Boresight alignment method for mobile laser scanning systems

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Abstract

Mobile laser scanning (MLS) is the latest approach towards fast and cost-efficient acquisition of 3-dimensional spatial data. Accurately evaluating the boresight alignment in MLS systems is an obvious necessity. However, actual systems available on the market may lack of suitable and efficient practical workflows on how to perform this calibration. This paper discusses an innovative method for accurately determining the boresight alignment of MLS systems by employing 3D-laser scanners. Scanning objects using a 3D-laser scanner operating in a 2D-line scan mode from various different runs and scan directions provides valuable scan data for determining the angular alignment between inertial measurement unit and laser scanner. Field data is presented demonstrating the final accuracy of the calibration and the high quality of the point cloud acquired during an MLS campaign.

Introduction

The problem of angular misalignment between the measurement axes of a laser scanning device and the measurement axes of an inertial measurement unit (IMU) is well known from airborne laser scanning (ALS) systems. Algorithms for calculating the boresight alignment angles have been introduced in the past and are widely applied. While the principles of the algorithms used are similar in aligning airborne laser scan data and mobile scan data the methods of data acquisition are inevitably different.

Due to the fact that an area of interest can easily be scanned from flight paths of different directions during an airborne laser scanning survey, enough valuable information is available to determine the system's boresight alignment parameters. MLS systems lack of flexibility in scanning the same objects multiple times from different directions. It is impossible to scan the same objects from runs of, e.g., opposite directions by a mobile system applying a side-looking 2D-laser scanner with limited angular field-of-view.

Various methods of acquiring suitable data for assessing the boresight angles between IMU and laser scanner of a MLS system are imaginable. Some of these methods require a terrestrially surveyed test site providing accurate absolute coordinates for, e.g., retro-reflective targets of known shape and size. Other procedures rely on scanning objects of known size and position from different driving directions and distances. All these approaches lack of flexibility and demand high efforts on preparing special test sites. Measurement errors possibly introduced by the terrestrial surveys of reference targets decrease the confidence in the accuracy of the estimated boresight angles. The assessment of the boresight angles by analyzing distances between one and the same object appearing in two scans is often not automated and based on manual trial and error algorithms.

A new principle of boresight alignment

A new approach of spatial data acquisition for calculating the boresight alignment angles relies on the application of a 3D-laser scanner as a core component of a MLS system (Figure 1). 3D-laser scanners suitable for the described process provide a scanning mechanism with two orthogonal axes of linear laser beam deflection, a so-called line axis and a frame axis. A single line of consecutive laser measurements is realized by deflection of a laser beam by a mirror surface rotating around the line axis. Rotating the line scan mechanism around the frame axis allows the acquisition of consecutive scan lines. Besides information on the target distance, every single laser measurement includes the accurate angular values of the line axis and frame axis providing the direction of the target with respect to the laser scanner's own coordinate system. An indispensable prerequisite is the knowledge of the instrument's internal calibration, e.g., accurate information on how the actual measured range, line- and frame angles transform into coordinates within the scanner's coordinate system. The internal calibration of the laser scanner is carried out on precisely surveyed test sites by the manufacturer. Within the depicted mobile mapping application, the line axis is approximately oriented in parallel with respect to the x- and y-axes, whereas the frame axes is aligned in parallel to the z-axis of the vehicle's own coordinate system.

