Laser Scanner Validation Methods for Land Surveyors

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SUMMARY

Increasing density in urban environments is leading to more and more complex 3D real property objects. In many cases the boundaries of these properties are defined by the surfaces of structures. Terrestrial laser scanners can be used to map 3D boundaries, provided that procedures that can stand up to rigorous examination are used. In most jurisdictions, by law land surveyors are required to calibrate their equipment. However, many surveying jurisdictions are not equipped with the proper infrastructure for calibrating laser scanners. This paper presents a method to validate the laser scanner self-calibration procedure, and the positions of planes derived from laser scans. A well calibrated, high-precision total station is used as the standard of measurement to validate the laser scanning results. Features surveyed to a high accuracy are used as the ground truth in the validation procedures presented. The results show that the self-calibration procedure provides very good results. However, planes extracted from the laser scans are not always valid due to factors such as the surface material and the planarity of surfaces. The conclusion is that laser scanning measurements can be used to assist the total station surveying, but cannot replace them.

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1. INTRODUCTION

One of the trends in urban development is a move towards an increasing number of 3D property objects and consequently an increase in 3D boundaries (Stoter and Oosterom, 2006). Surveyors performing as-built surveys within urban environments face new challenges when using new, advanced measurement tools for legal surveys. The long-standing test of a boundary survey is whether the results and the procedures to generate them can stand up to rigorous cross examination. That implies that the person managing the measurement process should be able to explain how results are generated and where errors might occur in this process. With terrestrial laser scanners this is problematic because laser scanners generate a “black box” solution as internal software adjusts the raw measurements before the user sees them.

Terrestrial laser scanners typically measure horizontal angles, vertical angles and distances, but the data available to the user are in the form of a 3D point cloud. The Cartesian point coordinates are computed by the manufacturer’s software which automatically corrects the measurements by an unreported amount. Procedures are required to ensure that the geometric point positions are valid, as should an understanding of the semantic information of the surfaces being surveyed (i.e. information about colour, texture, and material). This paper explores a point-based method of validating lines, planes and their intersection positions derived from terrestrial laser scanning data for 3D cadastral boundaries. The procedures provide one option for using laser scanners for 3D boundary mapping.

In brief, a calibrated high-precision total station was used to establish the coordinates of key points on a building where the positions of the walls, floors, and ceilings define the 3D cadastral boundaries of a spatial unit. Planar surfaces were extracted using a supervised point cloud segmentation method. The laser scanner was calibrated for systematic errors, using an accepted point-based self-calibration method, which included the rangefinder offset, collimation axis error, trunnion axis error, and the vertical circle index error. A review of the derived calibration metrics demonstrated that the measurement parameters were insignificantly correlated, both among themselves and between the exterior orientation parameters. The impact of the systematic error corrections on the positions of key points was negligible in this instance due to the procedures, instrument, and geometry of the network used.

The positions of the planes were analyzed in terms of precision and accuracy and found to be within acceptable standards for cadastral surveying. The determination of key point positions required careful consideration, because of the varying structure of the built form, discrepancies caused by different surfaces scanned, and the stringent requirements of legal-type surveys.

This paper is structured as follows. Section 2 provides the background and motivation for the study. Legal surveying of 3D property is described in a general sense, followed by an overview of laser scanners and their shortcomings in terms of legislation and point determination for legal surveys. Section 3 presents the equipment, methods and algorithms used in the experiment. In Section 4 the results of the experiments are presented and analysed. The final section presents conclusions and recommendations for future work.

2. BACKGROUND & MOTIVATION

Legal surveying must be done by professionals who guarantee that their work is valid and authentic and can withstand rigorous cross-examination. This means that every part of the process used by professional surveyors, from data collection to the finished plan, must be defendable if a challenge arises. Currently, static terrestrial laser scanning is gaining momentum as a measurement tool for surveyors. This momentum arises from a number of factors including, but not limited to: reduced cost of equipment, increased ease of use, increasing availability of processing software, and increasing pressure from both clients and manufacturers (Shaw, 2015). For surveyors, laser scanners are attractive because they have some distinct advantages over traditional survey methods when mapping 3D structures.

Scanners can provide a very large amount of dense spatial information in a relatively short amount of time which, in turn, reduces field time spent in potentially unsafe areas. Also, scanners have been shown to reduce the need for repeat visits to complicated sites where a traditional survey might have missed some important measurements, as a laser scanner can provide full coverage of all surfaces. In many cases a full, 360° scan can be completed in under ten minutes (Shaw, 2015).

