3D city modelling by combination of terrestrial laser scanning data and images

Dragoş BADEA, Assistant lect. PhD. Stud. Eng., Technical University of Civil Engineering Bucharest, Faculty of Geodesy, badea_dragos@yahoo.com
Andreea JOCEA, Assistant lect. PhD. Stud. Eng., Technical University of Civil Engineering Bucharest, ajocea@yahoo.com
Aurel NEGRILĂ, Assistant lect. PhD. Stud. Eng., Technical University of Civil Engineering Bucharest, negrilaa@yahoo.co.uk
Constantin COŞARCĂ, Associate professor, eng., Ph.D., Faculty of Geodesy, Technical University of Civil Engineering, Bucharest, constantin_cosarca@yahoo.com

***Abstract**: Terrestrial Laser Scanning data have been studied for many years. Several disciplines like urban planning, architecture, telecommunication, tourism, environmental protection and many others have an increasing demand for digital 3D city models, in order to use such complex data for planning, analyses, visualization and simulation in different applications. To satisfy this increasing demand for such data, the city models must be acquired quickly, precisely, in detail, and with full completeness and in an economic manner.*
Based on Terrestrial Laser Scanning data as well as data from other sensors, scientists have built an operational framework to extract spatial information, but also are facing challenging tasks to enhance current point cloud processes. Laser scanning will focus on new data, methodologies, algorithms and applications related to the processing of point clouds as well as sensor improvements and new sensor-driven calibration techniques.

***Keywords**: 3D city modelling, terrestrial laser scanning, point cloud, Leica Scan Station*

1. Introduction

In this paper, we describe how a virtual 3-D city model can be build from two data sources. After an introduction into Terrestrial Laser Scanner and Close Range Photogrammetry concepts, we describe in detail a selection of tools which can be used to model a wide range of objects. Having employed a number of those tools in a project where we modeled the sport hall of Technical University of Civil Engineering of Bucharest. We also show the overall workflow used to finally produce a video animation of the virtual model.
Many applications are based on city models, which contain in particular a three-dimensional representation of the buildings and other objects, sometimes complemented by a virtual reality representation of the surfaces. Since the acquisition and continuous update of 3-D data is much more pretentious than in the 2-D case, a high degree of automation is necessary in order to make 3-D models economically feasible. Consequently, automatic methods for the acquisition and update have been and still are a topic of research. However, there are nowadays tools commercially available which allow acquiring city models from aerial and terrestrial sources.
Surveying instrumentation has suffered a major transformation over the past 20 years, primarily due to the progress in electronics, including the microchip. The theodolite, the steel tape and the field book have been, in many cases, replaced by electronic field instrumentation such as the EDM, GPS and 3D laser scanning.

Each technique has come with something new: the EDM has introduced the electronically horizontal distance; GPS has introduced the “vector” and at present surveying with a terrestrial laser scanner generates a new set of information – *the point cloud*.

2. Terrestrial Laser Scanning - Idea and Concept

Large progress has been made in the area of terrestrial laser scanners during the last decade. A number of scanners is nowadays available which allow to measure millions of 3-D points in a matter of minutes. *(Lohmann, 2004)* Although it is usually the case that dense terrestrial 3-D data is acquired for selected objects only, using a fixed number of viewpoints, it is worth to note that there are commercial systems under development which allow to acquire dense, large scale 3-D point clouds from terrestrial laser scanning using moving platforms *(Wack et al., 2003; Kress-Lorenz et al., 2004).*

The laser scanner technology is an accurate and efficient way to collect and present field data; it provides rich and reliable information about the base design of buildings, monitor changes, etc. Moreover, one of the main benefits of this technology is the fact that the point cloud is an unambiguous measurement of what exists in the real world.

This technology allows us to obtain high fidelity and accurate 3D images, which can be used in common surveying applications:

- surface and volumetric calculation problems,
- creating topographic site surveys that describe planimetric features, legal boundaries, objects of interest, and contours of the terrain,

Laser scanners are optical measuring systems based on the transmission of a laser beam by moving (rotating or sweeping) mirrors on an object surface. The object is lighted point by point and then the reflected laser beam is detected. For each acquired point a distance is measured on a known direction: For each point can be calculated the X, Y and Z coordinates referenced to an internal coordinate system of laser scanner.

