Publication I

P. Rönnholm, E. Honkavaara, P. Litkey, H. Hyyppä, and J. Hyyppä. 2007. Integration of laser scanning and photogrammetry (Key-note). In: P. Rönnholm, H. Hyyppä, and J. Hyyppä (editors). Proceedings of the ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007. Espoo, Finland. 12-14 September 2007. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, volume 36, part 3 / W52, pages 355-362.

INTEGRATION OF LASER SCANNING AND PHOTOGRAMMETRY

P. Rönnholm [a, *], E. Honkavaara [b], P. Litkey [b], H. Hyyppä [b], J. Hyyppä [b]

[a] Helsinki University of Technology – petri.ronnholm@tkk.fi
[b] Finnish Geodetic Institute - (eija.honkavaara, paula.litkey, hannu.hyyppa, juha.hyyppa)@fgi.fi

Commission III/3, III/4, V/3, VIII/11

KEY WORDS: Laser Scanning, Photogrammetry, Registration, Integration

ABSTRACT:

The term "integration" can be defined as the fusion of two separate entities, resulting in a new entity. Integrating laser scanning with photogrammetry allows us to compensate for the individual weaknesses of each method alone, thus providing more accurate modelling, interpretation and classification of the surroundings. Laser scanners produce data that can vary in terms of point density, field of view, amount of noise, incident angle, and distribution method. Similarly, the accuracy requirements or level of automation may also vary. Therefore, no single registration method overcomes others. The most suitable method is usually case-specific. This paper presents a short overview of current registration approaches and proposes four levels of integration: object-level integration, photogrammetry aided by laser scanning, laser scanning aided by photogrammetry, and tightly integrated laser scanning and optical images. In addition, some examples are presented of integrated laser scanning and photogrammetric data.

1. INTRODUCTION

Both terrestrial (TLS) and airborne (ALS) laser scanning (LS) offer improvements over photogrammetric methods (Hyyppä et al., 2000; Jansa et al., 2004). LS methods are based on using active sensors that transmit and receive light rays for range measurements. In addition to range information, LS data can also include information on the backscattered intensity of the returning light. If the full-waveform is available, the accuracy of the range information can be improved in the post-processing phase, and other information can also be derived, such as the length of the returned echo. Some advantages of LS include the immediate generation of a 3D point model, ability to partially penetrate through vegetation and water, accuracy of the range measurements, ability to measure areas without texture, the ability to measure even in the dark, and competitive expenses.

Soon after LS devices had been developed to a commercial level, many people speculated that photogrammetry would be totally replaced by LS. After the initial enthusiasm, however, it has become more obvious that integrating optical information with LS has many advances. The major advantages of images are similarity to human vision, well-known internal geometry, good interpretability, ability to capture texture and multichannel reflectance information, ability to model moving objects, re-measurability, and use of a frame-based acquisition method. Because of the geometric stability of images, they are the most suitable references for inspecting laser point clouds.

The term "integration" can be defined as the fusion of two separate entities, resulting in the creation of a new entity. Properly integrating laser scanning with photogrammetry allow us to compensate individual weaknesses of each method alone, thus providing more accurate applications for modelling, interpretation and classification of surrounding objects.

LS devices can be categorized into two major classes based on the physical measuring method: triangulation and time-of-flight (TOF) (Blais, 2004). TOF methods have two major variants: pulse-based systems and those based on the phase differences of modulated light rays. In the triangulation method, the camera comprises a constant part of the device. In the case of TOF systems, an external camera is usually attached to a scanner or images are taken separately. In addition to normal lenses, cameras can have panoramic or fish-eye lenses or the panoramic camera can be based on line sensor.

Registration plays a key role when combining different types of data. If the registration fails or is incomplete, the integration may give misleading information. Since different laser scanners produce data that can vary in terms of point density, field of view, amount of noise, incident angle, distribution method, and the accuracy requirements or the level of automation may significantly vary, there is no single general registration method that would outperform the others. The most suitable method is typically case-specific.

This paper presents an overview of various registration approaches, proposes four levels of integration and provides examples of integrated LS and photogrammetric data.

2. REGISTRATION

Registration can be considered the foundation on which the integration is based. In principal, registration is completed either by determining the sensor orientations of the images and LS separately for the common coordinate system or by directly determining the relative orientation of the data sets (Fig. 1). By default, the latter method ensures better mutual accuracy, because it includes only one transformation and always uses the common tie features. In those cases in which a camera is permanently mounted to the laser scanner, the system only

---

* Corresponding author.

occasionally needs to be calibrated in order to ensure the registration of LS point clouds and images.
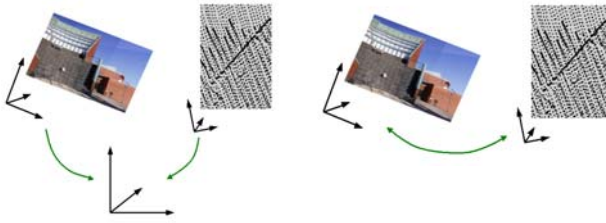

Figure 1. LS point clouds and images can be registered either separately into the common coordinate system (left) or by directly determining one relative orientation (right).

