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Semi-Automated Colour Registration and Evaluation of Digital Photogrammetry and Terrestrial Laser Scanning

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ABSTRACT

Photogrammetry and Laser Scanning fusion is becoming increasingly common. This paper outlines the evaluation and semi-automated registration of single colour image to laser scanning point cloud data using canonical transformation and Direct Linear Transformation (DLT) registration methods. Laser scanning acquires 3D data points and intensity values but is unable to directly obtain photorealistic colour in most cases. There are instances where digital images are taken of the object of interest with the intention to merge the 3D data and image to reconstruct a photorealistic digital representation. Currently limited methods exist for the registration of multi-sensor platforms; a common method seen requires specially designed camera mounting. Another possibility is to transfer colour information from 2D images to the 3D points using photogrammetric methods. This method was inspired by the SCI method (Forkuo and King, 2005); the registration process utilises synthetic imagery calculated from laser scanning point clouds and matched with a camera image for colour registration. Evaluation is necessary as it provides a metric indication of accuracy and precision. The proposed research intends to aid in heritage and city modelling, to further feature detection methods, to provide cost effectiveness in industrial applications and to potentially improve model visualisation times.

KEYWORDS: Direct Linear Transform, Fusion, Laser Scanning, Photogrammetry, Registration, Multi-sensor, Terrestrial, Matching, Camera Simulation

1 INTRODUCTION

Photorealistic reconstructions of cities, buildings and objects are aesthetically pleasing and provide a more complete representation than a simple 3D model with just intensity values. There are different methods that may be used to provide colour information to a 3D point cloud and texture mapping is one such method. In the perspective of a spatial scientist, metric information is of a key importance, thus a method providing a metric indication of colour accuracy is presented. This paper presents a method using synthetic images, a concept presented in the paper by Forkuo and King (2005) and another using Direct Linear Transformation to address this issue. The methods also presented use a single image for the purposes of registering colour onto point clouds.

In general, multiple images are utilised for 3D construction but, in the surveying application with terrestrial laser scanners, it may be possible to utilise 3D point clouds for estimating the depth information of some parts of 2D images. Then either with the DLT alone or the exterior orientation of a camera with its calibration parameter, it is possible to reconstruct additional 3D information next to the available 3D point clouds. Furthermore, it is also possible to obtain more depth information of the 2D images, which is located next to the laser scanner. This allows us to obtain much more detailed or additional information to the 3D point cloud, not just the colour information. In this paper, we present some preliminary methodology and results of this idea. For example, in cases of mobile laser scanning systems that have been gaining in popularity, a procedure to estimate the depth information of 2D images is important since it provides a way of obtaining metric information of objects other than 3D point clouds from terrestrial laser scanners that are usually installed next to a camera system, e.g. spherical multiple cameras. Although it may be possible to extract the depth information from multiple-images from this system, in practice, it is recommended for 3D terrestrial laser scanners to be utilised or assisted for this process because we may not solely rely on the camera location from GNSS and INS.

2 BACKGROUND

2.1 Photogrammetry

Photogrammetry encompasses the use of images to measure and interpret shapes and sizes and locations of objects (Luhmann et al. 2006). It is often used to make three dimensional (3D) digital representations or graphical representations of an object (Luhmann et al. 2006). 2D capturing methods such as cameras, scanners and digitisers are the main instruments used in photogrammetry for data capture. Space resection is a procedure used to calculate exterior orientation (Luhmann et al. 2006). Exterior orientation consists of six parameters describing the spatial positions and orientation of the camera with respect to the global object coordinate system (Luhmann et al. 2006). In order to produce a 3D representation of an object via photogrammetry, a minimum of two 2D images with sufficient corresponding points are necessary.

Instruments that contain a two camera setup or a single camera and a grid projector use photogrammetric principles to obtain 3D data. 3D photorealistic metric models can be created with such instruments, but reconstruction effort may be high. Furthermore, a targetless approach for this purpose has been investigated by scientific communities for some time. Although there are some available methods in specific conditions, a general solution is to be developed.

