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Automatic 3D modelling of metal frame connections from LiDAR data for structural engineering purposes

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ABSTRACT

The automatic generation of 3D as-built models from LiDAR data is a topic where significant progress has been made in recent years. This paper describes a new method for the detection and automatic 3D modelling of frame connections and the formation of profiles comprising a metal frame from LiDAR data. The method has been developed using an approach to create 2.5D density images for subsequent processing using the Hough transform. The structure connections can be automatically identified after selecting areas in the point cloud. As a result, the coordinates of the connection centre, composition (profiles, size and shape of the haunch) and direction of their profiles are extracted. A standard file is generated with the data obtained from the geometric and semantic characterisation of the connections. The 3D model of connections and metal frames, which are suitable for processing software for structural engineering applications, are generated automatically based on this file. The algorithm presented in this paper has been tested under laboratory conditions and also with several industrial portal frames, achieving promising results. Finally, 3D models were generated, and structural calculations were performed.

1. Introduction

Overall, in the Architecture, Engineering, and Construction (AEC) domain and particularly in industry, there is typically a need to update drawings of the main structures of buildings. These drawings are used to verify whether the structure will resist new loads due to changes in the layout or in its facilities. Often, the designed blueprints do not match with the as-built building nor do they record the modifications made throughout the lifetime of the structure. Consequently, it is always necessary to use reverse engineering to obtain the necessary dimensional blueprints. Thus, structural analysis is based on these field data. In recent years, LiDAR technology has significantly increased the efficiency of this task.

LiDAR presents several advantages compared with traditional measurement methods, for example, automatically obtaining large data in very short periods of time remotely. The result of this process is a set of points known as a point cloud. At present, the use of laser scanning for data collection is widely implemented in 3D modelling, particularly in construction (Tang et al., 2010). However, it is necessary to perform a tedious processing step before obtaining a useful 3D model. In regards to this process, significant progress towards greater automation has been achieved (Tang et al., 2010; Oude Elberink and Vosselman, 2011; Li et al., 2013), particularly for elements such as walls, ceilings, doors and windows (Huber et al., 2010; Okorn et al., 2010; Valero et al., 2012; Bosché, 2011; Xiong et al., 2013). Other elements, such as roofs and façades have been evaluated by Pu and Vosselman (2009), Kim and Shan (2011) and Huang et al. (2013). The process is still manual concerning other construction elements. The aim of this work is to bridge the gap between the field of metal structures, accounting for the advances in laser scanning technology and 3D modelling, as well as developing automatic processing algorithms for structural engineering purposes.

Steel structures are extensively used in construction, especially in industrial and commercial buildings. For example, in the UK, more than 90% of the buildings have a steel structure and approximately 50% are portal frames (King, 2001). Steel frames are mainly composed of elements (beams and columns) connected by joints (in this paper, these joints are called connections). The cross-sections of frame elements normally have a standard size and shape. According to structural design codes and handbooks, the coordinates of the

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connection centre is one of the most significant pieces of information regarding the geometric definition of a metal frame. To increase the stiffness to the bending of the connections, the haunches are normally disposed at the joint (Fig. 1) (Eurocode 3:Part1-1, 2005; Eurocode 3:Part1-8, 2003; King, 2001; MacGinley, 1997). These haunches are usually used in portal frames (Fig. 2), and their shape and size are not standard; therefore, their modelling is required for structural analysis.

The aim of this paper was to develop a new method for the detection, identification and automatic 3D modelling of connections and then whole metal frames from laser scanning data. This new method permits the whole model of the metal frame to be reconstructed from point clouds, including basic details, such as haunches or the coordinates of the connection centre. The final model is not only valid for obtaining geometric and semantics data but also for its direct use in structural analysis. After the introduction, Section 2 provides a background review. Section 3 outlines the proposed new methodology and describes the algorithm to identify the connections in the point cloud and the techniques on which the algorithm is based. Section 4 describes case studies where the algorithm was proven and the results were found. Finally, in Section 5, the conclusions are given.

2. Background review

Several works have tackled the 3D modelling of structures with the aim of performing subsequent structural calculations. Truong-Hong et al. (2013) presents an approach to extract building wall structures, where they combine voxelisation approaches with an angle criterion to convert point clouds in finite element models of building façades. Walsh et al. (2013) proposed an approach to extract 3D models of general structures based on the detection and segmentation of sharp features and subsequent object detection based on a predefined library. In the field of masonry arch bridges, there are several relevant works, such as Lubowiecka et al. (2011) or Riveiro et al. (2011). An analysis of bending and steel beam damage was presented by Lee and Park (2011) and Gordon and Lichti (2007). Bosché (2010) and Bosché and Haas (2008) have presented works on the automatic recognition of beams and columns and their conversion in CAD models for subsequent dimensional control in buildings.

