Performance Tests for Automatic 3D Geometric Data Registration Technique for Progressive As-built Construction Site Modeling

C. Wang[1], Y. K. Cho[2], and J. W. Park[3],

[1]Ph.D. Candidate, School of Civil and Environmental Engineering, Georgia Institute of Technology, Mason Building 3136, 790 Atlantic Dr., Atlanta, GA 30332-0355; email: cwang2@gatech.edu
[2]Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Mason Building 4140A, 790 Atlantic Dr., Atlanta, GA 30332-0355; PH (404) 385-2038; FAX (404) 894-2278; email: yong.cho@ce.gatech.edu
[3]Ph.D. Student, School of Civil and Environmental Engineering, Georgia Institute of Technology, Mason Building 3136, 790 Atlantic Dr., Atlanta, GA 30332-0355; email: jpark463@gatech.edu

ABSTRACT

This study aims to eliminate the labor-intensive target installation process and its associated costs and other issues commonly caused from the current practices of laser based as-built data collection and modeling process. In this study, a laser scan system was utilized with corresponding texture data simultaneously obtained from a digital camera. Based on identified common features in the texture data, an optimized transformation matrix for the point clouds is generated, then the point clouds are registered without using any physical external target. The proposed method was tested at an on-going building construction project. The interrelationships among registration speed, registered accuracy, and size of overlapping area were examined. The field experimental results demonstrate that the proposed target-free geometric data registration method can significantly reduce the registration time without compromising the registration accuracy; thus simplifying and promoting the current laser scanning and registration processes for progressive as-built modeling of construction projects.

INTRODUCTION

Rapidly updating as-built design with detailed 3D scenario is critical for construction applications such as progress monitoring and safety hazards detection (Huber et al. 2010, Teizer et al. 2010, and Golparvar-Fard et al. 2011). The terrestrial laser scanner (TLS) has been frequently used to collect as-built 3D point cloud in which each point has its local Cartesian coordinates. A point cloud can be post-processed to render real-size objects or environment by registering all individual scans onto the same coordinates. Point cloud registration is defined as registering multiple point clouds scanned from different viewpoints into one common coordinate system. The current state-of-the-art approach is to find at least three common points between two overlapped point clouds, and then calculate 3D rigid transformation matrix based on these three common points. Many types of commercial software are now available to realize the registration function by manually assigning three common points. However, this manual process is time-consuming and inaccurate when the data sets are huge and complicated. In order to resolve the registration problem, various methods have been proposed. The most popular idea is to manually or automatically find at least three common points using physical targets between two overlapped point sets, and then calculate the 3D rigid transformation matrix based on these common points. Figure 1 shows various types of targets.

Figure 1. Array of Targets (planar, sphere, and pipe for accuracy check)

Akca (2003) used a customized 2D planar target as a landmark, 3-D coordinates of which were measured with a theodolite in a ground coordinate system before the scanning process. Then the proposed registration algorithm can automatically recognize all the targets using radiometric and geometric information (shape, size, and planarity). Franaszek et al. (2009) developed a fast automatic registration algorithm using sphere targets. Two point cloud data sets can be registered by finding three matching points which are the centers of the spheres. Using 3D targets, the laser scanner can capture the same point cloud from different viewpoints. There is no need to re-orient the targets, not like using 2D targets, if the targets are properly placed. It could give users more flexibility and save more time on locating and setting up the equipment. Becerik-Gerber et al. (2011) tested three different types of targets (fixed paper, paddle, and sphere) with two different types of laser scanners (phased-based and time of flight). It was concluded that a sphere target with time of flight scanner yields the best results in terms of accuracy. It was also stated that scanning, setting up, and acquiring the targets were the three most time-consuming processes for target-based methods. The limitations of target-based registration are that the extra time is required for setting up and adjusting the targets during each scan and the target is not always allowed to be installed on the construction jobsites. Also, an additional target purchase cost is entailed. The manual processes of placing, maintaining, and relocating targets are time-consuming and could inevitably cause errors, which affect the quality of registration results.

