Mobile mapping system performance - an analysis of the effect of laser scanner configuration and vehicle velocity on scan profiles.

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Abstract

When a laser scanner is mounted on a moving platform and combined with a GNSS receiver and inertial navigation system, it is capable of producing millions of geo-referenced points which can then be used to create near-3D models. The development of processing algorithms for these point clouds has largely been the focus of the research community to date. However, given an arbitrary known static object positioned at a specific distance away from a mobile mapping system (MMS) the resolution of the resulting point cloud that will describe that object is unknown. This is the underlying limit of point cloud processing algorithms. We are in the process of developing a method for determining the quantitative resolution of point clouds collected by a MMS with respect to known objects at specified distances. Our previous work has demonstrated our initial investigations into the effect that scanner position, configuration and operating speed has on scan lines - both in profile spacing and scan line orientation at varying vehicle speeds. This paper focuses on the combined effect on profiles of both vertical and horizontal rotations of the scanner, explores in greater detail the effect on scan line orientation caused by vehicle motion and also incorporates point spacing as a function of range into our model. As with our previous work, we will develop a system to calculate this information and then verify our equations and analysis by comparing our simulated data to the point cloud data collected by our XP-1 mobile mapping system.

1 Introduction

The focus of the research community to date has largely been on developing automated or semi-automated algorithms for processing the large point clouds captured by modern terrestrial or mobile mapping systems [2, 7, 14]. However, other than accuracy tests on specific systems [1, 6] little research exists assessing the performance of generic mobile mapping systems. Further research in this area is important as one of the underlying questions facing research groups working with extraction algorithms is what point density to expect for objects at different ranges. For example, work by [12] and [13] require a minimum number of profiles on post objects for them to be detected. Circular objects need a minimum number of points on each profile to recognise a circular shape. Each algorithm performs differently, and from [10] we can see that point density directly impacts on the accuracy of the resulting extracted model. Mobile mapping systems (MMS) are new to the market, and to date there has been no concerted effort to assess their combined capabilities. This paper will focus solely on laser based systems.

One of the fundamental decisions when assembling a laser based mobile mapping system is the location and orientation of the scanner on the vehicle. Although there have been tests investigating the best scanner configuration to minimise occlusions [15], there does not appear to have been research carried out to find the optimal location for a single scanner (i.e. rear, side, front) that will provide the highest point density. Our system is a single scanner system, so we hope to provide a definitive view of its capabilities which we anticipate will then be of use to systems operating more than one scanner. The orientation of the scanner is also of importance. Scan lines cannot be perpendicular to the direction of travel or they will miss objects whose sides are also perpendicular to it. A horizontal rotation of the scanner solves this problem, and a vertical rotation deals with structures above the vehicle which would otherwise be missed, such as overhead road signs or bridge faces. We hope to be able to define what the optimum orientation is when surveying for particular features.

When safe to do so, mobile mapping systems are capable of operating at highway speeds. However, point density decreases as vehicle velocity increases and this necessitates multiple passes to ensure a dense point cloud (multiple passes are also employed to ensure all sides of an object are captured) that will meet project specifications. To ensure a high point density, projects have been carried out at low speed [4, 5], which in a commercial situation would impact on the productivity of a MMS. It is our hope that when completed our work will allow us define the maximum speed for specific scanner configurations that will provide a required point density, and also define the minimum number of passes required. This should help to minimise survey time, processing time and also the file size resulting from each survey.

To date there has been some interesting work in the area of point density acquired by mobile mapping systems. [11] and [8] have qualitatively measured profile spacing at certain mirror speeds and vehicle velocities. We hope to improve on this by providing a generic formula which will work for any mirror speed, vehicle velocity and importantly, will incorporate scanner orientation into the system. [9] have included in their work on theoretic point density some interesting results on the effect change in vehicle direction and velocity has on scan lines. We have previously [3] designed a method for calculating the profile spacing for a MMS on planar, orthogonal surfaces with a single axis scanner rotation, varying mirror frequencies and vehicle velocity.