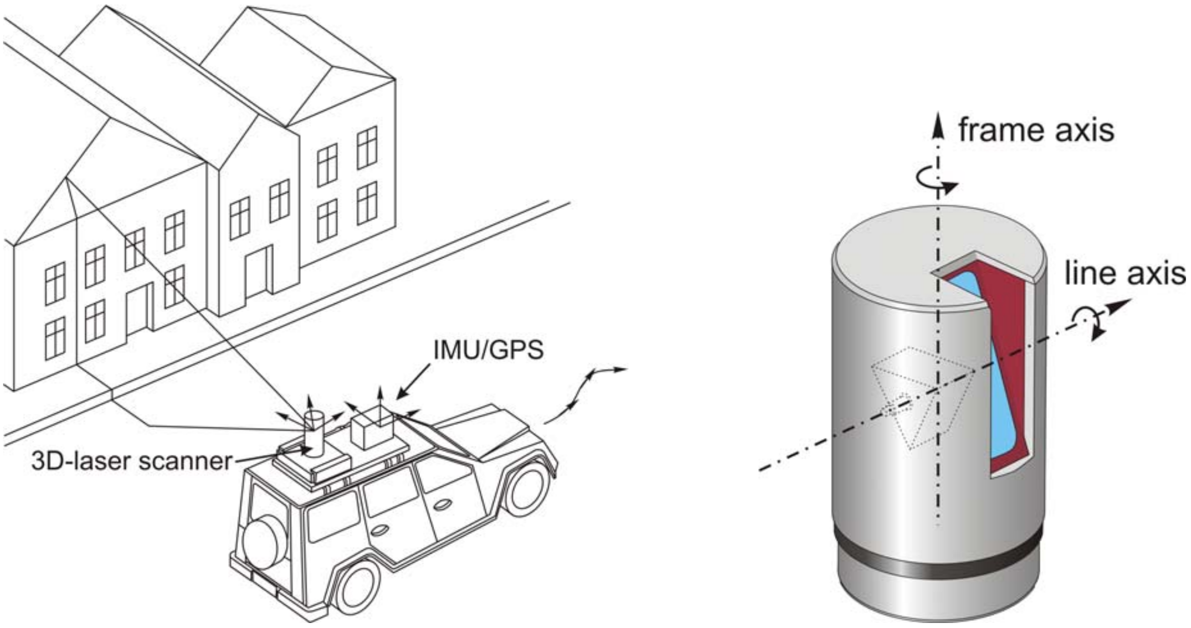


Fig. 1, left: Typical configuration of a MLS system comprising a 3D-laser scanner and a IMU/GPS sub-system
right: Line- and frame axis of a 3D laser scanner

In order to combine laser scan data and position and orientation data later on, measurement data of both subsystems, the scanner and the IMU/GPS sensor, have to be time stamped precisely. Furthermore, the feature of operating the 3D-laser scanner in a 2D-line scan mode at different frame angles is an essential requirement for the method presented. In the 2D-line scan mode the laser beam is deflected by the line scan mechanism, whereas the frame scan mechanism is locked. Nevertheless both angular values of the line- and frame axis are acquired for every single laser measurement.

Scan data acquisition is carried out in a suitable area providing objects containing preferably flat surfaces of variable orientation. Urban or sub-urban regions, with an adequate amount of flat façade sections and roofs of buildings along the street, provide valuable information as a basis for calculating the boresight alignment parameters. However, not every area is adequate for carrying out a system calibration. Obstructions of GPS reception caused by high buildings or tree canopy diminish the accuracy of position and attitude information significantly. Choosing appropriate values of pulse repetition rate, scan rate, and driving speed is essential in order to ensure sufficient point density on surfaces of the scanned objects

The proposed method of data acquisition bases on scans of objects, e.g., buildings with at least some planar surfaces oriented at different angles with respect to each other, acquired during several runs of the MLS system in opposite directions and variable angular alignment of the laser swath. For the first measurement the frame axis the laser swath is aligned, e.g., perpendicular with respect to the driving direction, scanning the facades and roofs on the left side of the street as shown in the left sketch of Figure 2. After finishing the first run, the frame axis of the 3D laser scanner is rotated by 180 degrees and a second run, with the vehicle driving in the opposite direction, is performed. Thus, the left side of the street is scanned again as depicted in the centre sketch of Figure 2. This procedure may be repeated several times at different angles of the laser swath and at both driving directions on the street, shown in the right sketch of Figure 2 respectively.