One of the parameters that influences the accuracy of each point in the cloud, relative to one another, is the “spot size” of the laser beam. Accuracy improves as the spot size is reduced. Other parameters that influence the accuracy of each point are the distance, the angle incidence of the laser beam, the surface properties, etc.

2.1 Principle of Laser Scanning

A terrestrial laser scanner requires a deviation mechanism in two different directions for surveying a certain region of the object of investigation. These two directions can be considered as vertical and horizontal. The laser beam travels from the electronic unit and hits the optical element, which is rotating with large velocity. On the surface of this optical unit (which behaves like a mirror) the beam is reflected and exits the laser scanning device with a specific angle β. Once the scanner has finished acquiring this β-profile the upper part of the scanner rotates with a very small angle (α) around the vertical axis in order to start capturing the next, adjacent β-profile [Kraus, 2004].

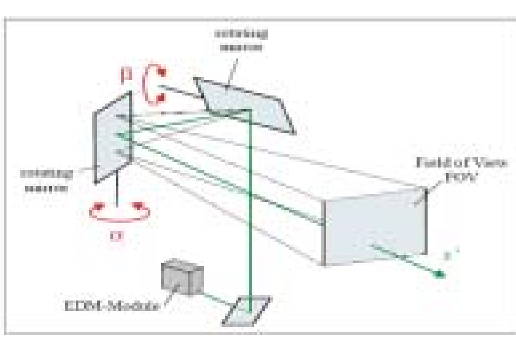


Figure1. Principle of laser scanning (Cyra, 2002)

A laser scanner can be considered as a high automatic entirely motorised station. Unlike entirely motorised stations, however, where the operator chooses directly the points to be surveyed, laser scanners randomly acquire a dense set of points. The operator only selects the portion of the object he wishes to acquire and the density of the points he desires in the scan.
During the data acquisition process a special attention must be paid to the selection of the parameters that characterise the acquisition procedure. The following aspects should be considered:
- image field of view: scanning angle in both horizontal and vertical direction
- area to be covered in a scan
- image resolution
- measurement time: accuracy is dependent on the measurement time
- diameter of the laser beam

When the laser scanner operates, the surveyed points are referenced to an internal coordinate system or directly to the chosen coordinate system. (Figure 2).

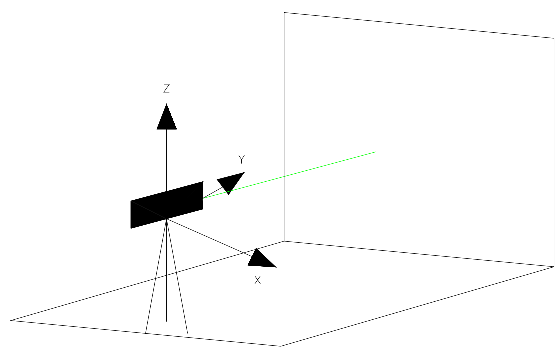


Figure 2. Internal reference system of a laser scanner

2.2 Registration and Geo-Referencing of Point Cloud to Local Control
The collected 3D data constitute in itself a 3D representation of a scene. It is not possible to have a complete 3D representation from data acquired at a single viewpoint. To resolve the occlusion which might appear in the scene it is required to have 3D data acquired from multiple viewpoints.