The main objective of this paper is to develop a target-free automatic point cloud registration method, based on identified common features between multiple images in point clouds. In this study, to increase registration speed and accuracy, a feature-based algorithm was developed and employed, which automatically matches 3D point cloud data by utilizing 2D common features. Following sections will firstly review the existing approaches, then discuss the proposed method and preliminary experiment results, and finally present conclusion and future work.

LITERATURE REVIEW

With the development of image processing and computer vision technology, target-free registration has been widely applied to eliminate the limitations described earlier. Current existing target-free registration methods can be categorized into three types: 1) ICP-based, 2) feature-based, and 3) geo-referencing based.

ICP (Iterative Closest Point) algorithm (Besl and Mckay 1992) has been widely applied in 3D point cloud registration. It uses the closest points in two different scans as relative control points. Then an error function is built between relative points, and the algorithm is iterated until the result satisfies the requirements of the error function. A considerable amount of work on improving ICP algorithm has been conducted over the past few decades. Men et al. (2011) integrated Hue value with ICP algorithm to develop a 4D ICP algorithm, in which the Hue value was calculated according to RGB data captured by a digital camera. With the assistance of the Hue value, the ICP algorithm can be improved by attaining higher accuracy and faster convergence. However, ICP-based registration is time consuming due to the heavy computation load. Also, the accuracy may not be reliable as it depends on the size of the overlapping areas and on the selection of initial starting points; the more overlapping areas there are, the better results are obtained.

For feature-based methods, Eo et al. (2012) utilized the feature points extracted from 2D intensity images using Scale-invariant feature transform (SIFT) algorithm. However, this method is highly sensitive to the size of overlapping area. In their test, 12 scans were collected for registering one corner of the building. The accuracy of transformation matrix was within 0.005–0.069 m. Feature-based registration can be realized without knowing initial starting points, and utilize the 2D image processing technology to assist the recognition of feature points. However, more scans are needed to achieve better performance, and also the methods using image feature are not fully independent on the illumination so that the performance accuracy can somehow be affected by the environment. The heavy computation load is another drawback for feature-based registration. Thousands of feature points can be extracted from each scan based on geometry or image information, while most of them are not filtered out because of the wrong or low accuracy match.

Geo-referencing based registration has also been utilized using the information collected from other sensors. Olsen et al. (2011) executed the registration with knowing the location of each view point obtained from GPS. This method is mainly used in outdoor survey, and the accuracy could be deficient due to the low accuracy of the GPS device. As for indoor registration, Valero et al. (2012) developed an automatic construction of 3D basic-semantic models of inhabited interiors using laser scanners with the help of RFID technologies. This method is only suitable for an indoor open space situation, and the laser scanner needs to set up closely to the objects, otherwise it will not be able to recognize the RFID tags due to its small size. It can be seen that the geo-referencing based registration cannot fit all the situations because of the limitation of the geo-sensors.

Therefore, there is an apparent need for rapid and accurate registration method suitable for complex data collection environment. The proposed data collection system and automatic registration method will be reviewed in the following sections.

HYBRID 3D LIDAR SYSTEM

An innovative robotic hybrid Light Detection And Ranging (LiDAR) system was developed, consisting of two 2D line laser scanners (80 meter working ranges at 100Hz scan speed, up to 2.5 sec / 360º scan, 190º for vertical line), and a regular digital 2D camera, as shown in Figure 2. The resolution of each line laser is 0.25 degree in a vertical direction and 0.0072 degree in a horizontal direction. The customized 3D LiDAR system provides more flexibility in hardware control and software programming than a commercial LiDAR scanner does. Based on the mounting configuration, we solved multiple degree-of-freedom (DOF) kinematics to obtain x-y-z coordinates from the LiDAR, and simultaneously collect real-time digital image data from the digital 2D camera. The transformation matrices for the LiDAR and the digital 2D camera share the first frame and split into two different kinematics frames at the second matrix (Figure 3). This kinematics frame allows an addition of more optical sensors, such as digital video or infrared cameras.

