration sheets to the users in order to

enable them to perform the calibration themselves. It is strongly recommended to perform this process frequently due to the non – measuring nature of these cameras.
In the cases when an external camera is preferred over the 3D laser scanner incorporated one, the user must perform the interior orientation. Usually, the processing software provides tools for such instances.

Towards the end of estimating the internal and external orientation parameters at once, which is the case in the Mensi CloudWorks Survey, for every single external camera image, a sufficient number of point targets and their corresponding image positions must be located on the point cloud and the video image respectively. The global point cloud positions and their image coordinates control points are therefore known. With a sufficient control point number it is possible to use the colinearity condition equations for a least squares adjustment which will provide at the internal and external orientation parameters. At least 5 control points are required for the total of 9 unknown parameters.

The discussion that follows shows the way to calculate their values in the case of the built – in CCD camera rigidly mounted on the scanner measuring head. These calculations do not apply in the case of external camera or CCD sensor otherwise mounted on the scanner.
For rigidly mounted on the scanner head CCD cameras, the angles ω_A , φ_A , κ_A can be calculated by the scanning head' s measured vertical and horizontal angles at the time of reception of the image, the estimated by the scan co – registration process rotation angles of the local scan from which the image was taken, and the construction angular deviations.

The above discussed angles define the camera optical axis attitude (orientation) to the global scan reference system. The position of the CCD camera optical center, in global scan coordinates X_0^G, Y_0^G, Z_0^G is provided by the following equation:

$$\begin{bmatrix} X_0^G \\ Y_0^G \\ Z_0^G \end{bmatrix} = \begin{bmatrix} X_i^G \\ Y_i^G \\ Z_i^G \end{bmatrix} + R(\omega_A, \varphi_A, \kappa_A) \begin{bmatrix} DX^{SCN\text{-}CCD} \\ DY^{SCN\text{-}CCD} \\ DZ^{SCN\text{-}CCD} \end{bmatrix}, \quad \begin{bmatrix} X_i^G \\ Y_i^G \\ Z_i^G \end{bmatrix} \text{ station global position}$$

In the cases when the imagery has been acquired with external camera, the computation process presented above is not valid. The user must estimate the external orientation parameters.
In the above development, the way to provide color to each point target was discussed. After the mesh generation process, the elementary triangle facets obtain a color which depends on the colors of its vertices. This “dyeing” of the mesh elementary triangles can be performed in different ways:

- Average RGB vector calculation by the vertices RGB vectors.
- Weighted average RGB vector calculation by the vertices RGB vectors, weights determined by means of their inverse distance or inverse squared distance from the barycenter of the elementary triangles.

However, the CCD camera RGB color assignment is a process that can take place after the mesh generation, (often referred to as triangulation). In that case, the point target positions are simply replaced by the positions of the elementary triangle barycentrers.

3. SCANNING AND REGISTRATION OF THE INDIVIDUAL POINT CLOUDS

For the complete coverage of the object to be surveyed, a total of 9 individual scans were required. All nine scans were of horizontal angle span confined according to the dimension of the part of the object to be surveyed, and 60° vertical angle spans – the full for this particular instrument. Seven of the scans were performed with the scanning instrument stationed outside the perimeter of the monument; the remaining two were performed from stations inside it, to fully cover the inside of the rooms.

The first link in the processing chain is the registration of the scan point clouds in a reference system, so that all points from all scans refer to a common reference system to enable their collective processing, and for the registration of the final product (true RGB textured mesh) to a suitable "external" reference system. With the Mensi GS200 system, this may be achieved by two methods:

- By means of a sufficient number of targets common (visible) to all scans. It is a two step procedure. By this way, the relative geometry (position and orientation) between the scan point clouds is computed first. This is the co – registration parameters estimation. If the total of the scans is required to be registered to an "external", already existing reference system - i.e. a national reference system – (geo - referencing), then the position of a sufficient number of common targets needs to be known.
- By means of a sufficient number of targets whose position is known to the selected "external" reference system, present in every single scan (not necessarily common to any other scan). In this case common visibility is not a prerequisite. This is a single step procedure. In this case, every single scan is registered (geo - referenced) individually to the same "external", already existing reference system.

