ESTIMATION OF EXTERIOR PARAMETERS OF SENSOR COMBINATION FOR EFFICIENT 3D MODELING

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ABSTRACT:

Laser scanning is the latest method to collect 3D spatial data and modelling. It becomes more and more popular in engineering applications such as 3D modeling, deformation analysis, reverse engineering and urban planning. However, laser scanners are not sufficient on their own for 3D surveying and modeling. It should be used together with the photogrammetric data especially in the orientation of point clouds, measurement of the non-scanning areas, and texture mapping. This task needs the combination of range sensor and image sensor. The sensor combination like this is a very efficient and flexible system for close-range measurement applications. Most of the laser scanners include integrated camera but most of them are low resolution and they can not be removed independent from the scanner. Therefore high resolution camera should be mounted to the laser scanner. In this study we consider mounting a camera onto laser scanner and estimating exterior parameters with strong control methods. We also made experimental studies by using exterior parameters.

1. INTRODUCTION

3D modeling and visualizing is very important research area many engineering fields. Terrestrial laser scanning is latest method to close-range 3D measurement applications and it has been used many applications such as documentation of cultural heritage, deformation monitoring, planning and 3D modeling so far. Especially it has been used for documentation of cultural heritage as extensively. It scans the object surfaces as point series with very high speed and point density and visualized as point cloud. Measurement speed and accuracy, adjusting of point spaces and visualizing different form of point clouds are superior of it. It measures distance, intensity value, horizontal and vertical direction of scan point from the instrument. The points are represented in a local coordinate system centered in the laser scanner. In addition, it can be record colour to scanning points via image of integrated digital camera (Ressl, 2005; Pfeifer and Briese, 2007; Altuntaş and Yıldız, 2008).

The first important step in processes of terrestrial laser scanner (TLS) data is registration of point clouds and it has still important research area. The point clouds have been registered according to coordinate frame of selected one of them. Registration methods can be classified in three groups such as object based methods, target based methods and image based methods. Iterative closest point (ICP) (Besl and McKay, 1992; Chen and Medioni, 1992; Zhang, 1994) and Least square 3D matching (Gruen ve Akca, 2005) methods are the most used object based registration methods. Also extracted details from point clouds such as corner or line are used to registration of point clouds (Briese and Pfeifer, 2008; Deveau vd., 2004). Object based methods need significant geometric detail on scanning area. If there is no significant detail, registration will not be success probably. At the target based method artificial targets are signalized on the object before scanning (Akca, 2003; Scaioni, 2002). It spends extra time and labor. In addition, target selection is very hard from point cloud. Image based methods are applied to digital images from the camera attached on the laser scanner. Images include very dense texture data of object surfaces or scene. The point clouds were registered by relative orientation of the images taken by digital camera top on the laser scanner in Al-Manasir and Fraser (2006a). The accuracy of registration is achieved as 3mm by bundle adjustment on measurement of test plane. In another experiments, accuracies were achieved as σ_x=0.027m, σ_y=0.025m, σ_z=0.025m in control points. Also at that study point clouds were registered by bundle adjustment of the images of the object for all scans. Forkuo and King (2003) estimated exterior parameters by real and synthetic camera image and registered point clouds. The effect of bas/height ratio on registration accuracy also investigated. The registration errors are acquired as 2mm-7mm for x,y and 0.06m-0.09m for z coordinates to all test. Corresponding points are extracted by SHIFT (Lowe, 2004) method from the optical images and extracted laser scanner coordinates of them at Barnea and Filin (2007). Afterwards, registration was performed by points having been found by RANSAC method. A similar method was applied Harris operator (Harris and Stephens, 1988) in Forkuo (2005). Tournas and Tsakiri (2009) were also used the same method and root mean square of registered laser scanner points are evaluated as σ_x=1.7mm, σ_y=1.6mm, σ_z=2.4mm. Addition, there are many automatic registration method applied by image of digital camera attached to the laser scanner (Kang et al., 2009; Al-Manasir and Fraser, 2006b). Dold and Brenner (2006) used patch from point clouds to registration and improve registration by the image matching. Our research and findings are basically in line with these results.

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In addition, colour values to scanning points and photo realistic model can be created by digital camera and laser scanner sensor combination. Especially photo realistic model needs known image position. Since it has been known according to the laser scanner beforehand, it can be mapped to the point cloud directly without control points to registration of the images. Integrated digital cameras of TLSs are low resolution and not remove independent from the instrument. Because of that we must be use laser scanner together with high resolution digital camera. TLS manufacturers also offer mounting digital camera to the TLS.

