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SCOPE FOR LASER SCANNING TO PROVIDE ROAD ENVIRONMENT INFORMATION

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ABSTRACT

Accurate 3D information is needed for road and street construction starting with the planning phase and ending with the maintenance phase. Demands for new types of environment information are now frequently being made. This paper shows some of the scope for airborne laser scanning to provide road environment information. The results are based on laser tests conducted in Espoo (southern Finland) between 2000-2003. The benefits of airborne laser scanning are the rapidness (up to 100,000 distance measurements per second), high quality (e.g. up to 20 measurements per square metre) and reasonable cost. The accuracy and the visibility of the roadside objects and environmental information obtained were evaluated in terms of the highway inventory. It is suggested that photo-textured three-dimensional models and animation be used in future planning practice.

1. BACKGROUND TO AND MOTIVATION FOR THE RESEARCH

Road engineering needs detailed three-dimensional (3D) surface or volume information in order to control and visualize the construction process and its impact on the natural surroundings, starting with the planning phase and ending with the maintenance phase. 3D models were mainly used in the 1990s only for visualization and to demonstrate the influence of planning on its surroundings. During the last decade great progress has been made in laser scanning methods. Aerial laser scanning applications for digital terrain models (DTM) have been implemented successfully worldwide. So far the 3D models used for road planning have included the terrain elevation as well as the buildings and part of the road structure but have not included a vegetation component. Thus, a realistic vegetation model has not been used. In Finland the environmental impact assessment, carried out in parallel with the road design, has been based mostly on an inventory in the field and the use of national GIS databases.

Ground surveying and photogrammetric mapping are the basic methods currently being used by the highway agencies or administrations to acquire digital terrain models (Veneziano et al. 2002). Some national road administration agencies have already applied airborne laser scanning for terrain model extraction. Aerial laser scanning has generally been used for some years to produce quicker and cheaper DTM, including on a national scale. Today the demands for totally up-to-date environment information are increasing. In addition to the terrain models, vegetation, buildings, bridges, and small structures above ground need to be mapped. Digital terrain models have been the basis for interactive computer-based road design. The information needed relates to society, landscape, culture, natural resources, and the environmental impact of the road construction process. Sustainable construction and the life-cycle analysis will set more demands for future road engineering (Mroueh et al. 2000). The design of horizontal and vertical geometry becomes more challenging when environmental aspects and terrain characteristics need to be taken into careful consideration. The collection of modern, up-to-date highway inventory data for design, maintenance and rehabilitation purposes should be a basic task for most highway agencies or administrations.

Most of the publications in the field of laser scanning deal with digital elevation or terrain models, such as works by Brüggelman (2000), Hyyppä et al. (2000), Kraus and Pfeifer (1998), and the extraction of buildings and building outlines (Haala and Brenner; 1999; Vögtle and Steinle; 2000). However, few preliminary studies have been made of road planning: laser-based elevation data for highway drainage analysis (Hans et al., 2003), forest road planning (Coulter et al., 2001), and the extraction of road geometry parameters from laser scanning and existing databases (Hatger and Brenner, 2003). Shrestra et al. (2001) have used laser data for highway mapping and DTM generation. The elevations produced by laser data were found to be accurate to within 5 to 10 centimetres. In both the Netherlands and Canada (Pereira and Jansen, 1999; Berg and Ferguson, 2000, 2001) studies were carried out to determine the suitability of laser scanning in highway planning and design. Pereira and Jansen focused extensively on the identification of breaklines that are an important component in the planning and design process. In Berg and Ferguson (2001), analysis revealed that laser data had an accuracy of 15 cm or better on hard surfaces and up to 0.5 metres on other surfaces, while low vegetation, rocks, and ditches led to discrepancies of over one metre in some cases. Difficulties were encountered with narrow features such as ditches. Pattnaik et al. (2003) suggested that laser data can be used to gather information on the road inventory. Laser scanning is considered to be best used in the early stages of initial route location and formulation of alternatives. Shamayleh and Khattak (2003) merged an aerial image and laser scan data and analysed them to extract information on highway contours, grade, side slope, and stopping and passing sight distances. According to Veneziano et al. (2002) laser data is incapable of completely replacing photogrammetric data in the final design of alignments. However, the estimated time and cost saving were 71% when laser mapping products were used instead of photogrammetric products in highway planning.

