

# Co-registration of Photogrammetric and Laser Scanner Data for Generation of 3D Visual Models

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## Abstract

Nowadays, most terrestrial laser scanner (TLS) systems provide the facility of mounting a digital camera on the laser scanner. This not only facilitates a means to generate better quality photorealistically textured 3D models from TLS point clouds; it also offers the opportunity of using photogrammetric orientation techniques to complement existing methods of TLS point cloud registration. This paper describes an approach whereby a registration procedure based upon photogrammetric means is employed as the first step in integrating TLS data and imagery for the generation of textured 3D models. The approach, called image-based registration (IBR), entails an estimation of transformation parameters between the individual scan data and between digital imagery using photogrammetric bundle adjustment. Once both TLS and photogrammetric data are registered in the same coordinate system, the process of forming a segmented structured surface model and its associated triangular mesh are carried out. Photogrammetrically derived constraints are used to convert the unstructured, registered laser scanner model to a structured model. Finally, texture mapping takes place via the rectification of image patches from the integrated images used in the IBR process onto individual surface elements. Test results obtained with the proposed approach are presented to highlight its practicability and accuracy.

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## 1. Introduction

Digital imagery is now being routinely used in conjunction with terrestrial laser scanner (TLS) data to generate photorealistic 3D object and scene models, since the use of recorded laser scanner intensities alone generally produces a texturing of insufficient visual quality, especially when there is other than a very high resolution scan. TLS manufacturers generally offer the option of having an SLR-type digital camera mounted on the scanner. This gives rise to the necessity of establishing the interior and exterior orientation of the camera such that the position and attitude of each image can be established with respect to the XYZ coordinate system of the TLS.

TLS scans can be registered in one coordinate system using the ICP algorithm [PJND92], which requires pre-alignment of the individual TLS point clouds, although automated registration of TLS scans is also possible without the requirement for initial values for the transformation parameters [Dol05]; [NC05]. A common alternative registration approach is to position automatically recognisable artificial targets such that they form

common or tie points between adjacent point clouds thus providing registration through 3D coordinate transformation.

With respect to imagery from the camera mounted on the laser scanner, the relative orientation of adjacent pairs of images, and indeed of a network of overlapping images, can be accomplished by measuring conjugate image points, either manually or automatically in cases where either special targets are used or where the geometry is such that image matching is feasible. Registration of the photogrammetrically derived 3D coordinates and the TLS point cloud is also achieved if the exterior orientation of the camera stations is known with respect to the TLS. Once the 3D model and the digital imagery are registered in the same coordinate system, the next step is to convert the point cloud into a structural surface, usually in the form of a triangular mesh. Finally the texture mapping can take place and colour patches from the imagery can be assigned to each individual triangular facet in the 3D model.

The scenario considered in this paper for the generation of a photo-realistically textured 3D model via the use of a TLS with attached digital camera is the following:

- In the first stage, scanning occurs at each station and digital imagery is recorded from the camera mounted on top of the laser scanner, so that the scene being scanned is also photographed. Since the camera likely has a limited field of view compared to the TLS, it is possible that some areas covered by the scan will not be imaged.
- After the scanning is completed, the camera is removed from the TLS and supplementary images are recorded to make sure that the entire object is covered.
- The TLS and photogrammetry point clouds are registered in the same coordinate system using the Image Based Registration (IBR) technique, first proposed in [AF06a]. The IBR registration provides a photogrammetric approach to point cloud registration. Images from the TLS-mounted digital camera are first used to relatively orient the network of images, after which the exterior orientation between TLS point clouds is determined based on the known relationship between the position and orientation of the camera and TLS.
- The photogrammetric network established for the IBR is supplemented by any additional images recorded using the camera dismounted from the TLS.
- Lines and planes are triangulated using the photogrammetric network. These photogrammetrically extracted features are then used as constraints to improve the segmentation process for the point cloud. They are also applied in the mesh generation process to preserve the geometric characteristics of the model.
- Finally the 3D model is segmented and converted into a triangular mesh and the texture mapping takes place using image patches from appropriate images forming the full photogram-metric network.

Each of these stages will now be discussed.

## 2. Image-based registration

The image-based registration method for TLS scan data is fully described in [AF06a] and a short summary of the process only will be presented here. First, a camera calibration is required. Second, the camera position with respect to the laser scanner coordinate system must be recovered via spatial resection. For a rigidly mounted camera, this process need only be carried out once. Finally, once the TLS and image data from two or more scenes are recorded, the registration process can be car-

ried out. Only the imagery must overlap; there is no requirement for the TLS point clouds to overlap.

The initial step of the IBR is an analytical relative orientation between two adjacent images using five or more suitably located conjugate points, which can be automatically detected and measured in cases where image-identifiable coded targets are employed. Whereas the TLS will be continually collecting laser range data throughout its lateral sweep, only one image needs to be recorded, with the requirement that there is suitable overlap with the image from the second station. From the five relative orientation parameters determined (three rotations and two translations) and from knowledge of the transformation parameters between the camera coordinate system and the TLS, the exterior orientation and hence the registration of the laser point clouds is established, without the need for point correspondence searching or an ICP registration procedure. In the situation where there are more than two overlapping images and TLS point clouds, a bundle adjustment can be applied for the initial multi-image orientation.