Sensor combination of TLS and digital camera must be calibrated before use. Namely relative exterior parameters are estimated between TLS and image frame. It means solving 2D-3D registration problem. Al-Manasir and Fraser (2006a) attached Nikon D100 camera on Riegl LMS-Z210 laser scanner and estimated the parameters on vertical test plane. Camera calibration was done separately before estimation of exterior parameters. To test measurement, test plane was scanned from one station and taken image by the digital camera. Exterior parameters were estimated by collinearity condition on 79 points. In the similar, exterior parameters were estimated close to 0.5pixel accuracy by optical image and 2D range image obtained laser scanner point cloud at Aguilera et al.(2009) and Forkuo (2005). While the digital image has got 2D pixel data only, 2D range image has also 3D spatial information additionally. They were used laser scanning data of selected any object to estimate of exterior parameters instead of special test area. Corresponding points were extracted from images by Förstner operator then image and object point matched by RANSAC method and have been estimated the parameters by collinearity condition (Fischler and Bolles, 1981). At Aguilera et al. (2009), exterior parameters were estimated as 1.1 and 2.1 pixel accuracy for laser scanning to 50mm and 20mm point spaces respectively. Spatial parameters of the camera were acquired as 3mm and 1mm for two test respectively. In Forkuo (2005), the parameters are estimated with 2 pixel accuracies. Wendt and Dold (2005) designed three dimensional test area to estimate of exterior parameters. They made two test as together and separately of camera calibration and estimate of exterior parameter. They demonstrated that the camera calibration are the most important effect on parameter estimation and it has been made very accuracies independent from estimation of parameters.

In this study we present mounting a Nikon P50 camera on to the Ilris 3D laser scanner and estimation of exterior parameters between 3D laser scanner and 2D image coordinate system. Exterior parameters define rotation (ω,φ,κ) and translation (X_c,Y_c,Z_c) of camera coordinate system relation to the laser scanner in this study. Then exterior parameters are checked by three strong control methods and we made experimental studies.

2. MATERIAL AND METHOD

Nikon P50 camera was attached top on the Optech Ilris 3D laser scanner with a special instrument (Figure 1). The instrument makes it possible for us to move the camera independently from the laser scanner and mounted again as fixed. Unless the camera is fixed on the scanner, exterior parameters will change in each mounting, hence it requires estimate of exterior parameters again. So it is very important to ensure that the camera is fixed to the laser scanner.

The computing of exterior parameters requires that solving of the registration problem between 2D image and 3D scanner coordinates. It is carried out by collinearity equations. Scanning and imaging from one station of the test area is enough to solve the problem. Minimum three common points on image and scanner data are enough to calculate six unknown exterior parameters (X_c,Y_c,Z_c,ω,φ,κ). However, the solution has to be realized with much more points to improve the reliability and the sensitivity of the results. When the number of points have been increased, the solution should be performed iteratively with linearized least squares method. Since the focal length, principle point coordinates and radial distortion coefficients will be used by the collinearity condition, camera calibration has been made sensitively before estimation of exterior parameters.

Different test areas and techniques can be used to calculate exterior parameters. In this study, test area was designed on a flat wall. Camera calibration was separately performed before the parameter calculation. If it is required, the camera calibration can be performed together with the parameter calculation. In this situation, it necessitates distribution of test points on different planes (Wendt and Dold, 2005).

2.1 Camera Calibration

Camera calibration defines estimation of the focal length, principle point coordinates, pixel dimension and distortion parameters. Different test areas and techniques have been developed to calibration of digital cameras used in the terrestrial photogrammetry. Remondino and Fraser (2006) summarized that the results of camera calibration using different methods and investigated effects of radial distortion in different colours.

We used Topcon PI 3000 camera calibration software to the camera calibration. The calibration grid of the software was printed out A4 sheet and taken images from different angles with Nikon P50 camera. The calibration was carried out by evaluating the images on the basis bundle adjustment, it was achieved with 0.1micron accuracies. Distortion was computed with Equation (3) (Kraus, 207).

$$\Delta r = g_{13}.\rho.(\rho^2 - \rho_o^2) + g_{14}.\rho.(\rho^4 - \rho_o^4) \quad (1)$$

$$\rho = \sqrt{x^2 + y^2} \quad (2)$$

$$\Delta x = (\Delta r/\rho).x \; ; \; \Delta y = (\Delta r/\rho).y \quad (3)$$

Where; g_{13},g_{14} is radial distortion coefficients, ρ_o is 1.3872mm (usually ρ_o is set to approximately 2/3 maximum radius of inner circle of the image (Luhmann et al., 2007).), ρ is radial distance, x,y is image coordinates, Δx and Δy are effect of radial distortion on image coordinates.