There are also disadvantages in using laser scanning as a professional surveyor. First, laser scanners are unable to directly measure to some points of interest (e.g. intersections of planes, corners) which means they must be derived from the point cloud. Second, rigorous procedures used to extract points of interest have not been fully analyzed. Third, data processing requires sophisticated, specialized software. Finally, the raw measurements are unavailable to the user which results in a “black box” solution for the point cloud.

The following sections present some background information from which the motivation for the work arises. The next section gives an overview of the differences and similarities between 2D and 3D surveys and the vast increase in complexity when incorporating the third dimension in legal surveys. Section 2.2 gives an overview of laser scanner operational principles. Section 2.3 discusses the requirements to use calibrated equipment and the shortcomings of many calibration baselines with regards to laser scanners. Section 2.4 shows some of the complexity faced by surveyors when determining where 3D boundaries should be located.

2.1 Legal surveying of 3D Property

Professional surveyors generally create legal survey plans when properties are divided into new parcels or when partial or secondary rights are allocated to non-owners. The creation of legal survey plans can be simplified as a two-step process, which presents two cases. The first case is when a property is first demarcated using monuments, and then a 2D survey plan of the boundaries is surveyed. In the second case the plan is created first and the boundaries are demarcated subsequently in accordance with the plan. In 2D and 3D situations the two cases presented above manifest themselves very differently. However, in all cases the positions of the boundaries must be expressed on a survey plan and verified in the physical world.

Current demands require professional surveyors to define properties in 3D and the task is complex. Three-dimensional survey plans, in contrast to the traditional 2D plans, can contain combinations of lines, planes, curved surfaces and other geometric sections. These features may be vertical, horizontal or inclined in any possible orientation and configuration. Three-dimensional boundaries cannot be demarcated like their 2D counterparts because it is not possible to place markers in the air. Instead, 3D survey plans must be made in reference to existing buildings, other built surfaces (e.g. walls, walkways, utility corridors, etc.) and reference marks. From the two cases presented before, in the first the surveyor will divide the property based on the locations of walls, floors, ceilings etc. after the building is constructed. In the second case, a surveyor must check that the building falls within the plan by performing an as-built survey to make sure that the physical structures agree with the plan.

In both the 2D and the 3D case, the surveyors' measurements have legal implications, and therefore they should use well calibrated equipment that is working properly. The next section outlines laser scanner calibration.

2.2 Laser scanning overview

The basic operational principle of the laser scanner is that range measurements are combined with horizontal and vertical angle measurements to create a 3D point cloud. The distance is measured by using a laser which is emitted from the scanner, reflected by a surface and returned to the scanner. At the same time when the laser pulse is fired, the horizontal and vertical beam deflection angles are measured by encoders. Internal scanner software is used to compute 3D coordinates for each laser pulse. The laser is rotated through a range of horizontal and vertical angles, and in many cases a full 360° horizontal view is obtained.

Each type of observation in the laser scanner has been shown to be effected by different types of systematic errors which stem from a number of sources (Boehler et al., 2003; Ingensand, 2006). Laser scanners are subjected to laboratory calibration procedures in order to mitigate errors which are inherent within the system. It is the responsibility of surveyors to ensure that their equipment is always calibrated, and to recognize when calibration is needed. The self-calibration method presented is effective in adjusting the laser scanner measurements and correcting the systematic errors. However in the view of legal surveying, this method is not completely acceptable. The next section presents more detail regarding the need to validate the self-calibration through other methods.

2.3 Current Calibration Legislation and Shortcomings

Legislation in many countries includes statutory calibration requirements for surveying equipment. Traditionally, total stations should be calibrated for theodolite axis errors and errors and EDM's should be calibrated against a standard baseline. In Alberta, Canada, the provincial law states that "a surveyor shall verify all electronic linear measuring devices used by comparison with calibration base lines" (*Alberta Surveys Act R.S.A.*, 2000 §11(2)(b)). On Federal lands in Canada the law states that "all equipment used in the survey must be calibrated to a reliable measure of distance or position" (*Canada Lands Surveys Act R.S.C.*, 1985 §23(2)(a)). Many other jurisdictions throughout the world have similar statutory requirements. Laser scanners are governed by these rules.