In the following section we will look at mobile mapping systems in general and the platform we have developed at StratAG, followed in section 3 by the theory behind our current work on calculating profile spacing. In section 4 we will present the theory behind our work on calculating point spacing. Section 5 will display the results of our test data, and finally in section 6, our conclusions.

2 Mobile Mapping and XP1

MMSs enable high density spatial data to be collected along route networks and in urban environments. These data can then be utilised in a number of ways, such as route safety audits, road authorities GIS, infrastructure surveys and change detection for national mapping agencies. Combining high accuracy GNSS/INS, LiDAR and imaging sensors on-board a moving platform enable surveys to be carried out rapidly and in a cost effective manner[6]. Land based MMS compliment existing ground based survey and aerial surveying activities in a number of ways. Large scale detail such as road sign detail or detailed infrastructure condition can be recorded. Additionally, extensive ground control is not required and these systems can capture features that are sometimes obscured from aerial platforms[1].

The multi-disciplinary research group StratAG, established to research advanced geotechnologies at NUI Maynooth have recently completed design and development of a multi-purpose, state of the art, land based Mobile Mapping System (XP-1). The primary components of the XP-1 are an IXSEA LANDINS GPS/INS, a Riegl VQ-250 300KHz laser scanner and an imaging system consisting of 6 progressive-scan cameras. Additional imaging sensors include a FLIR thermal (un-cooled) SC-660 camera and an innovative 5-CCD multi-spectral camera capable of sensing across blue, green, red and two infra-red bandwidths. We will now detail how to calculate laser profile spacing for this type of MMS.

3 Profile Spacing theory

Due to forward movement of the surveying platform between two mirror rotations, individual scan lines (or profiles) occur. Figure 1(a) illustrates a single axis rotations of the scanner in horizontal and Fig. 1(b) its effect on profile spacing. The green line in Fig. 1(b) is the distance travelled in one mirror rotation, and is the standard profile spacing. However, by introducing a rotation of the scanner, the blue line becomes the actual profile spacing as detailed in our previous work [3]. This section continues our investigation into the factors impacting on profile spacing.

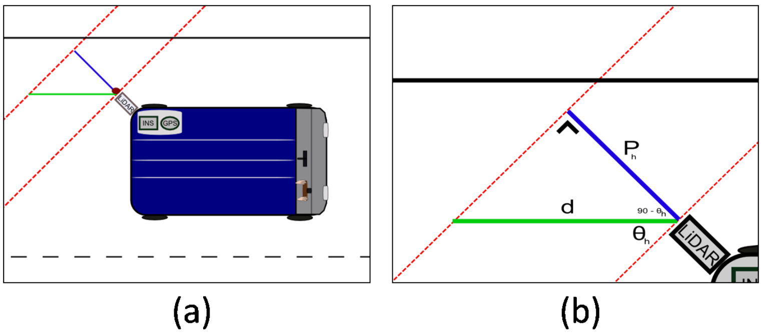


Figure 1: Profile spacing (a) horizontal rotation (b) amended profile spacing

3.1 Dual axis scanner rotation

Our method for calculating profile spacing was originally designed for planar orthogonal surfaces with a single rotation in one scanner axis only. To better approximate a real world system, dual axis rotations must now be taken into account. Our previous work on profile spacing has shown that

- a horizontal rotation of the scanner will alter profile spacing on a horizontal surface but not a perfectly vertical, parallel, planar surface.
- a vertical rotation of the scanner will alter profile spacing on a vertical surface but not a perfectly horizontal, parallel, planar surface.

It is our hypotheses that when a dual axis rotation is introduced into the system configuration, the angle of profiles falling on certain planes will be altered. It is important to identify this angular change, as omitting it will introduce an error into our profile spacing calculations and subsequently impact on any point density calculations.

