Creation of 3D Geometry in Scan-to-CAD/BIM Environment

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Abstract. Scan-to-BIM brings the documentation of existing buildings into line with the modern digital planning methodology called building information modelling (BIM). This article describes how scan-to-BIM uses 3D laser scanning to capture digitally an existing building as a point cloud, for the creation and updating of a BIM model. Renovation of an existing old lattice grid structure, out of service for more than ten years, was a real challenge for investigation, capturing geometry and determining the rest load-carrying capacity. The original structure was calculated and produced in Italy and assembled at Bulgaria during the 80s of 20th century and was covered with a single layer membrane. It was used for 30 years before it was left without service and maintenance for more than 10 years. Strong corrosion processes was investigated for some of the members and almost all applied bolts which reduce seriously the rest load-carrying capacity. Laser scanning technology was chosen for getting the complex 3D geometry of the lattice grid structure. It was a real challenge to find a software for processing the scanned data and extracting the axial geometry of structure. Investigations for determining of the applied steel class and class of bolts was done on the site and at laboratory. Different concepts for rehabilitation was discussed before choosing the double layered stressed textile membrane. Numerical FEM models was used for proofing the adequacy of chosen structural solution. Modelling is a necessary process for converting the point cloud to a useful CAD representation. It provides a complete picture of the as-built situation by filling the gaps coming from occlusions, by averaging the effects of noise and by providing the quality measures about the final results.

1. Introduction
The objective of this paper is to present new methods and techniques which can be used for automatic or more efficient semiautomatic 3D modelling of existing structure from point clouds. The goal is to use dense 3D information from the point clouds to create the object and structure present in the scene. To avoid manual editing the presented techniques uses models from a catalogue of commonly found CAD objects as templates for model fitting.

There is an increasing demand for accurate, as-built, 3D models of existing buildings. The following are some of the application areas which either require or can benefit from the availability of such models:
• Planning (clash detection, decommissioning, design changes)
• Revamping and retrofitting of old sites
• Implementation of services based on Virtual and Augmented reality.
• Safety analysis
• Change detection.
Although most of the new industrial sites are designed using 3D CAD techniques, in most cases the initial model represents a functional design rather than the final as-built situation. Moreover, industrial facilities are often very dynamic environments, where constant changes are required to improve health and safety, to increase efficiency, and to reduce hazardous emissions in accordance with the environmental regulations. As a result, after a few years there is a big gap between the documented model and the as-built situation. In most cases, it is not cost effective or practical to update these models at the end of construction or after each and every change. For old and legacy sites, the situation is even worse, as most of them were initially designed using old 2D CAD techniques and there is no 3D model available. Consequently, in both cases, when new changes are planned up-to-date, as-built 3D information is required.

Traditional methods for acquiring as-built information consist of manual measurements by tape and classical geodetic measurements. As-built modelling using measuring tape is accurate only up to 25–75 mm, which is not acceptable for most planning scenarios where measurement accuracy of ± 2 mm is usually required. Classical geodetic measurements provide high accuracy, but due to its slow speed combined with the limitations of the measurement technique, the density of the measured points is very low. As a result, the sparse 3D measurements have to be manually extrapolated to make an approximate 3D model which, except on the points explicitly measured, does not provide a true and accurate picture of the as-built situation. Moreover, as most industrial sites contain many curved faces like cylinders and bends, the sparse point clouds from classical geodetic measurements become even more inadequate.

2. Point clouds and then what to do with it?

2.1. Scan to CAD

For converting the point cloud to a CAD representation, we need the step of modelling, where different types of surfaces are fitted to a selected subset of the point cloud. The resulting surfaces are edited, extended, and intersected to get a full 3D model. Modelling is one of the most time consuming and costly processes during the reconstruction of any steal construction. This cost arises due to the high amount of manual input required from the human operator. Although the situation has improved a lot compared to the approaches based on traditional photogrammetry, still most of the current point cloud processing software provide minimal if any automatic modelling facilities. A question is often raised about the need for modelling. If it is fast and cheap to acquire dense point clouds using the current generation of laser scanners, why not use the point cloud directly, instead of deriving a 3D model from it? It is argued that a dense point cloud should be as good as a CAD model. There are certain weaknesses with this argument. In any typical steal construction, it is practically impossible to get a complete coverage of all areas by point clouds. Even if issues of time and effort involved are ignored, a high degree of occlusions arising from the clutter and complexity often makes placement of the scanner at arbitrary positions impossible. However, by fitting models the missing data has been estimated along with a high degree of compression in the amount of information from millions of points to a few parameters for each object in the fitted model. The engineering work flow in most industries is based on working with standard 2D and 3D CAD models which means that introduction of the point cloud as a new geometry representation has inherent integration problems. The space and time complexity of manipulating, storing and sharing huge amounts of data produced by laser scanners adds another dimension to this problem. To summarize, modelling is necessary because it provides a complete picture by filling in the gaps left by occlusions, averages the effects of noise providing better accuracy, reduces the amount of data and the resulting CAD models fits nicely in the engineering work flow of daily industrial practice.