With the particular 3D laser scanning system, these targets are materialized by 7cm diameter spheres made of high – reflectivity material (Figure 2). The way in which equivalence to a point target of these non – negligible size objects is achieved is explained later. To enable not only the relative geometry between scans calculation, but the absolute position of the total of the scans in an external, already existing reference system (i.e. a national reference system), these spheres are equipped with two small corner reflectors attached to the two ends of a rod whose middle point coincides with the center of the sphere. The averages of the coordinates of these reflectors provide the coordinates of the sphere. Consequently, it is possible for the position of the spheres to be determined by implementing conventional surveying instruments and techniques.

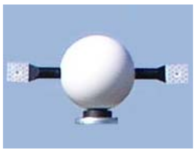

Figure 2: Mensi's sphere targets with corner reflectors.

As mentioned before, unlike other 3D laser scanning systems and the conventional terrestrial surveying instruments, the Mensi GS200 does have leveling capability. A direct consequence of this fact is the introduction of two rotation parameters in the registration of the scan point clouds, in other words, Mensi is using the scanning of the sphere targets for leveling. The scan registration – absolute registration in an external reference system, or relative registration between scans - comprises a total of six parameters, three translation parameters for a translation in space, one rotation for the direction azimuth difference, and two for the leveling difference of the instrument (between scans or instrument stations). The scanning of each sphere target provides three observation equations, one horizontal angle, one vertical angle and one slant distance. Therefore, at least two commonly visible spheres are required for the calculation of the relative geometry between two scans, and also two sphere targets with known position are required for the absolute registration of each scan. It is however strongly recommended to use at least three sphere targets, to enable blunder detection and avoidance, error estimation and increased accuracy in the registration by implementation of least squares adjustment.

Equivalence to a point target of these non – negligibly sized sphere targets is achieved by the following process, which takes place before the actual scanning:

- The instrument guided by the operator, confines its field of view to the particular area where the sphere target is located. The operator guides the scanning sensor by real time video grabbed by the on board CCD camera sensor and transmitted to the interfacing equipment. It is worth noticing that the camera's internal calibration (focal length, lens angular distortion, e.t.c.) and external calibration (geometrical relation with the scanning sensor) parameters are already known.
- The 3D laser scanner, with laser beam power higher than the one used in the actual scanner, with significantly smaller dot size, scans the sphere with higher resolution than the highest possible of the actual scan. In the process, the laser scanner rejects the points for which it determines that they do not belong to the sphere. If successful, the process leads to the scan measurement of all the visible surface of the sphere. If not, the user is prompted to repeat the guidance attempt of the scanner sensor to a more accurate attitude, or a narrower field of view.
- By implementation of a least squares adjustment, the position center of the sphere is determined. This is the desired set of the point target coordinates.

The process described above, is repeated for every sphere target.
In this work, six sphere targets were used, stationed at the same positions during all the scans. Care was taken so that at least four of them were visible in every scan, and cover the maximum possible extend of the object to be surveyed, for maximum geometry optimization.

All the sphere target positions were determined by a total station instrument. This was required because the final product should be georeferenced to the Hellenic National Geodetic Reference System of 1987.

The first scan point cloud registration procedure was preferred: The relative geometry between individual scans was established first by using the sphere targets as commonly visible targets to all scans, as described above, and the total of the scans was registered to an external reference system by using the determined positions to this system of the sphere targets.

The preference to this process was based on the assumption that the fine scan sphere target position determination described above, provides much higher accuracy compared to the determination by total station, even when a high accuracy one is utilized: In this case a Geodimeter 640 Pro offering 1mm ± 2ppm std. dev. distance accuracy and 0.25mgon std. dev. angle accuracy was used. Therefore, towards the end of maintaining this highly accurate relative point cloud registration, first the individual point clouds were relatively registered using the commonly viewed target spheres. The georeferencing of the global point cloud came next (two – step procedure). The residuals of the relative registration estimation ranged from 0.7mm to 1.4mm, while the georeferencing (absolute registration or georeferencing) residuals using the conventional surveying instrument ranged from 2.5mm to 3.5mm.

