UNIQUE AIRBORNE FIBER SCANNER TECHNIQUE FOR APPLICATION-ORIENTED LIDAR PRODUCTS

K. Schnadt [a, *], R. Katzenbeißer [a]

[a] TopoSys GmbH, Obere Stegwiesen 26, 88400 Biberach, Germany - (k.schnadt, r.katzenbeisser)@toposys.com

KEY WORDS: Airborne Laser Scanning, Fiber Scanner, Pushbroom Scanner, DEM, True Ortho Images, LIDAR applications

ABSTRACT:

Precise and dense elevation models are required for a variety of applications. This paper shall give a short outline of the technology behind a fiber scanner and why this technology fits best for the acquisition of high resolution DEM. Special emphasis is here paid on edge detection and forest penetration. The described optical line scanner acquires spectral data simultaneously with the laser scanner leading to combined evaluations of elevation data and true ortho image data. In addition to the standard products DSM, DTM, RGB and CIR, some derived application-oriented products are presented which are of fundamental importance for city planning, building extraction, forest management, change detection, coastline protection, nature conservation, river modeling and hydraulic analyses.

1. BACKGROUND

Airborne laser scanning has not long entered the market for the production of high resolution digital elevation models but soon has proved its suitability for the acquisition of accurate and reliable topographic data of the earth`s surface. Besides laser scanner systems which make use of an oscillating or rotating mirror for beam deflection, a different concept of LIDAR technology will be presented. The unique fiber scanner concept is based on fixed linear arrays of fibers which send the laser beams in a stable direction to the ground. The TopoSys sensor system Falcon is the only system worldwide which has implemented the fiber based concept described in this article. Furthermore, an optical line scanner is embedded into the Falcon system and simultaneously records spectral data for the generation of true ortho images in addition to the elevation models.

Harmonized with the scanner hardware a powerful software package performs processing of elevation and image data with speed and fidelity. The laser scanner 3D point cloud is basis for generating raster surface and terrain models with various resolutions adapted to different application purposes. The spectral image data is rectified with help of the surface model to generate true ortho images in true color (RGB) and color infrared (CIR).

In a further step, application-specific products can be derived from the standard LIDAR elevation and image data for use in coastal erosion and flood risk management, city planning and forestry among others.

2. LASER SCANNER SYSTEM FALCON

Laser scanner systems can be classified according to the concept they use for beam deflection. The laser scanner system Falcon achieves the sideward spreading of the beams through a mechanically fixed array of glas fibers with exactly defined orientation. The concept used for beam deflection has got a great influence on the quality of the acquired data as well as on flight parameters and sensor efficiency (Wiechert, 2004). Where mirror-device scanners can cause a deflection error due to mechanics, acceleration and wearout and additionally require a regular calibration, the TopoSys fiber scanner is free of these confinements. Stiff mounting of all components on a rigid carbon fiber plate ensures that the factory calibration remains valid over several years of operation. The stable pulse rate of 83 kHz is not coupled to flying height, viewing angle or number of resulting echos.

Falcon records both first echo (FE) and last echo (LE) with short discrimination, so that multiple echos result from objects separated by 1 m or more. The narrow viewing angle of about $\pm 7°$ guarantees high penetration into dense vegetation especially suitable for detection of forest ground. In addition, it assures very small shadowing of high objects, favorable for city mapping. The commonly known greatest advantage of the Falcon system is the high overlap of measurements in flight direction. Adjacent scans are displaced by just 12 cm (at flying speed of 65 m per second) and therefore permit a detectability of erroneous measurements caused by birds or clouds, a reduced dependancy from singular distance measurements and an enhanced edge detection and localization. Even small linear objects lying in flight direction between two successive pulses are detected as a swing mechanism has been implemented in the Falcon systems to generate regular wave patterns on the ground. By applying the swing mode the large overlap of measurements in flight direction remains while optimizing coverage at the same time.

In combination, all described technical parameters of the Falcon system lead to very high precision and reliable elevation models which are important basic data sets for various applications.