2.2 Laser Scanning

Laser scanners are the instruments used to acquire 3D data points (point cloud). The laser scanning device automatically captures a point cloud containing millions of points within a relatively short period of time to approximately millimetre accuracy (McGlone et al., 2004). Like photogrammetry, laser scanning data may be used for creating 3D models, but have limitations in terms of accurate colour representation. Colour representation on 3D point clouds still relies on instruments such as a camera. According to Jansa et al. (2004), laser scanners have the benefits of having high spatial resolution, very good spatial coverage, moderate reconstruction effort, high 3D point density and depth accuracy, while the limitations are its colour, texture reconstruction, and high instrument costs. In terms of cameras, the two main attributes that may be used to reduce the limitations of laser scanning are the ability to provide colour information and the means for texture reconstruction.

Presently laser scanners may not achieve the same precision as some electronic distance measurement devices (EDM) used in conventional surveying, but it is presently being used in conjunction with photogrammetry in the following applications:

- Architecture and Heritage preservation applications include city modelling, heritage preservation and restoration, and art and cultural analysis.
- Engineering and Surveying applications requiring measurement of deformations and change detection, tunnel profiles and concrete tanks, all of which require high measurement precisions

- Automotive applications requiring measurement of surface design models for parts analysis, for deformation and safety testing, and the inspection of parts.
- Industrial applications including pipe and machinery location for power stations; aircraft and aerospace requiring extremely high accuracy for measurement of corner fittings and mechanically and thermally stressed objects; and forensics using photogrammetry for crime scene and accident measurements and reconstructions and can potentially use laser scanning for a more efficient means of 3D reconstruction.

2.3 Registration

Registration is the process of transforming data from different sources and/or of different types into a reference system to allow for measurements and interpretations to take place. Generally registrations encompass components that relate to scale, skew, rotations and translations (Luhman et al., 2006). An example of the registration process can be seen in Kang, et al. (2007), Zitová and Flusser (2003) and Al-Manasir and Fraser (2006). In most cases registration takes place during the post processing of data, but some systems exist that do the registration processing on the fly (during data capture within the instrument) as presented in Jansa et al. (2004), Sapkota (2008), and Kern (2001). This paper proposes a method of registration for a single image to point cloud data. The currently available methods that exist are rigid systems, where the camera is mounted onto the laser scanning device, offering limited flexibility with the camera's properties, i.e. pixel resolution, colour quality, field of view and so on.

2.4 Projective Transformations

The similarity transformation and Direct Linear Transform (DLT) are two transformation methods used in this paper. The similarity transformation is a common method used for obtaining scale, rotation and translation parameter, but requires approximate initial values. DLT was introduced in 1971 and has the advantage of not requiring initial values (Abdel-Aziz and Karara, 1971), as it uses its own transformation coefficients. However, the DLT coefficients of transformation are not as versatile as the similarity transformation being that its coefficients aren't necessarily describing scale, rotations and translations. In this field of surveying and mapping, metric precision is valued over the aesthetics of image overlays and texture mapping. It is important to have the measurement data displayed accurately and precisely, so that it may reflect reality in terms of metrics. Outlined below are the DLT projection equation (1) and its transposed matrix format (2) as follows:

$$x_i = (H_{11} * X_o + H_{12} * Y_o + H_{13} * Z_o + H_{14}) / (H_{31} * X_o + H_{32} * Y_o + H_{33} * Z_o + 1) \quad (1)$$
$$y_i = (H_{21} * X_o + H_{22} * Y_o + H_{23} * Z_o + H_{24}) / (H_{31} * X_o + H_{32} * Y_o + H_{33} * Z_o + 1)$$

and

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & 1 \end{bmatrix} * \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \\ 1 \end{bmatrix} \quad (2)$$

where (x_i, y_i, 1) and (X_o, Y_o, Z_o, 1) are the 2D image and 3D point clouds in the homogeneous notation, respectively, and H_{ii} (i=1…4, for the 12 parameter cases) is the component of the DLT matrix. With the least squares method and DLT, we can estimate the DLT matrix (i.e. H_{ii}) up to scale (Hartley and Zissermann, 2003).

