Advanced Engineering Informatics 27 (2013) 466–476

Contents lists available at SciVerse ScienceDirect

Advanced Engineering Informatics

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

A videogrammetric as-built data collection method for digital fabrication of sheet metal roof panels

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ARTICLE INFO

Article history:
Received 22 October 2012
Accepted 29 April 2013
Available online 21 October 2013

Keywords:
Structure from Motion
Videogrammetry
3D roof modeling
Roof surveying
Sheet metal roofing
Digital fabrication

ABSTRACT

A roofing contractor typically needs to acquire as-built dimensions of a roof structure several times over the course of its build because a structure is never built to the exact drawing dimensions. In the construction phase and in order to digitally fabricate sheet metal roof panels, the contractor has to measure end-to-end dimensions of boundaries of every roof plane with a certain level of accuracy (i.e., errors less than ±2 cm). This is necessary to be able to cut sheet metal coil such that different pieces perfectly fit together. Obtaining these measurements using the exiting roof surveying methods could be costly in terms of equipment, labor, and/or worker exposure to safety hazards. This paper presents a video-based surveying framework as an alternative method which is simple to use, automated, less expensive, and safe. When using this framework, the contractor collects video streams with a calibrated stereo camera set. The captured data is processed to automatically generate a 3D wire-diagram of the target roof. Measurements from the wire-diagram are saved in a digital file (XML format) which could be loaded into an on-site sheet metal folding and cutting machine. Experimental analyses demonstrate applicability of the proposed framework.

1. Introduction

The roofing industry is part of what is known as the "building envelope" industry. A building envelope includes all the components that make up the shell or skin of a building and separate its exterior from interior (e.g., walls, roofing, windows, and doors). Roofing contractors deal with the covering on the uppermost part of a building. They, in general, install roofing, siding, sheet metal, and roof drainage systems. Three primary types of work are typically considered in this industry: new construction, maintenance/repair, and roof replacement.

Despite this categorization, the ecosystem of a sheet metal roofing project is almost the same for different types of work. In the bidding process, a contractor uses architectural drawings, a Building Information Model (BIM) file, or aerial photogrammetry services to estimate the roofing area. However, a roof structure is never built to the exact drawing dimensions; even in roof replacement projects, dimensions of roof planes are typically altered due to intrinsic restrictions of the construction process. This creates a discrepancy between as-designed and as-built dimensions. Hence, after the project is awarded and the underlayment is installed, there is a need to acquire as-built dimensions of the roof structure in order to cut sheet metal coil into precise, ready to install panels. According to standard specifications for a project, measurement errors should not exceed ±¾ in. (≈1.9 cm) and in some cases ±1 in. (≈2.54 cm) [1]. Hereafter, this paper considers ±2 cm as the maximum acceptable measurement error. Once the as-built dimensions are acquired, the covering material (i.e., sheet metal) is cut and overlaid. The finished project is then handed over to the client and the same process is repeated when a roof replacement is needed.

As can be inferred from the above discussed ecosystem, collecting accurate enough as-built geometry is an essential activity in every roofing project. Performing this task using an efficient method/device has been a long-standing challenge in the sheet metal roofing industry. Several surveying technologies have evolved over the years aiming to provide efficient, precise, and simple ways to geometrically document the as-built condition of a roof structure. Contractors use these methods for a variety of purposes such as estimating the area or volume of a building component [2] and digital roof modeling [3]. However, these methods either require expensive equipment and trained surveyors, which impede their adaption in small projects, or involve significant amount of human intervention and safety hazards which translate to high labor costs.

After acquiring as-built dimensions, sheet metal roof panels need to be formed and cut. Currently, this process can be done both

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http://dx.doi.org/10.1016/j.aei.2013.04.006

manually (using tin snips) and automatically (using roll forming and cutting machinery). The manual process is very time consuming and can lead to a lot of errors and leftover scrap metal. In the automatic case (i.e., digital fabrication), a digital file (in XML format) that includes all the geometrical information of roof planes in a specific data structure is prepared manually and then loaded into the on-site cutting machine; this can be also a labor intensive and error-prone process.