2.1 Registration through the common ground coordinate system

ALS obtains the position and attitude information from the Global Positioning System (GPS) and Inertial Navigation System (INS) sensors. The accuracy of these direct orientation sensors even challenges the conventional photogrammetric aerial triangulation (Heipke et al., 2002). If transformation to a local coordinate system is needed, the datum is typically found using planar areas. GPS and INS observations are nowadays used as additional observations in the block adjustment for determining the camera locations in aerial triangulation.

Both TLS and terrestrial images are typically registered to a known coordinate system using targets, since targets can be interpreted easier and measured more accurately than natural features.

2.2 Direct registration between laser scanning data and images

Registration of LS data and images basically follows the same workflow as registration of two or more images. According to Zitova (2003), the majority of registrations have four steps: feature detection, feature matching, transform model estimation, and transformation. Transformation may also include resampling.

The main problem with feature detection lies in finding features that can be robustly interpreted from both LS data and images. Moreover, possible perspective differences can further hinder interpretation. Appropriate feature selection depends greatly on the density of the LS point cloud. The resolution of currently available terrestrial laser scanners is high, especially when measuring short distances. In such dense point clouds, even small details are visible, thus enabling the detection and measurement of photogrammetric targets, for example. Typically, the intensity information from LS is used for identifying centres of 2D circular targets (Parian and Gruen, 2005) or natural features (Elstrom et al., 1998; Forkuo and King, 2004) that are also easy to identify from images. Most LS devices operate at an infrared band, which must be taken into account when natural tie features are selected from intensity images (Smith and Elstrom, 1999).

The point density of ALS is usually sparser than TLS data and can vary significantly depending on the LS device and flying altitude. In addition, customers may have specific desires for point density. Noise, outliers and the large footprint of the single laser beam, as well, may prevent the identification of finding robust and accurate tie features.

Several alternatives to the use of corresponding features have been proposed for the registration of LS data and images, including the edges of buildings (Schenk and Csatho, 2002; Zhang et al., 2005), conjugate straight-line segments (Habib et al., 2005), planar objects (Roux, 2004), and surfaces (Habib and Schenk, 1999; Postolov et al., 1999; Wendt and Heipke, 2006).

In addition to numerical methods, manual methods can also be useful for registration. Rönnholm et al. (2003) describe how ALS data and terrestrial images can be registered using an interactive orientation method. Similar to numerical methods, the interactive orientation method requires enough tie features within the image footprint. LS data usually include many small details, such as hits from street lamps, pipes, antennas, and trunks. In numerical registrations, all these details are filtered out because they are considered to be outliers. Nevertheless, small details can be valuable during the registration using interactive methods.

Physical models describe the geometrical aspects of the data acquisition process. In the case of images, the physical model is typically the collinearity model extended by suitable additional parameters. Physical models can also be determined for LS (Schenk, 2001).

Finally, the data sets are transformed using the selected transformation model. If regularly spaced data (e.g., image or laser data organized in a grid) is transformed, the new coordinates are non-integer and will require some interpolation. In the case of irregularly spaced laser data, interpolation is not needed.

2.3 Errors that affect registrations

Both images and LS data can have internal errors which can affect registration. Frame-based photogrammetry uses interior orientation for solving these errors. The internal errors of cameras can be minimized by accurately determining the principle point, the principle distance and lens distortions.

According to Schenk (2001), ALS data typically include LS range errors, scan angle errors, LS mounting errors, GPS mounting errors, INS errors, systematic GPS errors, error in the geoid normal, synchronization error, and interpolating error. These errors can be reduced using, e.g., overlapping laser strips, ground control features and photogrammetric references. Pushbroom images have GPS and INS errors similar to those for LS. It would be interesting to acquire simultaneously pushbroom images, frame-based images and LS data, and to investigate whether comparison of bushroom and frame-based images could be used for eliminating GPS and INS errors from LS data.

Terrestrial laser scanners can suffer from physical errors similar to those of total stations. Physical parameters, however, are not sufficient to describe all errors in TLS data. Therefore, also empirical parameters should also be used. Lichti and Licht (2006) give good information on calibrating terrestrial laser scanners.

Different surface materials may cause systematic shifts in the LS data (Boehler et al., 2004). Pfeifer et al. (2004) pointed out that surface types other than those used for calibration cannot

be expected to have correct heights. One factor causing variation in the range with different surface materials is the selected triggering method of the returning echo. Katzenbeisser (2003) gives illustrative presentation of how LS echoes interact with various surfaces. Wagner et al. (2004) proposed that different triggering methods or a combination of methods should be used to achieve optimal performance for each surface type. If full-waveform LS data is not available, it is not possible to re-process the triggering phase. Nevertheless, the effect of false triggering can be reduced by class- or object-based registration. Fig. 2 illustrates how some ALS echoes from white road paintings are shifted downwards from the level of the asphalt.

Figure 2. The cross-section of ALS data reveals how some echoes are shifted downwards from the asphalt level when hitting the white road markings.

In addition to internal error sources, the interpretation of tie features can reduce the accuracy of registration. Interpretation can be difficult, if the data is coarse, noisy or difficult to perceive.