DLT is one of the main transformations investigated in this registration project for the assignment of colour information obtained from the digital image, which will be referred to as Real Camera Image (RCI). DLT primarily uses 11 parameters, but a 12 parameter solution is also possible with further investigation whereby the 1 in the 3rd row and 4th column is treated as a parameter (Hartley and Zissermann, 2003). In order to produce a relevant 2D-3D projection matrix, the 3rd row of the DLT matrix is required to be independently investigated. A 2D-3D projection matrix in this paper refers to a matrix that allows the transformation of the 2D coordinates into 3D coordinates.

2.5 Synthetic Camera Image (SCI)

Creation of an SCI is required to provide the platform whereby a relationship can be determined between the 3D point cloud and the RCI. The SCI is a projection of the 3D point cloud into 2D to simulate a digital image, Forkuo and King (2005) provides the original explanation. The SCI created in this paper uses the 2D camera projection model (sometimes referred as canonical model; refer to Zeisserman and Hartley, 2003) as seen below:

$$\mathbf{r}_i = \mathbf{k}\,[\mathbf{M} \mid \mathbf{Tr}]\times\mathbf{r}_o \qquad (3)$$

where $\mathbf{k} \in R^{3\times3}$ is the camera matrix, $\mathbf{M} \in R^{3\times3}$ and $\mathbf{Tr} \in R^{3\times1}$ are the rotation and translation matrix, respectively, and $\mathbf{r}_i$ and $\mathbf{r}_o$ are the 2D image and 3D object points in the non-homogeneous notation, respectively. The camera projection model can be expressed similarly to the DLT projection transformation when transposed into matrix format.

2.6 2D Iterative Closest Point

This rigorous method is used for correspondences of points, lines and objects. (Besl and MacKay, 1992; Yang, C., and G. Medioni, 1992) A point based approach is implemented for 2D correspondences. Simulated data used in this paper is created mathematically, therefore having no systematic errors. These are 3D datasets simulating a perfect laser scanning system. It is assumed that trials with the simulated data after transformations will obtain a singular solution. Other variants of ICP exist that are based on other than point-to-nearest-point distance, which is the method used in this paper, as mentioned by Al-Manasir and Fraser (2006), Rusinkiewicz and Levoy (2001), and Vosselman and Maas (2010).

Outlined below in Figure 1 is a brief overview of the ICP procedure represented by pseudo-code; beginning with point selection, then calculating and applying the transformation components, and repeating the process until convergence is reached. Colour registration from 2D onto 3D may be quite common, using texture mapping and other mapping techniques. However, this paper intends to allow additional properties to be registered to single images from other sensor information, presents a method using DLT to attempt to preserve 2D image metric accuracy, while registering onto 3D point clouds.

```
procedure ICP (Points X1ij, X2ij)
for iteration = 1 to user specified do
        for j = 1 to length of X1 do
                find closest point (minimum distance) with the kdtree
                if distance < threshold distance
                then store corresponding points X1ij and X2ij
                else end
        end
        calculate rotations and translations with least squares
        apply transformation
        reduce threshold distance
        if converged && small residuals
        then break
        else end
end procedure
```

Figure 1: Brief summary of the conventional ICP algorithm

The ICP and its variants have been utilised for the automated registration of 3D point clouds, medical images, and pattern recognition. The most important and difficult part of the ICP algorithm is to develop metric criteria, e.g. Euclidean and Mahalanobis distances with consideration of statistical inferences, for the corresponding points in either 3D or 2D datasets.

