REGISTRATION OF AIRBORNE LASER SCANNING POINT CLOUDS WITH AERIAL IMAGES THROUGH TERRESTRIAL IMAGE BLOCKS

Petri Rönnholm[a], Eija Honkavaara[b], Anna Erving[a], Milka Nuikka[a], Henrik Haggrén[a],
Sanna Kaasalainen[b], Hannu Hyyppä[a], Juha Hyyppä[b]

[a]Helsinki University of Technology, P.O. Box 1200, FI-02015 TKK, Finland – first.lastname@tkk.fi
[b]Finnish Geodetic Institute, Geodeetinrinne 2, P.O. Box 15, FI-02431 Masala, Finland – first.lastname@fgi.fi

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ABSTRACT:

Integration of airborne laser scanning (ALS) point clouds and aerial images has a great potential for accurate and robust 3D modeling and recognition of objects in our environment. The integration requires, however, an accurate registration of data sources, which cannot be yet achieved by direct georeferencing using both the GPS and IMU. This research paper presents a method for registering aerial images with ALS data and for evaluating the accuracy of existing registration. An aerial image is included into a multi-scale image block, in which relative orientations of terrestrial close range images and aerial images are then known from the bundle block adjustment. Close range images provide more detailed view of possible tie features and also a new perspective compared to aerial images. For the actual registration of ALS data and image block, one or more images of the block can be chosen. Selected images can include only close range images or both close range images and aerial images. For the registration, the interactive orientation method was used. When selected images are registered with ALS data, the exterior orientations of all other images of the block can be calculated from the known relative orientations. Accuracies of interactive orientations were examined using the reference ALS point cloud that was transformed to the known geodetically determined coordinate system. The coordinate transformation was solved by applying the iterative closest point (ICP) method between the ALS data and the photogrammetrically derived 3D model, the absolute orientation of which was known. Before making experiments of interactive registration, the absolute orientation of the image block was changed in order to get incorrect initial orientation. The final results of interactive orientations were compared with the original orientation information from the bundle block adjustment. The comparison indicated that including an aerial image with a terrestrial image block, the registration of ALS data and aerial images can be improved or verified. The accuracy of the interactive registration was depended on selected images that were used in registration. The maximum differences between original and interactively solved locations of the aerial image varied between 2.3 and 9 cm.

1. INTRODUCTION

Integration of airborne laser scanning point clouds and aerial images has a great potential for accurate and robust 3D modeling and recognition of objects in our environment. These two data sources are in many ways complementary to each other but, in addition, also overlapping technologies. When any applications based on data integration are used, however, the registration of data sets should be as accurate as possible. Unsuccessful registration, in worst cases, may cause misleading information and even degenerate the accuracy of final application (Rönnholm et al., 2007).

Applications utilizing registration between images and ALS data include e.g. colorizing laser point clouds, creation of orthophotos, quality control, automatic classification and interpretation, and densification of laser data using image observations. Images can be taken either during laser scanning or in unrelated campaign. It is typical that the operational requirements are very different for laser scanning and photographing, and separate data acquisitions are therefore preferable. ALS data can also be acquired at night-time and aerial images can be collected from substantially higher altitude than laser data.

Images and ALS data are typically oriented separately to the ground coordinate system, which can lead to an inaccurate relative orientation. Currently, the main alternative for solving exterior orientations of images is aerial triangulation (AT) utilizing image points, 3D ground features and possibly direct georeferencing (DG) observations of orientations. For ALS data, DG is often applied alone utilizing direct GPS/IMU measurements of the exterior orientations and the existing sensor calibration information (Heipke et al., 2002).

Even if highly accurate georeferencing can be achieved using AT, some distortions usually remain, which may cause local systematic distortions of several pixels (Alamus et al., 2006; Honkavaara et al., 2006b; Cramer, 2007; Spreckels et al., 2007). Processes for solving absolute orientation for ALS data using ground control are still at early stage, except for solving correct datum.