2.2. Surface fitting to point clouds

Almost all modelling tools available on the market depend on heavy operator intervention for most of the modelling tasks. Although there are some semi-automatic tools like plane or cylinder growing but even there the operator has to start the growing process for each primitive. Furthermore, the fitted surfaces must be manually edited by the operator to convert them to a CAD description. The problem
of fitting CAD models to point clouds arises in many applications like model-based object recognition, surface reconstruction, reverse engineering and quality control [1], [2], [3]. Recent advances in laser scanning technologies have also added to their importance, as acquisition of dense point clouds has become both faster and cost-effective.

The plane is parametrized by its normal vector \( \mathbf{n} = (nx \ ny \ nz) \) and perpendicular distance from the origin \( p \). A sphere \( S \) is parametrized by its center \( \mathbf{c} = (cx \ cy \ cz) \), and the radius \( r \). The cylinder is represented by its axis \( \mathbf{a} = (ax \ ay \ az) \), the point on axis closest to origin \( \mathbf{c} = (cx \ cy \ cz) \), and the radius \( r \) (Figure 1).

![Figure 1. Parameters of the object models (Picture taken from [4])](image)

2.3. Cylinder fitting

Cylinders are one of the most commonly encountered geometric objects on industrial sites and steal constructions. Once the points belonging to a cylinder have been selected for the final estimation of the parameters is done through the least squares adjustment. Its equation in standard position (centered at the origin, axis along the z-axis) is given by

\[
x^2 + y^2 - r^2 = 0
\]  

(1)

For fitting a cylinder to the points in the least squares adjustment, the orthogonal distance of the point from the cylinder surface is required. The cylinder is represented by its axis \( \mathbf{a} = [ax \ ay \ az] \), the point on axis closest to the origin \( \mathbf{c} = [cx \ cy \ cz] \), and the radius \( r \) (Figure 1). As there are only five degrees of freedom for the cylinder, we have two constraints.

Firstly, the length of the axial direction vector must be one i.e. \( |a| = 1 \). Secondly, the point \( \mathbf{c} \) must be closest to the origin, which means that \( \mathbf{c} \) and \( \mathbf{a} \) should be perpendicular. The distance of a measured point \( \mathbf{p} = [px \ py \ pz] \) from the surface of the cylinder is given by

\[
d = [(p - c) \times a] - r
\]  

(2)

3. Laser scanning technology for determining the exact geometry

The Terrestrial laser scanning (TLS) technology is increasingly used in geodetic practice, because of the accurate 3D surface measurements with a big density in very short time. After the measurement, the point cloud is further processed and modelled for use in other applications such as deformation applications, building information modelling [5], 3D cadastre [6], cultural heritage documentation and renovation, reverse engineering.

The scanning of the lattice grid structure was performed with the Leica Nova MS60 scanning station with an angular accuracy 1” (according to ISO 17123-3) and a new optical distance measurement system based on Wave form digitizing (WFD) technology. Accuracy of measured distance 2 mm + 2 ppm for
surface measurements. This instrument can provide accuracy below 1 mm for final digital model after approximation. The grid structure was scanned from 12 stations to ensure the same accuracy and homogeneity of the point cloud [7]. The measurement was performed in 1000 Hz mode (dots/sec) and a scan density of 3 mm at 12 meters distance (Figure 2). Limits for minimum and maximum scanning distance is entered to limit scanning to the object only.

![Figure 2. Setting up Leica Nova MS60 scanning station](image)

The resulting point cloud of the lattice grid structure was imported in Autodesk Recap Pro (Figure 3) and CloudCompare software (Figure 4) for filtering and cutting the redundant scan data. Then transferred to the Bently software for further processing and calculating the axial geometry of the cylinders.

![Figure 3. Point cloud in Autodesk Recap](image)  ![Figure 4. Filtering of the point cloud data in Cloud Compare software](image)

In other to get cylinders from point cloud, it is necessary to make approximation by least square adjustment (Figure 5).