2.2 Test Measurement

A special test area was constituted in the Photogrammetry Laboratory of Selcuk University to estimate the exterior parameters. 270 test points were marked at 20 cm intervals in an surfaces of 3x3.6m^2. The test points were marked by white marker with 3 cm diameter on black surface. The camera was attached top on the laser scanner by using special instrument. Laser scanner was set remove 5.5m distance from the test plane and the scanning was performed about 2mm point spaces on the object surfaces, and captured single image by the camera at the same time (Figure 1).

Figure 1. Test measurement

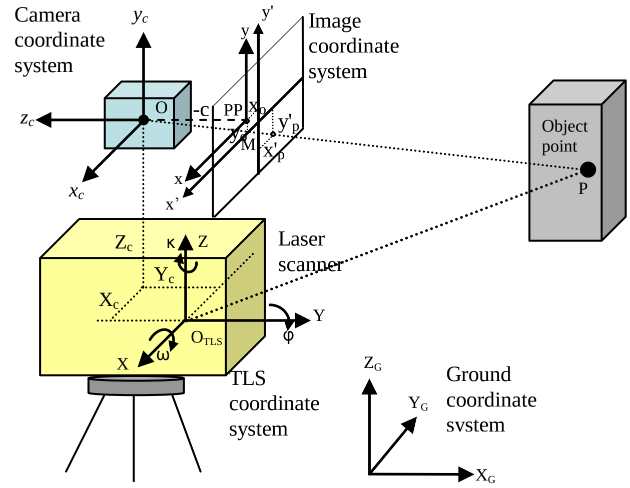

Figure 2. 2D image and 3D laser scanner reference frames

3. THE ESTIMATION OF EXTERIOR PARAMETERS

The estimation of exterior parameters is space resection problem and it has been solved by collinearity conditions as many problems in photogrammetry. Collinearity condition defines that the projection centre, image point, and the object point are lie in a line (Kraus, 2007). It can be extended by taking into account errors such as distortion error, refraction, earth sphericity, all of which have an impact on the picture coordinates.

The estimation of exterior parameters (X_c,Y_c,Z_c, ω,φ,κ) defines determine of camera position relation to the laser scanner coordinate frame and it has been solved by collinearity condition. It requires solving 2D-3D registration problem (Figure 2). Firstly, the scanner coordinates and the image coordinates of the test points were extracted. The code was developed in Matlab to ensure that the point coordinates from image and point cloud are exact from the centre of the target mark exactly. The scanner coordinates of the test points were extracted by intensity and range image (Karel and Pfeifer, 2009) created from the point cloud. The image coordinates were measured from centre of the target mark as pixel unit, and then registered to the image coordinate system, centre of that is principal point.

Equation (4) defines collinearity conditions between the image and laser scanner coordinates (Kraus, 2007). Effect of only the radial distortion on the image was taken into account in this study. As other distortion effects had been ignored because of their little effect.

$$x = x_o - c\frac{r_{11}(X-X_c)+r_{21}(Y-Y_c)+r_{31}(Z-Z_c)}{r_{13}(X-X_c)+r_{23}(Y-Y_c)+r_{33}(Z-Z_c)}+\Delta x$$

$$y = y_o - c\frac{r_{12}(X-X_c)+r_{22}(Y-Y_c)+r_{32}(Z-Z_c)}{r_{13}(X-X_c)+r_{23}(Y-Y_c)+r_{33}(Z-Z_c)}+\Delta y \qquad (4)$$

where; x,y is image coordinates, x_o,y_o is principal point coordinates related to the image centre, c is focal length, X,Y,Z is laser scanner coordinates, X_c,Y_c,Z_c is projection centre in laser scanner coordinate system, R is rotation matrix defined by Equation (5).

