Advanced Engineering Informatics 30 (2016) 298–311

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Full length article

Parametric as-built model generation of complex shapes from point clouds

Luigi Barazzetti

Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Via Ponzio 31, 20133 Milan, Italy

ARTICLE INFO

Article history:
Received 8 August 2015
Received in revised form 24 March 2016
Accepted 30 March 2016

Keywords:
As-built
Automation
Laser scanning
Parametrization
Photogrammetry
Point cloud

ABSTRACT

This paper presents a novel semi-automated method for the generation of 3D parametric as-built models from point clouds. Laser scanning and photogrammetry have a primary role in the survey of existing facilities, especially for the generation of accurate and detailed as-built parametric models that reflect the true condition of a building. Various studies demonstrate that point clouds have a sporadic adoption in large and complex parametric modeling projects. The lack of advanced processing algorithms able to convert point clouds into parametric objects makes the generation of accurate as-built models a challenging task for irregular elements without predefined shape.

The proposed semi-automated method allows the creation of parametric models from photogrammetric and laser scanning point clouds. The method is intended as a multi-step process where NURBS curves and surfaces are used to reconstruct complex and irregular objects, without excessive simplification of the information encapsulated into huge point clouds to avoid heavy models useless for practical purposes and productive work. Different case studies derived from actual BIM-based projects are illustrated and discussed to demonstrate advantages and limitations of the method.

1. Introduction

The generation of accurate as-built parametric models of objects surveyed with point clouds is a complex task of primary importance in reuse projects of existing buildings [41]. Laser scanning and photogrammetric point clouds provide a huge amount of metric information that reveals the actual shape. However, point clouds have to be turned into useful models for the different specialists (architects, engineers, restorers, etc.) involved in the project.

Direct geometric modeling is the process of creating static 3D models with both simple and complex surfaces. On the other hand, the use of Building Information Modeling is becoming more important for construction, renovation, reuse and management projects. Here, the static representation offered by direct geometric modeling is not sufficient. *Parametric modeling* can be intended as the process of "redrawing without redrawing". If (direct) geometric modeling aims at providing a static reconstruction of the objects, in parametric modeling distinct objects can be interactively modified by changing the numerical values in a set of predefined parameters stored in a database (Fig. 1).

According to Eastman et al. [16, Chapter 1], parametric objects (i) contain geometric information and associated data and rules, (ii) have non-redundant geometry, which allows for no inconsistencies, (iii) have parametric rules that automatically modify associated geometries when inserted into a building model or when changes are made to associated objects, (iv) can be defined at different levels of aggregation, and (v) have the ability to link to or receive, broadcast, or export sets of attributes such as structural materials, acoustic data, energy data, and cost, to other applications and models. Parametric modeling refers to a virtual construction with fully-defined objects that know where they belong, how they relate to other objects and what they consist of [43].

Automated reconstruction of indoor scenes from point clouds has a direct connection to parametric modeling. Nowadays, 3D indoor modeling in real construction projects is mainly a manual procedure, that is time consuming and labor intensive [27]. Automated algorithms assume that the scene is composed of several primitive such as planar parts and arbitrarily shaped clutters [32]. As mentioned, automated algorithms have a strong connection to as-built parametric modeling strategies for the need of planar shapes detected with robust data processing algorithms [11], i.e. automated procedures able to detect wall segments and remove outliers. Volumetric modeling approaches were also

E-mail address: luigi.barazzetti@polimi.it

http://dx.doi.org/10.1016/j.aei.2016.03.005
1474-0346/

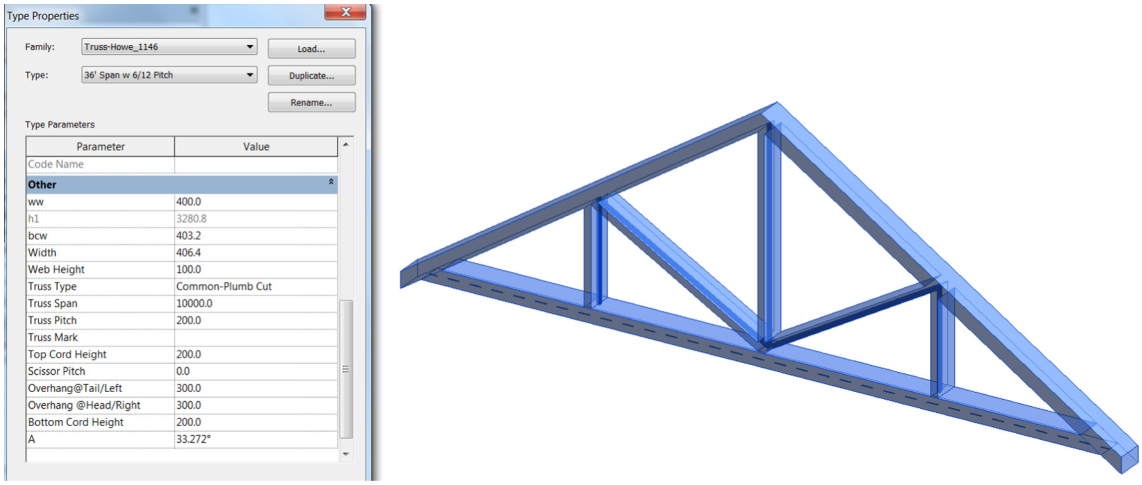

Fig. 1. In parametric modeling a database is associated to the different elements of the objects: the elements of the truss can be modified by changing the numerical values in the table.

proposed by Oesau et al. [33] to deal with multi-level buildings with arbitrary wall directions.