2.1 Laser Fiber Scanner

The laser fiber scanner consists of two arrays of 128 light guiding glas fibers, the transmitting and the receiving array (figure 1). In both arrays the fibers are arranged at one end in a circle and at the other end in a linear form. The laser sends 83,000 pulses per second through the center fiber to a motor-driven tilted mirror which reflects each light pulse into the circular array of 128 fibers successively. One of the fibers is used as reference fiber and is directly fed from the circular transmitting side to the receiving side. This reference fiber guarantees an immediate detection and correction of variations in the measurement electronics for each scan line. Through the remaining 127 fibers the light travels to the linear end of the transmitting array and is sent to the ground in a fixed direction. The beam divergence of 1 mrad results in a beam diameter on the ground of approximately 1 m at a flight altitude of 1000 m. The light is reflected from the ground and only accepted by the corresponding fiber of the receiving array where it is guided to the circular array and coupled by another tilted mirrow into the center fiber leading to the detector. The direction of the transmitted laser beams remains stable due to the fixed geometric orientation of each individual fiber. Any misalignment caused by the tilted mirrors can only cause a loss of energy but has no influence on the precision of the distance measurement.
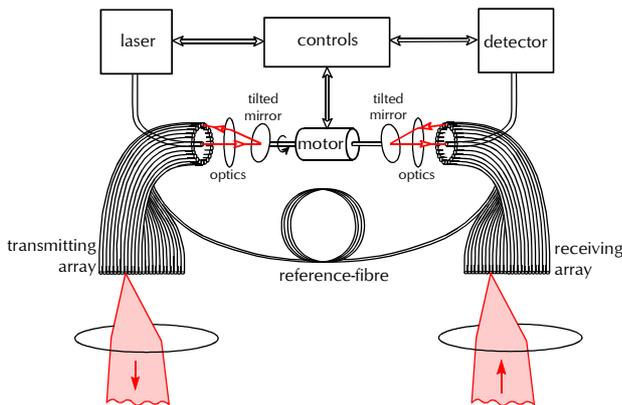

Figure 1. Fiber-based laser scanner

2.1.1 Edge Detection: The overlap between adjacent measurements does not only increase the reliability but provides one very unique and essential effect of precise edge detection. Equally spaced measurements by a narrow beam are either from the roof or from ground but rarely provide a dual measurement.
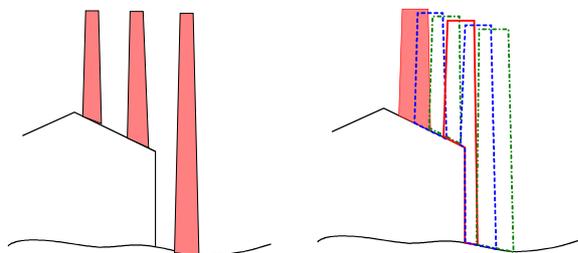

Figure 2. Edge detection with narrow beam (left) and wide beam (right)

The overlaps of adjacent measurements by Falcon provide a number of dual measurements at edges and thus give an essential means for edge detection and localization (figure 2 right).

2.1.2 Forest Penetration: Compared with other scanning methods Falcon provides a much higher probability to penetrate forest canopy. Assuming a regular spacing of 1 m and an illuminated circle of 0.3 m diameter (beam divergence of 0.3 mrad at 1000 m) gives that about 14 % of the scanned area is illuminated (red and green spots in figure 3). Let the gaps between the foliage (white areas in figure 3) be 20 % of the area then the probability to penetrate the foliage becomes about 3 % (0.14 × 0.2), indicated by the green spots in figure 3. Falcon illuminates about 75 % of the scanned area and thus might penetrate through all existing gaps shown by the green circles in figure 3.
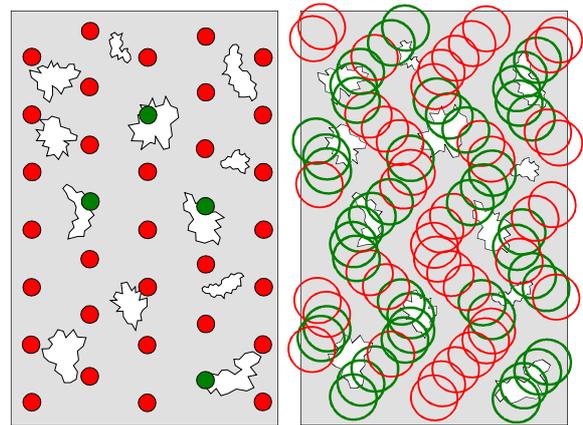