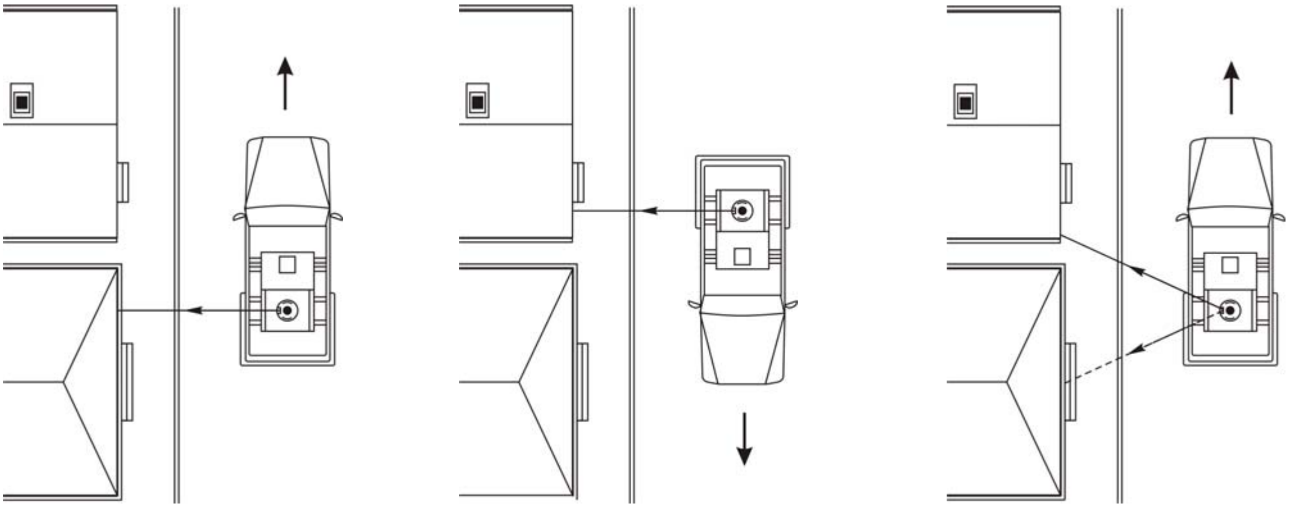


Fig. 2 **Mobile scanning of facades from different driving- and scanning directions.**

After the combination of scan data and position/orientation data the resulting data set is a collection of point clouds acquired at different runs, covering the same surfaces several times. When analyzing the point cloud misalignments between the measurement axes of the IMU and the measurement axes laser scanner are revealed. These misalignments appear in almost every MLS system and are based upon the fact that on the one hand the axes of the single units can not be perfectly mechanically aligned and on the other hand that every mechanical installation implies structural tolerances.

A possible angular deviation between IMU and laser scanner with respect to, e.g., the roll axis of the vehicle will result in a rotation of the point clouds of two scans acquired during consecutive runs in opposite driving directions as shown in Figure 3. The distance of two corresponding surfaces is approximately proportional twice as large as the unknown angular deviation between the scanner and IMU with respect to the roll axis.