$$R = \begin{bmatrix} \cos\varphi.\cos\kappa & -\cos\varphi.\sin\kappa & \sin\varphi \\ \cos\omega.\sin\kappa+\sin\omega.\sin\varphi.\cos\kappa & \cos\omega.\cos\kappa-\sin\omega.\sin\varphi.\sin\kappa & -\sin\omega.\cos\varphi \\ \sin\omega.\sin\kappa-\cos\omega.\sin\varphi.\cos\kappa & \sin\omega.\cos\kappa+\cos\omega.\sin\varphi.\sin\kappa & \cos\omega.\cos\varphi \end{bmatrix} \qquad (5)$$

Error Equations (6) were constituted by linearized collinearity condition to unknown exterior parameters. The 540 error equations were written totally as one of x and y components of each point.

$$v_x = \frac{\partial x}{\partial X_c}dX_c + \frac{\partial x}{\partial Y_c}dY_c + \frac{\partial x}{\partial Z_c}dZ_c + \frac{\partial x}{\partial \omega}d\omega + \frac{\partial x}{\partial \varphi}d\varphi + \frac{\partial x}{\partial \kappa}d\kappa$$

$$v_y = \frac{\partial y}{\partial X_c}dX_c + \frac{\partial y}{\partial Y_c}dY_c + \frac{\partial y}{\partial Z_c}dZ_c + \frac{\partial y}{\partial \omega}d\omega + \frac{\partial y}{\partial \varphi}d\varphi + \frac{\partial y}{\partial \kappa}d\kappa \qquad (6)$$

To solving equation (6) we needs to know initial approximate values of the unknown parameters at the beginning. Here, initial values have been determined with respect to the position of image and laser scanner coordinate frame. If it is required, they can also be determined by computing. The iteration is continued by using the values found in the previous iteration to the following iteration until there are no further changes of the unknowns. The exterior parameters were estimated at the end of six iterations with rms error of 0.34 pixel or 0.58μm. Accuracies to each of the estimated exterior parameters has been given Table 1.

X_c (mm)	Y_c (mm)	Z_c (mm)	ω (sec.arc)	φ (sec.arc)	*κ (sec.arc)*
0.8	*0.1*	*0.9*	*1.85*	*1.56*	*0.30*

Table 1. Accuracies of estimated exterior parameters

4. CONTROL OF EXTERIOR PARAMETERS

Control 1: Point to pixel coordinates

The image coordinates of 270 test points were calculated from the laser scanner coordinates by using the exterior parameters. It has been drawn by computed coordinates on the image plane and controlled the coincidence with the signs (Figure 3). The residuals on image coordinates are about 5 pixel.

Control 2: Colour assignment from the image to the laser scanner points

In this control, colour values (red, green, blue) were assigned to all laser scanning points from the image taken by the camera. In other words, the laser scanning points were coloured using the image. To find colour values of the laser points, we compute point to pixel coordinates using exterior parameters and determine colours for it. Then laser scanning points recorded with new colours to VRML-format file.

At the same time, the second VRML file was created on the basis of the laser scanner coordinates and the intensity values of the points. These two image files were displayed via VRML viewer (Figure 4). As new colours of the laser scanning points were calculated with the exterior parameters, this process also enabled to check out estimated parameters.