In recent years, parametric modeling has gathered more attention for the increasing demand of Building Information Modeling (BIM) in construction projects worldwide [9,46]. BIM relies on a 3D model made of objects with a rich set of attributes stored in a database. Objects are defined as parametric objects with relationships to other parametric objects. The 3D model is not only a static representation of the facility, but also an advanced computer technology to manage information for the automatic generation of drawings (sections, plans, etc.) and reports, design analysis, schedule simulation, thermal and structural simulation, facilities management, and much more. Although *as-designed* BIM (i.e. BIM generated in the design phase of a facility) has reached a sufficient maturity for practical purposes, *as-built* BIM generation (i.e. BIM of existing facilities generated from a preliminary survey, see Fig. 1) is still a challenging task where it is difficult to capture, interpret and represent as-built conditions in a complete BIM workflow [6,18,38]. As-built BIM refers to BIM of existing buildings where an as-designed BIM could be also available ("as-built" means "as-is"). In other words, it reflects the real conditions of the construction, which could be different than those reported in the as-designed BIM or existing drawings [42].

In the design stage of a facility, architectural, engineering and technical issues are analyzed in common workflow to arrive at the global definition of the construction process. Numerous researchers have explored the potential offered by integrated 3D modeling instead of a more traditional 2D design. The advantages of BIM technology can also be exploited for existing buildings [1,45]. The use of existing drawings (including CAD) to generate the as-built BIM can be a source of errors in the case of variation orders during the construction phase, which is a common problem in construction projects [23,31]. Only a detailed survey of existing buildings can reveal the actual shape of the structures, which can differ from the designed form because of local anomalies, degradations and damages.

Photogrammetry and laser scanning technology are rapid and accurate measurement techniques that can support the generation of as-built BIM. Both provide dense point clouds with millimeter level accuracy, revealing the real external shape of constructive elements. However, few commercial BIM packages can read and display point clouds (e.g. Autodesk Revit and AECOsim Building Designer) to facilitate the integration of point clouds and BIM objects. Some new plugins are able to improve the interactive (manual) creation of BIM objects of simple elements, such as regular walls and columns, as well as Mechanical Electrical Plumbing (MEP) elements (e.g. pipes and conduits).

Automatic as-build BIM generation refers to the creation of BIM objects from sets of raw point clouds registered in a common reference system [8,21], including information from existing reports, analysis on materials, destructive and non-destructive tests, infrared thermography, etc. Fully automatic as-built BIM generation is still in its infancy and as-built BIM are usually produced with manual measurements, making the whole process time-consuming and error-prone. According to Nagel et al. [30], automatic reconstruction of buildings has been a research issue over the last 25 years with little success to date. They point out that the main issues for a complete automation of the workflow are related to the definition of a target structure that covers all variations of building, the complexity of input data, ambiguities and errors in the data, and the reduction of the search space during interpretation [44]. It is not difficult to understand why fully automatic as-built BIM generation from point clouds is a complicated task. Although laser scanning and photogrammetry are very popular solutions in 3D modeling projects (see for example [5,25,7,12,17,20,13,22], most 3D modeling techniques available today in commercial and scientific software do not provide BIM models. Mesh surfaces generated from packages for point cloud editing (e.g. Geomagic Studio, Polyworks, 3DReshaper, etc.), image-based software (e.g. PhotoModeler, PhotoScan, 3D Zephyr, Pix4Dmapper, Smart3DCapture, etc.), and advanced 2D or 3D modeling environments (AutoCAD, Rhinoceros, Maya, 3D Studio Max, etc.) are not BIM objects. The geometric fitting of static primitives (e.g. planes, cylinders, etc.) is also a pure geometric process that does not fulfil the basic requirements of BIM projects.

Different BIM software (e.g. Revit, ArchiCAD, AECOsim Building Designer, Tekla BIMsight, etc.) are available on the commercial market and allow users to manually generate as-designed and as-built BIM. Some examples of complete as-built models from point clouds obtained in Revit and ArchiCAD were proposed by Murphy et al. [28], Baik et al. [3], Fai and Rafeiro [19], Oreni et al. [34], Barazzetti et al. [4], Dore et al. [15], and Quattrini et al. [39].

Because existing object libraries were mainly designed for design purposes (i.e. new constructions), the challenges faced in this paper can be described by the following questions: how can we generate an accurate as-built parametric model of irregular elements? Can we take into consideration geometric anomalies with