In theory, the accuracy of directly measured exterior orientations with high performance systems is at least 5-10 cm in position and better than 0.006° for ω and φ, and 0.01° for κ in rotations (Kremer, 2001; Heipke et al., 2002; Honkavaara *et al.*, 2003; Hutton et al., 2007). The problems with the DG, however, are that inaccuracies of the imaging model, insufficient satellite visibility, relative orientation of the imaging sensor and GPS/IMU-component, and the transformations between various coordinate systems propagate directly to the ground coordinates. This has been verified by analog photogrammetric frame sensors (Honkavaara et al., 2003; Jacobsen, 2004; Merchant et al., 2004) and the results with the first generation digital photogrammetric sensors indicate similarly unmodeled distortions as well (Honkavaara et al., 2006a; Cramer, 2007). In addition, there is not usually any control of the accuracy of the DG solution.

There is still a lack of direct methods for solving a relative orientation between an ALS point cloud and an aerial image. The main problem in solving the relative orientation of airborne laser scanning data and aerial images is that the density of data sampling is typically different. The low point density of ALS data (<100 points/m^2) makes it difficult to find directly conventional tie features, such as point and line targets. In practice, such targets can be found accurately only using indirect methods, such as intersection of planes (e.g. Vosselman, 1999; Schenk et al., 2001) or finding perspectively invariant geometric primitives, such as centers of circular objects. In addition, the internal geometry of digital images is much more robust than that in airborne laser data. ALS data also includes noise and other internal distortions (e.g. Schenk, 2001), which can distract the accurate feature extraction.

Aerial images are typically taken at a long distance from the ground, which causes limitations to obtained accuracies of photogrammetric measurements (Kraus, 2003). Having long distance to images and low point density in ALS data, it is difficult to have robust process for relative orientation. Close range images have more potential to see targets in detail than aerial images. In addition, a different viewing perspective gives new possibilities to improve existing initial registration of ALS data and images. Our previous experiences have revealed that superimposing ALS point clouds onto terrestrial images illustrates misalignment of registration, which can be detected and corrected (Rönnholm et al., 2003; Rönnholm et al., 2004; Litkey et al., 2007).

We have developed a concept, in which airborne laser scanning data and aerial images can be registered locally through terrestrial image blocks. The first step is to calculate bundle block adjustment that includes both aerial and terrestrial images (Zhu, 2007). Even if the images within the block are in different scales, same features are visible and detectable. After the creation of image block, all images are in the same coordinate system.

Registration of images and airborne laser scanning data can be applied using only terrestrial images or using both terrestrial and aerial images simultaneously. Close range images enable the detection of small details of objects, whereas aerial images cover larger areas providing a more general view. The image block should include several images in order to ensure sufficient geometry for the adjustment. In this paper, the registration of ALS point cloud and image block is solved using interactive orientation method that is previously validated to be suitable for registering laser point clouds and individual images (Rönnholm et al., 2003). Besides of actual registration, the concept is also usable for verification of existing registration.

In addition, an experiment of ICP (Iterative Closest Point) registration method with an image-derived 3D model and ALS point cloud is presented. The results of this approach were compared with the results from interactive registration of multi-scale image block and ALS data.

As an example of data integration after the registration, an ALS point cloud is colorized using image information. In this case, the colorized ALS point cloud differs from the typical, because both aerial and panoramic images were used as sources of colours. The selection, of which image type was used for colorizing, depended on visibility.

2. MATERIALS

The test area was chosen from the campus area of Helsinki University of Technology (TKK) in Otaniemi. The main area of interest was surroundings of TKK Amfi (Figure 1).

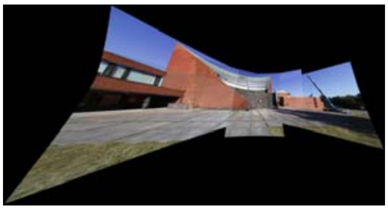

Figure 1. A panoramic image of TKK Amfi. Sub-images were taken concentrically using the special camera mount, which ensures the stationary projection centre.

Several kinds of digital cameras and images were used. Close range images were taken with Olympus E-10 and Nikon D200 with image sizes of 2240x1680 and 3872x2592 pixels, respectively. One panoramic image was created from a concentric image sequence acquired with Olympus Camedia c-1400 L. Concentric imagery was ensured using the special panoramic mount (Kukko, 2001; Pöntinen, 2002). The final size of the panoramic image was 10729 x 5558 pixels. An aerial image was taken with Hasselblad Landscape from the altitude of about 200 m. The sensor size of the Hasselblad camera was 3056x2032 pixels and one pixel corresponded to 4 – 4.5 cm in the ground, depending on the height of the object. Interior orientations of all cameras were known from camera calibrations.