Figure 3. Forest penetration with narrow beam (left) and wide beam (right)

Another effect for foliage penetration lies in the steep viewing angle of Falcon. To penetrate a fir or spruce stand requires a nearly vertical viewing. The further the beam direction diverges from vertical the higher becomes the probability that the light stucks at lower branches as shown in the left part of figure 4. Unlike for wide spaced buildings this can not be compensated by the adjacent flight strip, as the problem stays the same.
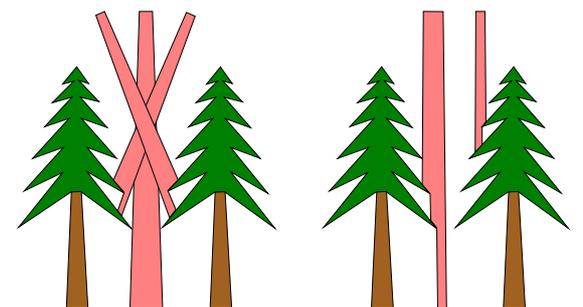

Figure 4. Effects of wide viewing angle (left) and beam divergences (right)

Frequently it is discussed whether a full digitization of an echoes wave-form will provide additional information about the shape of a tree's crown but also increases the volume of data by one magnitude. A narrow beam of less than 0.5 m diameter does not cover more than a few branches, as shown in the right part of figure 4. Even taking adjacent measurements will rarely provide the expected information about a tree's shape.

Falcon separates echoes from reflectors only about 1 m apart, which will provide a higher amount as well as more detailed multiple echoes compared to other systems. Thus the combination of a wide beam, a high penetration ratio and a fine separation makes Falcon unique for forest applications.

2.2 Optical Line Scanner

For obtaining additional spectral information of the earth's surface an optical line scanner is embedded into the Falcon system. The line scanner is also mounted on the carbon fiber plate and precisely oriented with the fiber scanner and the inertial measurement unit. The light sensitive pixels of the scanner are not spread over a matrix like in common digital cameras, but reduced to only one line. Therefore the term line scanner or pushbroom scanner is used to differenciate between the characteristics of a matrix camera. To gain an area-wide image a line scanner must be moved orthogonal to the scan line which is realized by the flight of the aircraft. The pixels are sensitive to the red, green and blue as well as to the near infrared spectrum.

An important part for the quality of the image data is the implemented lense. The chosen focal length of the TopoSys line scanner allows for a two times higher grid width and 1.5 times larger field of view compared to the laser scanner. The larger scan angle and the resulting high overlap between flight strips is beside the advantage of higher data density extremely useful for minimizing the appearance of shadowed areas without image information.

In contrast to the two-dimensional central perspective of matrix cameras the principle of pushbroom scanners involves shadowing effects only across flight direction as long as the scanner looks in right angle to the ground. In flight direction the perspective is quasi orthogonal and no shadowing occurs. If spectral information is missing in one scan line due to tall obstacles, the shadowed area can be filled with data from the overlapping adjacent flight strip thanks to the larger viewing angle of about $\pm 10.5°$ compared to the fiber scanner.