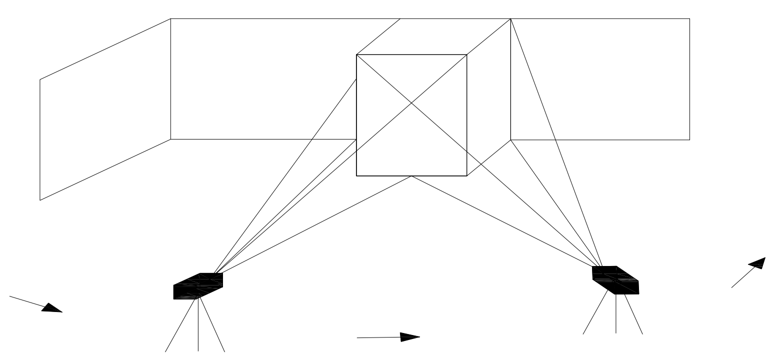
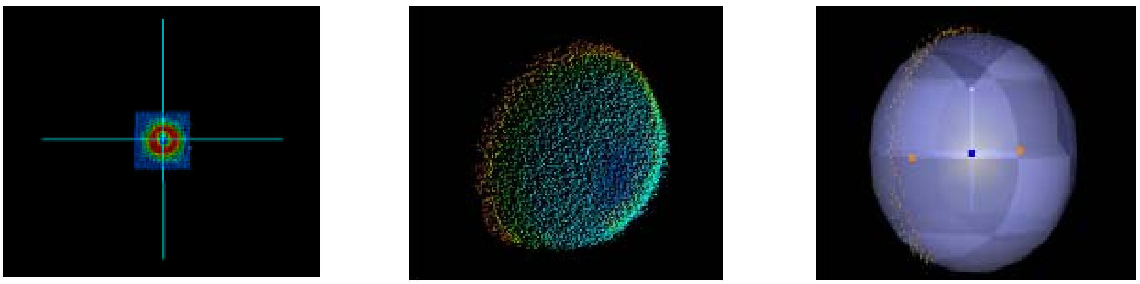


Figure 3. Multiple views

Afterwards, during the processing of the scanned images, the purpose is to realize the registration of the scans, acquired from a single station, in a common point cloud. This process is called registration or orientation. For this operation similar points extracted from the point clouds acquired from multiples views (tie-points) are necessary, that can be points on the scanned object or reflecting targets.

In this way, for each scan, the reflecting targets should be placed near/on the object in such a way that at least three targets can be found in the overlapping portion. Thus the integration of the internal coordinate system of laser scanner in the existing reference system is possible.



a. b. c.

Figure 4. Target examples: a. planar target; b. point cloud - spherical target; c. 3D model of a spherical target

In the investigation of the facilities offered by laser scanners for spatial data acquiring process a Scan Station 2 laser scanner was used from Leica Geosystems, which has the possibility to collect 50000 points per second to generate a point cloud that contains thousands and even millions of points. These points can be acquired with a relative precision of 4 mm at a range of 50 meters.

The scanner operation is controlled from a notebook by means of a cross-over cable. As the laser is sweeping across the site, an image is displayed via the screen of the connected computer, allowing the operator to navigate in the "virtual" scene and to see exactly what is being scanned.

To collect over a 1 million points in a single scan about 10 - 12 minutes are necessary. With a 360° x 270° field of view, the Scan Station 2 system covers a potential scan area of 20,000 cubic meters. Since the scanned objects are usually buildings, bridges, roadways, etc the scan area in the field of view can be reduced according to the distance from the scanner to the object(s).

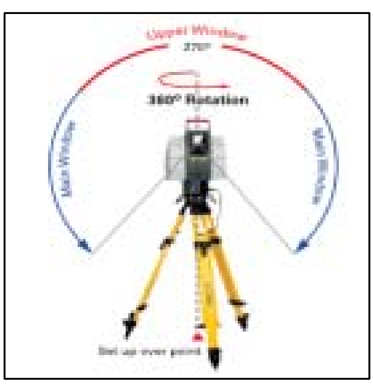


Figure 5. Leica Scan Station 2 System

The number of points in a scan is specified by first selecting the area to be scanned. This is accomplished by using a digital photo image of the scan site, taken by the scanner, and then selecting the area using the cursor. After the area is selected, the total number of points that needs to be acquired is set, in both the vertical and horizontal plans (e.g. 250 points vertical x 350 points horizontal).

Alternatively, it can be set the desired specific grid, for example, 5 mm vertical by 5 mm horizontal, at a specific range from the scanner. Specific areas that acquire special detail can be selected and scanned with a higher density of points.

Disadvantages of using only laser scanner data are data handling, registration, modeling, edges, and noise.

