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Proactive 2D model-based scan planning for existing buildings

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ABSTRACT

Creating a building information model (BIM) is known to be valuable during the life-cycle of a building. In most cases, a BIM of an existing building either does not exist or is out of date. For existing buildings, an as-is BIM is needed to leverage the technology towards building life-cycle objectives. To create an as-is BIM, field surveying is a necessary task in collecting current building related information. Terrestrial laser scanners have been widely accepted as field surveying instruments due to their high level of accuracy. However, laser scanning is a time-consuming and labor-intensive process. Site revisiting and reworking of the scanning process is generally unavoidable because of inappropriate data collection processes. In this context, creating a scan plan before going to a job-site can improve the data collection process. In this study, the authors have proposed a 2D proactive scan-planning framework that includes three modules: an information-gathering module, a preparation module, and a searching module. In addition, three search algorithms — a greedy best-first search algorithm, a greedy search algorithm with a backtracking process, and a simulated annealing algorithm — were compared based on 64 actual building site drawings to identify strength and limitations. The experimental results demonstrate that the greedy search algorithm with a backtracking process could be used to compute an initial scan plan and the simulated annealing algorithm could be used to further refine the initial scan plan. This paper will also introduce the results of a case study that deployed the proposed scan-planning framework. In the case study, the resulting 3D-point cloud that was generated based on the proposed framework was compared with the 3D point cloud created with data collected through a planned scanning process performed by a scan technician.

1. Introduction

As-is 3D building information models (BIM) of existing buildings are valuable in areas such as urban planning, historical building information storage, building renovation, facility management, and building energy simulations [1]. Creating an accurate 3D geometric as-is model is essential for linking all building-related data and producing an as-is BIM. However, 80% of existing buildings that were constructed in the U.S. before the year 2000 do not have 3D models [2,3]. To create such models, the most common approach has been to conduct a field survey using traditional tools such as sonic measuring devices and total stations. However, these traditional methods cannot obtain detailed building information such as building shapes and surface texture. With the advancement of non-contact and non-destructive laser-sensing technologies in recent years, a high-quality 3D point cloud can be obtained through terrestrial laser scanning [4-8]. A 3D point cloud consists of millions of points representing the spatial information of building surfaces. However, one of the major drawbacks of terrestrial laser scanners is that the data acquisition process is time-consuming and labor-intensive. Many existing works focused on reducing scanning time and labor by introducing fully automatic scanning systems and portable capture platforms [9,10]. In this study, the authors focused on improving the data quality and the efficiency of the scanning process that is performed by surveying professionals with stationary terrestrial laser scanners. The overall scanning process involves moving the laser scanner from one location to another, leveling the scanner and acquiring the image data at each location etc. Given these, minimizing number of scanning positions could be a way to enhance the efficiency of the entire scanning process. Here, the resolution setting is also a decisive factor as a finer resolution setting corresponds to more demanding time requirements. The authors handle that by assuming conservative resolution settings in the beginning, before refining them in a step-wise manner. This approach is discussed in detail within the following sections. Other drawbacks exist as surveying professionals find it challenging to decide on where to place the laser scanner and what resolution settings should be used [11]. These decisions that

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surveyors have to make on-site may lead to the situation where the collected data do not satisfy requirements (e.g., incomplete data and a low Level of Detail-LOD point cloud). It is worth pointing out that, point cloud with a low LOD can lead to a failure on post-activity such as scan-to-BIM process [12]. Thus, additional trips to the building sites and additional data collection are necessary. Considering such issues, having a proactive scan plan with a minimal number of scanning positions and appropriate scanning settings (i.e., desired angular resolution) may significantly reduce the required data collection time and the on-site decision making by surveyors. It may also improve the quality of the resulting point cloud and potentially avoid rework. Proactive scan planning here is defined as a plan developed off-site with the objective of providing the surveying team with the exact scanning positions and equipment settings that allow the development of a high-quality, complete point cloud. Although humans are relatively good at generating proactive scan plans for the coverage of simple-shaped buildings (e.g., rectangular-shaped building layouts), generating proactive scan plans for buildings with geometrically complex shapes can be difficult, even for experienced operators [13]. Thus, this study focuses on designing and developing an automatic proactive scan-planning framework that could generate a scan plan based on a given building layout and point cloud quality requirements.