If a registration to an "external" reference system such as a national one is required, and the target spheres have been registered to it by conventional surveying methods, then it is strongly recommended after establishing the relative registration of the individual point clouds, to register the total of the point clouds by using one position of a target sphere, and an azimuth computed by the positions of two sphere targets. A more elaborate technique, would be a weighted least squares adjustment taking into account both the fine scan sphere target position determination, and the conventional surveying (total station for example) measured angles and distances. In that case however, careful selection of the observation weights is required and consequently, rigorous computation of the a-priori uncertainties for both measurements is needed. Further discussion of that issue extends beyond the scope of this text.

In practice, the sphere target based registration process proved to be a time – consuming and often vexatious one, since it required at least 2mins per sphere target, careful guidance of the scanning sensor by the operator and in many occasions – 1 out of 6 – repeating it was needed.

An additional practicality issue comes up in cases when the spheres need to be removed from their carefully selected positions and placed again for the same survey to be continued, or when there are concerns about whether they have remained exactly were put during scans or between them. Towards the end of resolving that issue, it is recommended for some form of mechanical interface to be created in order for the sphere targets to be installable on a conventional surveying tribranch. In this way, it will be possible and easy to precisely center the spheres over a usual permanent survey marker.

4. MANUAL POINT CLOUD EDITING

The manual 3D point editing processing phase took place after the point cloud relative and absolute registration. The primary objective of this processing phase mainly had to deal with removal of noise point targets and confinement of each point cloud to the area which was planned to cover.

This process was necessary, because it was observed that a few points, generally distant ones, presented large deviations (up to few cm) from their true positions. The problem they created became apparent after the meshing (triangulation) phase: noise point targets were used to build mesh surfaces, which of course were erroneous as well, covering the correct surfaces. Confining the point scans to their predetermined areas, was actually aided by the nature of the object to be surveyed: straight line edges form relatively distinct and clear boundaries, facilitating the manual point cloud editing.

5. CCD CAMERA IMAGING PROCESSING

As previously mentioned, the CCD camera video is primarily intended to be used for mesh texturing purposes. It has also been reported in the previous section that with the particular 3D laser scanning system it is also necessary for the fine scanning procedure which enables the relative and absolute registration of the individual point clouds.

As described above, the 3D laser scanner operator guides the laser scanner head to confine its field of view to the particular area where the sphere target is located. The operator guides the scanning sensor utilizing real time video grabbed by the on board CCD camera sensor and transmitted to the interfacing equipment. In order for this operating concept to function properly, and of course for the mesh real color RGB texturing to be performed, the relation between the video imagery and the 3D point cloud needs to be established. In plain words, for every point in a point cloud is necessary to find the pixel in the video image to which it is depicted. This process has been described in detail in the "Reference Systems Involved in 3D Laser Scanning" section.

For this work, external camera imagery was preferred over the imagery obtained by the built - in camera of the scanner. The reason for this selection was the higher resolution provided by the available external camera – 2500 x 2000 – compared to the 768 x 576 resolution of the built – in CCD sensor.

The usage of the external camera however created the need for estimation of the external and internal orientation parameters. The tool provided for this purpose by Mensi's RealWorks Survey software was used for this purpose. Care was taken in the selection so that the control points were as clear and distinct as possible both on the image and in the point cloud. At least six points were selected for every image. Additionally, care was taken so that the control points to have the maximum possible spreading in space; control points contained in a small volume in space, or points confined on a generally flat area – like a wall – form a rather inappropriate control point group. Therefore, images containing only points located on generally flat surfaces such as close ups of walls or ceilings must be avoided. Groups of such control points lead to insufficient accuracy in the estimation of the exterior orientation parameters.

It is worth noticing that the most precise selection is possible when viewing the point cloud colored by grayscale intensity, and when viewing single point clouds (switching the other point clouds "off"). This is in order to avoid the effect of another point cloud whose scanner station is bigger distance, and consequently the irradiance on the particular part is lower, causing a radiometric "blurring".

The burden for the selection of the external camera images is that the external and internal orientation parameter estimation is a time consuming process.

