SENSOR FUSION FOR AIRBORNE 3D DATA CAPTURE[*]

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ABSTRACT

One of the major tasks for the rectification and mono–plotting of remote sensing data and photogrammetric images is the determination of a digital terrain model (DTM). With the advent of airborne laser range scanners the direct acquisition of DTMs became feasible. In order to determine the terrain surface the distance data provided by a laser scanner have to be georeferenced. Within this step, the exterior orientation (position, attitude) of the laser scanner at the time of measurement is determined by a combined GPS/INS sensor system. Additionally overlapping strips of range data are matched. Thus the system is callibrated and remaining errors e.g. caused by misalignment of the different sensor components can be corrected.

This paper is focussed on the description of the concept and the components of an integrated airborne laser ranging system. Especially, the GPS/INS part for determination of the exterior orientation of the laser scanner and the calibration routine for the acquired laser data will be briefly reviewed and demonstrated.

1.0 INTRODUCTION

Digital terrain models (DTM) required for the rectification and mono–plotting of remote sensing data or aerial images are captured usually by automated stereo image matching. Even though the photogrammetric determination of the terrain surface has proved to be a standard tool for the fast and efficient capture of DTMs and stereo image matching provides good results in open terrain, severe problems can occur for certain areas. One example are forest regions, because the terrain surface frequently is not visible in aerial images for these areas. Other problematic applications are coastline and wetland control, where the poor texture in aerial images and the unfavorable geometric conditions (strip adjustment along the seaside) cause difficulties in the photogrammetric evaluation. If height data has to be provided for build–up areas e.g. aiming on 3D visualizations of urban scenes or on simulations like the propagation of electro–magnetic waves to plan optimal locations of transmitter stations, image matching techniques suffer from problems due to occlusions and height discontinuities frequently occuring in these areas. Problems especially arise on the

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absence of sufficient texture on low contrast between roof regions and the terrain surface.
To overcome these problems, laser sensors have been developed to permit the direct acquisition of the terrain surface. Lindenberger (1993) used an airborne profiling laser for topographic data capture by flying parallel profiles along the terrain surface. Nevertheless, the accuracy of DTMs derived from this kind of data was limited by the relatively large distances between the neighboring profile lines. Using scanning laser systems, which became available for airborne range measurement in the past few years as the main component of the sensor system, the points on the terrain surface can be determined dense and well-distributed. This results in airborne systems for the area covering 3D–data acquisition, which are already in commercial use.

Similar to the tachymetric data acquisition, the three–dimensional coordinates of terrain points are determined by polar measurement. Therefore position and orientation of the laser beam at the time of range measurement have to be provided by additional components of the sensor system. These components are a NAVSTAR Global Positioning System (GPS) for the positioning task and an Inertial System (INS) for the orientation task. Remaining errors caused by uncorrected INS drifts, GPS cycle–slips or misalignment of the three components (laser scanner, GPS, INS) can be eliminated by the calibration of the sensor system. These calibration parameters, are determined by matching overlapping strips of range data. They can also be used as an additional control for the georeferencing process performed by the GPS/INS component.

After a brief description of the utilized laser scanner the paper will focus on position and attitude determination of the laser with an integrated GPS/INS system (section 2). The calibration of the sensor system by strip adjustment will be discussed in section 3 of the paper. Section 4 deals with the evaluation of height data to derive further products and will be followed by a brief conclusion.

2.0 COMPONENTS OF THE SENSOR SYSTEM

2.1 SCANNING LASER RANGE–FINDER

For the acquisition of range data by a scanning laser system, the laser beam has to be deflected normal to the flight direction. Within the system used to provide our test data sets, this is performed by a a nutating mirror, which sends the deflected laser beam through a linear fiber-optic array. The fiber-optic array consists of different single optic channels with different viewing directions. Therefore the laser scanner virtually defines a push-broom–system, which – in combination with the movement of the system in flight direction – results in a strip–wise data acquisition, similar to optical line scanning systems. Distances between the laser scanner and the terrain surface are determined by run–time measurement of laser pulses. Because one main goal of the system is the acquisition of *terrain* surfaces in forest areas, pulsed lasers, which are able to record the last reflected signal are required for the data capture.. Even though some pulses are completely reflected by leaves or branches of the trees, in most cases the last reflected pulse will refer to the terrain and can therefore be used to determine the terrain surface. Table 1 summarizes the main performance parameters of the flight segment (Lohr & Eibert 1995).