3.2 Motion Effect on profile spacing

In our previous work, we attempted to identify the impact that any forward motion of the vehicle might have on the orientation of a scan line. Our hypotheses was that the higher the vehicle velocity, the more the scan line would deviate from the angle it would exhibit on a surface at zero velocity and were in the process of designing a method to calculate this effect. We have since confirmed after consulting with the manufacturers that points are interpolated between each navigation point and then combined with subsequent time-stamped range measurements. This eliminates the motion effect issue except for very high-grade IMU's (operating at a frequency which is a multiple of the scanner mirror speed), and is not expected to impact any profile measurements taken from the current generation of land based MMS.

4 Point Spacing theory

The point density exhibited by a MMS on a surface per m^2 is a product of the number of profiles per m^2 and also the number of points along each profile in that m^2. To calculate the number of points on a profile requires knowledge of the point spacing and the surface. For our initial tests, we are assuming a planar surface and are also excluding angular resolution, beamwidth uncertainty and laser footprint size from our calculations. Each will be incorporated in our later work. Point spacing increases with range from the scanner and is influenced by a number of factors. The factors we are using in our initial investigations are detailed in Table 1. Factors influencing point density are the laser Pulse Repetition Rate (PRR) which is a measure of pulses per second, the range which is the horizontal distance from the centre of measurement of the scanner to the point, the angular step width which is the angular change between each laser pulse, the vertical rotation of the scanner which is system dependent, the height of scanner which is the distance from the scanners centre of measurement to ground level and the field of view (FOV) which varies per scanner. The Riegl VQ-250 operates a 360° FOV but this is user selectable and can be decreased for certain projects.

Table 1: Factors influencing point spacing

Pulse Repetition Rate	PRR
Scan Mirror Frequency	M_f
Angular Step Width	Θ_A
Points per Profile	P_n
Field of View	FOV
Range	d
Vertical Rotation	Θ_V
Height of Scanner	h

Unless already specified the angular step width for the scanner must be calculated, particularly if the FOV is restricted for a particular project. This is done by dividing the PRR by the mirror frequency M_f (giving the number of points per profile,P_n) as shown in Eqn. 1. For a 360° FOV, the FOV is then divided by P_n to give the angular step width as shown in Eqn. 2. It is important to note that if a vertical rotation of the scanner has been introduced, as displayed by Fig. 2(a), the amended vertical height must be calculated. Equation 3 details this process.

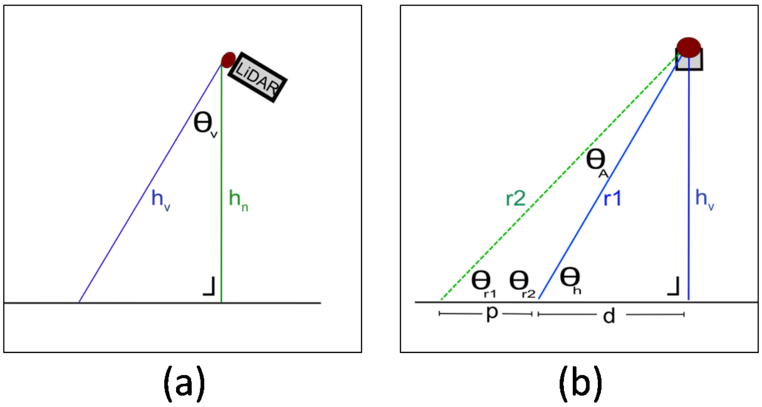


Figure 2: Point spacing (a) incorporating vertical rotation (b) method for calculating

$$P_n = \frac{PRR}{M_f}. \tag{1}$$

$$\theta_A = \frac{FOV}{P_n}. \tag{2}$$

$$h_v = \frac{h_n}{Sin90^\circ - \theta_v}. \tag{3}$$

Once the amended height (h_v) and angular step width (θ_A) have been found the point spacing can be calculated. Our geometrical method for calculating point spacing at any range several stages, Fig. 2 is a graphical aid to this process. To find the point spacing, p, at any range, the user must specify the distance, d. Equation 4 details the process of calculating r1 at range d with amended vertical height h_v