Once the relative orientation between two images  $i$  and  $j$  is determined, the point cloud registration can be established using the following equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_i = \mathbf{R}_{A_i}^{-1} \cdot \left( \mathbf{R}_C^{-1} \cdot \left[ \mathbf{R}_{j,i}^{-1} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}_j + \begin{pmatrix} bx \\ by \\ bz \end{pmatrix} \right] + \begin{pmatrix} X^c \\ Y^c \\ Z^c \end{pmatrix} \right) \quad (1)$$

where

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_j = \mathbf{R}_C \cdot \left[ \mathbf{R}_{A_j} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_i - \begin{pmatrix} X^c \\ Y^c \\ Z^c \end{pmatrix} \right]$$

Here,  $i$  is the reference point cloud and  $j$  is the data set whose coordinates are to be transformed; the 3x3 rotation matrix  $\mathbf{R}_C$  and the translation vector  $(X^c, Y^c, Z^c)$  express the camera position and orientation in the TLS coordinate system at a specific alignment of the scanner; the 3x3 rotation matrix  $\mathbf{R}_{j,i}$  and the vector  $(bx, by, bz)$  are formed by the exterior orientation of camera station  $j$  within the coordinate system of camera station  $i$ ; and  $\mathbf{R}_A$  is a 3x3 rotation matrix defining the TLS rotation around its Z-axis described by the scanner rotation angle  $A$  at the time of exposure. The accuracy of the registration can be enhanced through the addition of extra images (without TLS data) in the bundle adjustment. Experimental evaluations of the IBR approach have been reported in [AF06a] & [AF06b].

### 3. Integration of additional image data

The additional imagery recorded with the camera dismounted from the TLS can be integrated into the IBR-registered network via either photogrammetric means alone, ie added to the bundle adjustment or in the less likely case where there is insufficient image overlap, via spatial resection from the registered point cloud. At this stage it is also appropriate to carry out any point cloud preprocessing such as a point density reduction and outlier detection, especially in the overlap areas of the TLS point clouds where there will be redundant data [Rem03]. Gaps in the point cloud can subsequently be filled manually, semi-automatically or automatically. Point cloud decimation, outlier detection and gap filling processes all use surface gradient information for the preservation of the geometry (shape) of the model.

### 4. Photogrammetrically-derived constraints

The presence of very dense laser point clouds can complicate and adversely affect the accuracy of feature point identification and segmentation. Also, edge identification and definition is influenced by scan point density. As an aid in rectifying such problems, photogrammetrically derived constraints can be applied within the 3D Delaunay triangulation to yield a more accurately structured model. Photogrammetrically extracted features such as lines and planes are used as constraints both to improve the segmentation process for the laser point cloud and to preserve the geometric characteristics of the model.

### 5. Segmentation and reconstruction

After the scan data is transformed into a common reference system, the registered 3D model should be further processed to convert the unstructured point cloud into structured form, usually via predefined elemental primitives that represent the object. These include best-fitting edges, planes, spheres, planar facets and cylinders. This process, in which points with the same homogeneous properties are grouped into regions, is referred to as segmentation and surface fitting. The segmentation process can be divided into two categories, namely surface-based and edge-based segmentation. In the first, the segmentation process is based on point clustering for surface shape representation, whereas in the second, the process utilises discontinuities within the data.

Use of the surface normal to group points in clusters has been reported in [RAK87] and various methods for range data segmentation are summarised in [PR88], where an iterative region growing method for surface segmentation is also reported. In this method, the mean and curvature of a point cluster are used to group the data, curvature being invariant to rotation and transla-

tion of the coordinates. The solution is iterated and a best-fit surface is estimated until a threshold value is achieved.

### 6. Texture mapping

Once the object model has been completely created in term of a triangular mesh or via a parametric approach, the final step of the generation of a visually realistic digital model is the mapping of texture onto the individual surface elements. This can be achieved by mapping 2D image elements, with appropriate rectification, onto planar surface elements of the 3D object model. The following principal stages are involved in the texture mapping for each surface element (polygon or triangle) [SFCG98]:

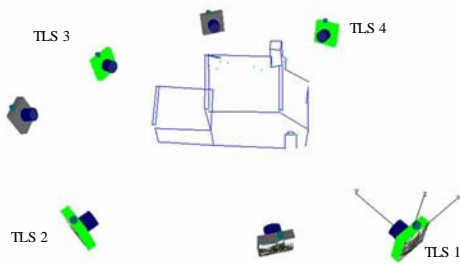
1. Selection of the appropriate image from the set of images in which the surface element appears,
2. Determination of 2D image coordinates for the points forming the surface element from the corresponding 3D object space coordinates and the exterior orientation of the image,
3. Specification of 3D and texture coordinates in a given modelling language such as VRML, and
4. Viewing the scene using a standard viewer.