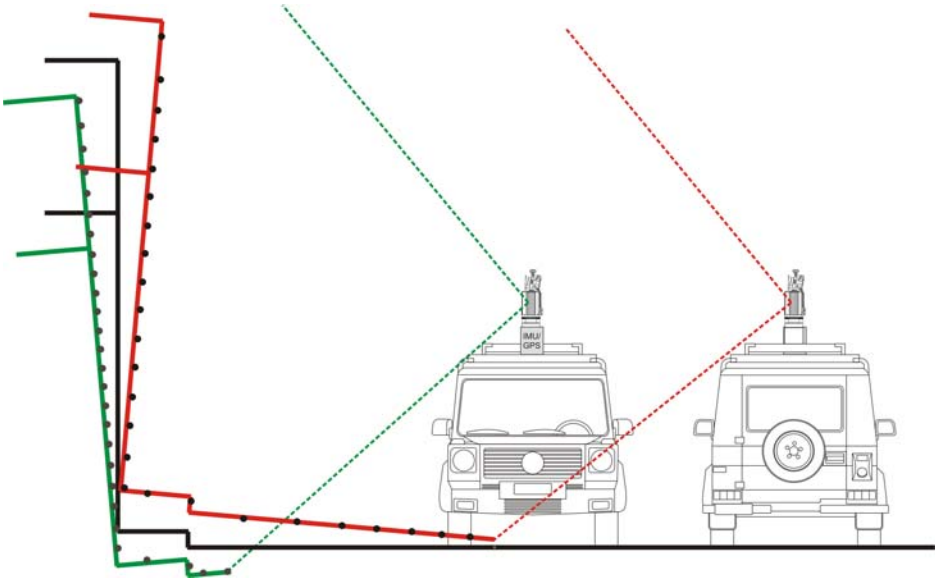


Fig. 3 **Appearance of boresight angles, e.g. the roll axis, in the three dimensional point cloud.**

The boresight alignment algorithm relies on corresponding planar surfaces located in the three dimensional point clouds. The method of identifying corresponding surfaces in overlapping scans and the calculation of the boresight alignment values for MLS systems is similar to the procedures already known as “boresight alignment and scan data adjustment” from airborne laser scanning. Within the overlapping regions of two or more scans an automated algorithm detects corresponding planar surfaces of defined flatness inside the point cloud. These surfaces are represented by their size, the location of their centre of gravity, and their according normal vector (Figure 4). The consecutive scan data adjustment applies a modified ICP (Iterative Closest Point) algorithm, varying roll, pitch and yaw angles iteratively reducing the mean square distance error (Equation 1) of all corresponding planar surfaces. The optimization process terminates when the improvement in reducing the residual mean square distance error is less than a specified value. The final result of the scan data adjustments are three alignment angles according to the vehicle’s roll, pitch and yaw axes to be applied when combining scan data and position and orientation data.

The proposed method of determining the boresight angles of a MLS system is not limited to systems employing only one 3D-laser scanner. It stands to reason that an extension of the system by additional 2D-laser scanners for special purposes is possible. The boresight alignment of the 2D laser scanners would be performed by defining the already adjusted point cloud data acquired by the 3D-laser scanner as a reference point cloud. By applying the same algorithms already used for aligning the 3D-scan data three boresight angles, unique for each additional 2D scanner, are calculated.

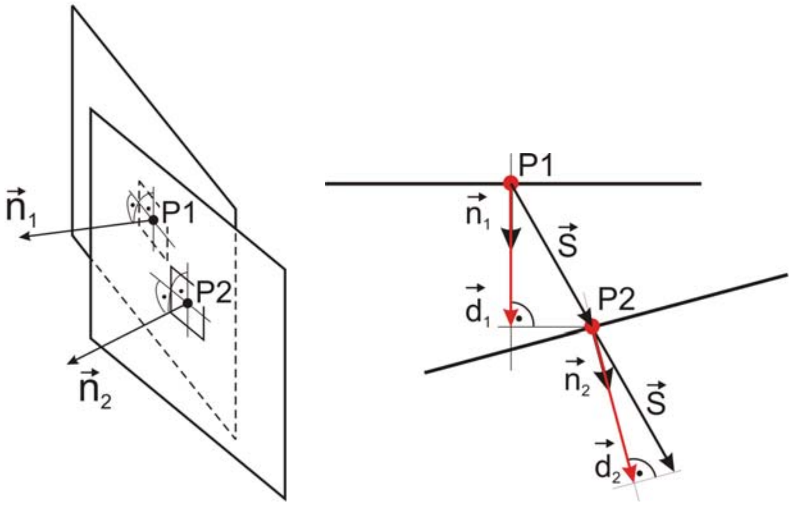


Fig. 4: Planar surfaces detected inside the point cloud are represented by their location and their normal vector.

$$\vec{d}_1 = (\vec{P}_2 - \vec{P}_1) \cdot \vec{n}_1$$
$$\vec{d}_2 = (\vec{P}_2 - \vec{P}_1) \cdot \vec{n}_2$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{d_1 + d_2}{2} \right)^2}{n}}$$

Equation 1: Mean square residual error distance of all corresponding planar surfaces.