3. ELEVATION MODELS AND TRUE ORTHO IMAGES

The described fiber and line scanner system collects elevation and image data simultaneously in one flight covering large areas with high precision and reliability. First step in data processing involves the combination of DGPS position data and IMU orientation data with the distance measurements calculated from the time the light needs to travel to the ground and back to the sensor. As a result, all laser echos are linked with a coordinate and a height separated in two 3D point cloud data sets for each flight strip, one containing first echo data and the other last echo data. Because of the high density of measurement pulses, the point cloud data is thinned out intelligently and sorted into a regular grid to speed up further processing and to reduce data quantity. The resulting raster model is called a digital surface model DSM which includes heights of vegetation and buildings. By chosing just one representative value of the many values in each regular grid cell, different modes of assignment can be applied according to the final application of the model. Four basic DSM models can be processed from the combination of first echo or last echo and assigning highest or lowest elevation values (Löffler, 2003). Basic model for generating a digital terrain model DTM is the DSM last echo highest values (including small dams which are important for hydraulic simulations) or DSM last echo lowest values (including small ditched which are important for groundwater modeling). The final DTM is a filtered model where all non-terrain points are removed.

The image data recorded by the optical line scanner is stripwise rectified and georeferenced with help of the DSM. Using both terrain and object heights for correction of image data results in a true ortho image where all objects are correctly positioned (Pflug et al., 2004).

In contrast to simple ortho images which are corrected by making use of just the terrain model (figure 5), buildings and trees in true ortho images are correctly projected onto the image plane and do not have a lean (figure 6).
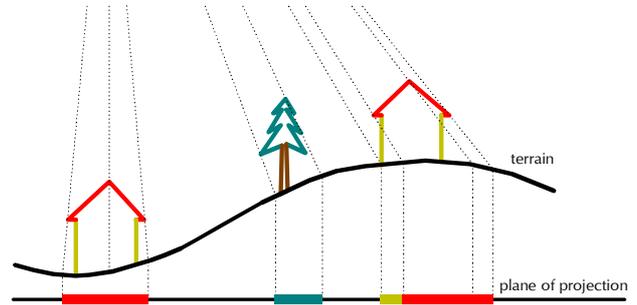

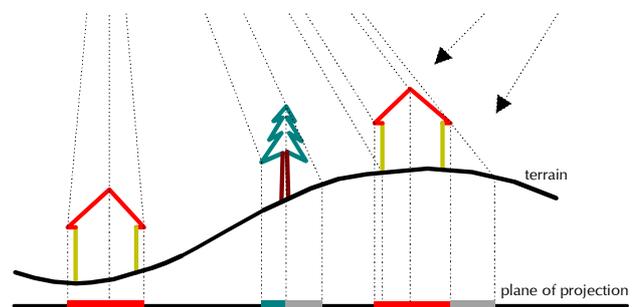Figure 5. Positional error in projection by using only terrain heights for correction

Figure 6. Error-free true ortho projection by using terrain and object heights for correction

True ortho images are perfectly suited for discrimination of sealed and non-sealed surfaces and as input in geographical information systems. The four channel true ortho image data is usually composed to form three channel true color images RGB and color infrared images CIR in georeferenced tif format.

4. DERIVED APPLICATION-ORIENTED PRODUCTS

Besides the standard laser and line scanner products DSM, DTM, RGB and CIR a variety of derived information for manifold application purposes can be extracted.

With regard to forest inventory and forest management specific stand- and tree-related parameters such as tree height, crown diameter, number of trees, 3D coordinates of tree tops can be extracted directly from the laser scanner data (Diedershagen et al., 2003). In order to extract outlines of buildings and vegetation, the calculation of difference values between first and last echo DSM is a very valuable dataset. For use in coastal erosion management and hydraulic simulations, cross and trans sections can be extracted and volumes calculated. An intelligent thinning of data can be performed for the water management sector and other authorities who need precise height values for undulating areas for the definition of breaklines but have software limits in data amounts.

Some examples of these application-specific products are given in the following sections to show the potential of simultaneously acquired laser and line scanner data for different applications as well as to demonstrate the fast and easy extraction of additional information with help of standard geographical information systems and image processing software.