In a multi-image network, there will likely be sufficient overlap between images such that a triangular facet in object space will appear in a number of images. Thus, several textures for the surface element will be possible. As one solution to this problem, the texture is selected from the image where the triangle appears largest. However, this may result in discontinuities in the adjacent triangles. In order to reduce the discontinuities in texturing which accompany the use of multiple images, a weighted averaging approach can be adopted [SFLM\*03].

## 7. Experimental modelling of Cooks' cottage

### 7.1 TLS and photogrammetric recording

As a test of the proposed approach, a TLS survey of Cooks' Cottage, a heritage site and popular tourist attraction in Melbourne, was carried out with a Riegl LMS-Z210 / Nikon D100 scanner/camera combination, with the geometry shown in Figure 1. Four images were recorded with TLS scans (TLS i) and four additional images were recorded with the camera removed from the scanner. Care was taken to ensure that there would be sufficient overlap between images to support robust relative orientation and subsequent bundle adjustment. However, little attention was paid to the extent of TLS point cloud overlap.



**Figure 1.** Scanner/camera station geometry for the survey of Cooks' cottage. (Images from the TLS-mounted camera are labelled TLS *i*)

A relative orientation was first performed between the images from stations TLS 1 and 2. This was followed by an initial resection of the images at stations TLS 3 and 4, and of those from the supplementary camera stations. A bundle adjustment, with an average of 30 points per image, was then performed using all seven images. This produced an RMS value of image coordinate residuals of 0.4 pixels and an estimated point positioning accuracy of 2 mm. Registration of the TLS point cloud data was then carried out via the IBR method using Eq. 1, with the resulting registered 3D model being shown in Figure 2. Following the IBR process, a registration using the ICP algorithm was also performed to produce a second 3D data set.

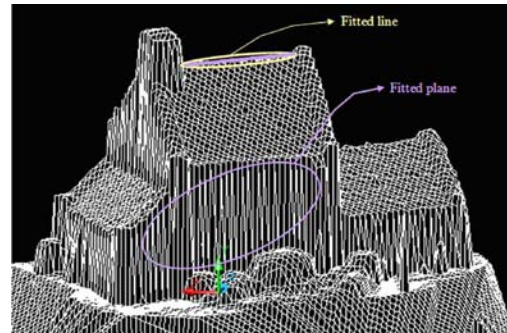
The accuracy of the registered 3D coordinates obtained with the IBR was verified using the coordinates of 120 well distributed photogrammetrically measured checkpoints of 2mm accuracy. These were manually identified in both the IBR & ICP generated 3D point clouds. The resulting RMSE values for the ICP and the IBR models, as assessed against the checkpoint coordinates, were 4mm and under 3mm, respectively. Given both the accuracy of the Riegl LMS-Z210 and the limited ability to precisely identify the checkpoints in the laser data, the results are consistent with expectations, though it is noteworthy that the IBR produces higher accuracy than the ICP approach. It must be remembered, however, that the test survey was specifically designed to produce a sub-optimal ICP solution, since an aim of the exercise was to show the merits of the IBR in cases where there is low overlap between point clouds from adjacent TLS stations.



**Figure 2.** Laser scanned 3D model of Cooks' cottage.

## 7.2 Model reconstruction and texture mapping

The triangular mesh-model shown in Figure 3 was created using the previously described constrained 3D Delaunay triangulation. Photogrammetrically derived features, mainly lines and planes, were used to convert the unstructured, registered TLS point cloud into a structured model.



**Figure 3.** Triangulated mesh-model of Cooks' cottage.

Following the reconstruction process, the texture mapping was carried out. Initially, aggregated surface areas such as planar walls and roof sections were assigned a texture via appropriate rectification from the most optimal image. Following this, irregular surfaces were textured on an individual mesh triangle basis, using the method discussed earlier. Views of the final texture-mapped model are shown in Figure 4.

The accuracy of the registered 3D textured-mapped model was quantified using the coordinates of 80 photogrammetrically measured checkpoints of 2mm accuracy. These were manually identified. The resulting RMSE value for the texture-mapped, photogrammetrically-constrained TLS model was 2.5mm.



(a)



(b)

**Figure 4.** Textured 3D model of Cooks' cottage.

## 8. Conclusions

A process for the creation of 3D texture-mapped models via the integration of terrestrial laser scanner and photogrammetric data has been described. The process commences with the technique of image-based point cloud registration. The step that follows then involves the use of photogrammetrically derived features such as lines and planes to form constraints in the generation of a structured model from the laser point cloud through 3D Delaunay triangulation. Finally, texture mapping is carried out using image patches from appropriate images forming the full photogrammetric network.

Promising results have been achieved with the approach, which can yield higher modelling accuracy in cases where the photogrammetric orientation and triangulation is inherently more precise than the particular TLS system being employed. There is also the advantage of likely better interpretability of object feature constraints in the imagery as compared to the TLS data. Further advantages of the method are that the use of the IBR method does not require any overlap between adjacent laser point clouds to perform the registration proc-

ess, and that supplementary images can be used to enhance the photogrammetric solution.

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