TopEye MK I helicopter-borne laser scanner flights were carried out with the first pulse mode from the altitude of 200 m with the average point density of 2-3 points/m^2. In this research, two parallel and partially overlapping scanning strips were used. The scan angle of the TopEye MK I was ± 20°, wavelength was 1.064 μm and the pulse repetition rate was 7 kHz.

Data from Faro LS 880 HE80 was used for completing the photogrammetric 3D model. Faro LS 880 HE80 is a terrestrial laser scanner with the maximum measurement rate of 120000 pulses/s, wavelength of 785 nm, vertical field of view 320°, horizontal field of view 360°, and linearity error of 3 mm (at 25 m and 84 % reflectivity).

Ground control points in the local coordinate system were measured geodetically using Leica TCA 2003 tacheometer. For the measurements, total of 44 targets were used, including both 2x2 cm reflective targets by Leica and self-made photogrammetric targets.

3. METHODS

The interactive orientation method (Rönnholm et al., 2003) was extended to be able to handle more than one image during the orientation. Interactive orientation method includes tools for manipulating exterior orientation parameters as well as for setting and using anchor points. For orientations, a complete laser point cloud or a selected subset of laser points can be used as a tie feature. The usability of the method is at its best with airborne laser scanning data, when its coarse sub-sampling of the scene usually prevents accurate tie feature extraction from laser data.

Relative orientations of images were solved in the bundle-block adjustment of several images. The image block was multi-scale consisting close range images, a panoramic image and a low altitude aerial image. The orientation of the image block was solved using the iWitness software (Frasier and Hanley, 2004). iWitness recalculates the complete block adjustment when new observations are added. Therefore, the accuracy of previously calculated 3D model decreases, if more inaccurate images, such as aerial images, are included in the adjustment. To get accurate 3D model, the first image block included only normal close range images. The 3D model points from close range image observations were changed to be as reference points, before aerial image and panoramic images were included.

The photogrammetric 3D model of the stairs of TKK Amfi (Figure 2) was measured using 33 close range terrestrial images within one block and the scale of the model was solved using geodetically measured ground points. Signals were placed on the target and measured in 3D both with tacheometer and images.

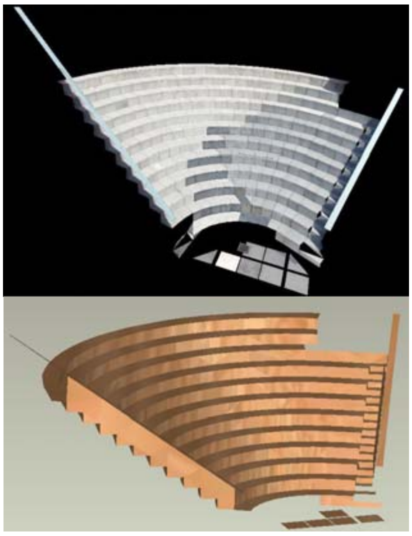

Figure 2. Photogrammetric models of the stairs of TKK Amfi. Top: photorealistic model from iWitness. Down: 3D model is imported and finalized in Geomagic Studio 9.0.

The laser point cloud from TopEye MK I was not aligned with the local coordinate system. When the point cloud was superimposed on the images, the misalignment was obvious. In order to get reference data, we used the Iterative Closest Point (ICP) method to register the laser point cloud with the photogrammetric model. Originally, the ICP method was developed for registering points-to-points (Besl and McKay, 1992), but in this case the registration between surfaces and points was applied (e.g. Chen and Medioni, 1992).

For the registration, both data sets were imported to Geomagic Qualify 9.0 software. Using the ICP method the distances between laser point cloud and photogrammetric model were minimized. Because the ICP method is highly sensitive with outliers, only laser points corresponding to the photogrammetric model were manually selected and used in registration. The laser point cloud was transformed into the coordinate system of the photogrammetric model.

When the transformed laser point cloud was superimposed on the images, it appeared that the symmetrical shape of TKK Amfi had caused problems. The coordinate systems of laser data and images had small rotation differences around the symmetrical centre of Amfi. The airborne laser data did not have enough information about the walls of the TKK Amfi for determination of rotation around Z-axis of the ground coordinate system.

In order to verify the applicability of ICP method in our case, much denser point cloud from Faro terrestrial laser scanner was used. The registration result was good, as expected, and also superimposing laser data on the images verified that no significant shift or rotation was detectable.