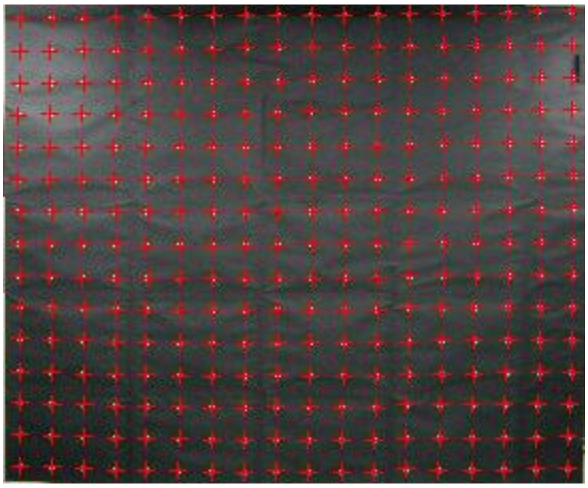

Figure 3. Computed image coordinates from laser scanning data on the image

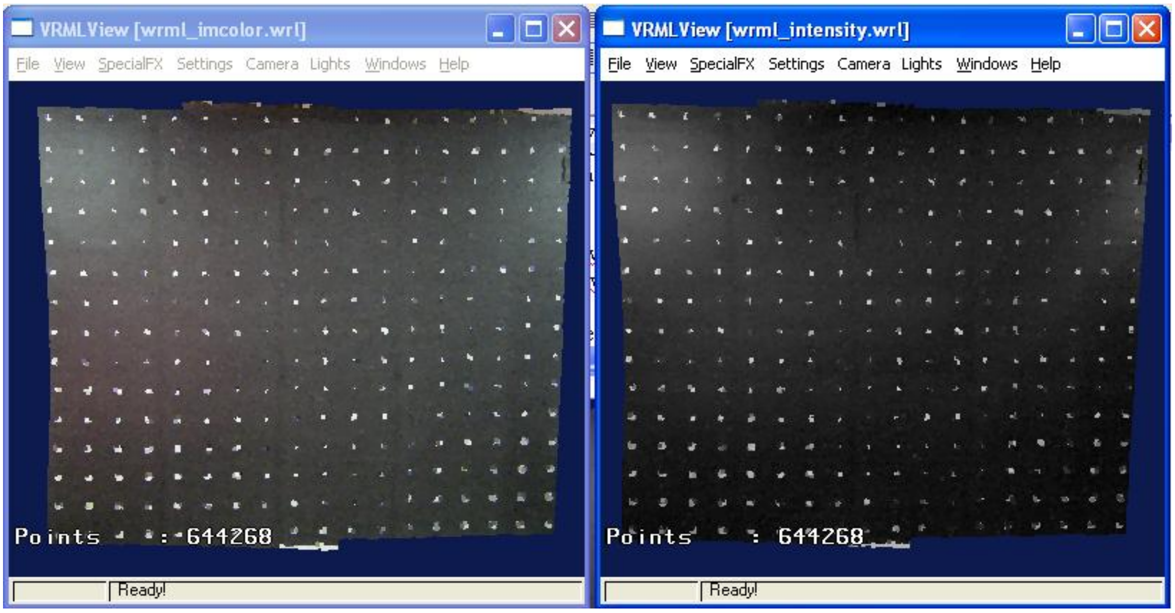

Figure 4. Laser scanning points with image colours and TLS intensities.

Control 3: Graphics of the image colours and intensity values of the point clouds

Image colours (from Nikon P50) and intensities (grey) (from Ilris 3D) of laser scanning have been shown on graphic. RGB colours have been converted to grey values. Thus, graphic of image grey and TLS intensity has been carried out. If exterior parameters are precise, this graphic should be expected a line with 45 degrees. As seen in Figure 5, the graphic represents a line which is close to ideal line, but some not linear behaviour can be seen. We conclude that this check indicates, that no gross error occurred and that the exterior parameters are estimated with high accuracy. If the parameters are inaccurate, a point on the light-coloured area in the image would have corresponded to the point on the dark-coloured area in the laser scanner data and it would have been randomly distributed on the graphic. The graphic include only a limited amount of scattered points. These scattered points may have been resulted from the beam reflection occurred during taking images and are a result of the different resolution of the devices.

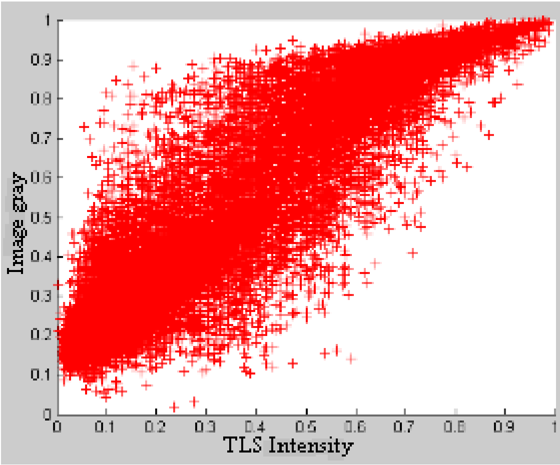

Figure 5. The graphic of relationship image colours and laser scanner intensities

5. EXPERIMENTAL RESULTS

We made image based point cloud registration using exterior parameters and the digital images taken by the camera mounted to the laser scanner. Test side was scanned from two stations (Figure 6). The digital image was captured by the camera while point clouds were being collected by laser scanner from the each stations. The point clouds of second station was registered by relative orientation (RO) of the images into coordinate frame of the first station. The registration results are compared with ICP with residuals on control points. The results have been shown precision of the estimated exterior parameters.