2.2 POSITION AND ATTITUDE DETERMINATION WITH AN INTEGRATED GPS/INS SYSTEM

Before starting processing, the laser scanner data have to be georeferenced. In this process the exterior orientation (position and attitude) of the sensor at the time of exposure is determined.

sensor type	pulse modulated Laser Radar
scanning principle	fiber optic line scanner
range	< 1000 m
measurement principle	run-time measurement
scan frequency	300 Hz (adjustable)
field of view	±7°
number of pixels per scan	127
swath width (at 10000 m flight height)	250 m
accuracy of a single distance measurement	< 0.3 m
laser classification	class 1 by EN 60825 (eye-safe)

Table 1: Performance parameters of the used laser scanner

Using these parameters of exterior orientation the ground coordinates of the laser points can be derived from the raw data provided by the laser scanner. Traditionally, in case of aerial images an indirect approach, so-called inverse photogrammetry, is used to determine the parameters of exterior orientation. In this process the image coordinates of known ground control points are measured, and neighboring images are connected via homologous points. Assuming a perspective projection the exterior orientation is determined and the images are related to the ground. The disadvantages of this method are well known: the process is quite time intensive, costly and highly skilled operators are necessary for the data evaluation. Additionally, and more important from our point of view, this conventional indirect method is not applicable for the orientation of airborne laser scanner data. Therefore, an direct approach for the determination of the exterior orientation has to be used. Using either inertial navigation systems (INS) or a multi-antenna GPS receiver or a setup of several GPS receivers, the exterior orientation of the sensor can be obtained directly. However, each of the individual solutions is of different error characteristics.

Almost two years ago the GPS system was declared as operational and now it provides data of high absolute and consistent accuracy. Generally, there are no time dependent errors. On the other hand these data are quite noisy and of a relatively low data rate (up to 10 Hz) which is not sufficient for the orientation of the high frequent laser scanner data. Additionally, the GPS observations can be deteriorated by the typical error effects like multi-path, variation of the antenna phase centers, receiver noise and remaining error influences that are not eliminated with the use of differencing techniques. Furthermore, in highly kinematic environments like in the airborne case the GPS phase observations are quite susceptible to carrier phase cycle slips. Additionally, due to the steep banking angles during the flight turns between the different strips outages caused by shading are possible. The GPS positioning and attitude accuracies for the different observables and processing techniques can be seen in table 2.

In contrary to the GPS the INS is a completely self contained system. It provides accurate relative position and attitude informations with a very high data rate (e.g. 50, 100 Hz) for almost near continuous determination of the exterior orientation by measuring the linear accelerations and

Model	Antenna Separation	Accuracy
pseudorange point positioning		100 m horizontal 150 m vertical
smoothed pseudorange (differential)	10 km	0.5 - 3 m horizontal 0.8 - 4 m vertical
	500 km	3 - 7 m horizontal 4 - 8 m vertical
carrier phase (differential)	10 km	3 - 20 cm horizontal 5 - 30 cm vertical
	50 km	15 - 30 cm horizontal 20 - 40 cm vertical
attitude determination	1 m	0.2 - 0.5 deg
	5 m	0.01 deg

Table 2: GPS position and attitude accuracies, from (Schwarz et al. 1994).

angular rates of the vehicle with respect to a fixed inertial frame. The INS data are of a high short term stability but this accuracy decreases rapidly caused by the systematic error effects of the sensor assembly (accelerometer bias, gyro drift). Due to the quality of the INS sensors the resulting errors are in the range of a few dezimeters up to several tens of meters for positioning and less than one milli degree up to almost 0.5 degree for attitudes over a time interval of one minute (see table 3).

	high	medium	low
Position			
1 h	0.3 - 0.5 km	1 - 3 km	200 - 300 km
1 min	0.3 - 0.5 m	0.5 - 3 m	30 - 50 m
1 s	0.01 - 0.02 m	0.03 - 0.1 m	0.3 - 0.5 m
Attitude			
1 h	3 - 8 mdeg	0.01 - 0.05 deg	1 - 3 deg
1 min	0.3 - 0.5 mdeg	4 - 5 mdeg	0.2 - 0.3 deg
1 s	$<$ 0.3 mdeg	0.3 -0.5 mdeg	0.01 - 0.03 deg

Table 3: System accuracy class of INS sensors, from (Schwarz et al. 1994).