In order to get more features for registration, some planes were extracted from the terrestrial laser point cloud and merged with the photogrammetric model. These additional features were selected in a way that they were also included in the point cloud data. The registration of the merged model and airborne laser point clouds was calculated. The registration was solved separately to both laser scanning strips. Superimposing of transformed point clouds verified that the registration was successful and no improvement could be done using images.

The extended interactive orientation preserved the relative orientation of all used images. If one of the images is shifted or rotated, the new location of all other images are calculated.

4. RESULTS

4.1 Photogrammetric 3D model and image blocks

The photogrammetric 3D model was created using 33 close range images from 15 different camera stations (Figure 3). The final model of 735 measured points consisted of both photogrammetric and natural targets. Overall, the estimated standard deviation (std) of measured 3D point coordinates was 0.6 cm. Photogrammetric targets were measured with tacheometer and used as ground control points in the absolute orientation. The overall std of photogrammetric targets after the transformation was 0.3 cm. The accuracy of applied natural targets, which require more interpretation, was lower than the accuracy of photogrammetric targets. In order to assist interpretation, also lines were used for finding corner points.

All 735 points from the close-range model were set as reference points, before panoramic and aerial image were included in the image block. In addition, 100 new tie points were measured to improve image block geometry. However, only part of the original 735 3D points was measured from panoramic and aerial images. Overall, the estimated accuracy of 3D point coordinates was 1.2 cm.

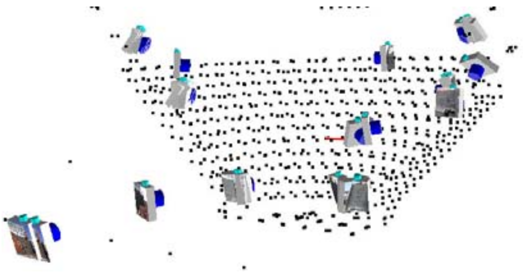

Figure 3. The geometry of the close range image block. The panoramic image and the aerial image are not yet included in the block.

4.2 Registration using the Iterative closest point (ICP) method

The photogrammetric 3D model of the stairs of TKK Amfi was used as the reference for ICP-based registration. The average error was 2.5 cm after the registration. When resulting ALS point cloud was superimposed into images it was obvious that the registration was not accurate (Figure 4). It appeared that the ALS data did not include enough points from the vertical structures of the photogrammetric 3D model allowing false rotation.

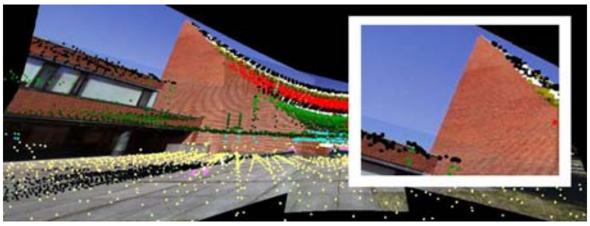

Figure 4. Superimposing the ALS point cloud, which was registered with photogrammetric 3D model using the ICP method, on the panoramic image illustrates how the registration is not successful, but includes some rotation.

A denser point cloud from Faro terrestrial laser scanner was relatively easy to register with photogrammetric 3D model. Some vertical planes were modeled from Faro data and merged with photogrammetric model (Figure 5). After applying the ICP method for registering ALS strips 13 and 14 with the merged terrestrial model, the average errors were 2.1 cm and 2.3 cm, respectively. Visual inspection with the terrestrial panoramic image revealed that registration was successful.

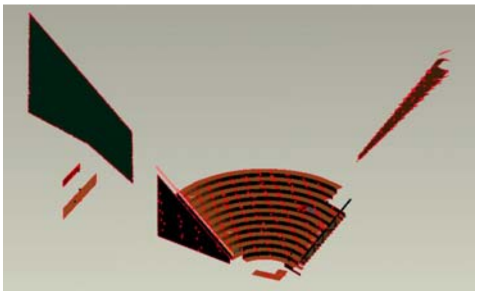

Figure 5. The flight-line 13 is registered to the combined 3D model created according to photogrammetric and terrestrial laser scanning observations.