$$r1 = \sqrt{h_v^2 + d^2}. \tag{4}$$

Following this, the missing angles in Fig. 2 (b) must be found to allow p to be calculated. Equations 5, 6 and 7 detail these steps. In Eqn. 5 to find θ_{r2} we must first calculate θ_h

$$\theta_h = ASin(\frac{h_v}{r1}). \tag{5}$$

We now find θ_{r2} as in Eqn. 6

$$\theta_{r2} = 180^\circ - \theta_h. \tag{6}$$

Having already calculated the angular step width θ_A, θ_{r1} can now be found as in Eqn. 7

$$\theta_{r1} = (180^\circ - \theta_{r2}) - \theta_A. \tag{7}$$

We have found each of the missing elements, and now the point spacing can be calculated by Eqn. 8

$$p = \frac{(Sin\theta_a)(r1)}{Sin\theta_{r1}}. \tag{8}$$

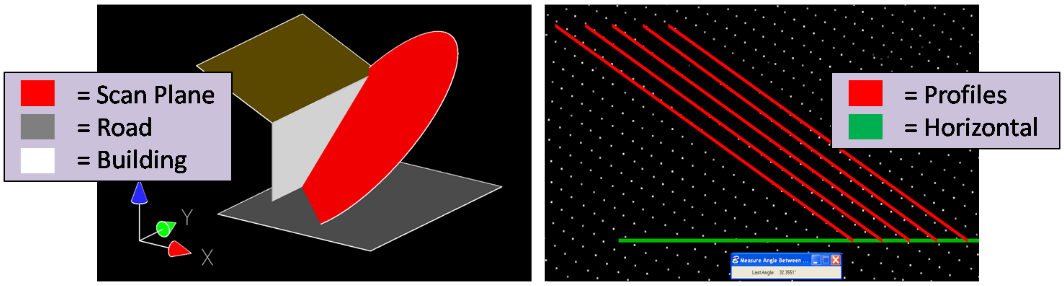
It is important to note that if a horizontal rotation of the scanner has been implemented, the user specified distance will have to be adjusted accordingly. The distance, d, is along scan line. We will now experimentally validate this method with real world LiDAR data.

5 Results

We hope to demonstrate the capabilities of our point and profile spacing prediction system by using two datasets. One is a theoretical dataset, designed in a computer aided drawing (CAD) environment, and the other a real world point cloud captured by our XP1 mobile mapping system. We will now display the result of our work on wall profiles.

5.1 Profile spacing results

This series of tests aim to identify the influence a dual axis rotation has on profiles falling on an orthogonal surface in the vertical plane. We have defined this qualitatively by a series of systematic angular changes and measurements taken in a CAD environment simulating a road surface and building as shown in Fig. 3(a). We have assessed this qualitative solution for a $45° \times 45°$ rotation by comparison with a wall identified in a point cloud captured by our XP1 as shown in Fig. 3(b). The red lines represent a series of profiles, whereas the green line represents the horizontal surface that we are measuring angles from. Figure 4 displays the qualitative results for a series of CAD measurements of the angle of profiles falling on a planar, parallel, vertical surface for a number of different vertical rotations combined with fixed horizontal rotations. We are currently working on a quantitative method for calculating this angular change for any combination of scanner rotations.



(a) (b)

Figure 3: Dual axis profiles (a) CAD model (b) point cloud measurements

Measurements for the angle of profiles falling on a planar, parallel vertical surface from a 45° horizontal $\times 45°$ vertical scanner rotation in our point cloud were approximately 32°, which deviates from our simulation measurements of 35° by 3°. The cause of this error is most likely due to the current lack of an adequate test site for experiments, and so we cannot be sure that the wall was exactly parallel and vertical with the vehicle at the time of the survey. Another possible source of error could be due to difficulties arising from ensuring the point of view for manual measurements was precisely perpendicular to the wall. We will now display the result of our work on calculating point spacing.