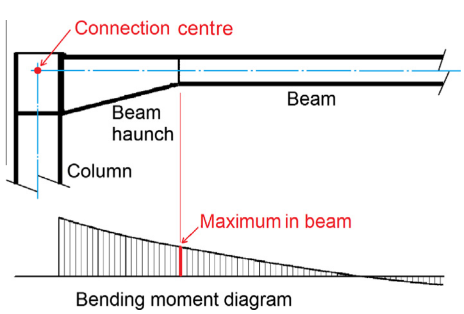

Fig. 1. Haunched beam that increases resistance to the bending moment.

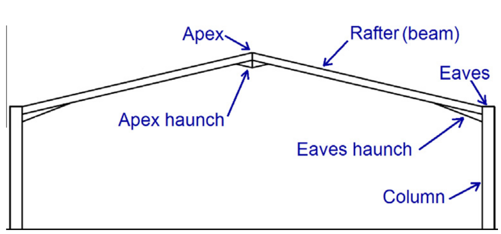

Fig. 2. A typical portal frame.

Overall, current modelling methods for metallic profiles are based on modelling extrusion (Tang et al., 2010). Advances in commercial software (Leica Cyclone, KubitUSA or Zf-laser software) have been conducted that have focused on the detection and automatic modelling of pipes and simple metallic cross-sections. However, these methods model the structures as single elements instead of considering them as forming items of a structural whole. Consequently, two main drawbacks were found in this methodology. First, there were significant errors in calculating the vertical position at the centre of the connection due to the insertion, fitting and extrusion of the profiles. This is caused by the curved shape of beams that are assumed to be straight (see Fig. 3). Note that for beams that are 6 m in length that are subjected to bending, errors may exceed 50 mm in maximum rise as allowed by L/300 standards in design. Consequently, the intersection between beams and columns in 3D space cannot be achieved because of the accumulated error in both elements. This error not only occurs if the insertion is performed, accounting only for points located at one of its ends (Fig. 3a), but also occurs when the insertion is performed in other beam zones (Fig. 3c). The second drawback relates to the modelling of haunches, which is not standardised and requires modelling for each particular connection.

3. New methodology

Instead of using the current methodology (shown in the flowchart in Fig. 4a), which begins with the modelling of elements (beam and columns), this paper proposes a new methodology that states that connections are geometrically, topologically and semantically the most important elements of the structural frame. The new methodology is summarised in the flowchart in Fig. 4b, the main steps of which are as follows. First, the regions containing the connections of the structure are selected. Then, the connections are identified in those areas automatically. Subsequently, the coordinates of the connection centre, composition (cross-section, size and shape of the haunch) and direction of their elements are extracted. The connection is automatically modelled from these data, and finally, the 3D model of the whole metal frame model is generated using the modelled connections. The resulting geometric model is directly converted into the structural model for calculation.

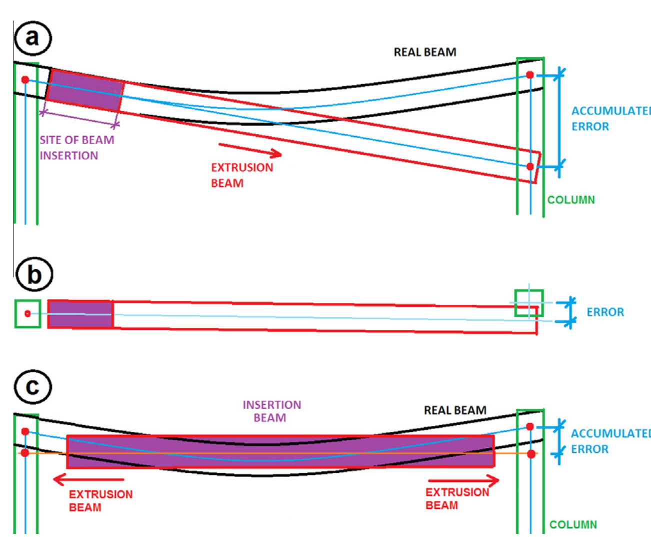

Fig. 3. Error in beam model caused by inaccurate extrusion (a) elevation view of an insertion in the end of the beam. (b) Plan view. (c) Elevation view of the insertion in most of the parts of the beam.