Experiments and sample data

The main components of the MLS system are the 3D-laser scanner system *RIEGL* VZ-400 and an Applanix POS LV 420 position and orientation system. Both units are mounted on a rigid submount, mechanically closely coupled as shown in Figure 5. The POS LV system consists of the POS Computer System (PCS) and four sensors: an IMU, a DMI, and two GPS antennas. The operating computer and the PCS for data storage are located within the car.

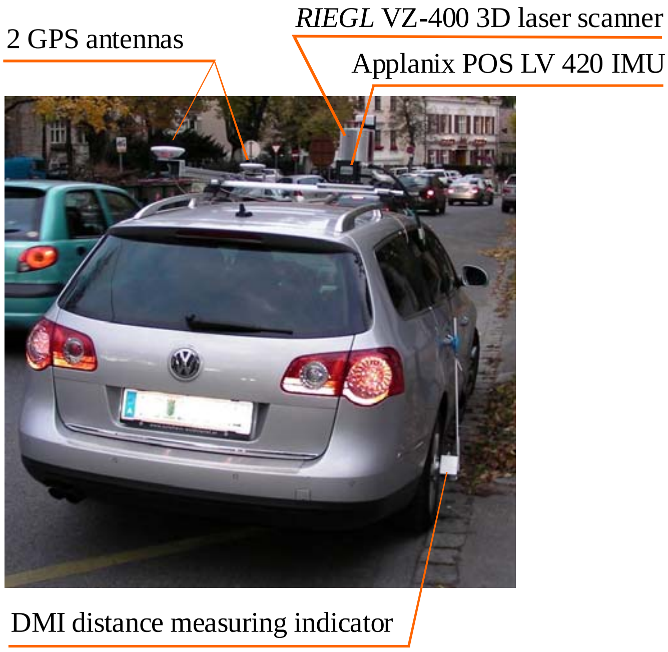


Fig. 5: Experimental mobile laser scanning system mounted on a car

<u>*RIEGL*'s new V-line of 2D and 3D laser scanners</u>

RIEGL's V-line laser scanners rely on the principle of pulsed-time of flight range measurement. They operate at unprecedented measurement rate, range resolution, and precision, enabled through echo digitization and online waveform processing. Multiple targets can be identified for every laser shot which leads to true 3D data, enhancing data acquisition even behind vegetation, dust or fog.

Vegetation penetration alleviates boresight alignment due to increasing the number of facade targets in urban environments with, e.g., alley trees or bushes in between.

Short laser pulses are transmitted at a certain pulse repetition rate (100 or 300 kHz for the VZ-400). The optical signal detected by the receiver is digitized at a sampling rate matching the laser pulse duration. An advanced signal detection module sifts relevant samples out of the data stream. Subsequent high-speed waveform processing algorithms estimate target properties precisely online without the need of a computer for post processing.

Online signal processing in the V-Line is capable of discriminating the echo pulse shape with respect to the emitted pulse shape. The deviation of the pulse shapes is a valuable indicator for the reliability of the range result and is provided with every measurement.

	measurement range	up to 500 m (80%) @ laser class 1, invisible laser beam
	repeatability and accuracy	better 5 mm
	effective measurement rate	up to 125.000 meas./sec
	field of view	100 deg x 360 deg

Table 1: *RIEGL* VZ-400 Specification

Setup and data collection

The profile scan data and the raw data for the calculation of the trajectory are collected separately. The integrated GPS receiver of the *RIEGL* VZ-400 was used for time stamping the laser scans.