The most important problem in the image acquisition for outdoors 3D laser scanning surveys, are the color discontinuities, which appear mainly due to the differentiations of the lighting conditions between the times of image reception: Changes of the sun elevation, as well as cloud cover alterations cause severe color discontinuities, which as expected affect the final product. One such example is shown in figure 3. Usually, this is not the case in interior surveying with stable lighting conditions.

In order to minimize the magnitude of this problem, it was attempted to acquire the CCD camera images within the shortest possible time span. Other guidelines that one must heed to are elementary photography rules, such that if detail is the issue – which is for 3D laser scanning – sun or other intense light sources, must not be included in the image field of view.

Another way to deal with this problem possibly could be the reception of the camera images during nighttime, with artificial lighting, although this would require very careful spotlight arrangement. It also might be not an appropriate solution if the final product needs to be textured with natural sunlight.

For whatever concerns processing, experience has shown that no algorithmic deterministic process can deal with the problem satisfactorily, possibly due to the non – deterministic nature of this phenomenon. To the author's opinion, the most effective way to deal with this problem is the conventional image processing, mainly by careful adjustments of the color balance, brightness and contrast. For this purpose any powerful image processing software suffices. This was the selected way to deal with the color discontinuities in this work.

6. MESH GENERATION TRIANGULATION

The mesh generation process followed the processing of the CCD camera images. The Mensi RealWorks Survey software provided two different versions of the Delauney triangulation, the 2.5D and 3D.

The first is appropriate for objects for which a reference plane (datum) exists whose points have a bi – univocal relation with the object's points. Such objects are walls, floors, ceilings, ground etc. It is a version of the 2D Delauney triangulation extensively used in digital elevation model generation. The 3D triangulation requires no such reference surface and is more appropriate for objects for which no such reference surface can be found. The 3D model of such object is displayed in figure 5.

In order to apply different the above different meshing algorithms segmentation was applied to all of the point clouds in order to create groups of point targets from each one of them one mesh was created. Another reason, for which this segmentation was a necessity, was the exaggerative amount of memory required for the meshing process to be performed for larger point sets.

Particular caution must be exercised when defining the boundaries for the point cloud segmentation in order to avoid gaps.

7. TEXTURE MAPPING

Texture mapping is the final phase in the processing. It is the 3D projection of the 2D images on the mesh generated in the previous phase. Texture mapping is performed by implementation of the colinearity condition, as explained in the "Reference Systems involved in 3D Laser Scanning" section.

With the Mensi RealWorks Survey software, the order by which the images is important: The last image covers the one that has been previously mapped on the mesh. A general rule when working with this particular software must be that the best, most appropriate images for mapping on a particular area of the mesh must be mapped last. By the terms "best" or "most appropriate" images, the closest to the object images are meant.

The segmentation mentioned above which facilitated the 2.5D triangulation, also proved to ease the texture mapping procedure: It was useful when mapping images on one partial mesh created in the previous section, portions of the image which do not have mesh correspondence – to this particular partial mesh - and correspond to another partial mesh which is covered by other images. This is the case when texture mapping a wall and significant part of the images taken for it, also display part of the floor. Other images however exist for the floor, and consequently an overlap occurs. In such cases, this overlap portion of the images is automatically rejected; therefore it does not interfere with the mapping of the other mesh, allowing the user to deal with establishing the correct order of fewer images.

8. OUTCOME - CONCLUSIONS

Snapshots from the obtained real color RGB textured mesh are shown below.
Figure 3 left, reveals low color resolution which is due to excessive illumination because of direct sunlight incidence. Additionally, the impact of the color discontinuities on the mesh texturing appears. The left portion of this mesh part has a very much higher brightness than the right one. The corresponding images do exhibit the same color balance and contrast / brightness deviations. Figure 3 right, shows the same portion of the surveyed building, after texture mapping of more appropriate camera images (not under direct sunlight incidence) for the left portion, and after color and brightness balancing of the images. Careful inspection of the textured mesh, revealed very high spatial resolution and very detailed RGB texturing.