3 METHODOLOGY

3.1 3D reconstruction with the SCI and back-projection

The initial dataset uses simulated data for the process of this registration method with the assumption that it will provide a solution with a known outcome and a controllable environment (i.e. manual input of systematic errors and distortion profiles). The simulated dataset does not incorporate any simulated errors and it is assumed that it should achieve a near-perfect solution under these test conditions. Since a simulated dataset is used, an image of the object cannot be obtained using a camera, thus the camera image (RCI) will also need to be simulated. This simulated camera image will be referred to as a Synthetic Real Camera Image (SRCI), and it is created in the same process as the SCI. The difference between the SCI and the SRCI is that some distortion parameters (principal point offsets and small rotations) are introduced when the SRCI model is created. The SRCI is treated as an image taken in the real world (RCI), see Figure 2(b) and Figure 3(a).

Arbitrary parameters are given for the initial SCI, such as rotations, translations, focal lengths and pixel sizes. However, the SCI should have the parameters reflecting the RCI. The initial test case will assume that the SCI has converged closely to the SRCI. Therefore, the parameters are set so that there will be only a slight shift in the SRCI to the SCI, as shown in Figure 2(a). In the case of an RCI under normal circumstances, exterior orientation parameters can be obtained via methods based on co-linearity equations or projective relations (Luhman et al., 2006), and calibration parameters should be applied to remove the systematic errors from the image. The correspondence process aims to bring SCI to correspond closely to the RCI. The SCI contains parameters to transform 2D back to 3D. There are several methods to attempt to bring the SCI into the same viewpoint as the RCI, such as finding exterior orientation parameters via resection process or using a least squares DLT method which will be discussed later on. In the paper by Forkuo and King (2005), the SCI image obtained contains slight differences to the RCI. These differences are assumed to be caused by the systematic errors of the laser scanner and the random errors during the transformation estimation process, such as the varying width of a light post. To respond to the SCI errors causing irregularities to the RCI/RSCI, ICP is performed to match the two datasets. The 2D ICP method used in the initial dataset is based on corresponding control points in the SCI and RCI. However other ICP methods may be implemented for non-simulated datasets to achieve better results based on the object scanned.

The reverse transformation parameters are obtained by performing a pseudo inverse on the projection matrix, i.e. Eqs. 1-3. The SCI contains the projection parameters which will be used along with the individual scale components to calculate the back-projection from 2D into 3D. Each SCI scale component will be assigned to the corresponding RCI coordinate so that colour may be obtained on performing the back-projection. The 3D point cloud obtained may have deviated from the original point cloud and the colour that has been registered onto the 3D point may not correspond perfectly to the features, but this is expected and explained above about the sources of error.

3.2 Extraction of colour using the DLT

In order to only extract colour information from 2D image, the DLT coefficients can be determined with the iterative least squares. Obtaining the DLT projection matrix simply requires the 3D points and their corresponding 2D image points for a solution (Abdel-Aziz and Karara, 1971). Notably in this method, the solution obtained will show a good match for the 3D points to the image. However, the DLT transformation coefficients will not allow the solution to revert back to the original 3D using the same parameters since the depth information of the 2D image is not always available in real cases.