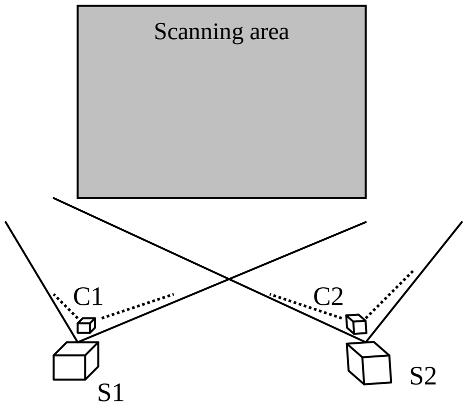

Figure 6. Measurement configuration to experiments

The images were captured while scanning was being done from every stations as overlapping (Figure 6). The registration were performed by relative RO of the images. Since the images were captured from the scanning station as stereoscopic, we can compute rotation and orientation parameters of one of them to the other as relative by photogrammetry. We computed RO parameters of the second image by 45 corresponding points. The scale of stereoscopic model was computed by laser scanner coordinates of corresponding points and achieved model coordinates (b_x,b_y,b_z) of the second projection centre in object spaces. Registration of second station (S2) was performed using exterior and relative orientation parameters by Equation 7 given Al-Manasir and Fraser (2006). More information about registration of point clouds by relative orientation can be found at Al-Manasir and Fraser (2006). Here R_1 and R_2 are rotation matrix designed by angels of exterior and relative orientation parameters respectively.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{S1} = R_1 . \left[R_2 . \left[R_1^{-1} \left[\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{S2} - \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \right] \right] - \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \right] + \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \quad (7)$$

After the registration, residuals of coordinates on 220 control points are shown in Figure 7. We have tested residuals as statistically and achieved normal distribution. We computed mean residuals and rmse of it (Table 2). The residuals compatible with expected accuracies (max 1cm at 100m) of the laser scanner. In addition we compared the results with ICP, it has been seen that the registration accuracy is more fine.

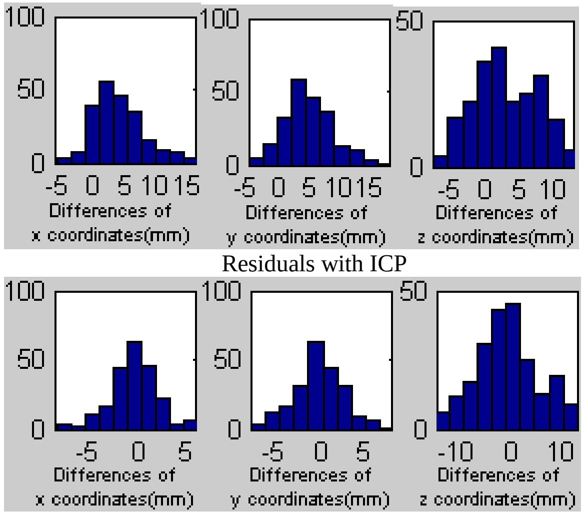

Figure 7. Histograms of residuals on control points after the registration by ICP and RO.

Method	Mean differences(mm)			Standart deviation of mean differences (mm)		
	d_x	d_y	d_z	σ_{dx}	σ_{dy}	σ_{dz}
ICP	4.09	4.76	2.93	3.81	3.92	4.76
Relative Orient	-0.48	-0.25	-0.76	2.46	2.82	6.02

Table 2. The residuals on control points after the registration

6. CONCLUSIONS and OUTLOOK

In this study, we mounted Nikon P50 camera top on the Optech Ilris 3D laser scanner and the exterior parameters between them were estimated. The parameters were estimated with rms error of 0.39 pixel or 0.66µm. The controls and experimental results shows that the exterior parameters are estimated quite satisfactory.

We achieved better results by relative orientation than by ICP (Table 2). ICP is not successful that the scanning object or scene is not consist of geometric details like test plane in this experiment. We correspond similar problem in experiment but ICP can be performed by good initial alignment. We can still registered point clouds by RO of the images. Details can be selected easily from the image than from point clouds. In the same time the registration results the accuracy of the estimated exterior parameters is shown.

The exterior parameters between coordinate systems of 3D laser scanner and 2D image are estimated with precisions in this study. We suggest to estimate the exterior parameters of the sensor combination initially. The images of the digital camera mounted on the laser scanner can be used for registration and texture mapping of point clouds. The registration have been performed in different forms by the image. Automatic registration method is also performed by the image extensively. In the texture mapping, the most important step is estimate position of the image in object coordinates. It has been known image position from exterior parameters beforehand, we can use it directly without control points to estimate of projection centre.

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