![Figure 5. Approximation of a cylinder from the point cloud with known low-degree polynomials](image)
4. Geometry modelling
When we are modelling an ordinary building, it is often enough to consider planar objects for representation of walls and roofs. Industrial sites and other steal constructions are typically composed of slightly more complicated geometric primitives, such as sphere and cylinders. Several software packages nowadays offer the possibility of fitting such primitives to a point cloud in a semi-automatic way, where the user has to select of the point cloud or seed point together with a suitable primitive. Software that have instruments to convert laser scan data into 3D models include Cyclone Cloudworks, Faro Scene, LupoScan, Autodesk Revit, Trimble, Bentley Pointools.[8]

4.1. Software Interoperability
Interoperability is a critical issue for users of software design and engineering, which is often seen as the missing link between different software systems, the existence of which allows effective collaboration of different systems and organizations.[9] Ensuring interoperability allows the best possible sharing of common objects, geometry and properties between different applications by building common 3D models or defining information and geometry in one system to be used in another. An example of this is a 3D model of a building or facility from a modelling application that is transferred and used by the analysis and design system. Interoperability is achieved by designing direct links between different software applications or indirectly through universal file formats.

Two big competitors in the development and application of software in the industry, Autodesk and Bentley Systems, have an explicit agreement to expand interoperability between their portfolios of software for architecture, engineering and construction (AEC). Autodesk and Bentley provide the ability to share software libraries, including Autodesk RealDWG and Bentley DGN, to ensure the reliability of information when reading and writing DWG and DGN formats when working in mixed environments. There is also an agreement between the two companies to facilitate interoperability between the respective applications for architecture, engineering and construction by supporting the reciprocal use of available application programming interfaces (APIs). This finds practical expression in Bentley's direct access to DWG through RealDWG and API access and technical support for applications developed for AutoCAD, Revit and other Autodesk applications. Bentley users can take advantage of the ability to run AutoCAD-based objects in Bentley activated products. Autodesk, for its part, has access to Bentley's MicroStation, ProjectWise, and other architectural, engineering, and construction product development tools, and Bentley is developing a type of library for Autodesk to include in its products. This cooperation in favour of interoperability reduces errors and allows for the development of joint products.

4.2. Numerical modelling
When a detailed three-dimensional model is required for the structural analysis of a structure, including all the relevant features about the complex geometry, it can be created by using the 3D modelling tools (primitive fitting tools, cross-section methods, extrusion techniques, etc.) of CAD platforms. This approach consists of using directly the original or improved point cloud into the CAD software, avoiding the intermediate step of mesh generation. However, the CAD software must incorporate specific modules for point cloud visualization when dense point clouds need to be handled[10]. Alternatively, it would be necessary to draw the contour of the object to be modelled from different orthogonal views in the point cloud editing software to be subsequently imported into the CAD software and use the aforementioned modelling tools to create the model. By repeating the operation for all parts and properly defining the assembly of all parts, the entire 3D model is created.

3D modelling primitive fitting tools are used in this research. Several software applications are used to build the exact 3D geometry of the old lattice structure, as follows:
1) Axial geometry of cylinders from point cloud is extracted with BentleyMap Enterprise (Figure 6, 7, 8);
2) Axial model of the construction is built with 3D AutoCAD (Figure 10);
3) Three-dimensional construction model Autodesk Structural Detailing 2015 (Figure 9);
4) Computational model in SOFiSTiK is built from the axial geometry (Figure 11, Figure 12). SOFiSTiK software has a graphical input from AutoCAD. The program is German and is better known among bridge engineers.

**Figure 6.** Isometric view on which is shown that the tubes are in front of the membrane and the tubes and its axis coincide precisely to the Point Cloud;

**Figure 7.** Front view of the bottom view with fitted cylinders in yellow and green.

**Figure 8.** 3D tubes with axial line generated from Bentley software, only one fourth of the whole structure.

**Figure 9.** Closer view of the 3D structure initially scanned with Point Cloud technology.

**Figure 10.** 3D axial model build on the basis of model from Bentley software.
Figure 1. 3D model of the finalized structure.

Figure 12. 3D model with a membrane stressed surface of the finalized structure.

5. Conclusions
Laser scanning data has proven to be very useful, not only as source data for the creation of geometric models needed for structural analysis operations of real structures in a direct manner, but also it has been demonstrated how the data acquired by these instruments can provide the necessary data (in terms of detail and accuracy) when inverse problems need to be solved. This paper focuses on demonstrating how laser scanning is a technology that not only provides accurate and detailed geometric information for further 3D modelling, but also can provide the necessary data to solve inverse problems.
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