The combination of GPS and INS in an integrated system tries to join the advantages of both systems and therefore, the accuracy and the reliability is improved significantly compared to the stand-alone solutions. First, the GPS observations are used as external updates to correct the systematic errors of the INS. Second, the INS measurements are used to bridge GPS outages during flight turns since GPS carrier phase cycle slips or losses of lock can be detected and corrected. Additionally, the exterior orientation data are obtained with much higher frequencies. Therefore, the flight trajectory can be described more precisely and possible interpolation errors are reduced. These interpolations are necessary since the laser scanner and the GPS/INS system have different measurement frequencies and therefore in most cases at the exact time of a range measurement no directly measured position and attitude is available. Hence, it appears that an integrated GPS/INS system provides the best solution for the direct determination of the exterior orientation of airborne sensors. The potential of this direct approach is investigated in a recent test performed by the Department of Geomatics, University of Calgary and the Institute of Photogrammetry, Stuttgart University. Using a navigation grade INS, integrated with differential GPS carrier phase observations subdecimetre positioning accuracy and attitude accuracies of about 30 mdeg are achieved. These accuracies can satisfy the requirements of all low to medium and high accuracy airborne remote sensing applications. For more details see (Skaloud, Cramer & Schwarz 1996).

In principle, the integration of GPS and INS can be done on two different levels. In the first strategy the integration of both systems is done on the hardware site. The GPS and INS components are tied together in one filter. The integration is done on the raw measurement data level of both subsystems instead of the position and velocity level. In general, this so-called centralized approach is straightforward from the processing point of view, GPS data from less than four satellites can be used for update, but this strategy is not flexible enough for the combination with other sensors, because the whole master filter has to be re-designed for adding an additional sensor. To overcome this problem a decentralized approach can be chosen. In contrary to the centralized filter the data of the sub-systems are preprocessed in local filters and these results are feed in the global master filter. This integration is more flexible to add other sensors without modifying the whole master filter, and it is more reliable since blunders of the different sub-systems can be detected before all data are combined in the master filter. Most of the time the filters are running separately. Nevertheless, periodically the output of one filter is used to update the other filter. For example, a predicted position from the INS filter can be used for the detection and correction of poor GPS data (e.g. cycle slips). More details about centralized and decentralized filtering of INS and GPS data can be seen in (Wei & Schwarz 1990).

3.0 CALIBRATION OF THE SENSOR SYSTEM BY STRIP ADJUSTMENT

If the GPS/INS system for the determination of the exterior orientation is combined with an airborne laser scanner for range measurement a powerful system for the direct acquisition of 3D terrain data is available. Using the orientation parameters $(X_0, Y_0, Z_0, \omega, \varphi, \kappa)$ and the measured range S_L, the 3D coordinates (X_L, Y_L, Z_L) of a specific laser footprint are computed by

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \mathbf{R}(\omega, \varphi, \kappa) \cdot \begin{bmatrix} 0 \\ 0 \\ S_L \end{bmatrix}$$

Similar to an aerial image flight the laser scanner data have to be acquired by flying several overlapping strips to achieve coverage of larger areas. Nevertheless due to remaining uncorrected errors of the GPS and INS positioning and orientation components, or caused by misalignment of different sensor components, these adjacent strips do not fit each other exactly. Especially for high precision data acquisition e.g. in build–up areas a calibration of the laser sensor system to determine additional parameters for the transformation of the single strips to a homogeneous ground coordinate system will be necessary. Additionally, this step provides control information to verify the GPS/INS positioning and orientation.