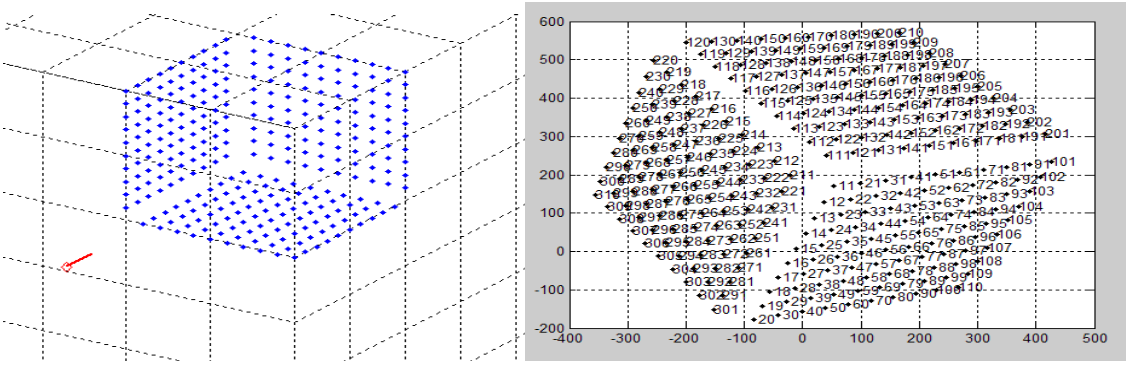
To register colour to the 3D points, corresponding transformed points (2D) are assigned the colour information from the image. The point cloud data contains image coordinate (pixel) information via transforming with the DLT matrix; these coordinates will relate to the RCI coordinates. Colour information in the RCI can be assigned for each matching point pair.

4 RESULTS/ANALYSIS

4.1 Simulated Dataset

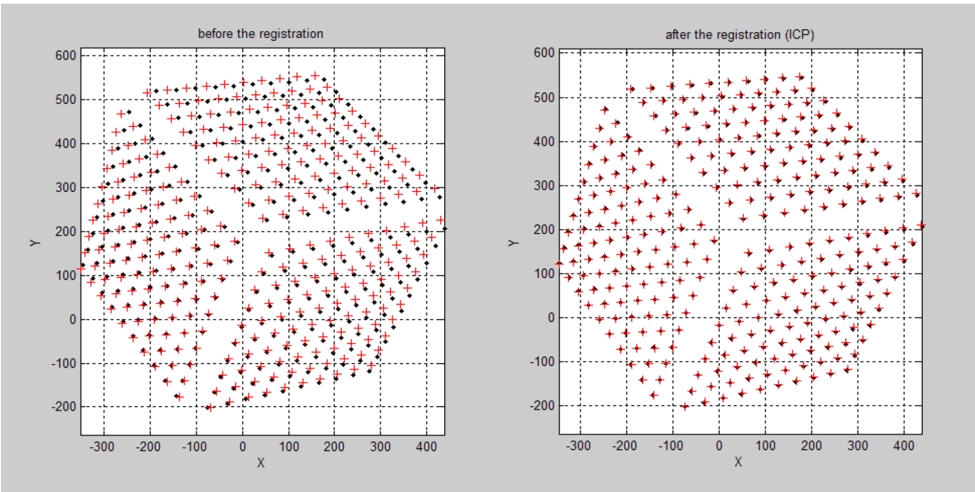
The simulated dataset presented, resembling a corner (Figure 2a), is used to create the SCI (Figure 2(b)) as well as the SRCI (simulated RCI) for testing purposes. Figure 2(a) has a line extending from the origin indicating the simulated camera direction for both the SCI and SRCI. As mentioned earlier in section 3.1, the SRCI created has a slight deviation from the SCI as shown in Figure 2(b).

ICP is the method of correspondence used to match the two similar images together, as seen in Figure 3(b). As shown, this ICP method used is able to obtain a good enough correspondence and these slight offsets will carry through when back-projected into 3D. Alternatively a different correspondence method may be used that may produce a closer and much more complete match.