4.1 Sealed and Non-Sealed Surfaces

Identifying the extent of sealed and non-sealed surfaces on premises is an important task for city authorities in order to determine the amount of waste water tax the owners have to pay. Up to now, sealed surfaces are calculated based on aerial photographs or estimated based on questionnaires which the owners of the premises have to complete. Both methods are very time-consuming and cost-intensive as a lot of manual work has to be done to generate reliable maps of sealed surfaces within an urban area.

By employing spectral information of the red and near infrared channels from digital line scanner data, areas of green vegetation can be distinguished from non-vegetated areas. The geo-referenced raster images in the red and near infrared spectrum are used to calculate the normalized difference vegetation index (NDVI) computable with any common GIS or image processing software (e.g. ERDAS Imagine, PCI Geomatics, ESRI ArcGIS, Clark Labs IDRISI). The NDVI image delineates areas of green vegetation in contrast to areas without green vegetation. By applying the threshold of zero, a binary vegetation mask is created which can be furthermore draped over a true color image RGB to check the results interactively.

Figure 7 shows an RGB image as well as the vegetation mask for a part of the city of Friedrichshafen, Germany.

Figure 7. RGB image (left) and vegetation mask (right)

4.2 Multiple Echo Differences

Multiple echos are detected by the Falcon system at the time when the laser beam on the ground covers objects which are separated in their height by at least 1 m. Multiple echos occur at the edges of buildings as well as in areas covered with vegetation. The first echo is reflected from the roof or the tree top whereas the last echo is reflected from the ground. Therefore two distances are measured for each pulse which add considerably to the quality of elevation information. By calculating the differences of the first and the last echo data set, the single echo values are reduced to zero while the multiple echo differences describe either the height of the building or the height of the vegetation. The differences of DSM raster data can be accomplished with any raster calculator in standard GIS and image processing software, while the differences of first and last echo for each individual laser beam have to be computet by LIDAR specialists. The computations result in a difference layer which highlights in a distinctive way the contours of buildings and trees giving their precise height at the same time (figure 8). The difference layer therefore makes up a valuable input data set for automated 3D building extraction algorithms as well as for tree cadastre refinement.
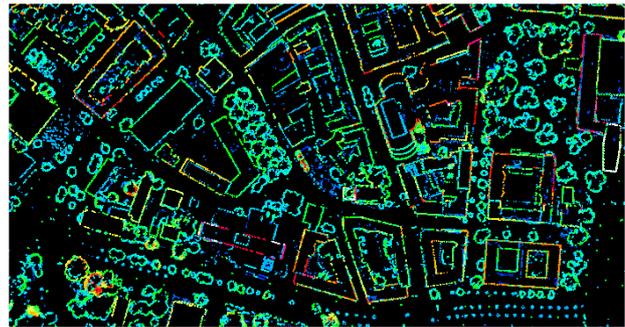

Figure 8. Color-coded difference model first echo – last echo

4.3 Volumes

Volumes are created by calculating the differences between two 3D surfaces based on the height values of each raster element. Depending on the application, volumes are determined based on surface data acquired by laser scanning at the same time or at different times. Using both the digital suface model and the interpolated terrain model acquired at the same time, volumes of objects above the ground can be specified. For monitoring and change detection purposes the elevation models acquired at different times are subtracted to identify changes which occurred within the time span. Estimating these changes precisely becomes increasingly relevant for coastline and island protection, nature conservation and managing waste deposits.

With help of repeatedly acquired high precision LIDAR data demolition of cliffs can be documented, erosion and accumulation areas localized and calculated, peat loss and subsidence recorded and landfill determined.

Capacities of reservoirs and storage lakes are easily calculated by surveying the drained basins and subtracting the 3D data of the basin ground from a fictitious plane representing a predefined water level.

4.4 Breaklines and TINs

The very dense elevation models provide such detailed information that breaklines can be extracted precisely. Thus these models are an ideal basis for river modeling and hydraulic analysis.