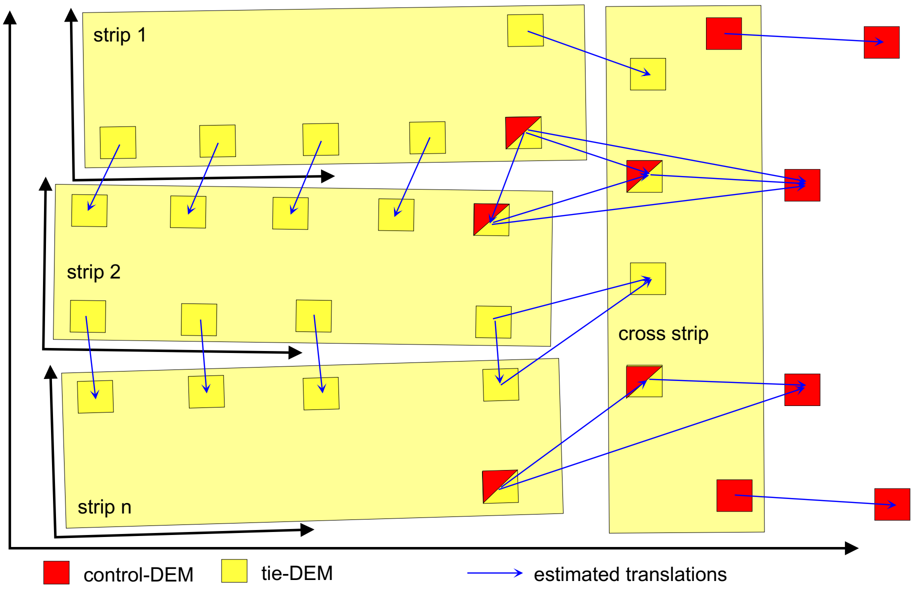

Figure 1: Tie and control points for DEM matching

The calibration of the system is performed applying a matching process to estimate translation parameters between identical windows of different laser strips. These translations are used as tie–point information between windows of overlapping laser strips (see figure 1). The laser data is additionally matched against external information to get pass-point information. As external information ground plans of buildings (position control) and points of known height in flat areas e.g. street crossings (height control) can be used.

For each pair of overlapping windows three translation parameters dX, dY, dZ are determined. Therefore an algorithm originally developed for intensity based image matching (Haralick & Shapiro 1993) using grey-values available in matrix form was modified to handle the height data of irregular point distribution. An example of the matching process applied on two overlapping windows is given in figures 2 and 3. The figures show height data, which was acquired in a build–up area. The height data of the first strip is represented by the shaded surface, the height data of the second strip is represented by the dark lines. Before the matching (figure 2), both data sets do not fit exactly due to uncorrected errors of the georeferencing process. These differences are eliminated by the matching process (figure 3). After this step the remaining differences of the height data are only caused by different viewing angles of the scanner due to different positions of the sensor system at

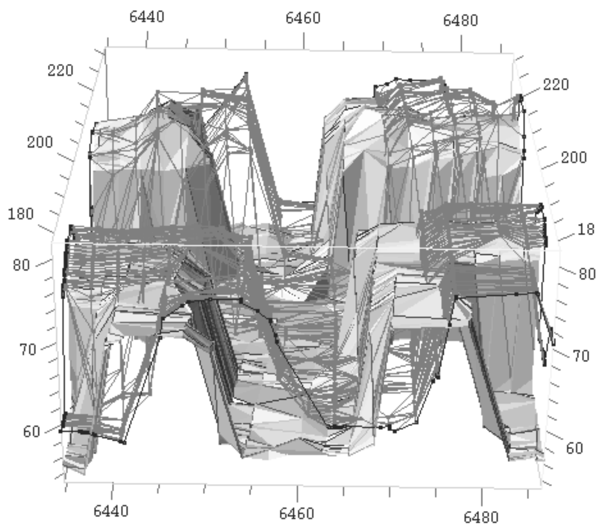

Figure 2: 3D–view of two tie points before matching

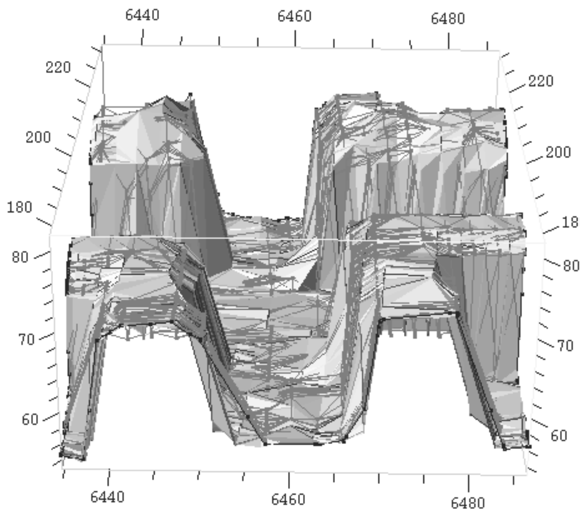

Figure 3: 3D–view of two tie points after matching

the time of measurement.

