Automation in Construction 89 (2018) 38–48

Contents lists available at ScienceDirect

Automation in Construction

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

SLAM-driven robotic mapping and registration of 3D point clouds

Pileun Kim[a], Jingdao Chen[b], Yong K. Cho[c,*]

[a] Department of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, USA
[b] Institute for Robotics and Intelligent Machines, Georgia Institute of Technology, 777 Atlantic Dr. N.W., Atlanta, GA 30332-0355, USA
[c] Department of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, USA

ARTICLE INFO

Keywords:
Simultaneous Localization and Mapping (SLAM)
Point cloud registration
Laser scanning
Mobile robot

ABSTRACT

With the rapid advancement of laser scanning and photogrammetry technologies, frequent geometric data collection at construction sites by contractors has been increased for the purpose of improving constructability, productivity, and onsite safety. However, the conventional static laser scanning method suffers from operational limitations due to the presence of many occlusions commonly found in a typical construction site. Obtaining a complete scan of a construction site without information loss requires that laser scans are obtained from multiple scanning locations around the site, which also necessitates extra work for registering each scanned point cloud. As an alternate solution to this problem, this paper introduces an autonomous mobile robot which navigates a scan site based on a continuously updated point cloud map. This mobile robot system utilizes the 2D Hector Simultaneous Localization and Mapping (SLAM) technique to estimate real-time positions and orientations of the robot in the x-y plane. Then, the 2D localization information is used to create 3D point clouds of unknown environments in real time to determine its navigation paths as a pre-scanning process. The advantage of this framework is the ability to determine the optimal scan position and scan angle to reduce the scanning time and effort for gathering high resolution point cloud data in real-time. The mobile robot system is able to capture survey-quality RGB-mapped point cloud data, and automatically register the scans for geometric reconstruction of the site. The performance of the overall system was tested in an indoor environment and validated with promising results.

1. Introduction

Laser scanned point cloud technology is widely used in many fields to obtain 3D geometric information of buildings and infrastructures. Especially, it has been extensively used in construction management, structural damage assessment, urban planning, historical building restoration, building renovation, facility management, and building energy analyses to render real-sized objects or environments in the form of dense point cloud data [1,2]. Although previous studies had revealed that 3D reconstruction of the work environment contributed to improvements in material tracking, schedule control, and construction defect control, there are still many difficulties in gathering 3D reconstruction data because they involve unstructured and unpredictable environments [3].

Most of the current commercial 3D laser scanners, which gather data under static conditions, can collect millions of three-dimensional points in a short period of time accurately and safely. However, the point cloud registration process, which is a critical step in the post-processing stage, is still a labor-intensive and time-consuming process. First, multiple scans from different scan positions have to be manually gathered by the operator. Then, these collected data have to be registered with common features or iterative methods. However, the operator does not know until the end of the registration process that the collected data contain imperfections due to incomplete scans, hindering structures, absence of targets and lack of common features for registration in many cases. This is because current laser-scanning methods provide limited feedback to the operator during the scan process and registration process [4]. On the other hand, Simultaneous Localization and Mapping (SLAM) technology is actively studied in various engineering fields to dynamically estimate the current scan position and to build a map of the environment for 3D reconstruction automatically. However, this dynamic solution has limitations such as lower point cloud resolution, higher noise due to motion distortion and difficulty to obtain RGB-mapped point cloud. Thus, this study proposes a framework to build 3D high-resolution point clouds registered in real time using a hybrid laser scanning system with a mobile robot.

---

* Corresponding author.
E-mail addresses: pkim45@gatech.edu (P. Kim), jchen490@gatech.edu (J. Chen), yong.cho@ce.gatech.edu (Y.K. Cho).

https://doi.org/10.1016/j.autcon.2018.01.009
Received 1 May 2017; Received in revised form 23 December 2017; Accepted 11 January 2018
0926-5805/

2. Literature review

2.1. Mapping with photogrammetric approach

One method of achieving 3D mapping is by using photogrammetry. Photographs provide large amounts of information regarding construction progress, which could be automatically processed and converted into 3D formats through Structure from Motion [5–7]. Golparvar-fard [8] introduced an image-based as-built modeling technique based on computation from images, the photographer's locations and orientations, and a sparse 3D geometric representation of the as-built scene using daily progress photographs. Bae et al. [9] further improved on photogrammetry frameworks by proposing a fast and scalable method for 3D modeling using cameras on mobile devices. The advantage of image-based modeling methods is the availability of texture information which enable material recognition [10] and CAD model-based object recognition [11]. However, different lighting (e.g., indoor vs outdoor) and weather conditions make it difficult to use time-lapse photography for performing consistent image analysis at occluded and dynamic site conditions [8,12,13]. Further, the geometry of the area will be inaccurate if common features from multiple images cannot be found due to plain or repetitive textured surfaces [14]. If there has been significant construction progress for which photo images were not taken or if some objects were moved (e.g., equipment or scaffoldings) during that period, it would be challenging to find common feature points in the collected photographs. In addition, manually taken photos could not completely avoid discontinuity of spatial information [8,12]. Bhatla et al. [15] showed that the technology in its present state is not suitable for modeling infrastructure projects.