(a) (b)

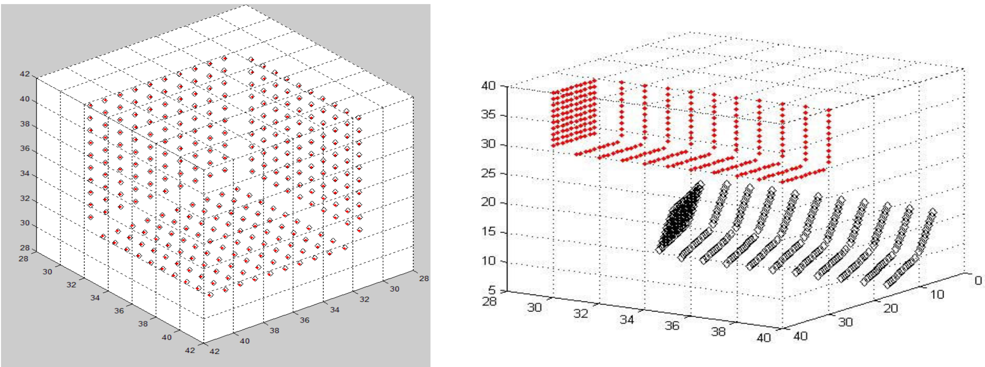
Figure 2: (a) A 3D representation of the simulated point cloud used. (b) The SRCI created from the simulated data, as an image in pixels.



(a) (b)

Figure 3: (a) Before performing the ICP registration (b) The updated image coordinates (dots) after the ICP.

After the ICP registration, Figure 4(a) shows the results of applying the individual scale components and the back-projection parameters to the SRCI. As expected, small deviations still exist between the SCI and SRCI, Table 1 shows the average overall error offset for the image between the SCI and the post-ICP SRCI, as well as in terms of its X, Y components. Also, the RMS error offset between the original 3D data and the back-projected data is calculated. The overall error of 1.68 pixels upon performing the back-projection will relate to 26.9cm overall error in the point cloud at a distance of approximately 60m. It is worth noting that in this simulation, the camera resolution is not fixed like a standard camera and is a factor that will affect the result of the colour registration. Some limitations exist for this method when using non-simulated datasets in that the exterior orientation parameters have to be well defined in order to produce an SCI that represents the RCI well. Without good orientation parameters, especially translation, it would presumably affect the scale giving an erroneous solution as shown in Figure 3(b).



(a) (b)

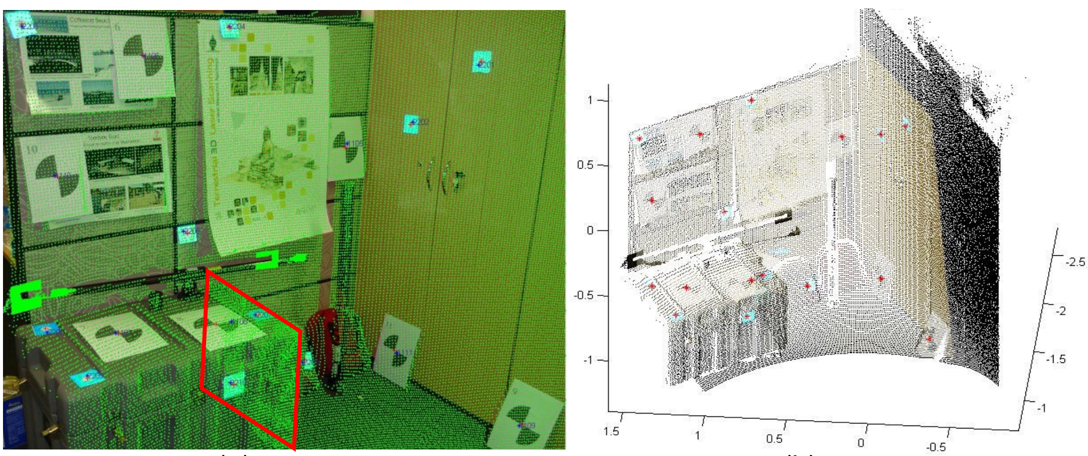
Figure 4: (a) The dots indicate the back-projected results, diamonds represent original (b) Erroneous data (diamonds) due to inaccurate parameters.