3. LEVELS OF INTEGRATION

The integration of laser point clouds and images can have different levels depending on the desired end-product, the nature of the original data or differences in emphasis. The four main levels of integration are:

1. Object-level integration
2. Photogrammetry aided by laser scanning
3. Laser scanning aided by photogrammetry
4. Tightly integrated laser scanning and optical images

In this chapter, the levels of integration are described in greater depth and some examples from the literature are presented as examples to illustrate the applications of each integration type.

3.1 Object-level integration

In object-level integration, LS and photogrammetric data are processed and interpreted separately (Fig. 1). A typical example of object-level integration is the creation of hybrid 3D virtual models, in which digital terrain model is created from laser point clouds, but breaklines and buildings are measured from images. Integration is not limited to involve only either airborne or terrestrial data. Actually, the most complete 3D virtual models may integrate information from ALS, TLS, aerial images, terrestrial images, and geodetic observations.

Orientation to the common coordinate system is usually done separately for LS and images. However, if common features can

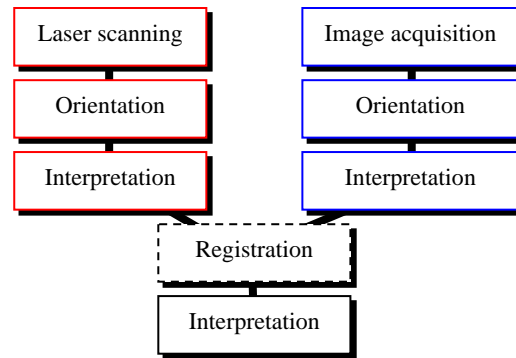be found, registration of interpreted 3D objects can also be used.

Figure 3. Object-level integration of LS and photogrammetry.

3.2 Photogrammetry aided by laser scanning

The second level of integration is photogrammetry aided by LS. Although the main focus is on images, LS data is also necessary. In this approach, LS data and images are either separately oriented or directly registered into a common coordinate system. A typical example of this level is the creation of orthophotos using LS-based surface modes (e.g., Wehr and Wiedemann, 1999). The relief displacement errors are eliminated from the original images using the information from the LS-based object models or, in the case of aerial images, digital terrain models.
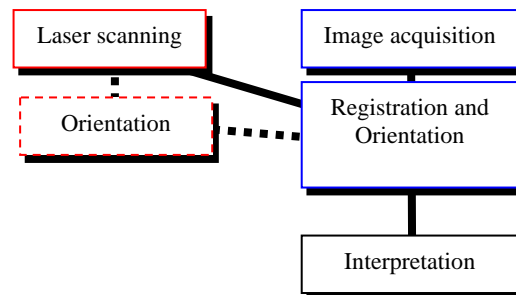
Figure 4. Photogrammetry is aided by LS.

By augmenting photogrammetry with laser data, the popularity of mono-plotting can be significantly improved. The principle is that the features can be selected from the image plane, and the depth information is derived from laser data. Mono-plotting applications have been proposed, for example, by Abdelhafiz et al. (2005) and Ressel et al. (2006).

Kern (2001) made an interesting proposal to reduce the effects of shadows from the original images using LS-derived 3D models. The idea was that circumstances similar to those occurring during image exposure are reconstructed using 3D model and ray-tracing software. Although this approach has yet to be implemented, it could be beneficial both with aerial and terrestrial photogrammetry.

Haala and Brenner (1999) used an ALS-derived normalized digital surface model with colour-infrared aerial images to improve image-based classification of streets, grass, trees, buildings, and shadows.

Wendt (2007) used TLS point clouds for choosing planar tie features from image-derived set of interest points. This method enabled automatic registration of images and laser scans.

Visualization of 2D images or videos in 3D is possible, e.g., using 3D depth maps (Harman, 2000; Fehn et al., 2002). Similar methods are used with some autostereoscopic displays, such as lenticular or barrier displays, in which several sub-images are created from one 2D image and the depth map. With this technique, only one image and a depth map need to be stored, instead of five sub-images, for example. The conversion of regular 2D video stream with associated depth maps to autostereoscopic displays will be included in the new MPEG-C standard, ISO/IEC 23002-3 (Bourge et al., 2006).

3.3 Laser scanning aided by photogrammetry

The third level of integration is LS aided by photogrammetry. The main focus is on LS point clouds, though image data provide additional information. The most typical approach involves the colour coding of the laser point cloud. In this approach, the colour values are taken from registered images and are attached to 3D laser points. In addition, the textures can be extracted from images and attached to LS-derived 3D meshes. This approach is useful for creating detailed and photorealistic impressions even with quite an approximate mesh.
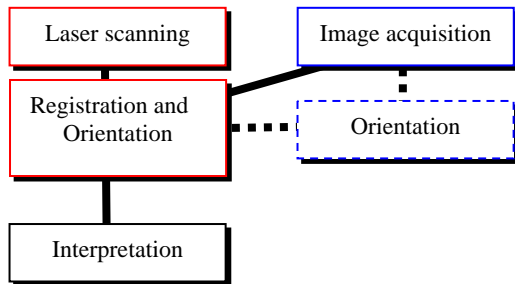

Figure 5. LS is aided by photogrammetry.