3. Close range photogrammetry

Close range photogrammetry is a very established procedure, its first roots dating back as early as 1860, where Albrecht Meydenbauer made his first investigations into architectural photogrammetry. Nowadays, there are highly automated close range measuring systems, especially in industrial environments where artificial targets can be used *(Atkinson, 2000).* In architectural applications, the selection and measurement of points is still mostly carried out manually, however, matching and bundle adjustment procedures in the background speed up the acquisition process considerably. Powerful software packages are available nowadays, such as PhotoModeler, ShapeCapture, or Pictran.
Dimensional surveys of structural features are generally required to document existing conditions for engineering analysis and planning. Traditionally, survey crews obtain measurements using conventional equipment and methods, which involve physically placing measurement devices on every key feature. Using digital sensors like laser scanner combined with digital close-range photogrammetry to measure structural features with high accuracy, increased safety, and minimal impact on getting measurements on objects hard to reach.
Close-range photogrammetry is a technique for accurately measuring objects directly from photographs or digital images captured with a camera at close range. Multiple, overlapping images taken from different perspectives, produces measurements that can be used to create accurate as-built 3D models. Knowing the position of camera is not necessary because the geometry of the object is established directly from the images.
The attractiveness of relative orientation is simply that it requires no object space coordinate data. Moreover, it is well suited to image measurement scenarios where conjugate points are 'referenced' between two images, point by point, for example within a stereoscopic model. It is well known that for a given image pair, a minimum of five referenced points is required to solve for the unknown parameters in a dependent relative orientation via the coplanarity model.
Close-range photogrammetric methods have been successfully applied to projects in archaeology, architecture, automotive and aerospace engineering, and accident reconstruction.
Surveyors are able to obtain precise measurements without physically accessing each measurement point. The method is non-intrusive, creating minimal impact on activity carried at the location.
The same process can be used to obtain dimensional measurements efficiently on inaccessible structures such as tunnels and dams, and large or complex facilities such as refineries or water treatment plants. Close-range photogrammetric measurements together with Laser scanner measurements can be integrated with 3D modeling and reverse engineering processes. The acquired data is infinite and the cost savings substantial.
Disadvantages of using only close range photogrammetry are, camera calibration, time consuming while is a semi automated process and image resolution.

Single Camera Geometry principles
The basic model is the *central perspective projection* (also called pin-point camera model). The primary coordinate system is positioned arbitrarily in object space, while the secondary system as its origin at the perspective camera center ***O***, its z-axis coincides with the principal axis and is directed away from the projection (image) plane . The scale factor is set to unity.
In the primary system we have the coordinates of the perspective center, ***O***, and an object point in space, ***A*** : (X_0, Y_0, Z_0) and (X_A, Y_A, Z_A), respectively. The projection of ***A***, through ***O***, in the image plane, expressed in the secondary system, give the coordinates of point ***a*** : $(x_a, y_a, -c)$, where "*c*" is the *principal distance* (sometimes called effective focal length), between ***O*** and the principal point, ***PP***. Points ***A*** and ***a*** are called *homologous*. Thus, we have : $\boldsymbol{X}_A = \boldsymbol{X}_0 + (-\mu)\boldsymbol{R}^t \boldsymbol{x}_a$, where **μ** is a

positive scalar quantity proportional to the object distance from ***A*** to ***O***. The reverse tansform is then given as Note that the vectors $(X_A - X_0), x_a$ are collinear but of opposite sense.
The 3rd equation of the reverse transform above can be written explicity in terms of the scaling μ and subsituted in the other 2 equations, leading to the *Collinearity equations*:

$$x_a = \frac{-c\,[r_{11}(X_0 - X_A) + r_{12}(Y_0 - Y_A) + r_{13}(Z_0 - Z_A)]}{[r_{31}(X_0 - X_A) + r_{32}(Y_0 - Y_A) + r_{33}(Z_0 - Z_A)]} \quad \text{and} \quad y_a = \frac{-c\,[r_{21}(X_0 - X_A) + r_{22}(Y_0 - Y_A) + r_{23}(Z_0 - Z_A)]}{[r_{31}(X_0 - X_A) + r_{32}(Y_0 - Y_A) + r_{33}(Z_0 - Z_A)]}$$

$$\begin{bmatrix} x_a \\ y_a \\ -c \end{bmatrix} = \mu^{-1} \begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix} \begin{bmatrix} X_A - X_0 \\ Y_A - Y_0 \\ Z_A - Z_0 \end{bmatrix}$$

Resection - Exterior parameters
Once the interior (calibration) parameters are known, their remains 6 exterior orientations parameters to determine (3D translation and rotation). This evaluation is called ***resection***. At least 3 non-collinear targets, called *control points*, are needed.