For road and street design, it has been difficult to obtain an overall understanding of the surrounding environment in 3D. With laser scanning it is possible to characterize forests and parks even at the individual tree level. In particular, when an improvement to an existing road is being considered and when defining visual obstacles, the inventory of the surroundings is most important. Laser scanning can also be used for detecting the changes in the surroundings (new houses, growth of vegetation, harvested trees) as well as for defining the value of the trees needed to be cut down during the construction process. While volume functions based on tree diameter give estimates with a random error of level 15%, laser scanning assisted with aerial images can provide errors of between 25-30% at the individual tree level (Hyyppä et al., 2005). The cost-effectiveness of laser scanning is, however, significantly better. In previous studies, estimates of tree height to an accuracy of between 0.5 to 1.3 m have been obtained depending on the laser system and pulse density (Hyyppä and Inkinen, 1999; Persson et al., 2002).

The main objectives of the paper were the collection and visualization of road environment information using the integration of laser scanning and aerial images. The secondary objectives were to specify the accuracy and quality of laser scanning in road engineering needs.

2. MATERIAL AND METHODS

2.1 Test sites and laser scanner acquisition

The test sites were located in Espoo in southern Finland, a few kilometres west of Helsinki. The test-area in the Otaniemi (3 square kilometres) university campus area is an urban test site with university and office buildings, flat terrain and a small forest. Espoonlahti is a suburban test site (4 square kilometres) with urban settlements and forests.

Laser campaigns have been conducted using TopEye, Toposys-1 and Toposys Falcon instruments in 2000-2003. The helicopter-borne TopEye system (wavelength of 1.064 µm, maximum scan angle ±20°) was used to collect laser data in September 2002 at the Otaniemi test site from flying altitudes of 200 m and 550 m with a pulse density of approximately 2.6 and 1 pulse(s) per m2, respectively. Toposys-1 and Falcon (wavelength of 1.54 µm, maximum scan angle ±7.1°) campaigns were carried out during June 2000 and May 2003 at both test sites. The flying altitudes were 400 m and 800 m above ground with pulse densities of about 10 and 4 pulses per m2, correspondingly. The Espoonlahti area was also covered with five overlapping laser strips with a flying altitude of 400 m.

2.2 Field measurements and digital images

Ground truth data was recorded with the Finnish Geodetic Institute (FGI) at the Otaniemi and Espoonlahti test sites. In order to verify the accuracy of laser points at Otaniemi, the coordinates of the reference points were measured using an RTK (Real-Time-Kinematic) GPS receiver.

RTK was mainly applied for reference ground truth data collection, because the accuracy was needed at centimetre level. The horizontal accuracy of the RTK was verified at about 1.5 cm (RMSE) and the vertical accuracy 2 cm (Bilker and Kaartinen, 2001). Altogether, 3002 tacheometer and RTK-points were measured, 2/3 of them were ground points and 1/3 were buildings, walls, trees, lamps, curbs etc. Ground truth data (6156 points) at Espoonlahti were recorded using automatic tacheometer, tacheometer and RTK by the FGI.

Also a Leica DISTOpro laser hand-held distance meter (with accuracy of up to ±1.5 mm) was used to record the heights of buildings (21) and roadside objects (102) because of its rapidness.

During the TopEye laser flight at Otaniemi, 2002 digital photos were simultaneously taken with the Hasselblad digital camera based on LightPhase CCD 3056 * 2032 resolution. The flight altitude of 200 m resulted in a 4.5 cm pixel resolution for the images. The initial positioning for images was computed from GPS+INS data. The aerial triangulation was implemented using tie points, ground control points and camera calibration parameters. The orthorectification was carried out using laser surface and buildings.

Figure 1. Digital image and superimposed laser points.

Terrestrial digital image capturing was done simultaneously during the laser tests using digital cameras (Olympus C1400L and Canon Powershot S45) calibrated at the HUT photogrammetric test field.

The digital camera, hypsometer and levelling rod were also used to measure vegetation.

2.3 Classification of laser points

The preprocessing of the data (including the coordinate transformation and geoid correction) into the georeferenced point cloud was carried out by Toposys GmbH, TopTerra Ltd, the FGI, and the HUT. The laser scanner survey provided millions of laser points, the x, y and z coordinates of which are known.