One interesting approach is the registration of separate terrestrial laser scans using the relative orientations of images from a camera integrated into a laser scanner (Al-Manasir and Fraser, 2006; Kang et al., 2007). Image-based registration provided better registration than the commonly used Iterative Closest Point (ICP) method (Al-Manasir and Fraser, 2006).

St-Onge and Achaichia (2001) proposed integrating laser-derived digital terrain models and photogrammetric tree height models to bring out the temporal aspect that is essential for many practical applications.

St-Onge (1999) overlaid the rectified multispectral videography onto the canopy height model to help in locating trees. He also suggested using imagery for providing information on tree species. Later (St-Onge and Achaichia, 2001), the canopy height models were extracted from historical aerial images bringing out the temporal variations of forests.

Matikainen at al. (2003) used colour information from aerial images to classify segmented ALS point clouds with fuzzy logic. Lichti (2005) classified TLS point clouds using the colours of terrestrial images together with near infrared information from TLS as input for the thematic classifier.

Persson et al. (2004) presented a method for tree species classification using integrated data. Individual trees were first extracted from the ALS data. Then, the corresponding spectral information was taken from near-infrared images and was used to separate different tree species.

Rönnholm et al. (2004) suggests that terrestrial images can be used for understanding how ALS data interact with various structures. Their examples illustrated cases in which ALS data underestimated tree heights.

3.4 Tightly integrated laser scanning and optical images

The last level of integration contains tightly integrated LS and optical images. The main difference between this level and the previous ones is that registration after data acquisition is unnecessary. Typically, the laser scanner and camera are integrated at the device level by mounting both sensors rigidly on the same platform. After system calibration, the relationship between LS data and images is known. However, the data can be used identically to three other levels of integration. The trend in the development of laser scanners is towards tightly integrated systems.
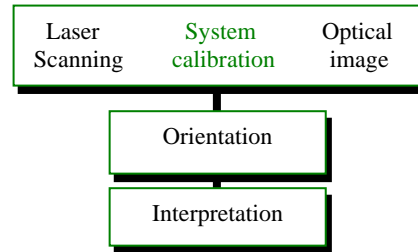

Figure 6. Tightly integrated laser scanning and photogrammetry with simultaneously data acquisition.

The first impression is that in each case when the laser scanner and camera are attached to a common platform, the system is tightly integrated. In principle, this is the case. However, there is some doubt as to whether all TLS devices with externally mounted cameras and mobile systems can truly be categorized as tightly integrated, or whether they are only approximately integrated. In the case of TLS, the point density can be very high. Thus, the registration of images and LS data should be accurate. In many cases, the position of the camera slightly changes when the camera is remounted onto the system, creating the need for on-site system calibration. Laser scanners that are based on triangulation can be categorised with more certainly as tightly integrated systems.

Despite a few exceptions (e.g. Zhao and Shibasaki, 2003), current air- and vehicle-borne mobile systems typically employ frame-based image acquisition and non-frame-based laser scanners. Even if the location of the laser scanner can be accurately known at the time of image exposure, the scanner can take only a few observations before the location is changed. Therefore, a laser point cloud that covers the footprint of the image can have non-homogeneous internal geometry, and the data acquisition perspective is changing continuously.

The most desired application would be a simultaneously taken frame-based optical and range images. In applications that require high accuracy, the data acquisition of both methods should share the same line of collimation. The imaging system based on focal plane arrays fulfils these demands (Steinvall,

2003). Frame-based 3D range cameras using the time-of-flight principle already exist, such as SwissRanger, in which the optical image and range information can be collected simultaneously. Thus, the resolution of the range image is still low compared to optical images.

4. EXAMPLES OF INTEGRATING ALS DATA AND IMAGES, EXPERIENCES AT TKK

In this section, we present our experiences in integrating LS with images at the Helsinki University of Technology (TKK). All registrations of ALS point clouds and terrestrial or oblique images are solved using the interactive orientation method (Rönnholm et al., 2003).

4.1 Coloured point clouds

Coloured point clouds can be very photorealistic if the viewing distance is set to meet the resolution of the LS data (Fig. 7). With some limitations, increasing the point size can fill the gaps between individual points in visualizations. Image data can also include information from various bandwidths. In Fig. 8 false-colours from UltraCam-D are associated with the ALS point cloud. The point cloud is visualized with both ortho and perspective projections.

Figure 7. Top: coloured 3D ALS point cloud looks photorealistic when viewed from a distance that meets the resolution of ALS data. Bottom: the structure of the ALS point cloud becomes visible when the viewing location is close enough. The images are created with TerraScan.
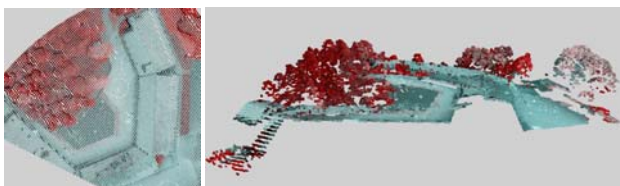

Figure 8. False-colours from UltraCam-D's digital aerial images have been associated with the laser point cloud. Left: the point cloud in ortho projection. Right: perspective side view.