Baselines created for electronic distance measurement units (EDMs) are not suited for calibrating most terrestrial laser scanners. Existing baselines were developed for EDMs which have a much longer range (e.g. distances greater than 1 km are measurable) when compared to terrestrial laser scanners which typically measure distances from 1.5 m to 300 m. Current baselines were also designed for calibrating EDMs which use different carrier wave frequencies from laser scanners and are unsuited for determining periodic errors in laser scanner range measurements. Additionally, the laser scanner is not capable of pointing directly at targets to measure the distances and thus algorithms are required to extract targets from the point cloud which also affect the determination of the standard calibration parameters. In many situations, the baseline distances far exceed the designed operational range of the laser scanner and it is possible that no target is detected at all. Finally, because the baseline distances are so large, they could present unrealistic calibration specifications which arise from Earth curvature and atmospheric effects, for example, which are not present under most scanning conditions.

2.4 Key Point Derivation

The required parameters for creating legal survey plans are not directly observable within the laser scanning point cloud and must be derived using dedicated algorithms. This is in contrast to conventional surveying methods for which points of interest can be directly observed. The main segments of the point cloud which are of interest in 3D parcel determination are planes. Through the intersection of planes, the locations of boundary lines and points can be derived, which are required on 3D survey plans.

The determination of these surveying key points is not a trivial task, even though determining planes, lines and points is relatively straightforward. A problem arises when one tries to determine the validity of the derived points. Valid points are ones which satisfy the requirements of the survey and are precise and accurate. It is up to the surveyor to decide what constitutes a valid point. For example, a valid point could be either on the outer surface of a wall, the inner surface of a wall (given knowledge of the wall thickness), or some distance from these. A surveyor may decide to use the extremities of the building as the property definition or the structural foundation. The work presented here uses the outer surface of a building only. However, these issues are presented in order to illustrate the complexity which surveyors face in determining 3D boundaries.

3. EXPERIMENTAL METHOD

The experiments involved three main stages: (1) point-based laser scanner self-calibration, (2) validation of calibration parameters, (3) derivation and validation of key point positions. A suitable site was selected on the University of Calgary campus that is characteristic of a typical urban setting and includes a wide variety of features useful for different experiments. Features available at this site include a road with an overpass and buildings on both sides; a wide variation in plane surface size and orientation; and a wide variety of construction materials (See Figure 3.1).

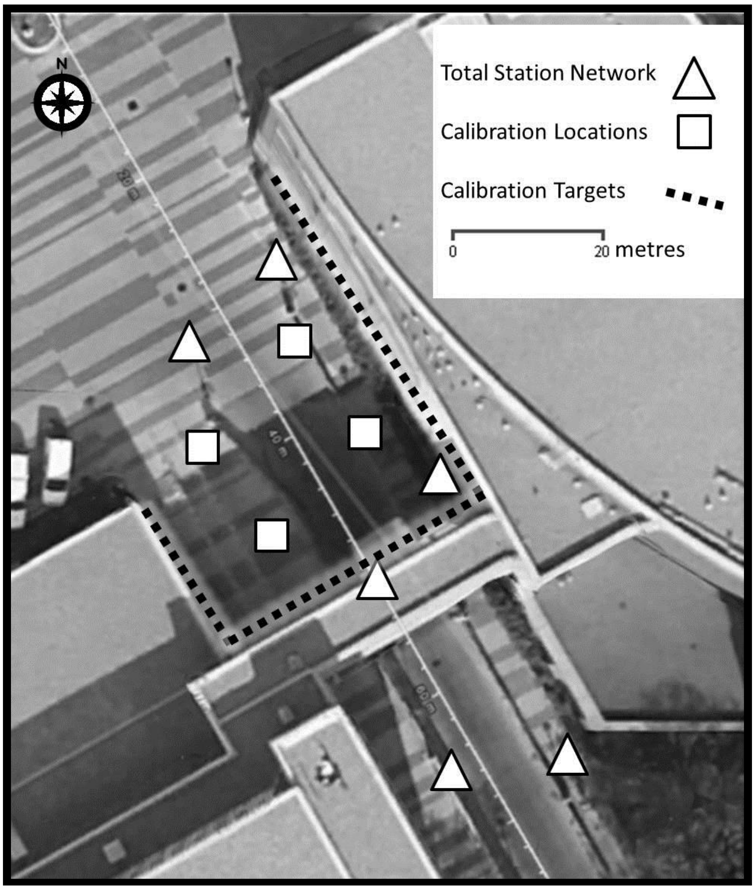

Figure 3.1: Plan view testing site at University of Calgary campus (Google Maps)

All observations were obtained with the Leica HDS6100 laser scanner; specified range accuracy ≤3 mm and angular accuracy ≤25”(Leica Geosystems AG, 2009), and the Leica TS30 total station; specified range standard deviation of ±(0.6 mm +1ppm) and angular standard deviation of 0.5”(Leica Geosystems AG, 2011). The Leica TS30 was calibrated on a baseline prior to the experiments. All processing was done using either Leica Cyclone software, or MATLAB. Leica Cyclone was used to convert scans from the encrypted data format into a user-friendly format, and to automatically extract target locations from the scans. MATLAB was used to compute the analysed parameters.