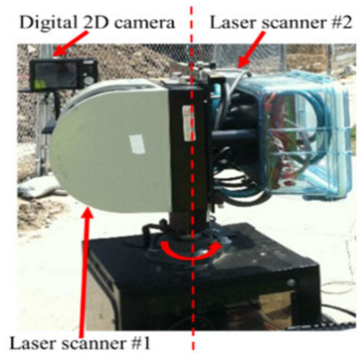

Figure 2. Prototype of hybrid 3D LiDAR system

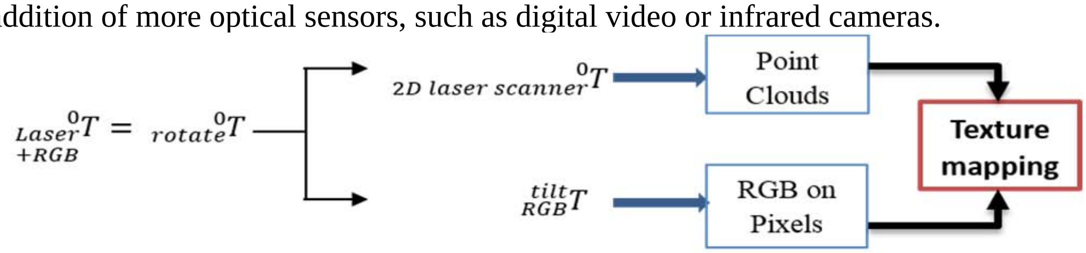

Figure 3. Integrated kinematics frame for the hybrid 3D LiDAR system

OVERVIEW OF THE PROPOSED METHOD

This study proposes a feature-based automatic data registration method to minimize overlapping areas, and accurately and rapidly estimate common feature points from the overlapping areas from two scan sets. In this research, a new target-free automatic registration method was developed by adopting the Speeded-Up Robust Features (SURF) descriptor (Bay et al. 2008) and Kinematics theory. The overview of data and process in the proposed method is presented in Figure 4.

As shown in Figure 4, textured point clouds can be collected by our hybrid LiDAR system. A SURF descriptor was employed and implemented in each textured point cloud in order to recognize the feature points. The common feature points can be found through feature points matching algorithm. Once at least three pairs of common feature points between two overlapped point sets are located, the 3D rigid transformation matrix can be calculated for coordinates' transformation.

To improve the accuracy, a triangle relationship based filtering method was developed to remove the outliers from the extracted common features. The main goal of registration is to calculate the 3D transformation matrix between two point clouds. Take one group of triangle $P_{1a}P_{1b}P_{1c}$ and $P_{2a}P_{2b}P_{2c}$ as an example, first, set point P_{1a} as $(0, 0, 0)$, move point P_{2a} to the point P_{1a}. The final transformation matrix can be summarized as

$$T = \begin{bmatrix} R_1 & R_2 & R_3 & L_x \\ R_4 & R_5 & R_6 & L_y \\ R_7 & R_8 & R_9 & L_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(Equation 1)}$$

Where matrix R is the transformation of coordinates involving rotation, and L is the transformation of coordinates involving translation between two point clouds. Then all different point clouds can be sequentially registered by multiplying the calculated matrix T to the point clouds which need to be transformed to others' coordinate system.