4.2 The significance of the perspective

Typically, LS data and images are acquired as closely as possible from the same perspective. Such data acquisition is ideal for colouring LS point clouds, because each LS point is separately visible when superimposed onto an image. In addition, both sensors can see all objects identically with no shadows caused by perspective differences. Fig 9. illustrates the typical integration of ALS and an image. In this case, all low points are discarded leaving only upper tree canopies, street lamps, and signs visible. Because the perspective of both data sets is very close to each others, it is easy to detect planimetric correspondences. Using single images, the height correspondences can be inspected only at the sides of the images. For practical purposes, however, stereo images are needed.
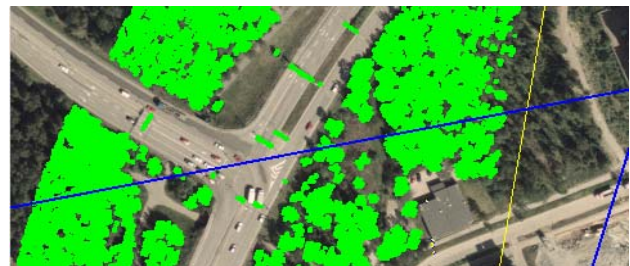

Figure 9. Typical integration of orthoimage and an ALS point cloud (TopoSys-1).

If the LS point cloud is integrated with an image that has a different acquisition perspective, the vertical structure of LS data is seen (Fig. 10). Because of perspective differences some LS points have no corresponding feature in the image, because they are located at the backside of a solid object.
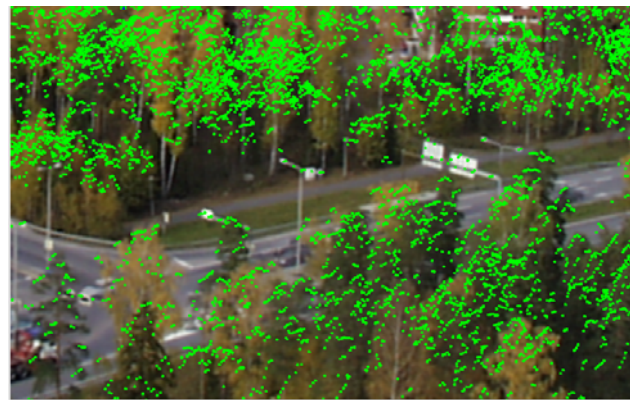

Figure 10. The vertical structure of the ALS point cloud (TopoSys-1) is visible, when data is superimposed onto an oblique image.

Fig. 11 illustrates the usefulness of stereo images when examining LS point clouds. Using stereovision enables comparison of the 3D correspondences between optical images and LS data. In addition, possible gaps in the LS data can be filled with photogrammetric stereo measurements. On the other hand, the LS can also assist in the interpretation of images. For example, the altitude-based colour coding of LS data attaches the height scale to the images, thus allowing the relative heights of objects, at very different distances from the camera, to be understood more easily.
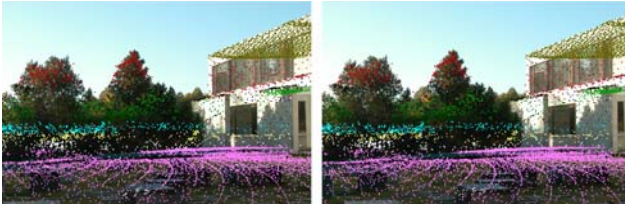
Figure 11. Cross-eye stereo images with superimposed LS point cloud (TopEye MK-II).

4.3 Comparing more than one LS data sets on the image plane

Sometimes, it is advantageous to compare LS point clouds from different devices. Laser scanners produce point clouds that can differ in density, accuracy and distribution. Comparison with the image as a background (Fig. 12) can help significantly, when the usability of point clouds is evaluated for some specific purposes.
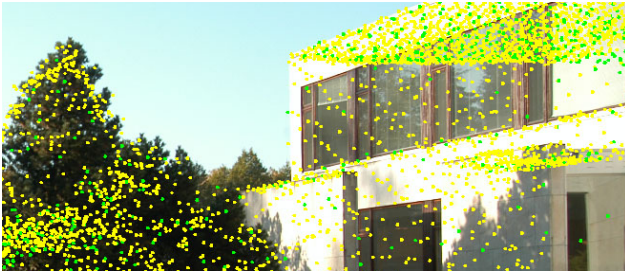

Figure 12. Comparison of two TopEye's laser scanners: yellow (TopEye MK-II), green (TopEye).