By classifying the points to ground, low vegetation, high vegetation, high vegetation and building points, it was possible to produce different kinds of digital models in order to support the planning tasks. The ground classification process started separately with first and last echoes and by eliminating points below the ground (i.e. low points) and above the objects (i.e. in the air). So-called low points were classified using neighbourhood information. Then the iterative ground classification process started using initial point logic that controlled building size, terrain angle, iteration angle and distance. (Soininen, 2004)

The ground points were triangulated using the progressive TIN densification method originally developed by Axelsson (2000), in which the surface is allowed to fluctuate within certain values, controlled by minimum description length, constrained spline functions, and active contour models for elevation differences. Ground points were connected in a TIN. A sparse TIN was derived from neighbourhood minima, and then progressively densified to the laser point cloud. In every iteration, points were added to the TIN, if they were within defined thresholds. The method has been implemented in Terrascan software. In order to produce accurate digital terrain models laser points were classified at ground, low vegetation, middle vegetation, high vegetation, building, and error points. The DTM was calculated using classified ground points for each individual strip. The proper elevation and XY offsets were calibrated using measured RTK information on roads and buildings. Low vegetation was considered to be a layer between the DTM with a maximum height of 1 m. Other vegetation was classified as high vegetation.

2.4 Verification of ground model

The vertical accuracy of laser scanning is evaluated using the root mean square error test

$$RMSE_z = \sqrt{\frac{Z_{\mathrm{ground}} - Z_{\mathrm{reference}}}{\mathrm{n}}} \qquad (1)$$

where $z_{\mathrm{reference}}$ is a point measured using a tacheometer or RTK, z_{ground} is the corresponding point interpolated from TIN ground and n is the number of reference points used. The RMSE was split into systematic and random error.

2.5 Matching laser scanning data and terrestrial image orientations

The combination of laser scanning data and terrestrial images into the same coordinate system was achieved using direct relative orientation matching. The detailed description of the interactive orientation method used is described in Rönnholm et al. (2003). The method is based on backprojecting the existing 3-D data in the 2-D image plane with coarse orientation parameters. The result of backprojection is interpreted by the user in order to decide whether the orientation parameters require improvement. For data backprojection, the following collinearity equations were applied

$$\begin{aligned} x &= -c\frac{r_{11}(X-X_0)+r_{21}(Y-Y_0)+r_{31}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)}+x_0 \\ y &= -c\frac{r_{12}(X-X_0)+r_{22}(Y-Y_0)+r_{32}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)}+y_0 \end{aligned}, \qquad (2)$$

where c is a camera constant, (X0, Y0, Z0) is the projection centre of a camera, (X, Y, Z) is a 3-D ground point, terms (r11… r33) are elements of 3-D rotation matrix, and (x0, y0) is the location of a principal point. The interactive orientation method is an iterative process where shifts, rotations and backprojections are repeated until the laser scanning data fits the image.

2.6 Estimation of object heights

The verification of roadside objects (height) was done by selecting the highest value of laser scanning for the structure and subtracting the corresponding value from the TIN ground model.

2.7 Visualization

The animation and demonstration of the 3D city model in Otaniemi were created as follows. The laser points were first classified into terrain, low vegetation, vegetation and building classes. Secondly, the terrain was classified into so-called model keypoint class, in which point clouds were sparsified in areas, where high density was not needed to describe the terrain changes. The terrain was also smoothened. Finally, the triangulated surface model was created.

The basic approach of the vectorization method is to find planar surfaces from laser points, detect symmetry and adjust plane equations, find boundaries of planes, and align boundary lines using images or intersection lines. Vectorization of buildings is a manual approach using aerial images that were taken simultaneously during the laser scanning flight. Images were used for finding more accurate edge positions. Wall textures were extracted from terrestrial digital images. TerraPhoto was used to render city model scenes. Simultaneously taken Hasselblad images were used as texture for building roofs and terrain surface.

3. RESULTS

3.1 Laser scanning derived digital terrain model

The TIN densification method and Terrascan software were applied to derive the digital terrain model. In the Otaniemi test area, helicopter and aeroplane-based scanning systems were used. The accuracy of the obtained triangulated digital terrain models is shown in Table 1.