Aiming to address the abovementioned problems, this paper presents a videogrammetric roof surveying framework that can be used by a roofing contractor. The contractor captures stereo video streams using a calibrated set of two cameras. Having the videos as input, the framework is expected to generate a 3D wire-diagram of the target roof. It then automatically extracts the necessary measurements from the wire-diagram, and outputs them in a digital file. Therefore, the overall contribution of this paper is a close-range stereo vision-based framework that has the potential to acquire roof measurements with $\leqslant$2 cm error. It significantly reduces the cost per job when compared to the existing solutions; the anticipated cost reductions stem from a combination of lesser time spent to acquire measurements, training time, time to convert the measurements to the specified format and prepare the digital file, hardware costs, and/or exposure to safety hazards. The framework has been tested on two roof structures. The accuracy of the measurements has been assessed by comparing them with corresponding measurements from total station surveying (ground truth).

2. State of practice in roof surveying

A number of surveying methods can be used by roofing practitioners: tape measuring, total station surveying, aerial photogrammetry, and laser scanning. These methods are discussed below and their advantages and limitations are analyzed.

2.1. Tape measuring

Manual measurement with a tape measure is the most common form of roof surveying methods [1]. It includes a team of roofing workers who climb on top of a roof with a sketch outlining the roof perimeter and take measurements manually. This process is simple and needs minimal expertise. However, it is time-consuming, expensive in terms of labor costs, and not always accurate [4,5]. The most important disadvantage is the necessity for physical contact that results in higher cost of operation and exposure of the measuring crew to fall hazards [5]. Falling is one of the most critical safety hazards [6], particularly on sloped roofs (Fig. 1), and contributes to the very high number of occupational injuries and fall deaths which occur in the construction industry (35% of worker fatalities in the US private construction industry in 2011 [7]). Despite its inherent deficiencies, tape measuring is still the standard practice in the industry.

Fig. 1. Worker exposure to safety hazards.

2.2. Total station surveying

This roof surveying method provides accurate as-built measurements by using a total station which typically costs \$3000–\$8000. It requires surveyors who are trained in surveying methods/techniques, hardware (survey instrument and computers), software (SDMS, DTM, etc.), data transfer, and metric conversion [8]. Moreover, having knowledge about different parts of a roof structure is necessary. Before taking measurements, a surveyor needs to prepare a sketch that outlines the roof perimeter. When collecting data, the surveyor locates a point on the ground to set the total station over. The point should be selected such that necessary surveying points (i.e., where roof planes come together, corners, and center points) are visible. This presents challenges in complex roofs with many intersecting planes where some important points are not visible from the ground. In this case, the surveyor would need to find a "stable" and somewhat "flat" location on the roof to place the instrument; the location should provide adequate stability which is required for taking precise measurements. The surveyor can then start recording X, Y, and Z coordinates of desired points and meanwhile marking them on the sketch. Once the required data is recorded for all points, the surveyor can use a laptop at the jobsite or go back to the site office to transfer the collected data into an appropriate software program. Roof measurements are then extracted. More details about this process can be found at [9]. In general, this surveying method is a safe practice because the surveyor stands on the ground or a fixed position on top of the roof, but it requires surveying expertise.

2.3. Aerial photogrammetry

In this process the address of the property is typed in an on-line request form. The longitude and latitude of the property are calculated using geocoding to enable extracting the correct imagery from the available satellite images. CAD professionals then provide roof measurements using photogrammetric software programs. This technique is inexpensive, safe, and easy to use. It does not need any on-site measurements and hence eliminates on-site labor requirements. However, the measurements are not accurate and reliable enough for digital fabrication of sheet metal roof panels. A case study, that has been performed to evaluate the accuracy of aerial roof measurements on 1291 roof structures, indicates that measurement errors are expected to be in the range of ±4% of the actual length [10]. Hence, this method is only used for estimation purposes. Moreover, it is unusable if satellite images are not available for a specific property or if the satellite images do not include recent renovations that have changed the geometry of the roof.

2.4. Laser scanning

A laser scanner can provide a dense cloud of 3D points by measuring the distance of 10,000–100,000 points every second with mm level accuracy [11]. In general, the process is simple and does not expose the crew to safety hazards. The instrument is set up on a fixed location (sometimes it is required to put the instrument on top of the roof for proper visibility). A trained surveyor then collects the necessary data and performs post processing steps for extracting roof planes and perimeter of the roof. The main limitation of this method is the high hardware costs. A laser scanner may