In Fig. 13 Toposys-1 data from 800 m and Topeye data from 200 m flying height are superimposed onto the image. Because the data sets are collected at different years, some temporal changes can be detected: two deciduous trees in the middle do not have any hits in TopEye data (black spots).
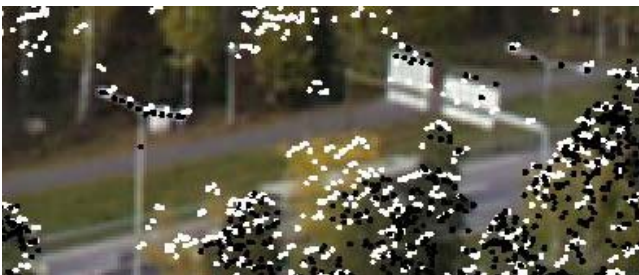

Figure 13. White spots (TopoSys-1) are scanned from 800 m with a pulse repetition rate of 83 kHz and black points (TopEye) are scanned from 200 m at a scanning rate of 7 kHz. (Rönnholm et al., 2003)

4.4 Understanding LS data using images

In Fig. 14a, a perspective side view of the ALS point cloud gives the impression of a building. When the point cloud is superimposed onto the image (Fig. 14b), we gain additional information on the building, such as the textures of facades, the amount of floors and the temporary structure on the roof build to cover repairs, for example. After half a year, the temporary structure is removed from the roof, though its shape remains in the ALS data (Fig. 14c). This example reveals one disadvantage

of LS, if it is used without any other information source: range information alone is not enough for advanced understanding of target.
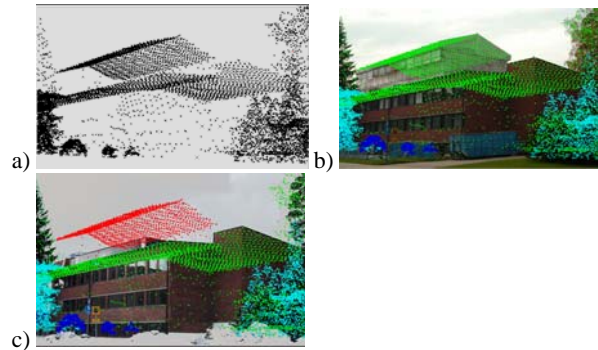

Figure 14. a) Perspective view of the ALS point cloud b) ALS data is integrated with the terrestrial image c) after half a year, the temporary structure was removed from the roof.

In Fig. 15, the full-waveform LS data is superimposed onto the image. Close-range images are the most suitable reference for increasing our understanding of waveform data and extracting the most interesting echoes from the entity (Litkey et al., 2007).

Figure 15. Full-waveform ALS data is superimposed onto the terrestrial image (Litkey et al., 2007).

5. DISCUSSION AND CONCLUSIONS

Integration of LS and photogrammetry is an essential step towards being able to provide accurate and photorealistic 3D modelling methods. LS alone does not include enough information for an advanced understanding of the target. Combined use of all variations of optical imagery and all properties of LS data will provide us with material for robust classification and interpretation of our surroundings. The intensity information for LS should be calibrated (Kaasalainen et al., 2007) if it is to be used for automatic classification.

Registration provides the fundamental basis for any integration. Incompletely registered data sets may disturb automatic decision-based algorithms. In addition, misalignments are easily seen during visualizations giving an unreliable impression of the accuracy of the entire data. Accurate registration, especially automatic ones, is not an easy task. Although functional examples of registration methods exist, there is still need for developing more robust and computationally more feasible methods.

Integration, in this context, can be divided into four levels: object-level integration, photogrammetry aided by laser scanning, laser scanning aided by photogrammetry, and tightly integrated laser scanning and optical images. We have discussed these levels of integration and given some illustrative examples. More examples can be found, e.g., from Kaartinen et al. (2006). The full potential of integration is, however, not yet utilised and more research is needed on this subject.

In the future, 3D modelling systems that have tightly integrated LS and images will become increasingly popular. The final revolution in 3D modelling will occur when frame-based LS devices are developed to meet the resolution of optical images. Although the resolution of frame-based range sensors is currently too coarse for accurate modelling, the direction of development is obvious. It will, probably, take considerable before such 3D ranging cameras can be used for commercial aerial data acquisition.

In some conditions, LS and images must be acquired separately. For example, when the laser scanner is an active sensor, the lightning conditions do not prevent measuring campaigns. Commercially, it is not tempting to wait proper weather conditions for optical images, if LS could operate. To conclude, the need for robust registration methods will not disappear even if the devices become highly integrated.

In addition to integrating of images and LS data, other sources, such as geodetic observations, maps, and CAD design models should also be used. Complete integration of all available data sources would be beneficial in the fields of mapping, planning, constructions, simulation, and in the entertainment industry, to just mention a few.

6. REFERENCES

Abdelhafiz A., Riedel B., Niemeier W., 2005. "3D Image" As a Result From the Combination Between the Laser Scanner Point Cloud and the Digital Photogrammetry. In: *Optical 3-D Measurement Techniques VII*, Volume 1, pp. 204-213

Al-Manasir, K. and Fraser, C., 2006. Registration of Terrestial Laser Scanner Data Using Imagery. *The Photogrammetric Record* 21(115), pp. 255-268.

Blais, F., 2004. Review of 20 Years of Range Sensor Development. *Journal of Electronic Imaging,* 13(1), pp. 231-240.

Boehler, W., Bordas Vicent, M. and Marbs, A., 2003. Investigating laser scanner accuracy. In: *Proc.* of *XIXth CIPA Symposium,* Antalya, Turkey, 30 Sept. – 4 Oct. 2003.