The translation parameters provided by the matching process are used as tie and control point information for a strip adjustment to estimate a set of transformation parameters for each single strip, enabling the transformation of each strip to the superior coordinate system (Fritsch & Kilian 1994). For each strip 12 unknowns are estimated. These are 6 offset parameters with $\Delta X(t_0)$, $\Delta Y(t_0)$, $\Delta Z(t_0)$ representing an offset for the translation parameters, $\Delta\omega(t_0)$, $\Delta\varphi(t_0)$, $\Delta\kappa(t_0)$ representing an offset for roll, pitch and heading of the sensor system and 6 parameters v_X, v_Y, v_Z, v_ω, v_φ, v_κ representing a time–dependent drift for each of the 12 parameters. With the variable t representing the time of measurement, each estimated translation results in the following three observation equations for the unknown calibration parameters.

$$\begin{aligned}
dX(t) &= \Delta X(t_0) + v_X(t) + f\left((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t))\right) \\
dY(t) &= \Delta Y(t_0) + v_Y(t) + f\left((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t))\right) \\
dZ(t) &= \Delta Z(t_0) + v_Z(t) + f\left((\Delta\omega(t_0) + v_\omega(t)), (\Delta\varphi(t_0) + v_\varphi(t)), (\Delta\kappa(t_0) + v_\kappa(t))\right)
\end{aligned}$$

Figure 4 shows a result of the area covering data acquisition enabled by the system which is described in this paper. The figure represents a part of Hanover city and was computed using a DEM generated from 4 overlapping strips of laser data. To get a better visualization of the DEM and to demonstrate the correct georeferencing, image data was additionally overlaid.