According to the BIM guide provided by the General Services Administration [14], the quality requirements for the scanning of building facades and building interiors are generally different and the scanning processes are usually performed separately [14]. In this study, the proposed proactive scan-planning framework focuses on the scanning of building facades rather than building interiors. The authors assume the existence of a 2D site drawing of a target building. The proactive scan plan is generated based on the given 2D site drawing and known point cloud-quality impact factors. We consider the well-established fact that searching for optimal scan plans with all necessary constraints is an NP-hard problem. Three searching algorithms, including a greedy best-first search algorithm, a greedy search algorithm with a backtracking process, and a simulated annealing algorithm are compared based on 64 actual building site drawings to identify algorithmic strengths and limitations in finding the minimum number of scanning positions. It should be pointed out here that, in the comparison study entitled, “Experiments with Building Site Drawings,” the scanner angular resolution was assumed to be constant. Based on the experimental results, the proposed proactive scan-planning framework utilized a greedy search algorithm with a backtracking process to find an initial scan plan. To further refine this scan plan, a simulated annealing algorithm was adopted. Following that, in this paper, the authors introduce a greedy searching strategy that is designed to find the desired angular resolution for each scanning position in the scan plan. To validate the proposed proactive scan-planning framework, a case study was conducted, and the results are subsequently discussed.

2. Background and literature review

The proactive scan-planning problem is often stated as the view-planning problem (VPP). The VPP has been widely studied over the last two decades. Approaches for solving this problem generally fall into two categories: online (non-model-based) and offline (model-based) [13]. Online VPP is crucial in mobile robotics. When a robot is introduced to an unknown environment with no prior knowledge about the scene, a 3D object reconstruction of the world is the first needed step. Solutions for online VPP are applied in real time, and the differences between existing algorithms are often found in the design of the utility function for choosing the next viewing position [9, 15-20]. As previously mentioned, the proposed proactive scan-planning framework is using a 2D site drawing as the initial model to generate a scan plan. Thus, the remainder of this section focuses on offline view planning approaches as well as various point cloud-quality impact factors related to the scanning process. Offline view planning approaches assume that an initial model of the target object is available. A 2D model-based VPP is often stated as an art gallery problem. Chvátal [21] outlined and answered the art gallery problem that was originally posed by Klee. The objective of the art gallery problem was to find the minimum number of surveillance positions inside an art gallery to guard the entire building. Chvatal's art gallery theorem proved that with an $n/3$ number of surveillance positions the entire building could be guarded, where n is the number of building geometry vertices on the 2D floor plan [21]. Many extended versions of the art gallery problem were posed following the original one, such as an art gallery with holes inside, or a mobile guard art gallery problem in which each guard could travel inside the building [22]. The traditional geometric solutions to the art gallery problems assume that guards have unlimited viewing distance, a 360-degree field of view, and that no overlapping surveillance portions are required between any two guards [23-26]. However, none of these assumptions are true for data acquisition planning with laser scanning. For instance, each laser scanner has its own maximum- and minimum-viewing distance provided by manufacturers' specifications. At least 20% of overlap data among different point clouds collected at various scanning positions are crucial for the post-point cloud registration process [27]. Here, overlap data are defined as data that are captured in one scanning position and are also captured by another scanning position. It is calculated as the ratio between the amount of overlap data and the amount of scanned data at each scanning position. In addition, a laser scanner can lose its level of accuracy (LOA) and level of detail (LOD) with large incidence angles [16,28]. In this research, LOA and LOD are defined as the accuracy of the derived point cloud compared with the actual building and the smallest detail on a building that can be captured, respectively. The original art gallery problem is known to be an NP-hard problem. With the previously described sensor constraints, the problem is not simplified, and it is still an NP-hard problem.

Researchers have resorted to various alternatives in approximating the optimal solutions to the abovementioned problem. González-Baños [29] proposed a greedy search algorithm with a random sampling strategy to place the sensor inside a building. Both the viewing distance and the incidence angle constraints of the sensor were embedded in the proposed problem formulation. Amit et al. [30] provided experimental results with different greedy heuristics that were designed to solve the problem. In order to improve the optimality of the greedy solution to the problem, Bottino and Laurentini [31] proposed using a lower bound of sensor positions for a given polygon to refine the solution iteratively. To extend González-Baños's work and make the derived data acquisition positions more suitable for laser scanning, data overlap between the scanning positions was included as a constraint in the first phase (i.e., a offline planning phase) of Blaer and Allen's approach [16]. Bungiu et al. [32] focused on improving the computational time and proposed a triangular expansion algorithm. However, most of the previous proposed algorithms were designed for and tested with polygons that were generated randomly [30,31]. For additional details on polygon-random generations, readers should refer to Auer and Held's work [33]. As stated in the previous section, this research focuses on scan planning only for the exterior of a building. Frequently, a building layout composed of regular polygons is preferred during the building design phase due to well-known advantages over other design forms regarding structural feasibility, constructability, and cost effectiveness from the owner's perspective (e.g., energy saving and optimization of the space usage) [34-38]. Thus, in general, polygons that are formed by a building's exterior walls (i.e., a building's 2D floor plan) are not with the same shape as randomly generated polygons. Therefore, a comparison of different search algorithms based on actual 2D building floor plans is needed. Several studies have focused on view planning approaches that are specifically designed and developed for terrestrial laser scanning. Ahn and Wohn [27] have argued that in the case of laser scanning with human operators, the operators' knowledge should not be neglected. Therefore, a knowledge-guided, scan-planning approach that