Table 1. Accuracy of laser DTMs. Mean height difference (systematic error) and standard deviation (random error). The accuracy was defined separately for asphalt and other surface types. Terrain type "All" consists of gravel, asphalt, grass and other terrain.

Test Site	Type of Terrain	Mean height differences (m)	Standard deviation (m)	Pulse density (/m^2)	Flight altitude (m)	Reference	Leaf on/off	Laser sensor
Otaniemi	All	0.014	0.068	2.6	200	RTK	On	TopEye
Otaniemi	Asphalt	0.001	0.042	2.6	200	RTK	On	TopEye
Otaniemi	All	-0.008	0.114	1	550	RTK	On	TopEye
Otaniemi	Asphalt	-0.022	0.100	1	550	RTK	On	TopEye
Otaniemi	All	0.034	0.035	10	400	RTK	On	TopoSys
Otaniemi	Asphalt	0.002	0.042	10	400	RTK	On	TopoSys
Otaniemi	All	0.050	0.122	3	800	RTK	On	TopoSys
Otaniemi	Asphalt	0.010	0.048	3	800	RTK	On	TopoSys
Espoonlahti	Asphalt	-0.031	0.026	10	400	tacheometer	Off	TopoSys
Espoonlahti	Gravel	-0.020	0.016	10	400	tacheometer	Off	TopoSys

Table 1 shows the accuracy obtained using TopEye and Toposys flights from flight altitudes of 200, 400, 550 and 800 m. The flight altitudes of 400 m obtained from aircraft and 200 m obtained from the helicopter seem to be feasible for giving accurate digital terrain elevation information for road design purposes. These models are almost comparable to those obtained with RTK.

Figure 2. Example of DTM errors at RTK-measured reference points [m] at Otaniemi, TopEye 200 m.

The TIN model of the road was compared with RTK measurements. There was a systematic difference between RTK measurements and the heights in the TIN model near the curb. The errors were larger the further from the curb the nearest laser point was on the road. Height differences near the curb in the TIN model were determined. (R=0.61, statistically significant at 95% confidence level.

Figure 2 shows the accuracy analysis for TopEye (altitudes 200 and 550 m) system. The accuracy was defined for four target materials: asphalt, grass (lawn), gravel and natural (covered) terrain. The random errors obtained from 200 m are approximately 0.04-0.06 m for hard targets. For natural, modulating terrain the corresponding accuracy was 0.08 m.

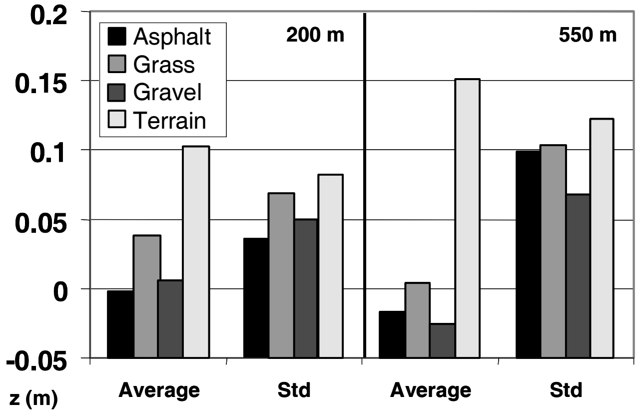

Figure 3. Effect of flight height on four target materials using TopEye laser scanner.

The verification of pure flight height is not unambiguous, because the higher the flight height the sparser the point density and the larger the footprint (beam size) on the ground. In this study in the Otaniemi area, the flying heights used were 200 and 550 m with TopEye and 400 m and 800 m with TopoSys. TopoSys flight lines were individual strips and the TopEye flight consisted of 20 strips.

Figure 4 illustrates the quality difference of laser-derived DTM with a better-known DTM model, namely the national DTM (25 by 25 m grid, National Land Survey, NLS). Systematic and random differences for the NLS model for streets and roads were –0.48 m and 1.01 m, respectively, and for the whole area they were 0.59 m and 1.23 m, respectively. The corresponding comparison with laser scanning DTM and RTK surveyed points showed systematic and random errors of 0.014 m and 0.068 m. The roads and streets are visible in the laser-derived models, whereas in the NLS model there are some large land areas where the elevation is not up-to-date.