Table 1: The RMS error between the SCI and updated RCI

	RMS Total	RMS in X	RMS Y	
Image: (pixels)	1.68	1.65	1.71	
	RMS Total	RMS in X	RMS Y	RMS in Z
Point Cloud: (m)	0.0269	0.0246	0.0224	0.0325

4.2 Trial Scan Dataset

This dataset is acquired using the Leica Scanstation 3000, with roughly 80,000 points at the distance of 1.5m. The Figure 4(a), shows the image of the area with the corresponding point cloud data being mapped on using DLT. The targets used in the Figure 2(a) were a mixture of Leica HDS targets and printed black and white targets. Once the point cloud contains the image coordinate information, the RCI colour data for the corresponding point is assigned to give the result shown in Figure 4(b). The red asterisks in the image are the image target points after projection, to visually indicate the extent of the shifts due to back-projection. The DLT method projection has an error of 11.8 pixels, signifying that the colour misrepresentation in the point cloud is approximately 0.018m.



(a) (b)

Figure 4: (a) Light-green dots on camera image represent point cloud data (b) 3D metric photorealistic point cloud data.

Table 2: RMS error between the original control points and the DLT control points.

	RMS Total	RMS in X	RMS Y
Image: (pixels)	11.8	16.5	2.5

Some apparent limitations are; erroneously stored colour data, outlined in red in Figure 4(a) where the region of the point cloud is not shown in the image, but present in the point cloud. A method suggested to avoid this occurrence is to apply some threshold parameters. To achieve good results, sufficient amount of well-located and defined control points, or a well-defined set of exterior orientation parameters for the projection matrix are needed.

5 CONCLUSION AND DISCUSSION:

Though photorealistic models can be obtained using two images and photogrammetry techniques, alternatively this method obtains a photorealistic metric model with a single image and point cloud data. As shown, it can be seen that the registration of 2D to 3D points using the DLT method achieves results that are satisfactory for photorealistic metric models. Using an SCI, RCI, ICP and DLT we can transform between 2D and 3D, whilst accounting for metric accuracy. However, there are limitations to the method at this stage, whereby this method can only be applied to small rotations and translations. Further investigation is necessary to improve the determination of the DLT coefficients, and examination into the SCI method and components are required to find a solution for its current limitations.

There are several possibilities that require further investigation to acquire the depth information for the estimation of the 3rd row of the DLT matrix, such as calculations using the 1st and 2nd row coefficients along with focal length and object scale relationship or defining the 3rd row via geometric means by finding rotation and translation elements. Factors that influence the accuracy of the registration also includes distance of images taken from scanner and pixel resolution of the images taken. In addition, we plan to implement a complete error analysis with a Gauss-Helmert model including the error model of 3D point clouds and possible 2D images after the separate calibration procedure.

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Kwang-Ho Bae obtained a BSc in Physics from Korea University, Seoul, Korea and his BSc (Hons) and MSc in Physics from the University of Adelaide. He gained a PhD in Spatial Sciences from Curtin University of Technology in 2006. He has been a lecturer in Photogrammetry and Laser Scanning in the Department of Spatial Sciences at Curtin and now is with Fugro Spatial Solutions from September 2011. His research interests are Laser Scanning data analysis such as registration, segmentation, calibration and positional error analysis, Photogrammetry and 3D range cameras.

David Belton received the BS degree (1^{st} Honours) in Computer Sciences and Mathematics from Curtin University of Technology in 2003 and completed the PhD degree in Spatial Sciences in 2008 at Curtin. In 2008, he took up a research associate position with the CRC for Spatial Information and Curtin University of Technology after submitting his PhD thesis. He also received the International Society for Photogrammetry and Remote Sensing (ISPRS) Prize for Best Papers by Young Authors at the ISPRS congress, Beijing, in 2008. He also received D. B. Johnston Award for Excellence in postgraduate studies in the spatial sciences area from the SSI and Curtin University of Technology in 2009. His research interests lie in 3D point cloud processing, error analysis, and optimisation techniques.