Figure 9 shows the relief image of a DTM and the extracted areas with highest gradient change while figure 10 displays the derived TIN, maintaining the essential features such as floor, slope and summit of a dike without explicitly extracting breaklines and by this reducing manual work.
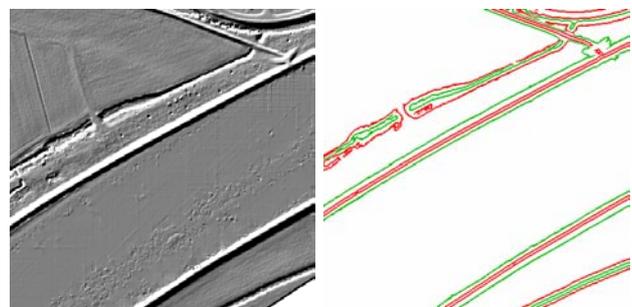

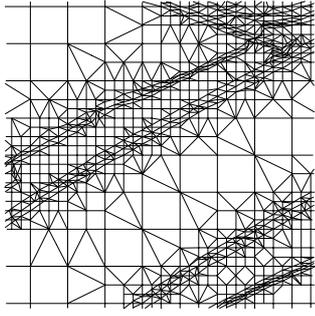Figure 9. Relief image (left), highest gradient change (right)

Figure 10. Derived TIN

Depending on the relief of an area and the accuracy required the number of data can be reduced by a factor of 20 to 200. An area of 1 km² contains 1,000,000 elevation values at a 1 m grid. By applying the modified TIN the number of values is reduced to about 10,000 without a remarkable loss of accuracy. This type of TIN is a reliable basis for 2D hydraulic modeling of rivers and flooded areas. Due to the low number of data and the high accuracy reliable flood simulations can be processed in a reasonable time frame allowing a number of iterative stages for a precise verification.

5. CONCLUSIONS

High precision multi-sensoral data sets acquired simultaneously with an airborne system provide an essential basis for the detection, classification and evaluation of geographic features on the earth's surface. The laser scanner system Falcon is the only system worldwide which couples the airborne fiber scanner technique with a digital line scanner for generating precise and high resolution elevation and true ortho image data. The unique fiber scanner design of the TopoSys Falcon system combines high effective measurement rate, fine pulse separation and overlapping wide laser beams with a narrow viewing angle resulting in a high penetration ratio and reliability of elevation data.

Development of both scanner hardware and processing software is consecutively accomplished by TopoSys to meet new evolving customer demands. Last year the swing mode has been implemented while this year a roll compensation will be incorporated into the system.

Besides the standard elevation and image data sets generated by an airborne laser scanner system, further application-oriented products can be derived for various application purposes. On the one hand derived products can be easily calculated with standard GIS and image processing software (e.g. vegetation indices, difference models and profiles), on the other hand some application-specific information has to be extracted and processed by expert LIDAR service providers (e.g. vectorized buildings, water/land border, crown diameter and TINs).

The future will show the potential of combined laser scanner and image data for both traditional applications and newly arising LIDAR application areas such as archeology, nature conservation and landscape monitoring.

6. REFERENCES

Diedershagen, O., Koch, B., Weinacker, H., Schütt, C., 2003. Combining LIDAR- and GIS data for the extraction of forest inventory parameters. *Proceedings of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests*, Umeå, Schweden, pp. 157-165.

Löffler, G., 2003. Aspects of raster DEM data derived from laser measurements. *ISPRS workshop „3-D reconstruction from airborne laserscanner and InSAR data"*, Dresden, Germany.

Pflug, M., Rindle, P., Katzenbeißer, R., 2004. True-Ortho-Bilder mit Laser-Scanning und multispektralem Zeilenscanner. *Photogrammetrie, Fernerkundung, Geoinformation*, 3, pp. 173-178.

Wiechert, A., 2004. Production of ALS and RGB/CIR true ortho images. *GIS@development*, 8(5), pp. 30-32.