Figure 3.1 shows the approximate locations of the calibration scan stations and targets, and the total station network used for validation experiments. The next section gives an overview of the laser scanner calibration model. Section 3.2 explains the methodology for determining the validity of the calibration results. Finally, Section 3.3 describes how to determine the validity of the key points derived from laser scanner data for legal surveying.

3.1 Point-based Self-calibration

Laser scanner self-calibration is used to determine the systematic errors in the measurements. Additional parameters (APs) to the measurement model are determined through a parametric least-squares adjustment (Lichti, 2007). Calibration models have been reported which use points (Lichti, 2007; Schulz, 2007), planes (Bae and Lichti, 2007) and other geometric features available in the built environment (Chan et al., 2015).

The main concept of the point-based calibration is to scan a large number of features (points) in a large number of scans in order to achieve good network geometry. Scans and point features positioned so that a significant number of widely spaced points are visible in each scan. Using the point to point correspondence in a parametric least squares adjustment three main parameter sets can be solved, namely; (1) point coordinates, (2) laser scanner position and orientation, and (3) additional parameters (APs) of the systematic errors models that augment the measurement model.

The calibration was done using 70 six inch, black-and-white Leica targets placed on three building walls in a “U” shape (black dashed line in Figure 3.1). Figure 3.2 shows a portion of the targets which are regularly spaced to improve network geometry in the calibration. The targets were printed on normal letter-sized paper and were securely affixed to walls so that their positions remained stable throughout the calibration. It was important to affix the targets very rigidly to avoid effects caused by the wind or other unforeseen factors. The target locations were not accurately surveyed.

The area was scanned a total of six times from four different positions. Two of the positions were used twice with the scanner being physically disconnected from the tribrach and rotated by 120° between scans. This rotation of the scanner helps to reduce correlation which exists between some parameters within the self-calibration model (Lichti, 2010). Point targets were identified within each point cloud using proprietary software (Leica Cyclone), and the self-calibration method was used to determine the following four additional parameters (APs): the rangefinder offset, the collimation axis error, the trunnion axis error and the vertical circle index error (See equation (2)).

Figure 3.2: Point-based self-calibration set up showing Leica black-and-white targets placed on walls at the University of Calgary

The scanner range and angular measurement models with the basic set of APs (Lichti, 2007) included is shown in equations (1)-(3). This basic set of APs is chosen because it has been shown to compensate for the most significant systematic errors. The rangefinder scale factor was not determined in the calibration because it requires an independent definition of scale that is an order of magnitude more accurate than the laser scanner range measurements.

$$\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + a_0 \qquad (1)$$

$$\theta_{ij} = \tan^{-1}\left(\frac{y_{ij}}{x_{ij}}\right) + b_1 \sec(\alpha_{ij}) + b_2 \tan(\alpha_{ij}) \qquad (2)$$

$$\alpha_{ij} = \tan^{-1}\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + c_0 \qquad (3)$$

where,

ρ_{ij}, θ_{ij}, and α_{ij} are the range, horizontal angle and elevation angle, respectively, from scan location i to target point j;

x_{ij}, y_{ij}, and z_{ij} are the coordinates of target point j computed from the position and orientation of scan location i;

a_0 is the rangefinder offset;

b_1 and b_2 are the collimation axis error and trunnion axis error, respectively; and

c_0 is the elevation angle offset.

3.2 Validation of Laser Scanner Self-Calibration

An independent check was performed by using accurately surveyed targets to validate the outcome of the self-calibration routine. This experiment was performed at a different time from the calibration experiment. Leica black-and-white targets were set up on tripods over accurately surveyed marks. The target coordinates were determined from two independent sets of measurements using the high-precision total station in a coordinated network (triangles in Figure 3.1). The targets were observed in direct and reverse face in order to reduce additional systematic errors. These are the six ground control points used for the validation experiment.