4. Recording of the sport hall of Technical University of Civil Engineering of Bucharest

4.1 Location

The application involved scanning of sport hall of Technical University of Civil Engineering of Bucharest. The site is located near Lacul Tei garden, Lacul Tei County, in northern part of Bucharest.

Figure 6. Location of sport hall

Besides acquisition, a major concern was the integration of all data sets into a single model. Our purpose was mainly the visualization of the results. The subsequent sections first present the overall workflow we used for building a 3-D city model, then each of the acquisition techniques as well as on the integration stage is described in more detail.

4.2 Field operation (Data acquisition)

Topographic data

Before scanning a local geodetic network was determined, which was supposed to be used for the subsequent geo-referencing of the different scans. About 9 points were collected with a total station Leica TCR 802. The network measurements (horizontal directions, vertical angles, and distances) were processed using the least squares method. The network has been compensated as a free network, obtaining for the planimetry a standard deviation of 5.7 mm and for the altimetry a standard deviation of 3.8 mm. The point coordinates and their standard deviations can be found in the following table:

Point	X (m)	St.dev. (mm)	Y (m)	St.dev. (mm)	H (m)	St.dev. (mm)
S1	4999.999	4.3	3000.000	3.9	100.000	0.0
S2	5012.164	4.6	3037.441	3.6	99.660	2.8
S3	5053.282	4.6	3043.866	3.6	99.752	3.7
S4	5070.421	4.2	3031.737	3.6	100.257	4.2
S5	5015.690	4.3	2968.176	3.9	100.207	2.8
S6	5054.643	4.2	2981.016	4.0	100.262	3.7
S7	5097.044	4.1	2996.169	4.3	100.398	4.2
S8	5102.062	4.0	3023.030	4.0	100.977	4.4
S9	5096.960	4.2	3039.405	3.4	100.829	4.4

Laser scanning data

The recording of the complete object by the laser scanning system required nine different scanner stations which provided 14 scans in total using a grid width of 5 cm. The measuring distances to the object were between 15-50 m. In total 1.5 million points were collected which yielded a file size of 302 Mb. The data acquisition with the laser scanner was accomplished on two workdays.

Photogrammetric data

Photogrammetry technigues allow you to convert images of an object into a 3D model. Using a digital camera with known characteristic (lens focal length, imager size and number of pixels), you need a minimum of two pictures of an object. If you can indicate the same three object points in the two images and you can indicate a known dimension you can determine other 3D points in the images.
Photogrammetry is a very good tool if you have limited access time to the object to be modelled. Images can be captured very quickly. The trade-off is that it can take a lot of time to process the images. If the number of points required to create a useful model is large, it can be very tedious with photogrammetry.
The quality / accuracy of the 3D model can be affected by several things. The quality of the camera lens and the resolution of the imager chip, the camera calibration, and the number of images taken are all important.
There were used about 30 images because of the difficult conditions on one side of the building like short distance and an abundance of vegetation.

Office operation (Data processing)
The data processing was carried out exclusively in the Cyclone software modules. The first step of the processing was the transformation of all point clouds from the local scanner coordinate system into the common coordinate system (**registration**). This processing step was performed in Cyclone software by a 3D Helmert transformation without scaling factor. The registration was carried out as an automated process using HDS Leica targets. These targets were already recognized semi-automatically by the software during the scanning phase. The registration that could be obtained was 22 mm.

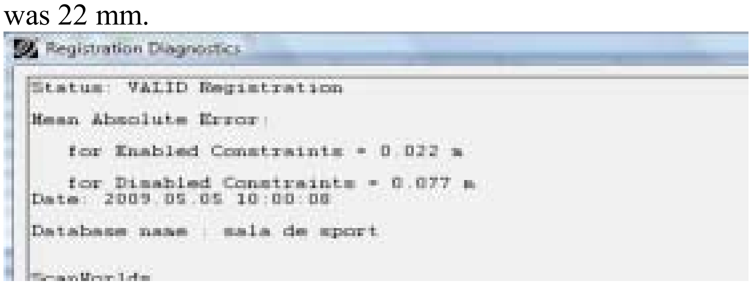


Figure 7. Registration diagnostic

For the creation of more realistic realizations of the building facades we used close range acquisition techniques. For this task we used a non metric digital still camera from

Nikon. The acquisition of high resolution photos, the reconstruction of geometries and the rectification of the facade textures using the well known program PhotoModeler, and the processing of terrestrial laser scanning data to derive different types of elements from highly detailed facade parts to even complete building geometries.
For selected buildings, from the registered and geo-referenced point-cloud, a detailed CAD model was derived using the software Cyclone, which is based on fitting primitives to the original terrestrial laser scan data set.