Bourge, A., Gobert, J. and Bruls, F., 2006. MPEG-C Part 3: Enabling the Introduction of Video Plus Depth Contents. In: *Workshop on "Content generation and coding for 3D-television"* June 2nd 2006, Eindhoven, The Netherlands.

Elstrom, M., Smith, P. and Abidi, M., 1998. Stereo-Based Registration of Ladar and Color Imagery. In: *Proceedings of the SPIE Conference on Intelligent Robots and Computer Vision XVII: Algorithms, Techniques, and Active Vision*, 3522, pp. 343-354.

Fehn, C., Kauff, P., Op de Beeck, M., Ernst, F., IJsselsteijn, W., Pollefeys, M., Van Gool, L., Ofek, E., and Sexton, I., 2002. "An Evolutionary and Optimised Approach on 3D-TV". In: *Proceedings of International Broadcast Conference*, Amsterdam, The Netherlands, September 2002, pp. 357-365.

Forkuo, E. and King, B., 2004. Automatic Fusion of Photogrammetric Imagery and Laser Scanner Point Clouds. In: *Int. Archives of Photogrammetry, Remote Sensing*, Vol. XXXV, pp. 921-926.

Haala, N. and Brenner, C., 1999. Extraction of Buildings and Trees in Urban Environments, *ISPRS Journal of Photogrammetry and Remote Sensing*, 54(2-3), pp. 130-137.

Habib, A., Ghanma, M., Morgan, M., and Al-Ruzouq, R., 2005. Photogrammetric and Lidar Data Registration Using Linear Features, *Photogrammetric Engineering & Remote Sensing*, Vol. 71, No. 6, pp. 699-707.

Habib, A. and Schenk, T., 1999. A New Approach for Matching Surfaces from Laser Scanners and Optical Scanners. In: *Int. Archives of Photogrammetry and Remote Sensing*, Vol. XXXII, pp. 55-61.

Harman, P., 2000. Home Based 3D Entertainment – An Overview. In: *Proceedings of International Conference on Image Processing, ICIP00, Vol I*, pp. 1-4.

Heipke, C., Jacobsen, K., Wegmann, H., Andersen, H., and Nielsen Jr., B., 2002. Test Goals and Test Set Up for the OEEPE Test "Integrated Sensor Orientation". In: *Test Report and Workshop Proceedings*, OEEPE, Official Publication No. 43, pp. 11-18.

Hyyppä, J., Pyysalo, U., Hyyppä, H., Samberg, A., 2000, Elevation accuracy of laser scanning-derived digital terrain and target models in forest environment. In: *20th EARSeL Symposium and Workshops, Dresden, Germany, 14-17 June, 2000*, pp. 139-147.

Jansa, J., Studnicka, N., Forkert, G., Haring, A., Kager, H., 2004. Terrestrial Laserscanning and Photogrammetry – Acquisition Techniques Complementing One Another. In: *International Archives of Photogrammetry and Remote Sensing*, Vol XXXV, Part B/7, pp. 948-953.

Kaartinen, H. and Hyyppä, J., 2006. Evaluation of Building Extraction. In: *EuroSDR, Official Publication* No. 50, pp. 9-110.

Kaasalainen, S., Hyyppä, J., Litkey, P., Hyyppä,, H., Ahokas, E., Kukko, A., and Kaartinen, H., 2007. Radiometric Calibration of ALS Intensity. In: *Int. Archives of Photogrammetry and Remote Sensing* (this workshop proceeding).

Kang. Z, Zlatanova, S. and Gorte, B., 2007. Automatic Registration of Terrestrial Scanning Data Based on Registered Imagery. In: *Proc. 2007 FIG Working Week*, 13-17 May 2007, Hong Kong SAR.

Katzenbeisser, R., 2003. Technical Note on: Echo Detection. http://www.toposys.de/pdf-ext/Engl/echo-detec3.pdf (10 May 2007).

Kern, F., 2001. Supplementing Laserscanner Geometric Data with Photogrammetric Images for Modelling. In: *Int. Symposium CIPA*, pp. 454-461.

Lichti, D., 2005. Spectral Filtering and Classification of Terrestrial Laser Scanner Point Clouds, *The Photogrammetric Record* 20(111), pp. 218-240.

Lichti, D. and Licht, G., 2006. Experiences with Terrestrial Laser Scanner Modelling and Accuracy Assessment. In: *International Archives of Photogrammetry, Remote Sensing*, Vol XXXVI, Part 5, pp. 155-160.

Litkey, P, Rönnholm, P., Lumme, J., Liang, X., 2007. Waveform features for tree identification. In: *Int. Archives of Photogrammetry and Remote Sensing* (this workshop proceeding).

Matikainen, L., Hyyppä, J. and Hyyppä, H., 2003. Automatic Detection of Buildings from Laser Scanner Data for Map Updating. In: *International Archives of Photogrammetry, Remote Sensing*, Vol XXXIV, Part 3W13, pp. 218-224.