2.2. Mapping with LiDAR-based approach

Compared to photography, laser scanners allow for wide-range measurements at higher resolution and accuracy, and are generally not limited by ambient conditions during operation [16]. Compared to other 3D remote sensing technologies, laser scanning can holistically address all of the listed inefficiencies associated with the current practice of progress monitoring through rapid and detailed geometric data collections [12]. In the domains of construction and facility management, researchers have conducted various studies investigating the issues related to utilizing laser scanners for a wide range of purposes including fast workspace modeling for equipment operations [2,17–22], construction progress monitoring [23–26], defect detection [27–29], as-built modeling [30–34], deflection assessments of bridges [35–38], and pavement thickness assessments [36]. However, laser scanning requires significant time to complete a full scan; depending on the size of the construction site, this can take a crew of two people several days. The generation of as-built models of construction projects requires the registration of multiple scans obtained at different locations due to their limited data capture ranges as well as occlusions on site [16,39]. Point clouds registration is the process of fitting and matching multiple scans collected at multiple locations in a global coordinate framework or into a complete model. To register multiple scans in one coordinate system, many planar, sphere targets or markings are required to be installed in advance in overlapping scanning zones, which are also costly, labor intensive and time consuming.

Although great progress has been made in automating point cloud data acquisition workflows, creating complete as-built models during the construction process has not yet been fully supported. This is because even state-of-the-art data collection devices still require engineers to manually adjust data collection parameters and decide the locations of data collections. Such manual adjustment relies on the engineers' experiences and skills of operating sensors, and is subject to human errors. On the other hand, an automated robotic scanning system would enable more frequent, accurate, and holistic data collection and modeling for as-built conditions of construction sites.

2.3. Simultaneous Localization and Mapping (SLAM) approach

SLAM in robotic mapping is a method to enable a robot to estimate its current position and orientation as well as a map of the environment. SLAM techniques are well studied in the literature but still face several limitations. For example, Davison et al. [40] recovered the 3D trajectory with a monocular camera in an unknown environment. This method, so-called Visual SLAM, was unable to handle sudden movements and faced limitations in getting a detailed map of the surrounding environment. Leberl et al. [41] developed a photogrammetric 3D workflow over the directly measured laser point clouds with vision-based techniques. Using this method, the density of surface points was higher but it required multiple cameras and hardware to achieve real time SLAM. Roca et al. [42] used a Kinect sensor to build a 3D model of a building and the result was compared to another model generated from a laser scanner. Although it can detect discontinuity points using a vision-based system, they revealed that the measurement results are highly affected by material and lighting conditions. Therefore, the generated point cloud is noisy and not uniform. The advantage of visual SLAM is that cameras are relatively less expensive, lighter and consume less power per unit instrument than laser scanners. In addition, visual SLAM is able to detect colors and other visual features of objects which are difficult to detect using laser scanners in an unknown environment. Despite its advantages, there are some limitations such as: visual SLAM generates errors in large distances, is vulnerable to lighting conditions, and is difficult to use in dynamic environment [43].

There have been several research efforts to build 3D maps using SLAM in unknown environments with laser scanners. Chong et al. [44] studied precise localization in 3D urban environments using 2D Light Detection and Ranging (LiDAR) and odometry data. However, the work focused only on localization so the 3D map is insufficient for precise as-built site modeling. Chen and Cho [4] developed a mobile platform using an orthogonal pair of LiDAR to build a 3D point cloud map for indoor environments. The method achieved reasonable accuracy but did not include visual information in the reconstructed 3D map. Another approach to solving the SLAM problem is utilizing multiple robots and integrating the pose estimations of the robots and individual maps to create a more accurate model of the environment [45]. However, the method did not allow the operator to view a real-time map until the end of the exploration task and after performing the optimization process.

2.4. Lidar-based SLAM

There have been several research efforts tackling the SLAM problem using mobile LiDARs. Bosse and Zlot [46] used a SICK laser scanner on a spinning platform mounted on a skid-steer loader to perform SLAM in an outdoor environment. A voxel-sweep-matched method was used to align the point clouds and recover the sensor trajectory. Similarly, Zhang and Singh [47] used a motor-rotated Hokoyu laser scanner to perform real-time Lidar-based odometry and mapping. Feature points extracted from edges and lines were used to obtain transformation parameters between consecutive laser scan frames. Moosmann and Stiller [48] used a Velodyne Lidar-based SLAM to estimate the vehicle trajectory without using wheel speed sensors or other information. Tsai [49] developed a feature-based real-time monocular SLAM with a small camera. However, these works have mainly focused on the odometry aspect instead of the mapping aspect, and as a result, the generated point clouds tend to be noisy and have low resolutions.

Table 1 demonstrates the advantage of the proposed framework in comparison to the different SLAM methods, including camera-based (Tsai [49]) and Lidar-based SLAM. In summary, although great advancement has been made in 3D data collection and processing, it is still difficult to address the challenges discussed above with current technologies. Especially, no effort has been attempted to automate the setup and control processes of robotic sensors for ensuring data quality and comprehensiveness, particularly for sensors capturing non-visual