5.2 Point spacing results

As with our previous work, for the initial investigations we are assuming a planar surface with no occlusions and a single echo return. For the preliminary tests, a basic 2D structure was created in a CAD environment incorporating the scanner height, the angular step width and a selection of user specified distances. The measurements taken in the CAD environment were in agreement with the output from our point spacing formula. However, to test a system designed for planar surfaces in an external environment, a surface with a

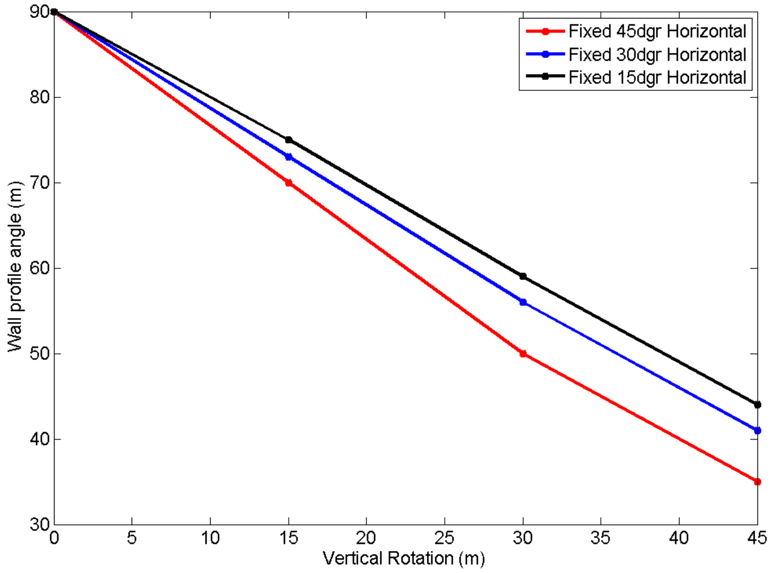
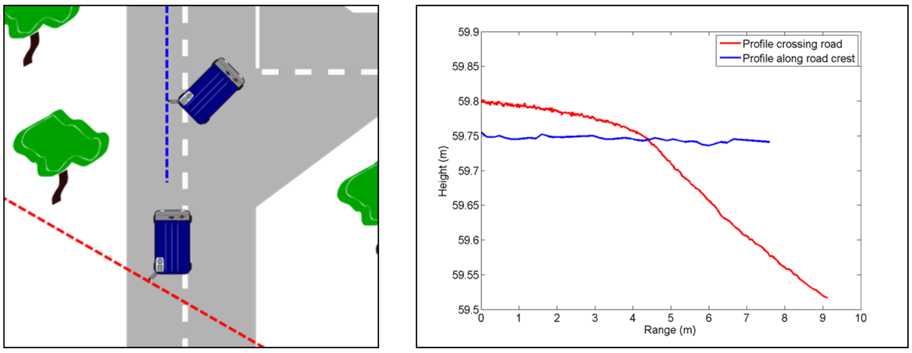


Figure 4: Angular profile on vertical structures

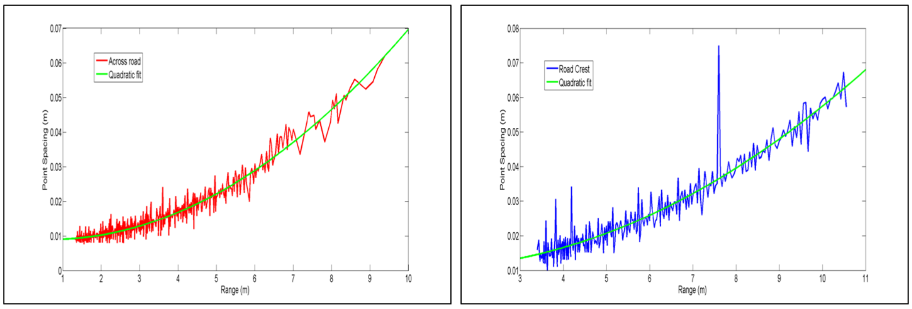
minimum of height deviation was required. A scan line running across the road will show significant elevation change, however, we identified the crest of the road as an area which would most easily approximate areas of relatively small deviation in height. If the vehicle is turning at a junction we can obtain a scan line which extends down the road. Figure 5(a) demonstrates this principle. We have selected two scan lines to demonstrate the difference in elevation change. Figure 5(b) displays the difference in height variation between profiles crossing the road and those running along the road crest. The navigation data was then examined for course changes of 90° to locate when the vehicle turned at a junction, as the scan line would then be oriented in the desired direction. Profiles with a minimum height variance were then selected manually.