The targets were scanned from five different locations and their coordinates were automatically extracted from the scans using the Leica Cyclone. Some targets were not visible in particular scans because of occlusions or an insufficient number of sampling points reflected from the target. In total, 19 target observations were used. These are the scanned target points.

The scanned target points were then transformed into the ground control point coordinate system using a six-parameter transformation (i.e. scale omitted). The differences in coordinate positions were then analyzed to determine if the calibration is valid or not. In the self-calibration method used, scale was treated as known, and so a six-parameter transformation was suitable.

3.3 Validation of Extracted Planes

The validation of extracted planes was performed by comparing them with accurately-surveyed key points. Point clouds from surfaces believed to represent planes (e.g. floors, walls, ceilings) were manually identified and extracted. The supervised segmentation method allowed for the extraction of suitable planes. Suitable planes are those which have corresponding surveyed key points, are of a sufficient size for plane fitting, and are void of outliers. Principal component analysis (PCA) was used to determine the plane parameters for comparison with the key points. This method was chosen for its ease of implementation. Mathematically, PCA provides identical results to least squares plane fitting when all points representing a single plane are used (Pauly et al., 2002).

Figure 3.3: Calibrated spike used to determine key point coordinates

Key point coordinates were determined from two independent surveys using a high-precision total station network (triangles in Figure 3.1). The key points were observed using the bar in Figure 3.3 in direct and reverse face in order to reduce additional systematic errors. All total station observations were combined to determine the most probable position of key points.

Figure 3.4 shows an example of key points (a), (b) and (c) and extracted planes (1), (2), and (3). When validating the positions of the planes, a single key point can be used to validate multiple planes. For example, in Figure 3.4, point (b) can be used to validate all three planes because it represents their intersection point. The normal distance from point (b) to the three planes ((1), (2), and (3)) should be zero in the ideal situation. Plane (3) can be considered valid if three key points (i.e. points (a), (b), and (c)) corresponding to that plane are within tolerance, because three points can define a plane.

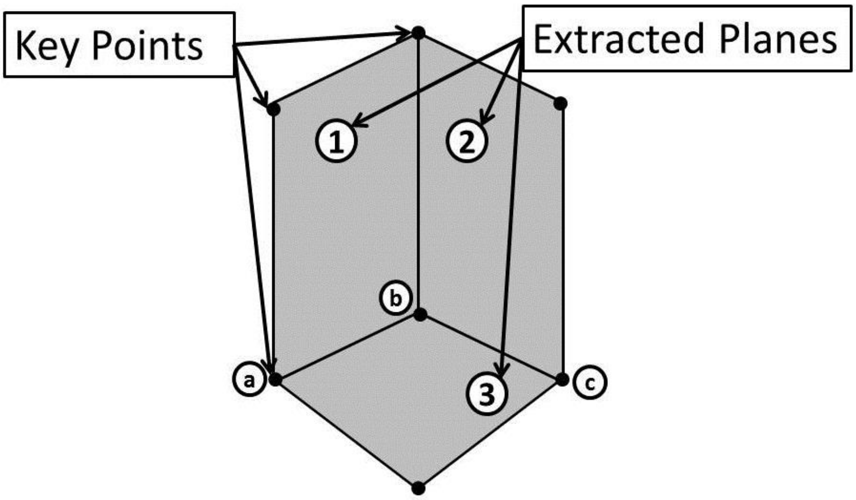

Figure 3.4: Laser scanning validation using key points (a, b, c) and extracted planes (1, 2, 3)

4. EXPERIMENTAL RESULTS & ANALYSIS

4.1 Point-based Self-calibration Results

Table 1 shows the RMS of the residuals before calibration (APs not included) and after calibration including APs. The results clearly show that the instrument being used was well calibrated, and that the inclusion of APs in the measurements did not greatly improve the point cloud precision. Considering the maximum range in all experiments is less than 100 m and the change in horizontal angle of 1.6", the total position error possible is approximately 1 mm.

Table 1 Precision of point-based self-calibration

	Before Calibration	After Calibration
RMS ρ (mm)	0.82	0.79
RMS θ (")	16.5	14.9
RMS α (")	14.4	13.1

4.2 Validation of Laser Scanner Self-Calibration

The results from all observations were considered to be of equal precision and were averaged to find the best estimate. For these reasons, the coordinates obtained from the total station were assumed to be without error.