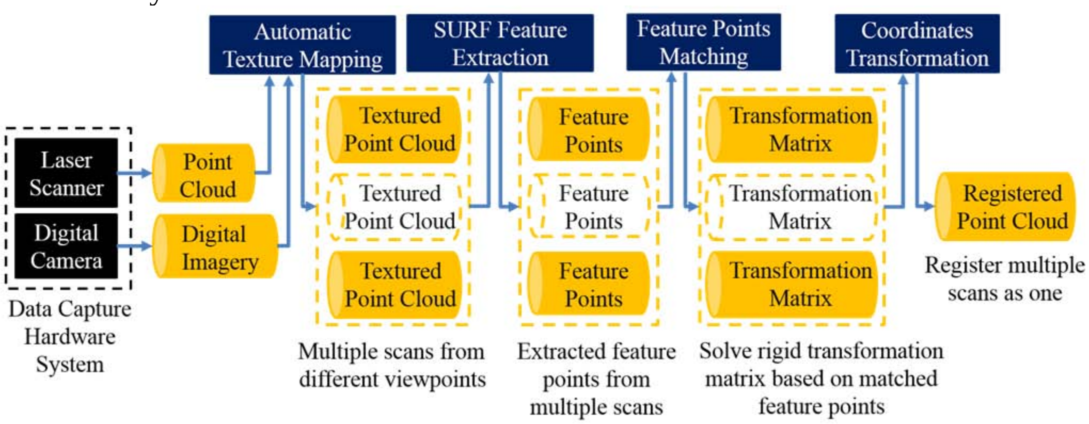

Figure 4. Framework of the proposed method

FIELD TEST AND DISCUSSION

Field experiments have been conducted to validate the proposed method, and the test-bed object selected is an on-going building construction project (Figure 5). In order to obtain digital images for texture mapping, a digital 2D camera set at 10.2 megapixel was used. The hybrid 3D LiDAR system was mounted on

Figure 5. Onsite experiment

a mobile cart as shown in Figure 5. The system was moved to another location for a different scan (a 360° point cloud and 50 images were taken). Then, the collected scans were examined to validate the proposed target-free automatic registration method. Technical data of digital 2D camera is shown in Table 1. All tests were benchmarked on an Intel Core i5 CPU with 4GB RAM on a 64 bit Windows platform.

Figure 6 shows the registration process and results of the selected two sets of point cloud data which have about 35% overlapping area. Common features were firstly extracted from the corresponding images, and were then paired by feature points matching algorithm. Three best matched pairs of feature points were obtained by the proposed triangle relationship based filtering method, and were used to calculate the transformation matrix. The registration results shown in Table 2 illustrates that there were more error caused by the transformation of coordinates involving translation which varies from 10.19 mm to 12.11 mm. It took about 93 seconds to calculate transformation matrix and register source point cloud (Figure 6 (d)) to target point cloud (Figure 6 (c)) by processing two images shown in Figure 6 (a, b). Higher accuracy can be obtained with more images although it may need more processing time. The processing time, however, can be significantly reduced by using a graphics processing unit (GPU).