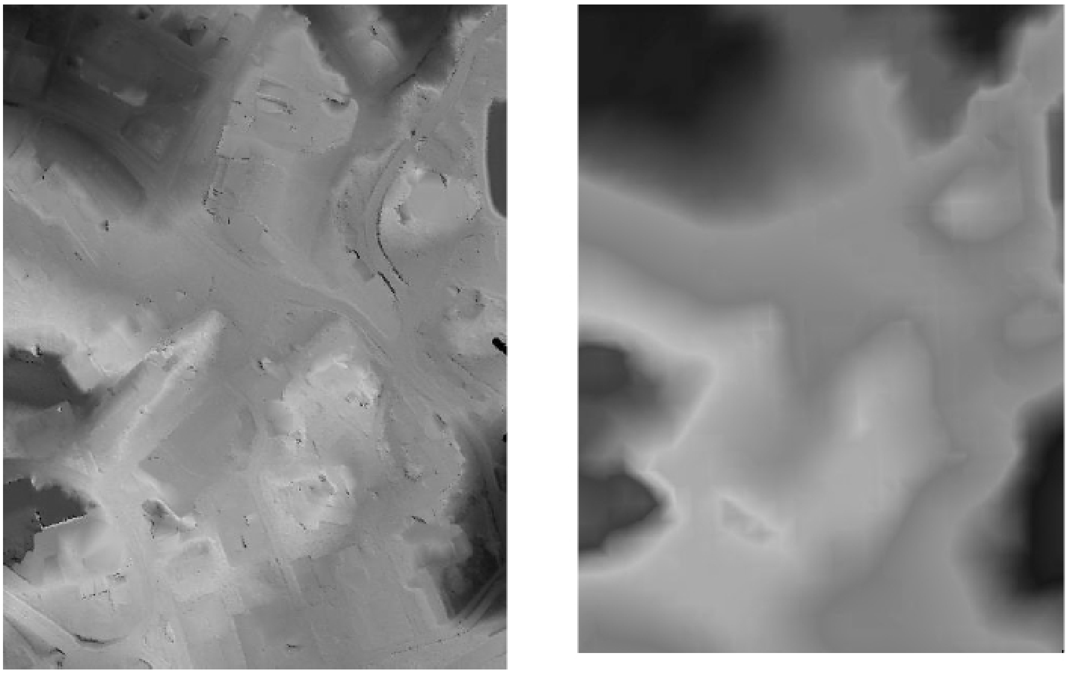

Figure 4. Laser-derived DTM from Otaniemi and corresponding interpolated NLS DTM (25 by 25 m grid) of the National Land Survey.

3.2 Auxiliary information for highway inventory

A laser scanner produces accurate 3D models and continuous cross-sections of terrain and auxiliary information. Demonstrations of some structures that can be extracted for road inventory are shown in Figure 5. The left image shows a parking lot and the right image shows individual trees and a building. The tree species, height and width of the trees can be determined. The low local variability of the data provides credence for the quality of laser scanning data.

Figure 5. Demonstration of accurate cross-sections.

The capability to characterize the height of man-made structures was examined using walls, fences and traffic lamps. The height of traffic lamps was obtained with a systematic error of 0.01 m and random error of 0.15 m. Walls and fences were obtained with corresponding errors of –0.03 and 0.04 m with the TopEye 200 m data at Otaniemi.

A Leica DISTOpro laser hand-held distance meter was used to provide a reference for 21 building heights. The building heights obtained with laser scanning resulted in a systematic error of 0.05 m and a random error of 0.12 m.

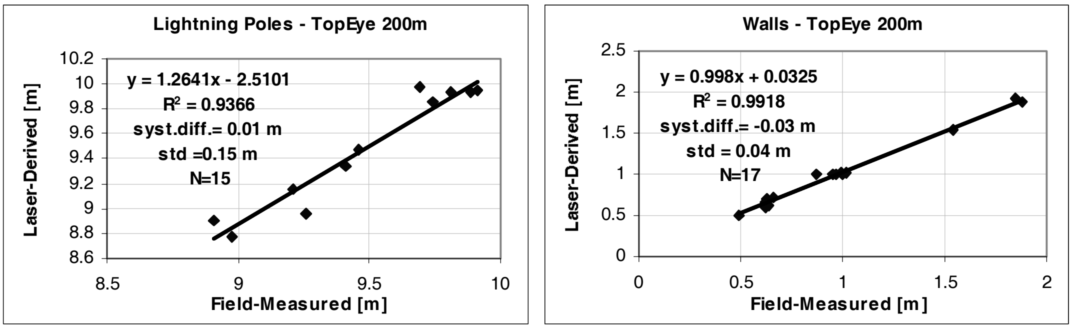

Figure 6. Accuracy of height estimates of lightning poles and walls.