4.3 Interactive registration using a panoramic image and aerial image

The applicability of the derived interactive orientation was examined using laser point cloud that was transformed to the known geodetically determined coordinate system. First, a panoramic image was used alone for the determination of registration between an image and laser point cloud. An exterior orientation of an aerial image was calculated according to the known relative orientation. The initial location and rotation of the panoramic image were randomly chosen. After the registration, the resulting exterior orientations were compared with known orientations of images from the original bundle block adjustment (Table 1). As a next step, both panoramic image and aerial images were used for registration. Again, the initial location and rotation of the image pair was arbitrary. The differences are presented in Table 2.

	Panoramic image	Aerial image
dX	4 cm	7 cm
dY	-2 cm	7 cm
dZ	5 cm	-9 cm
dOmega	-0.262 deg	-0.155 deg
dPhi	-0.096 deg	0.215 deg
dKappa	0.028 deg	0.123 deg

Table 1. Orientation differences (interactive - known). Only one panoramic image was used.

	Panoramic image	Aerial image
dX	10.7 cm	0.6 cm
dY	-3.4 cm	2.3 cm
dZ	-0.6 cm	1.8 cm
dOmega	0.009 deg	0.075 deg
dPhi	0.075 deg	0.010 deg
dKappa	0.003 deg	-0.003 deg

Table 2. Orientation differences (interactive - known). A panoramic image and aerial image were both used.

4.4 Registration using two close range images and aerial image

In the previous example, all six exterior orientation parameters were set as free. ALS data is typically too coarse for providing accurate breaklines making interpretation difficult. Because it was expected that rotations cause significant uncertainty to positioning of the camera, the interactive orientation of the leveled points was examined. The point cloud leveling is a common procedure, where the attitude of laser data is corrected using flat open areas and also heights are attached to local datum. In this example, the initial rotation of the image block was changed only around the ground Z-axis. The location of the image block was arbitrary. Also, the initial kappa rotation of the aerial image was deflected. The results of interactive orientation using two close range images and the aerial image are presented in Table 3 and Figure 6.

In this case, corrections of kappa rotation were done only around the z-axis of the aerial image. Even if the aerial image was very close to the case of nadir image, this might add small error to the results, which is most clearly visible when dZ values are examined.

	Close range image 1	Close range image 2	Aerial image
dX	-0.3 cm	0.9 cm	-3.7 cm
dY	-0.3 cm	2.2 cm	1.5 cm
dZ	0.9 cm	0.8 cm	1.0 cm
dKappa			0.002 deg

Table 3. Orientation differences (interactive - known). Two close range images and the aerial image were used.

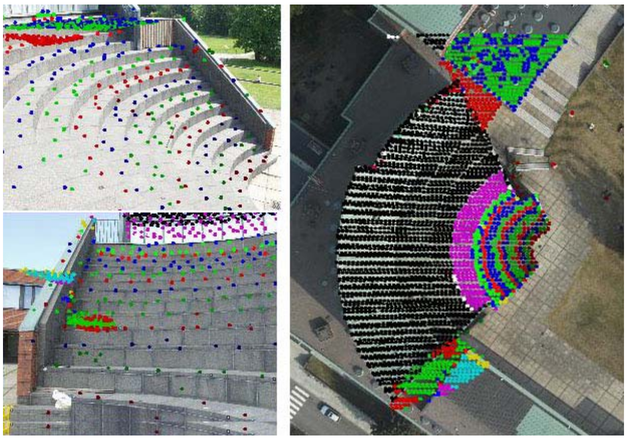

Figure 6. The results of the simultaneous registration of two close range images, the aerial image and the leveled ALS point cloud.

4.5 Colored ALS point cloud

The TopEye laser point cloud was colored after the registration was complete (Figure 7). Colors were selected either from aerial or terrestrial images. Terrestrial images were used only to acquire colors of the walls, which were not visible from the aerial image. Accurate coloring of laser points is not possible, if the registration is not successful.

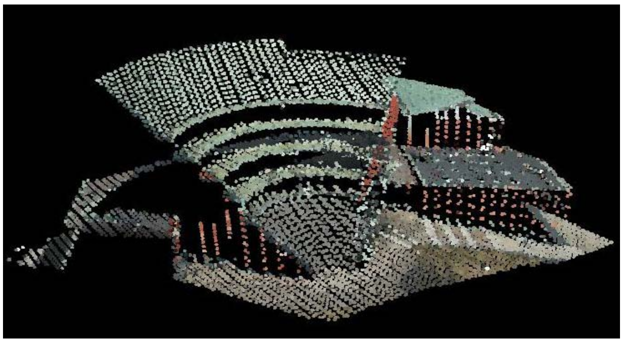

Figure 7. The laser point cloud was colored using two different image sources. The main part of points has got the color from the aerial image. However, the panoramic image was used as the color source for vertical structures when visible.