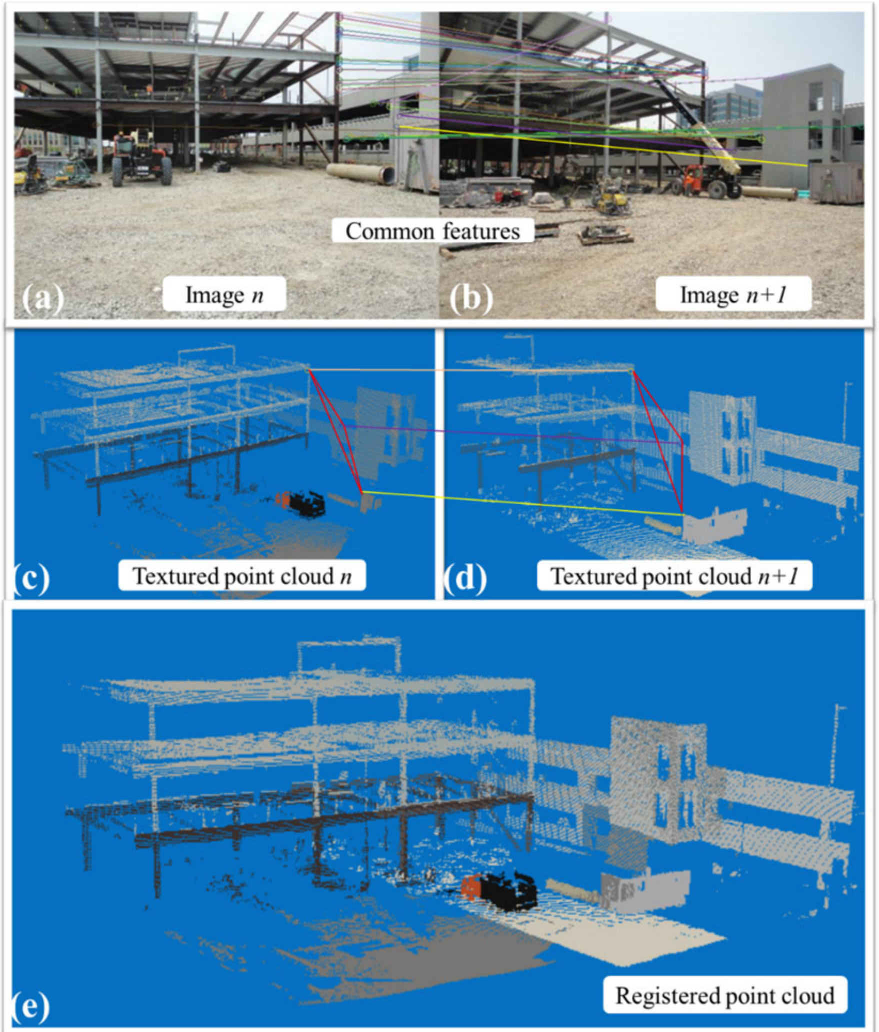

Figure 6. Automatic Point Cloud Registration Process and Results

Table 1. Technical data of digital 2D camera used in experiments

Type of camera	Single-lens wide angle digital
Effective pixels	10.2 megapixel
Image resolution	3648 x 2736

Table 2. Registration results

Accuracy	Distance offset (mm)	X Axis	10.19
		Y Axis	15.37
		Z Axis	12.11
	Angle offset (degree)	X Axis	0.07
		Y Axis	0.03
		Z Axis	0.24
Registration time (s)			92.56
Overlapping area (%)			34.51

Table3. Factors that influence the performance

Factor	Impact
Image resolution	Higher resolution, more feature points, higher accuracy, lower processing speed
Image quality	More colorful image, more feature points, higher accuracy
Overlapping area	Bigger overlapping area, higher accuracy, more data collection time
Feature types	More symmetrical objects or similar objects in the scan, lower accuracy
Data collection environment	More dynamic environment, lower accuracy

The performance of the proposed method can be significantly impacted by several factors, such as image resolution, image quality, feature types, and overlapping area size. Table 3 summarizes these factors and their potential impacts on the performance. Higher resolution images can provide more details of the scanned objects which possibly result in higher accuracy but lower processing speed. The quality of the collected images are also important because it can affect the process of feature points extraction and matching. It is preferred to have higher image contrast and stable light condition. Size of overlapping area is another key factor which can result in a failure of the registration without enough common features, or a time-consuming data collection process for redundant data. As for dynamic construction jobsite, frequent mobility of the equipment and workers can cause incorrect feature points matching which may cause lower accuracy or failure of registration.

CONCLUSION

A target-free automatic point cloud registration method was introduced using SURF descriptor and triangle-based outlier filtering method in this paper. A hybrid LiDAR system equipped with a digital camera was utilized to collect featured point clouds. Common features were extracted from texture data in the overlapped area and used to calculate the transformation matrix. An on-going building construction project was used as a field study to validate and evaluate the proposed method. The interrelationships among registration speed, registered accuracy, and size of overlapping area were discussed from the field data analyses. The field experimental results demonstrate that the proposed target-free registration method can significantly reduce the registration time without compromising the registration accuracy, thus promoting as-built modeling process for monitoring construction progresses.

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