Figure 7. Use of interactive orientation and terrestrial images together with point clouds.

3.3 Assessment of vegetation characteristics

In addition to a digital terrain model, a laser provides a digital surface model (DSM), which is the model following the highest objects at each location. The DSM can be used for extracting the road environment information.

Object height models were computed as the difference between the digital surface model and digital terrain model. An example of a DTM and a DSM is shown in Figure 8.

Figure 8. Such models give a good understanding of the required modifications to the surroundings when, for example, a road needs to be widened: a) the DTM and b) the DSM derived with a laser scanner.

In traditional street and road design, individual tree information has been very difficult to assess, until now. With terrestrial methods this time-consuming procedure is in most cases feasible only for sample plots. With laser scanner data 3D information can be used, which will improve the process of automated crown delineation. Location-based (position-dependent) individual tree information is essential in various highway engineering applications, e.g. in environmental impact assessments and virtual reality.

At Otaniemi and Espoonlahti, individual trees (72) were assessed with a laser-scanning object height model. The bias of height estimation was -0.51 m, and RMSE was 0.82 m.

At Otaniemi the location of the stem can be obtained with a 1.5 m random error and systematic shift of 0.6 m, as confirmed in Pyysalo and Hyyppä (2002). The crown location can be correctly mapped, and depending on the test site properties, 40 to 95% of the individual trees can be correctly delineated with laser scanner data. In dense forests, individual trees fuse into groups.

In addition to trees, random selected individual bushes were mapped and measured in parallel with the laser surveys on the ground. Some of the bushes were homogeneous, as is shown in Figure 9, some of them were of varying height. The height of bushes varied between 0.4 and 2.5 m. The obtained accuracy was good, with a systematic underestimation of 0.08 m and random error of 0.18 m. The reference accuracy was estimated to be between 0.05 and 0.10 m. The reference measurements were done for the dominant branches giving the highest points of the bushes, where as the laser mainly gave the average bush height.

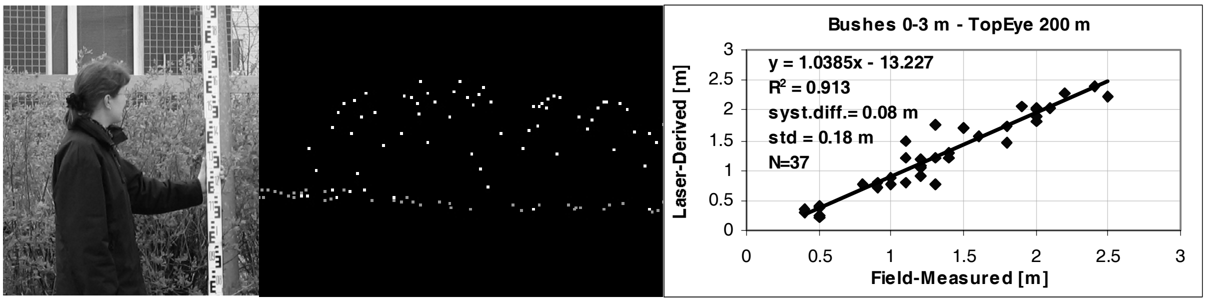

Figure 9. Demonstration of laser scanner to measure bushes. From left to right: reference measurements, point cloud representing the bushes, and regression between laser and reference measured values.

3.4 Use of simultaneous aerial images to obtain breakline information

The use of simultaneously acquired aerial images improves the geometrical properties of laser data. Laser data is typically co-registered with aerial images using the intensity channel of the laser. Typical targets for co-registering are white road paintings that are also clearly visible in the laser data. Aerial imagery was mosaiced (Soininen, 2003) and they deviated significantly less than 2 pixels (less than 10 cm) from the reference points in Figure 10.