Figure 3: Room RGB Textured Mesh Overview with color discontinuities (left) and inappropriate lighting conditions and without (right)

The snapshots of figure 4, the same mesh part is shown, viewed from slightly different angles. In the left image, many elementary mesh triangles appear not to have been textured. This is simply because no image correspondence was found for these tiny surfaces. Taking images from one more direction (from a position right of the wall) would resolve this problem.

Figure 4: Mesh details on same flat object. Slight rotation reveals inadequate imagery on intense relief objects

The details shown in the three close up snapshots of fully or partially textured meshes in figure 5, verify the overall success of the mesh generation and their RGB texturing.

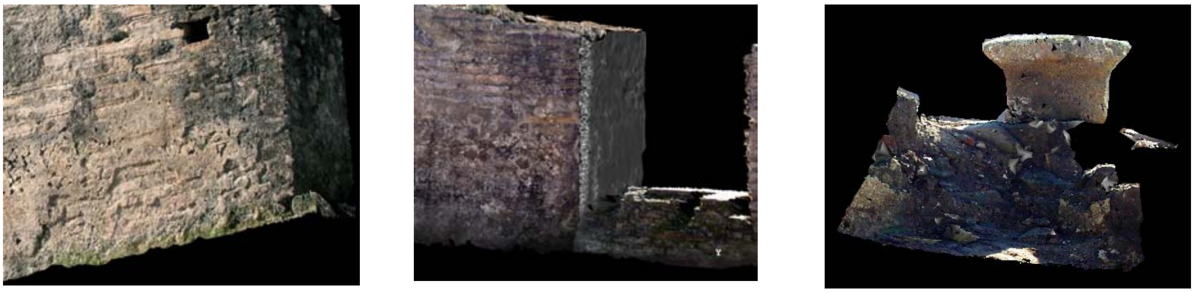

Figure 5: Mesh Details on angled more complex shapes

In figure 6, wall masonry detail is shown. Carefully navigating with the software's 3D viewer, verifies the full correspondence of the image resolution and the generated mesh accuracy: the clearly visible gaps between the carved stones are clear in the 3D textured model.

Figure 6: Partially and fully textured mesh of intense relief surfaces

Generally, the mesh generation and the RGB texture mapping were beyond any doubt fully successful and satisfy even the most demanding specifications for the archaeological surveying of monuments of this kind.

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BIOGRAPHICAL NOTES

Dr. Vaios Balis, Surveying Engineer, is a senior partner of Geotech Ltd.

Mr. Spiros Karamitsos, Surveying Engineer, is a Ph.D. candidate in Higher and Satellite Geodesy Laboratory of School of Surveying of National Technical University of Athens, and employer of the Ministry of Environment and Public Works. He also is an application professor at Athens Technological Institute.

Mr. Ioannis Kotsis, Surveying Engineer, is a Ph.D. candidate in Higher and Satellite Geodesy Laboratory of School of Surveying of National Technical University of Athens, and works as technical consultant in TopoMet Consultant Engineers S.A.

Dr. Christos Liapakis, Surveying Engineer, is a senior partner of Geotech Ltd.

Mr. Nikos Simpas, Surveying Engineer, is managing director of TopoMet Consultant Engineers S.A

CONTACT INFORMATION

Vaios Balis
Geotech Ltd.
10 Travlantoni Str.
Zographou15773 Athens
GREECE
Tel. + 30 210 747 0001
Email: vbalis@geotech.gr

Mr. Spiros Karamitsos
National Technical University of Athens
Iroon Polytechniou 9
15780, Zografou
GREECE
Tel. + 30 210 772 2667
Email: karamits@central.ntua.gr

Ioannis Kotsis
National Technical University of Athens
Iroon Polytechniou 9
15780, Zografou
GREECE
Tel. + 30 210 772 2667
Email: jkotsis@survey.ntua.gr

Christos Liapakis
Geotech Ltd
10 Travlantoni Str.
Zographou 15773
Athens
GREECE
Tel. + 30 210 747 0001
Email: cliapakis@geotech.gr

Nikos Simpas
TopoMet Consultant Engineers S.A
40 Michael Aggelou Str.
Ioannina, 45332
GREECE
Tel. + 30 265 108 3300
Email: simpas@topomet.gr