Table 2 Accuracy and precision of validation results

	Northing (mm)	Easting (mm)	Height (mm)	Distance (mm)
Mean Error	3.0	2.0	2.4	4.9
Std. Dev. (1σ)	3.6	2.2	3.4	2.3
Max Error	7.2	4.0	7.0	9.8

Table 2 shows the results of the validation of the self-calibration procedure. The Northing, Easting and Height displayed are in the locally defined coordinate system created by the high-precision survey. The errors expressed above are all within acceptable limits for legal surveying in Alberta (ALSA, 2014), and show that the calibration parameters are indeed valid. The maximum total position error in any point was 10 mm ± 2.3 mm (1σ).

4.3 Validation of Extracted Planes

First, the normal distances from the key points to corresponding extracted planes are analyzed to give insight into the validity of the location of the plane. Second, the planes are determined to be valid if three or more points representing the plane are valid. Finally, the extracted plane precision was used to determine the quality of the extracted planes.

In total 83 normal distances were computed from 14 extracted planes and 36 key points. A normal distance was considered to be valid if it was less than 20 mm (ALSA, 2014). The number of valid normal distances is shown in Table 3. In total 57 of the 83 normal distances were considered to be valid, meaning that 69% of the time, the fitted plane location was in the expected position. This represents the location of the plane, not the quality of the extracted plane.

A plane is considered valid if at least three key points corresponding to that plane (i.e. the number of points needed to define a plane) have a normal distance of 20 mm or less. Of the 14 planes which were identified in the point clouds 11 were valid. Three of the valid planes were uniquely defined by having only three matching key points. Two of the invalid planes were horizontal planes on the ground. The third invalid plane comes from a wall which has a very slight curve in it and thus the plane model was applied incorrectly to a non-plane surface. This curve was discovered by looking at a cross-section of the point cloud. Without the benefit of the point cloud this surface might be incorrectly represented as a plane by the surveyed key points.

In all 14 planes the precision of the plane fit was less than 10 mm. Eleven of the planes derived had a precision less than ±5 mm (1σ) and only three were greater than ±5 mm. The precision of the plane fit is used because it provides a representation of the planarity assumption in the PCA. It can be used in conjunction with *a priori* knowledge of the surface roughness and measurement noise to determine the quality of the plane fitting. The three planes with precision greater than ±5 mm were the same three invalid planes from the previous analysis.

Table 3: Results of plane extraction validation

Total number of normal distances (n)	83	Total number of planes	14
Valid plane positions (n < 0.02 m)	57	Valid planes (3 or more valid points)	11
Invalid planes positions (n ≥ 0.02 m)	26	Invalid planes (less than 3 valid points)	3

5. CONCLUSION

The methods presented here show one procedure surveyors can use to validate planes which are derived for legal surveying work by laser scanners. The positions of extracted planes alone are unable to withstand rigorous cross examination. The built form provides a complex set of conditions which all detriment the position of surface planes. Positions of planes, even in this highly supervised segmentation method, are affected by protrusions, depressions and surface roughness. Additional factors which affect the plane position but are not analyzed here are the incidence angle of the laser beam, surface reflectivity and atmospheric conditions.

The approach presented here clearly shows that extracting planes from laser scanned point clouds is not sufficient for surveyors to guarantee their work is both valid and accurate. The merits of both methods should be used in conjunction to determine the best position of the boundary. In many instances it may be possible to use the laser scanned location as the true boundary, but this is not always the case. This paper also shows that surveyors must be prepared to use all tools available to ensure that the boundaries of 3D properties are represented accurately and precisely.

Future work will include analyzing the effect surface roughness, incidence angle of the laser beam, surface reflectivity, and atmospheric conditions have on the derived plane positions.

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BIOGRAPHICAL NOTES

Sam Rondeel holds a Bachelor of Science degree with distinction in geomatics engineering from the University of Calgary. Previously, he worked in land surveying in Central Alberta focusing on work in municipal infrastructure and rural subdivisions. In 2011, Sam embarked on an internship at a land surveying firm where he gained experience in oil and gas surveying and construction surveying. His current research is in M.Sc. program at the University of Calgary and focuses on 3D cadastral systems and terrestrial laser scanning in urban environments.

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Dr. Derek Lichti is currently Professor and Head of the Department of Geomatics Engineering at the University of Calgary, Canada, and Editor-in-Chief of the ISPRS Journal of Photogrammetry and Remote Sensing. His research program is focused on developing solutions for the exploitation of optical and range-imaging sensors for the automated creation of accurate, 3D models for measuring human motion, monitoring structural deformation and compiling asset inventories of the built environment.

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