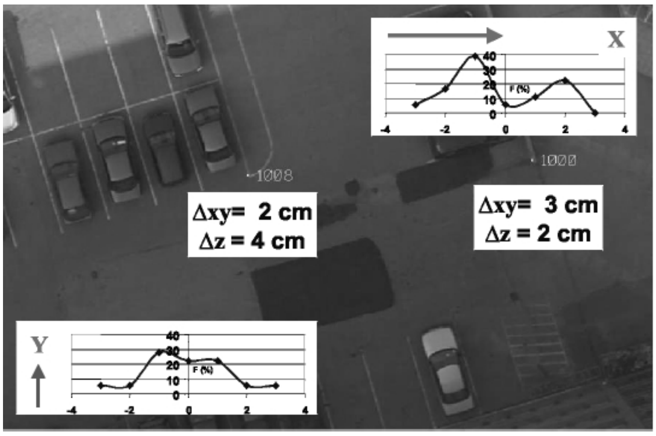

Figure 10. The planimetric (xy) and height (z) differencies between reference measurements and digital orthophoto. The original aerial image was taken during laser flight.

3.5 Visualization

Terrascan was programmed to find point groups matching a tree shape. Instead of laser scanning point clouds, an RCP cell is placed in the model for each tree. RCP cells consist of 300-600 photos taken of sample trees that are used to build up the virtual trees.

Examples are shown in Figures 11-13. By this means, a virtual reality of the environmental impact of a road construction process can be visualized from the defined perspective and with fly-through movies.

Figure 11. Ring I visualization using TerraScan in digital terrain model and in the extraction of buildings and using TerraPhoto for combining digital aerial photos.

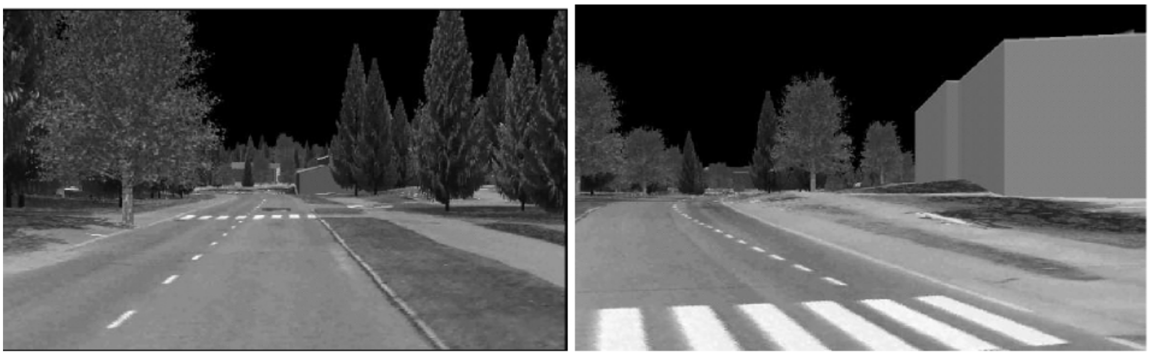

Figure 12. Clip-off of the Otaniemi fly-through animation done with uStation + Terra software using laser scanner data and simultaneously acquired aerial images.

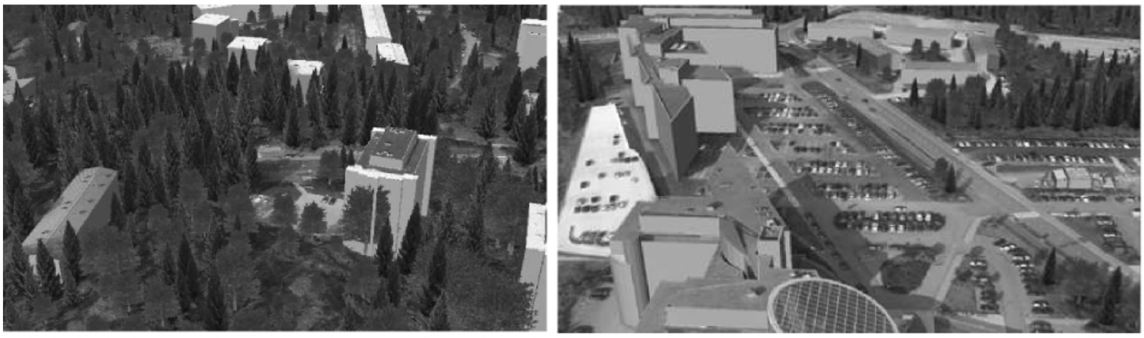

Figure 13. View of Otaniemi animation using laser scanner points in building and tree heights and texture from aerial images.