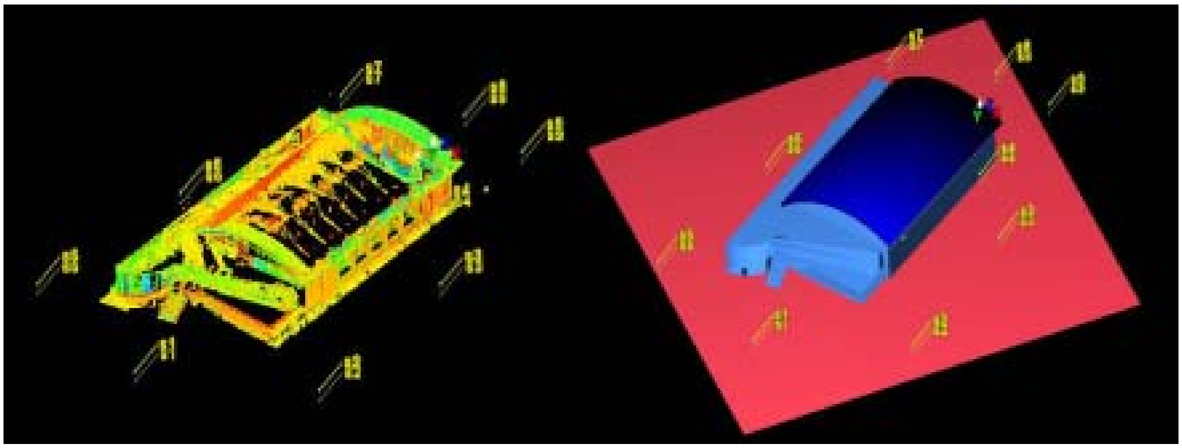


Figure 8. The point cloud and the CAD model

Textures for these geometries have been acquired separately using a Nikon D200 still image camera. The rectification was done using the imaging application Adobe Photoshop Elements. There are also specialized tools like RectifyIt, however Photoshop has been used to reduce the amount of training and because this software offers all functions for image management, cropping, rectification, image editing, composition and simple radiometric corrections.
After all buildings and elements were reconstructed to the desired extend, the goal was to visualize the results. Different ways are conceivable, as there are still images, animations and video-sequences or navigable 3D environments. The decision for the user-sufficient way of visualization is application-dependent. The creation of still-images or animations can be performed with any 3D modeling software which is capable of handling the amount of data which is needed for the visualization (e.g. 3D Studio MAX, Maya, Cinema 4D, etc).
For the sport hall of TUCEB Project, the creation of a video-sequence has been selected as the best way for a judicious visualization solution. The whole 3D-project has been integrated into the modeling application ARTLANTIS and a short movie has been rendered.

Modeling in ArchiCAD

Integrated, object oriented 3D CAD is fast becoming the mainstream design and documentation tool for architectural and design practices all over the world. Traditional drafting-based systems are being phased out in favor of model-based solutions because the allow you to create rather then draw, build rather then draw.
The reason that we choose ArchiCAD for modeling is it's flexibility to create a digital model of the real building. Graphisoft ArchiCAD has been developed, from its inception based on the principles of "building information modeling".
ArchiCAD is mainly oriented for architectural planning, but because its function of Import and Export in CAD standards we were able to use the 3D shapes created in AutoCAD or Cyclone. Doing so, we override the architectural aspect of modeling because we already have the real building. The rest of the procedures were to give a realistic 3D view of our object, based on the

program's capabilities to integrate doors, widows, stears, textures and drape images over, directly in a 3D environment, properties for those were being extracted from measurements that we carried on with laser scanner equipment and from images.

