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Rapid data quality oriented laser scan planning for dynamic construction environments

Cheng Zhang, Vamsi Sai Kalasapudi, Pingbo Tang *

School of Sustainable Engineering and the Built Environment, Arizona State University, United States

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ABSTRACT

In construction environments, laser-scanning technologies can perform rapid spatial data collection to monitor construction progress, control construction quality, and support decisions about how to streamline field activities. However, even experienced surveyors cannot guarantee comprehensive laser scanning data collection in the field due to its constantly changing environment, wherein a large number of objects are subject to different data-quality requirements. The current practice of manually planned laser scanning often produces data of insufficient coverage, accuracy, and details. While redundant data collection can improve data quality, this process can also be inefficient and time-consuming. There are many studies on automatic sensor planning methods for guided laser-scanning data collection in the literature. However, fewer studies exist on how to handle exponentially large search space of laser scan plans that consider data quality requirements, such as accuracy and levels of details (LOD). This paper presents a rapid laser scan planning method that overcomes the computational complexity of planning laser scans based on diverse data quality requirements in the field. The goal is to minimize data collection time, while ensuring that the data quality requirements of all objects are satisfied. An analytical sensor model of laser scanning is constructed to create a "divide-and-conquer" strategy for rapid laser scan planning of dynamic environments wherein a graph is generated having specific data quality requirements (e.g., levels of accuracy and detail of certain objects) in terms of nodes and spatial relationships between these requirements as edges (e.g., distance, line-of-sight). A graph-coloring algorithm then decomposes the graph into sub-graphs and identifies "local" optimal laser scan plans of these sub-graphs. A solution aggregation algorithm then combines the local optimal plans to generate a plan for the entire site. Runtime analysis shows that the computation time of the proposed method does not increase exponentially with site size. Validation results of multiple case studies show that the proposed laser scan planning method can produce laser-scanning data with higher quality than data collected by experienced professionals, and without increasing the data collection time.

1. Introduction

Timely, detailed, and accurate geometrical information for decision making will improve the safety, quality, and productivity in construction projects [1,2]. Reliable sensing methods and comprehensive data collection are, therefore, requisite and highly desirable in construction management environments. Compared with conventional data collection methods such as laser tapes and the Global Navigation Satellite System, laser scanning technologies have many advantages that include high accuracy (mm level), faster data acquisition (up to hundreds of thousands of three-dimensional points per second), and more detailed spatial resolution [3–6]. Researchers and project engineers, thus, have been actively exploring the uses of laser scanning technology in construction.

The use of laser scanning in the construction field, however, comes with its own set of challenges. First, acquiring high quality 3D imagery data within the parameters of changing jobsites and diverse projects is challenging even for experienced engineers, primarily because data quality, environmental conditions, scanning locations, and the technical parameters of laser scanners (e.g., data density options) all combine to create complex interactions [7]. Second, 3D imagery data collection is time-consuming, and in a fast changing construction environment, the data can become quickly outdated, which leads to misleading information for decision makers. Finally, when using sophisticated 3D imagery data

* Corresponding author.
E-mail addresses: cheng.zhang.7@asu.edu (C. Zhang), vkalasap@asu.edu (V.S. Kalasapudi), tangpingbo@asu.edu (P. Tang).

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collection, project managers must hire experienced surveyors who can properly operate laser scanners and achieve high quality data collection, which can be costly [8,9].

To overcome the above challenges, this paper describes the development of a new automatic laser scan planning method. For a given jobsite, the objective is to determine a laser scan plan by specifying a sequence of scanning positions and parameters at each position as a means to minimize the data collection time while optimize the coverage and quality of the data. A fast and reliable laser scan planning method can thus save costs related to: (1) poor decision-making due to low-quality data; (2) interruptions in construction processes caused by data collection activities; and (3) training and hiring laser scanning professionals for high-quality data collection.

This paper attempts to address three questions that have remained unresolved in previous studies about the laser scan planning problem in construction:

(1) how to quantify and model the relationship between 3D imagery data quality and data collection parameters to develop a planning algorithm that uses the quantitative relationship for guiding the generation and assessment of laser scan plans [10];
(2) how to explore the extremely large search space of laser scan plans in the limited time of decision-making in the context of dynamic environments [11,12];
(3) how to achieve scalability of laser scan planning so that engineers can apply the same scan planning method to sites of different shapes and sizes [13].