4. DISCUSSION AND CONCLUSIONS

Simultaneous aerial images improve the geometrical properties of laser data. Laser data are typically co-registered with aerial images using the intensity channel of the laser. Typical targets for co-registering are white painting on the roads, which is also clearly visible in laser data. Since lasers provide digital terrain models with high accuracy (5 cm), and optical images taken at the same time provide high planimetric accuracy (5-10 cm), it is possible to use such data sets to derive important road inventory data, such as grade, lane width, vertical and horizontal alignments, centreline, and edge of the shoulder, signs, lamps, walls, roadside barriers, bus stops etc.

The images provide major breaklines whereas the laser information gives the height of the breaklines and the height of terrain points. Laser scanning is best used for highway location process from preliminary route design to final design. However, when laser scanning is used for detailed road planning it is necessary to create new algorithms for smoothing and classifying the laser data. The extraction of breaklines is done manually from laser data and aerial images, but techniques exist to assist that process.

The paper shows that the lower flight altitudes of 400 m obtained from aircraft and 200 m obtained from the helicopter seem to be feasible for giving accurate digital terrain elevation information for road and street design purposes. These models are almost comparable to those obtained with RTK. The random errors obtained from 200 m are approximately 4-6 cm for hard targets. For natural, modulating terrain the corresponding accuracy was 8 cm. It should be noted that such good accuracies could be obtained only with carefully preprocessed data.

In addition, there are different systematic errors for each land type category, especially when flying height differences are taken into account (Hyyppä and Hyyppä, 2003). Small changes in systematic errors can be caused by the beam size and sensitivity changes of the systems. Since random errors can be calibrated by a relatively small number of the ground points, instead of RMSE the customer of road inventory data should specify the random error (or systematic and random errors separately) of the process.

The capability to characterize the height of man-made structures was examined using walls, fences and traffic lamps. The height of traffic lamps was obtained with a systematic error of 0.01 m and random error of 0.15 m. Walls and fences were obtained with corresponding errors of -0.03 and 0.17 m with the TopEye 200 m data in Otaniemi. The height of buildings was obtained with a systematic error of 0.05 m and random error of 0.12 m.

The interactive orientation can be used to match laser point clouds with aerial images and terrestrial images. Terrestrial images can be used to assist in describing the source of laser backscatter from street lamps, and in describing the breaklines and the amount of masses.

Laser scanning can also be used for detecting changes in the road surroundings (new houses, growth of vegetation, harvested trees) as well as in the defining the value of the trees needing to be cut down during the road construction process. At Otaniemi and Espoonlahti, individual trees and tree groups were assessed with a laser scanning object height model. The bias of height estimation was -0.51 m, and RMSE was 0.82 m. The location of the stem can be obtained with a 1.5 m random error and systematic shift of 0.60 m. The obtained accuracy for bushes was good: systematic underestimation of 0.08 m and random error of 0.18 m.

If 3D models derived from laser scanning were used, the calculation of accurate cut and fill volumes could produce better cost estimates, because the cost estimates are better the more accurate the digital terrain model is.

Terrain models derived from laser scanning assist with evaluating the stopping distance and the sight distance by using the effect of vegetation and buildings.

The relatively accurate data produced by laser scanning can be used in future for more detailed modeling of the environment. For example, if it is combined with existing GIS information, noise modeling can be significantly improved. The effect of not only every building and man-made structures but also of vegetation can be more reliably taken into account in the new noise models. The new models can even take into account the leaves on the trees. The applications of such models are better functioning homes. There are numerous ways of applying an accurate terrain model, surface models and object model information.

The virtual reality of the environmental impact of a road construction process can be visualized from a defined perspective and with fly-through movies. The multitemporal datasets can also reveal slow and fast changes occurring in the environment.

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