5. DISCUSSION

When multi-scale images are used, the geometry of an image block is not conventional. Observation accuracies from aerial images and close range images differ greatly. Therefore, the block of close range images should be processed and fixed before aerial images are included. Alternatively, it is possible to set more weight to the observations of close range images than to aerial images. The iWitness software, however, does not support user-defined weights for observations.

The footprint of an aerial image is wide whereas a close range image block typically covers much smaller area. Therefore, tie features of close range image block may be located at quite small area in the aerial image. However, it is easier to find good tie features between close range images and aerial images than between ALS point clouds and aerial images. In this research, only a low altitude aerial image was used and it is possible that high altitude aerial images should be connected to close range images partially through low altitude aerial images in order to gain most accurate relative orientation. Such multi-scale image block could be extended to cover images from close range images, through several aerial images of different altitudes up to satellite images.

One close range image block can provide registration information only from the area of limited size. Therefore, the registration is local. If strip-wise or global registration is needed, there should be more than one local registration.

The scale of the photogrammetric 3D model in this research was determined using geodetic observations. However, if the scale is solved using e.g. scale bars, registration of ALS data and multi-scale scale image block could be done using interactive orientation method without known ground points. This could be advantageous in the areas like forests, in which it can be difficult to make ground measurements.

One advantage of using the original ALS point cloud as a tie feature during the interactive orientation is that there is no need for filtering data or extract features, such as lines, from laser data. ALS data includes many small details that are usually lost when filtering is applied. These small details, however, are most useful during interactive fine-tuning of registration.

6. CONCLUSIONS

This research illustrated how registration of ALS point clouds and aerial images can be solved using interactive orientation and multi-scale image blocks, which also include terrestrial close range images. Accuracies of interactive orientations were examined using the reference ALS point cloud that was transformed to the known geodetically determined coordinate system. The coordinate transformation was solved by applying the ICP registration method between the ALS data and the photogrammetrically derived 3D model, the absolute orientation of which was known. The photogrammetrical 3D model was, however, extended with surfaces from terrestrial laser scanning in order to get more corresponding areas between data sources. Superimposing the ICP-registered ALS point cloud onto close range images was illustrative when the quality of registration was verified. Before making experiments of interactive registration, the absolute orientation of the image block was changed in order to get incorrect initial orientation. The final results of interactive orientations were compared with the original orientation information from the bundle block adjustment.

Relative orientation of multi-scale images is more robust, if the image block includes several images. For actual interactive orientation, only some images of the block are needed.

Typically, the requirements for placing of images are different for traditional photogrammetric measurements and for interactive orientation of ALS point clouds.

The registration of airborne laser scanning data and terrestrial images requires only one image, at minimum. However, the accuracy improves, if two or more images are used for registration or an aerial image is also included with orientation process. As a result, the shift differences of the exterior orientation of the aerial image, in ground coordinate system, were 7, -7 and -9 cm and "ω, φ, κ" -rotation differences were -0.155, 0.215 and 0.123 degrees, when only one terrestrial panoramic image was used. Differences when interactive orientation was done simultaneously using the panoramic image and the aerial image, were 0.6, 2.3, 1.8 cm in shifts and 0.075, 0.010 and -0.003 degrees in rotations.

The last example of interactive orientation was done using levelled data. This case is also realistic, because it is easy to level laser data using a flat terrain as the height reference, which results in well levelled data with the correct datum. This procedure, however, does not reveal planimetric shifts accurately. Therefore, improvement in the registration of levelled data is relevant. The interactive orientation was done using two close range images and the aerial image. The differences in shifts of exterior orientation of the aerial image were -3.7, 1.5 and 1.0 cm. The only rotation that was included in the experiment was the kappa of the aerial image with 0.002 degrees difference.

Registration accuracy of interactive orientation depends on the distance of targets, opening angle of image, number and location of interpretable targets in the image footprint and capability of an operator to understand the laser point cloud, for example.

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