Our system performed well on a planar surface. By varying the input into Eqn. 4 we can estimate point spacing at different distances. We then compared these measurements with points from profiles along the road crest and those crossing the road and have plotted these as a function of range. We then fit a curve to the data for comparison with the theoretical model as shown in Fig. 6 (a) for profile crossing the road and (b) for the road crest. The final plot of quadratic fits for both surfaces and predicted values as a function of range is shown in Fig. 7. The predicted and the point spacing for a flat surface are qualitatively comparable which experimentally validates our system. The point spacing for the profile which runs across the road gradient deviates from the predicted value, due to the change in elevation of the scan line crossing the road. It is interesting to note that the deviation begins to become more pronounced at approximately 6m range, close to where the crest in the road lies. We expect to be able to compensate for this by incorporating information about the road surface in our formula.



(a) (b)

Figure 5: Point Spacing (a) standard profile / road crest (b) height difference



(a) (b)

Figure 6: Quadratic fit (a) across road (b) road crest

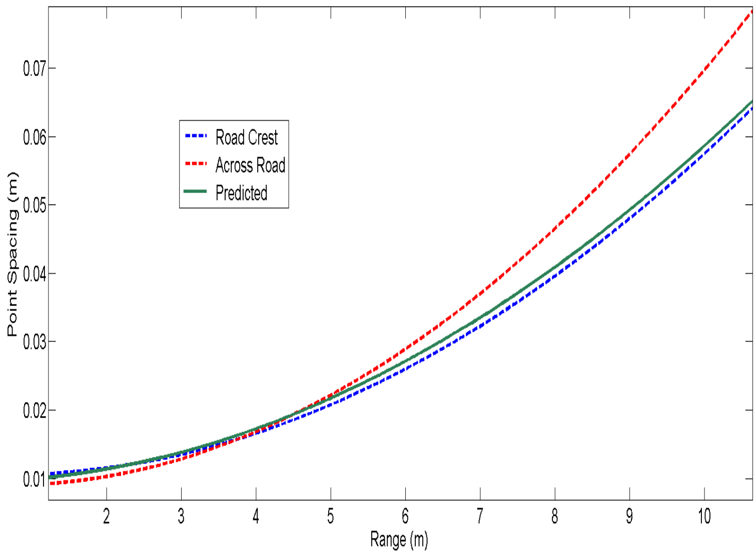


Figure 7: Point Spacing on road surface

6 Conclusion

This study has taken our previous work on quantifying profile spacing for different mobile mapping systems and incorporated a qualitative prediction method for dual axis rotations on planar, orthogonal surfaces. We have verified this method theoretically and experimentally for a vertical surface with our own MMS and are currently working on a quantitative method for predicting profiles for differing dual axis rotations. Following this, non orthogonal surfaces will be introduced. In our work on exploring the effect of motion on scan lines, we have identified that vehicle velocity will not affect the angle of profiles as previously suspected and therefore will not impact on our profile measurements, simplifying the procedure. Additionally, we have incorporated point spacing calculations for planar horizontal surfaces into our system and have verified these theoretically and experimentally with our own MMS. Further work on point spacing will incorporate vertical surfaces, gradients and laser footprint size.

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References

[1] D. Barber, J. Mills, and S. Smith-Voysey. Geometric validation of a ground-based mobile laser scanning system. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63(1):128–141, 2008.

[2] S. Becker and N. Haala. Grammar Supported Facade Reconstruction from Mobile LiDAR Mapping. *International Archive of Photogrammetry and Remote Sensing*, XXXVIII Pa(2009):229–234, 2009.