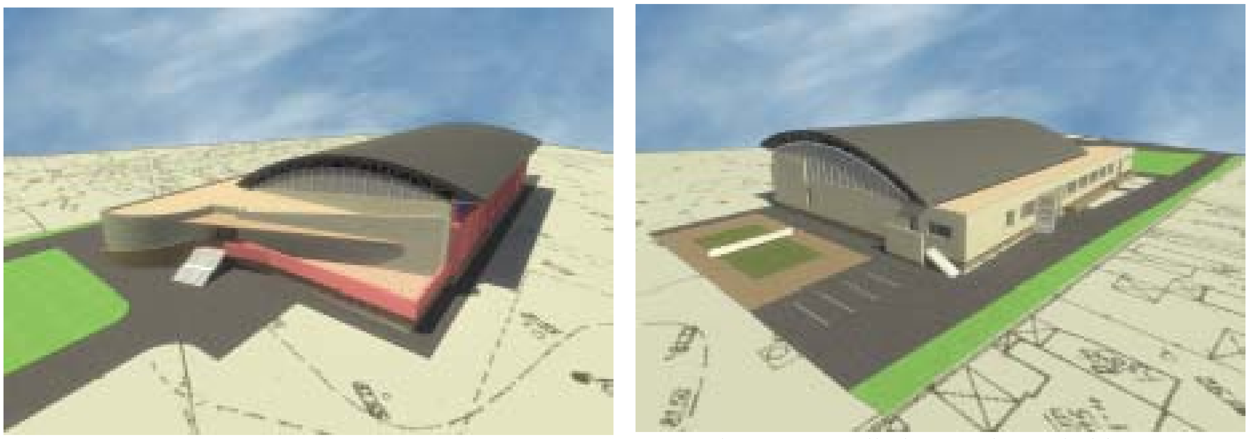


Figure 9. Realistic 3D view of object

Artlantis is a powerful ArchiCAD extension wich is able to display, modify and update the 3D model. We use it to generate a realistic scene of our 3D model and the short movie.

5. Conclusions

Image-based approach and laser scanner are not competitive but rather complementary. The former is more suited when higher accuracy is required, while laser scanner is useful when a high amount of data is required in a short time. Combination of the methods allows good results. In both approaches the modeling part (from 3D point to surface) is still the most problematic and time consuming.

6. Bibliography

1. Coiner Ch., Bruno A.:"3D Laser Scanning for Common Surveying Applications", 2002
2. Cyra Technologies, Inc.: "Cyclone 4.0-User's Manual", 2002;
3. Cyra Technologies, Inc.: "Cyclone Cloud Worx-User's Manual for AutoCAD", 2003;
4. Fröhlich C., Mettenleiter M.: "Terrestrial Laser Scanning - New Perspectives in 3D-Surveying", 2004
5. Jacobs G.: "Extracting Points, Lines, Surfaces, Features and Models from Point Clouds", 2005
6. Jocea A. : Terrestrial 3D Laser Scanning Applications In Civil Engineering Projects, Diploma Thesis, 2005
7. Conf univ. dr. ing. Ion Ionescu – "Fotogrametrie terestra"
8. Brian Norris • James W. "Close-Range Photogrammetry 2003 Nova Award Nomination 29"
9. Claus Brenner and Guido von Goesseln „Tools And Workflow For The Rapid Acquisition Of 3-D City Models" - Institute of Cartography and Geoinformatics, University of Hannover
10. F. Remondino, A. Guarnieri, A. Vettore, "Photogrammetry or Laser Scanning?" - Institute of Geodesy and Photogrammetry ETH Hönggerberg - Zurich, Switzerland, Cirgeo - Interdept. Research Center of Geomatics, University of Padua – Italy
11. Neffra Matthews, "Close-Range Photogrammetry"
12. Clive Fraser, Harry Hanley and Simon Cronk "Close-Range Photogrammetry for accident reconstruction" 2005 - Department of Geomatics, University of Melbourne
13. Graphisoft U.S., Inc. "Graphisoft Archicad Residential"
14. Graphisoft U.S., Inc. Archicad tutorials

15. Graphisoft U.S., Inc. "Structural design with ArchiCAD, and its integration with structural software"
16. Graphisoft U.S., Inc. "Modeling Terrain with ArchiCAD"
17. Abvent Artlantis , "Artlantis for ArchiCAD Users"