4.0 EVALUATION OF HEIGHT DATA

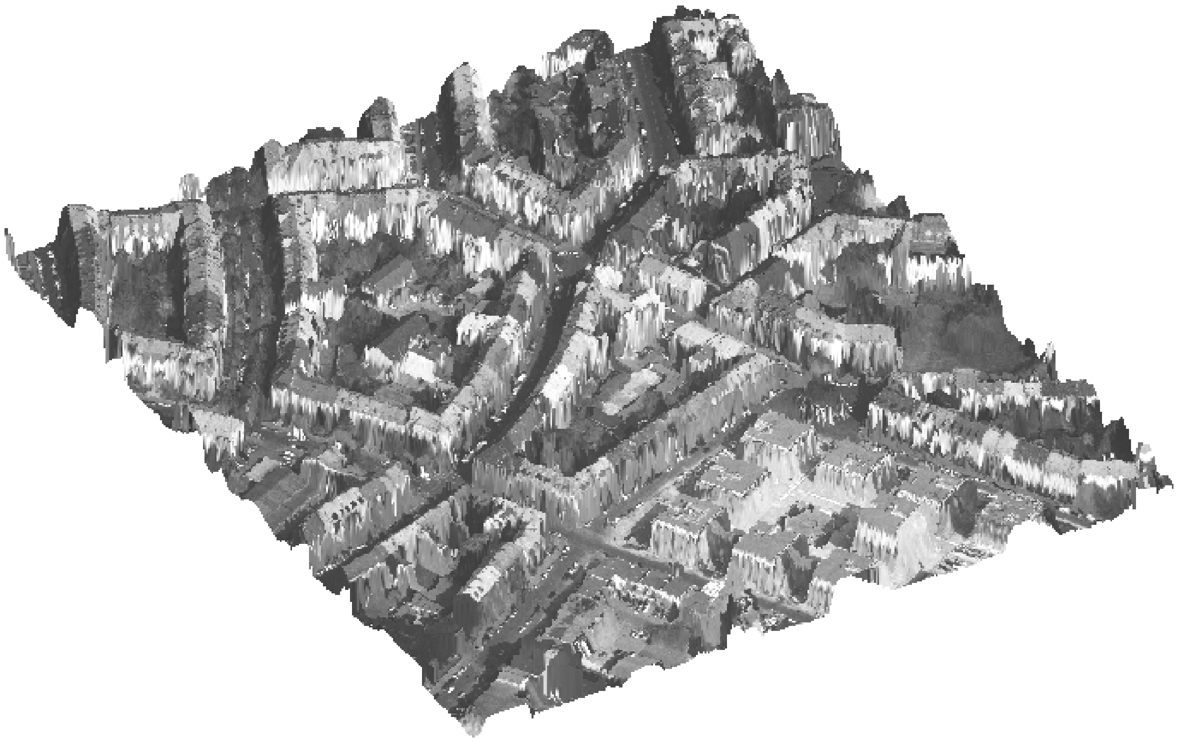

Figure 4: DEM of Hanover city

4.1 FILTERING AND CLASSIFICATION OF THE MEASURED LASER POINTS

Especially in forest areas and in build-up areas airborne laser sensor systems have great advantages compared to conventional methods for 3D data capture, like tachymetry and photogrammetry. In areas covered by vegetation the terrain surface frequently is not visible in aerial images. Nevertheless the topographical terrain surface can be derived using laser data since at least a part of the signal penetrates the tree-top and reaches the ground. To filter out reflections referring to leaves or branches only the last reflected signal of the laser beam is recorded. Yet not each laser pulse reaches the ground, a number of measured laser points still refers to reflections on leaves or branches of trees and bushes. To separate measured laser points on the the topographical terrain surface from topographical non relevant points a filtering process based on morphological operations has to be applied. These filter processes also enable a classification of the measured laser points to distinguish between areas of different meaning (e.g build-up areas, areas with forest), so after the classification different surface descriptions can be derived (Kilian, Haala & Englich 1996).

4.2 FURTHER PRODUCTS

A Digital Terrain Model (DTM) representing just the terrain surface can be derived, if only the points classified to lie on the topographical terrain surface are considered for the processing. If regions are created by combining points with the same classification attribute, a more detailed description of the terrain surface is possible. This information can be used in build–up areas to get hints on the presence and shape of buildings (Haala 1995).

Figure 5 gives an example of a 3D building reconstruction using height data. To get a 3D description

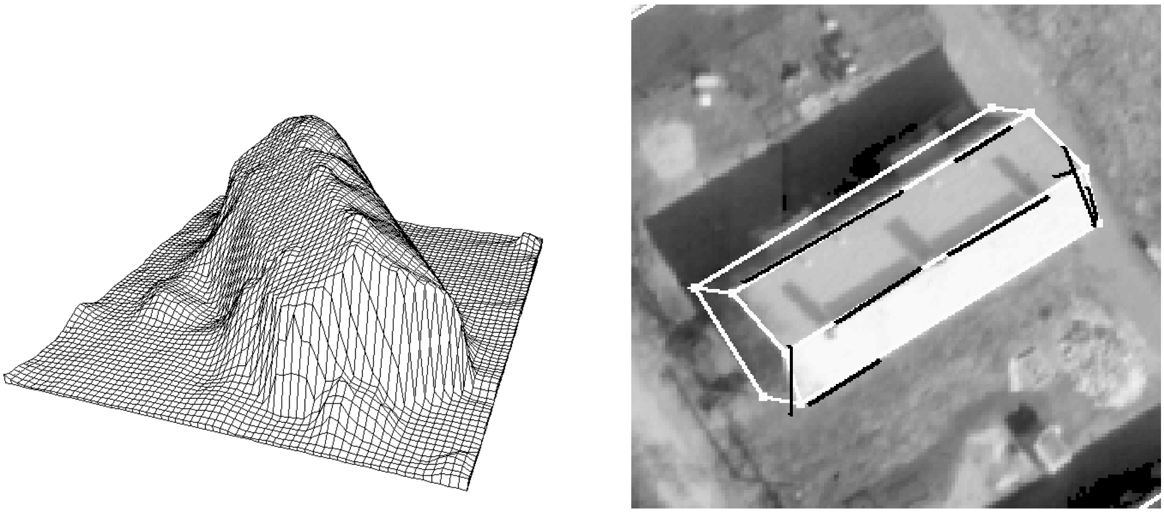

Figure 5: Height data and corresponding image section with extracted break–lines (black) used to reconstruct the building (white lines)

of a building break-lines are extracted from the height data and matched against a building model. The left part of figure 5 shows the height data used for break-line extraction, the right part shows the resulting CAD–like description of the building (white lines), which is projected to the corresponding image section for better visualization. Even though for this example the height data used for reconstruction could be produced by stereo image matching, usually laser data will be prefereable, since only this kind of data acquisition provides results of homogeneous quality in build-up areas.

5.0 CONCLUSIONS

With the availability of airborne line scanning laser systems the production of area–covering high precision DTMs has become feasible. Especially for regions like forest areas, coast-lines or build–up areas, where photogrammetric data acquisition is difficult or even impossible the presented system provides an excellent tool for fast and efficient 3D data capture. Also other applications like the three-dimensional reconstruction of buildings fusing height and image data show the enormous potential and growing importance of these kind data bases.

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