[3] C. Cahalane, T. McCarthy, and C.P. McElhinney. Mobile mapping system performance - An initial investigation into the effect of vehicle speed on laser scan lines. In *Remote Sensing & Photogrammety Society Annual Conference - 'From the sea-bed to the cloudtops'*, Cork, Ireland, 2010.

[4] F Goulette, F Nashashibi, I Abuhadrous, S Ammoun, and C. Laurgeau. An integrated on-board laser range sensing system for on-the-way city and road modelling. In *Proceedings of the ISPRS Commission I Symposium,'From Sensors to Imagery'*, volume 61, Paris, France, 2006.

[5] G. Graefe. Kinematic surveying with static accuracy. In A Grun and H Kahmen, editors, *8th Conference on Optical 3-D Measurement Techniques*, pages 142–149, Zurich, Switzerland, 2007.

[6] N. Haala, M. Peter, J. Kremer, and G. Hunter. Mobile LiDAR mapping for 3D point cloud collection in urban areas: a performance test. In *Proceedings of the 21st International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS08*, volume 37, pages 1119–1124, Beijing, China, 2008.

[7] K. Hammoudi, F. Dornaika, and N. Paparoditis. Extracting building footprints from 3d point clouds using terrestrial laser scanning at street level. *International Archive of Photogrammetry and Remote Sensing*, XXXVIII Pa(2009):65–70, September 2009.

[8] C. Hesse and H. Kutterer. A mobile mapping system using kinematic terrestrial laser scanning (KTLS) for image acquisition. In A Grun and H Kahmen, editors, *8th Conference on Optical 3-D Measurement Techniques*, pages 134–141, Zurich, Switzerland, 2007.

[9] S. Hofmann and C. Brenner. Quality assessment of automatically generated feature maps for future driver assistance systems. In *Proceedings of the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems - GIS '09*, number 2009, pages 500–503, New York, New York, USA, 2009. ACM Press.

[10] H Kaartinen, J Hyyppä, E Gülch, G Vosselman, H Hyyppä, L Matikainen, A D Hofmann, U Mäder, and ÅPersson. ACCURACY OF 3D CITY MODELS : EuroSDR comparison. In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36 (Part 3/W19)*, pages 227–232, 2005.

[11] A. Kukko, C. Andrei, V.. Salminen, H. Kaartinen, Y. Chen, P. Rönnholm, H. Hyyppa, J. Hyyppa, R. Chen, H. Haggrén, and Others. Road Environment Mapping System of the Finnish Geodetic Institute-FGI Roamer. In P. Ronnolm, H Hyyppa, and J Hyyppa, editors, *Proceedings of the ISPRS Workshop Laser Scanning 2007 and SilviLaser 2007, Espoo, Finland, 12-14 Sept. 2007*, volume XXXVI, pages 241–247, Espoo, Finland, 2007.

[12] Antero Kukko, Anttoni Jaakkola, Matti Lehtomaki, Harri Kaartinen, and Yuwei Chen. Mobile mapping system and computing methods for modelling of road environment. In *2009 Joint Urban Remote Sensing Event*, Shanghai, China, May 2009. Ieee.

[13] M. Lehtomäki, A. Jaakkola, J. Hyyppä, A. Kukko, and H. Kaartinen. Detection of Vertical Pole-Like Objects in a Road Environment Using Vehicle-Based Laser Scanning Data. *Remote Sensing*, 2(3):641–664, 2010.

[14] S. Pu and G. Vosselman. Extracting windows from terrestrial laser scanning. In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences Voll XXXVI, (Part 3/W52)*, volume 36, pages 320–325, Espoo, Finland, September 2007. ISPRS.

[15] H. Yoo, F. Goulette, J. Senpauroca, and G. Lepere. Simulation based comparative analysis for the design of laser terresttrial mobile mapping. In *Proceedings of the 6th International Symposium on Mobile Mapping Technology*, pages 839–854, Sao Paolo, Brazil., 2009.