Measurement rate has been set to maximum, line scan rate and car speed have been selected to achieve balanced point spacing of about 5 cm on objects at an average distance of about 30 m. The resulting acquisition parameters are summarized in Table 2.

average measurement distance	approx. 30 m
average point spacing @ 30m	5 cm
speed of the car	approx. 20 km/h
angular resolution of two subsequent laser measurements within one line scan	0.1 deg
scanning rate	120 line scans per second

Table 2: Used parameters for the surveying drive

Data processing and boresight alignment

RiPROCESS, *RIEGL's* software solution for processing the mobile scan data, covers four major tasks:

1. Organize, process, and archive all data related to a single project.

2. Visualize data on different scales, i.e., on a large scale as rasterized data, on a small scale as point clouds in 3D

3. Calibrate the system and/or adjust the scan data to minimize inconsistencies in the laser data, also addressed as strip adjustment.

4. Export data in widely supported formats for further processing

The following example illustrates a calibration process. For this example six scan runs were carried out along a street. While driving in opposite directions, the same side of the street was scanned six times. The 3D laser scanner looked alternately to the right and the left side of the car as shown in Figure 6. The point cloud color indicates the scan direction.

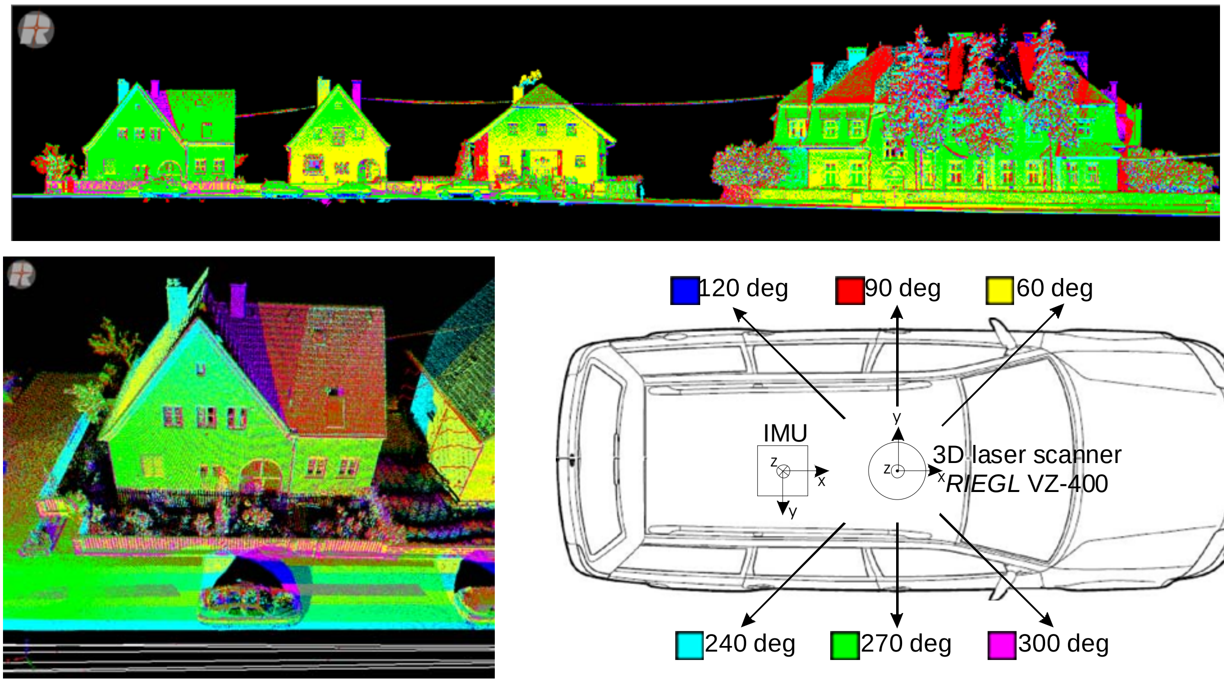


Fig. 6: Top: Orthogonal view of the common point cloud of 6 different scans, Left bottom: Perspective view of one single house, Right bottom: The arrows indicate the directions and colors of the six different scans.