Parian, J. and Gruen, A., 2005. Integrated Laser Scanner and Intensity Image Calibration and Accuracy Assessment. In: *Int. Archives of Photogrammetry and Remote Sensing*, Vol. XXXVI, part 3/W19, pp. 18-23.

Pfeifer, N., Gorte, B. and Elberink, S., 2004. Influences of Vegetation on Laser Altimetry – Analysis and Correction Approaches. In: *Int. Archives of Photogrammetry, Remote Sensing*, Vol. XXXVI, part 8/W2, pp. 283-287.

Postolov, Y., Krupnik, A. and McIntosh, K., 1999. Registration of Airborne Laser Data to Surfaces Generated by Photogrammetric Means. In: *Int. Archives of Photogrammetry and Remote Sensing*, Vol. XXXII, part 3W14, pp. 95-99.

Persson, Å, Holmgren, J., Söderman, U., and Olsson, H., 2004. Tree Species Classification of Individual Trees in Sweden by Combining High Resolution Laser Data with High Resolution Near-Infrared Digital Images. In: *Int. Archives for Photogrammetry and Remote Sensing,* Vol. XXXVI, Part 8/W2, pp. 204-207.

Ressl, C., Haring, A.,Briese, C., and Rottensteiner, F., 2006. A Concept For Adaptive Mono-Plotting Using Images and Laserscanner. In: *Int. Archives for Photogrammetry and Remote Sensing*, Vol. XXXVI/3, pp. 98 - 104.

Roux, M., 2004. Registration of Airborne Laser Data with One Aerial Image. In: *Int. Archives of Photogrammetry and Remote Sensing*, Vol. XXXV, pp. 1043-1048.

Rönnholm, P., Hyyppä, H., Pöntinen, P., Haggrén H. and Hyyppä, J., 2003. A Method for Interactive Orientation of Digital Images Using Backprojection of 3D Data. *The Photogrammetric Journal of Finland*, Vol 18, No. 2, pp. 58-69.

Rönnholm, P., Hyyppä, J., Hyyppä, H., Haggrén, H., Yu, X., and Kaartinen, H., 2004. Calibration of Laser-derived Tree Height Estimates by means of Photogrammetric Techniques, *Scandinavian Journal of Forest Research*, Vol. 19, No. 6, pp. 524-528.

Schenk, T., 2001. Modeling and Analyzing Systematic Errors of Airborne Laser Scanners. *Technical Notes in Photogrammetry* No. 19, Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, Columbus, OH., 40 pages.

Schenk, T. and B. Csatho, 2002. Fusion of Lidar Data and Aerial Imagery for a More Complete Surface Description. In: *Int. Archives of Photogrammetry and Remote Sensing*, XXXIV/3A, pp. 310–317.

Smith, P. and M. Elstrom, 1999. Automatic Feature Correspondence for Scene Reconstruction from Multiple Views. In: *2nd international conference on 3-D digital imaging and modeling, IEEE proceeding, Ottawa, Canada*, pp. 463-472.

St-Onge, B., 1999. Estimating Individual Tree Heights of the Boreal Forest Using Airborne Laser Altimetry and Digital Videography. In: *International Archives of Photogrammetry and Remote Sensing*, Vol 32, part 3-W14, pp. 179-184.

St-Onge, B, and Achaichia, N., 2001. Measuring Forest Canopy Height Using a Combination of Lidar and Aerial Photography Data. In: *International Archives of Photogrammetry and Remote Sensing*, XXXIV-3/W4. pp. 131-137.

Steinvall, O., 2003. Laser Systems for Vegetation and Terrain Mapping – a Look at Present and Future Technologies and Capabilities. In: *Proceedings of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests*, September 3.-4. 2003 Umeå, Sweden, pp. 8–19.

Wagner, W., Ullrich, A., Melzer, T., Briese, C., and Kraus, K., 2004. From Single-Pulse to Full-Waveform Airborne Laser Scanners: Potential and Practical Challenges. In: *Int. Archives of Photogrammetry and Remote Sensing*, Vol. XXXV, pp. 201-206.

Wehr, A. and Wiedemann, A., 1999. Fusion of Photogrammetric and Laser Scanner Data. In: *Int. Archives for Photogrammetry and Remote Sensing*, Vol. XXXIV, Part 5C1B.

Wendt, A. and Heipke, C., 2006. Simultaneous Orientation of Brightness, Range and Intensity Images. In: *Image Engineering and Vision Metrology, ISPRS Commission V Symposium, Dresden, 25.-27. September 2006*, pp. 315-322.

Zhang, A., Hu, S., Jin, X., Sun, W., 2005. A Method of Merging Aerial Images and Ground Laser Scans. In: *Geoscience and Remote Sensing Symposium. IGARSS '05*, pp. 222-225.

Zhao, H. and Shibasaki, R., 2003. Reconstructing a Textured CAD Model of an Urban Environment Using Vehicle-Borne Laser Range Scanners and Line Cameras. In: *Machine Vision and Applications*, vol. 14, no. 1, pp. 35-41.

Zitova, B, Flusser, J., 2003. Image Registration Methods: a Survey. In: *Image and Vision Computing*, No. 21, pp. 977-1000.

7. ACKNOWLEDGEMENTS