To address the first question, we develop a 3D-imaging sensor model that shows the mathematical relationship between 3D data collection parameters and spatial data quality. To explore the second question, we propose a "divide-and-conquer" planning method for achieving efficient optimization of laser scan plans. To ensure the scalability of this laser scan planning method (question 3), the divide-and-conquer method adaptively adjusts its parameters according to building size and shape to produce reliable laser scan plans.

The organization of the paper is as follows: Section 2 introduces previous studies about laser scan planning, while highlighting the contributions of this paper. Section 3 provides a problem statement and a discussion of the three research questions. Section 4 describes the laser scan planning method. Section 5 validates the developed laser scan planning method using case studies on real buildings. Sections 6 and 7 present validation results, the conclusion, and future research plans.

2. Background studies

Previous studies have stressed the importance of efficient and effective construction inspection using laser-scanning technologies. Akinci et al. [7] and Gordon et al. [11], for example, discuss how manual inspection could miss important site changes and defects, while the use of laser scanning could improve construction inspection through the delivery of timely and comprehensive as-built data. Turkan et al. [6] emphasize the need for effective laser scan planning to achieve effective construction progress control. Park et al. [14] illustrate the need for the best practices in collecting, searching, and reusing defect information for construction quality control in the field.

While construction industry practitioners acknowledge the importance of laser scanning, they are also confronted with the many obstacles that prevent both the effective and efficient use of laser scanning in construction [15–17]. One such obstacle is related to acquiring high quality 3D imageries for field applications [14]. Since 3D image quality greatly influences as-built Building Information Model (BIM) quality [18–20], examining quantitative relationships between data quality, scanning locations, and environmental factors become critical to the overall process [10,21–25]. In this context, manually reviewing a large number of such relationships is a challenging task, even for experienced engineers. In addition, manual data quality checks of numerous objects on jobsites against data quality requirements is tedious and error-prone [13]. This second obstacle is the difficulty of optimizing data collection time while minimizing interferences from the data collection and productive activities [7,11,26]. It has been shown, for example, that a badly designed workflow may need up to 300% data collection time when compared to a standard workflow for the same laser scanning task [26]. Yet another obstacle relates to the high cost of training and hiring laser scanning professionals [8,27]. Eid et al. found that the cost of laser scanning for the evaluation of forest inventory is approximately twice the cost of using photogrammetry [8].

Effective laser scan planning methods are lacking in the literature to date. Many existing studies focus on occlusion and visibility analysis for capturing the entire surface of a targeted object, but these studies lack detailed analysis of data quality [28–33]. Most are marked by high computational complexities that result in long computation times when generating laser scan plans [12,28,34]. Finally, the current array of studies fail to use flexible scanning parameters for each scanning position, according to varying data quality requirements of different objects [12,13,29,35]. Lack of flexibility can potentially lead to unnecessary planning computation time as well as redundant data collection. In a recent study by Ahn et al. [35], a semi-automatic scan planning method was used to decide the scanning position for achieving horizontal data quality requirements. However, it required manually selecting the same scanning resolution for all scans, thus failing to identify optimal plans that could have mixed use of scans with different resolutions. In addition, the proposed semi-automatic method was not able to handle buildings with curve-shaped walls.

The research methodology presented below will address this gap in order to improve the quality of field laser scanning significantly in dynamic construction environments.

3. Problem statement

The goal of laser scan planning is to create a method that can automatically generate laser scan plans for efficient collection of high quality 3D imageries of a given jobsite. The generated laser scan plans should achieve the following:

(1) The laser scan plans should specify scanning positions and parameters at those positions, so that an engineer with limited surveying experiences can rapidly collect comprehensive 3D imagery details of the jobsite with sufficient accuracy.
(2) Following the laser scan plan, the engineer should be able to achieve optimal data collection time to minimize the interferences between data collection and construction workflows.
(3) The time for generating a laser scan plan should be less than a few minutes in order to satisfy the dynamics of a construction jobsite.

Fig. 1 shows an IDEF0 process model describing the laser scan planning problem. The inputs of the IDEF0 process model are point goals, which include objects of interest or geometric features. Section 4.1.1 details the representations of point goals. The outputs of