The axes of the **s**canner's **o**wn **c**oordinate **s**ystem (SOCS) and the IMU coordinate system, as shown in Figure 6, are approximately parallel or anti-parallel, hence the boresight angles were initially set to zero. For the transformation of each laser measurement into the WGS84 coordinate system, following transformation matrix was used:

$$C_{IMU}^{SOCS} = \begin{pmatrix} 1 & 0 & 0 & 0.209 \\ 0 & -1 & 0 & -0.008 \\ 0 & 0 & -1 & -0.204 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Figure 7 shows three screenshots of the resulting point cloud: The left image represents the point clouds from the 120° and 300° scan, covering the front and the right side of the house. The middle image represents the point clouds from the 90° and 270° scan, covering the front of the house. The right image represents the point clouds from the 60° and 240° scan, covering the front and the left side of the house. The white lines in front of the house indicate the trajectory of the six different scans.

This procedure allows finding common plane patches in minimum two independent scans achieved while driving in opposite directions.

Figure 7:

Point cloud of the scan to left backwards (120 deg) and to right forwards (300 deg) with respect to the car

Point cloud of the scan to the left (90 deg) and to the right (270 deg) with respect to the car

Point cloud of the scan to left forwards (60 deg) and to right backwards (240 deg) with respect to the car

This procedure allows finding common plane patches in minimum two independent scans achieved while driving in opposite directions. The identification of such corresponding planar surfaces and the calculation of the boresight angles are done automatically by RiPROCESS. For the shown example, to the following angular values were determined:

Roll = -0.032 deg, Pitch = 0.209 deg, Yaw = -0.868 deg

The effect of boresight alignment is illustrated in Figure 8, a cross section of the building of 0.5 m width. In the left images, prior to calibration the multiple line profiles are misaligned, while on the right side the different scans fit together after the calibration process.

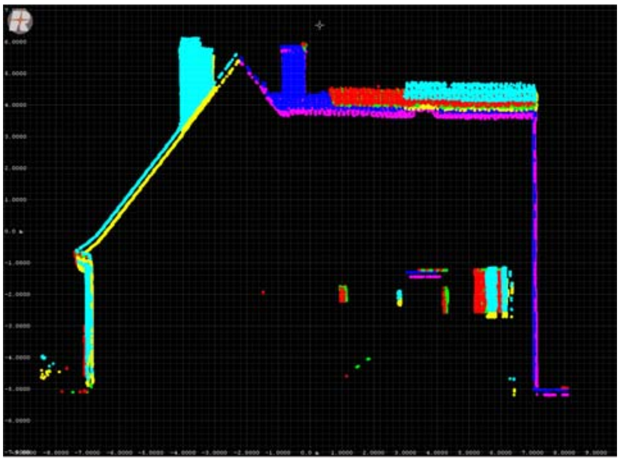
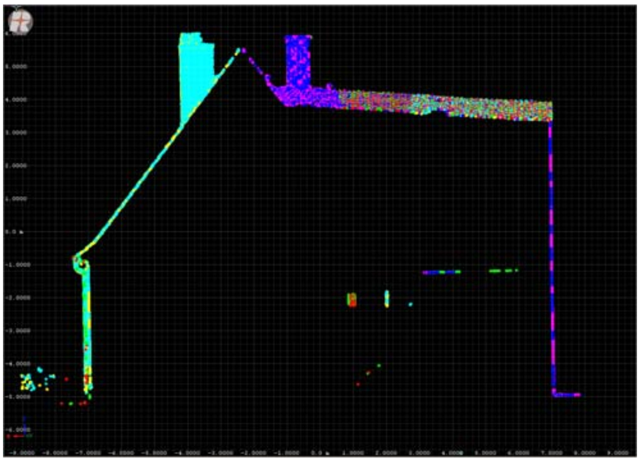
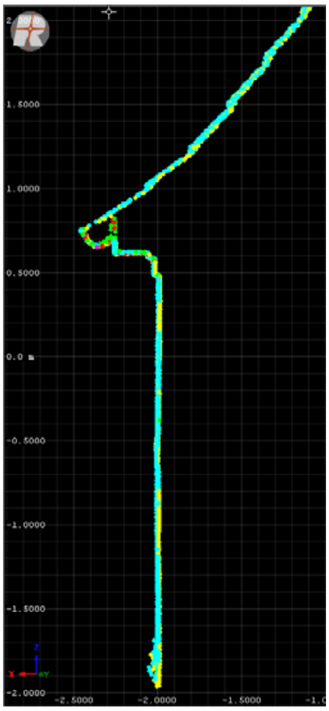


Figure 8a: Composite pointcloud cross section of the house before boresight alignment



Composite pointcloud cross section of the house after boresight alignment

Figure 8b: Detail of the left facade



Detail of the left facade

In addition to the visual check of the calibration, the following adjustment protocol of RiPROCESS shows the accuracy of the common MLS system. 471 observations of corresponding planar surfaces, where used for calculating the boresight angles. The remaining standard deviation is about 14 mm. Figure 9 shows the histogram of residues and orientation chart of the observations.

Calculation mode:	Adjustment (least square fitting)
Calculation time:	8 secs, 79 msecs
Min. change of error [m]:	0.000100
Search active:	True
Search radius [m]:	1.000
Angle tolerance [deg]:	5.000
Max. normal dist. [m]:	1.000
Quadtree cells - active:	True
Quadtree cells - count:	629

Calculation results

Number of observations:	471
Error (Std. deviation) [m]:	0.0143

Name	Roll	Pitch	Yaw
VZ-400 (VZ400, 9996063)	-0.032	0.209	-0.868

Table 3: RiPROCESS Scan Data Adjustment Protocol

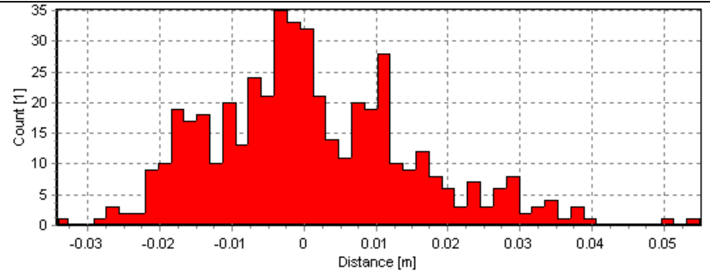
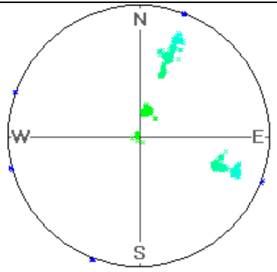


Figure 9: Histogram of residues



Orientation chart

Conclusion

The application of 3D-laser scanners in mobile laser scanning applications is a new technique which allows acquiring data suitable for determination of the boresight alignment. The procedure has been well proven in surveying campaigns applying the latest RIEGL LMS VZ-400 3D-laser scanner in combination with an APPLANIX POS LV 420 IMU/GPS system. The exceptionally high pulse repetition rate and the technique of real-time waveform processing provide high point densities covering surfaces even hidden behind vegetation. These planar surfaces are input to the subsequent scan data adjustment algorithm which enables a robust estimation of the systems boresight angles.

The accuracy of the estimated boresight calibration values depends strongly on the quality of the position and attitude data. A high point density is required to enable the applied algorithms in detecting suitable planar surfaces. An IMU/GPS system of high long term measurement accuracy, insensitive to short term loss of GPS coverage and a fast and accurate 3D laser scanner are the key components to a state-of-the art mobile laser scanning system delivering precise and accurate spatial point cloud data.

The advantage of the proposed method is the possibility of determining the boresight angles of a MLS system by analyzing scan data acquired in any desired area providing at least some planar surfaces. Even user data can be an input to the described algorithms as long as objects have been scanned at least twice from different driving and scanning directions. Special test areas providing exactly surveyed targets or objects of known size for boresight alignment become obsolete.

References:

1. RIEGL Laser Measurement Systems GmbH. Technical data at www.riegl.com, 2008
2. Applanix Corp. Technical data at www.applanix.com, 2008