Merging and processing of laser scan data and high-resolution digital images acquired with a hybrid 3D laser sensor

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Key Words: *RIEGL*, laser scanning, photogrammetry, 3D laser scanner, calibrated digital camera, RiSCAN PRO

Abstract:

We present a hybrid sensor consisting of a high-performance 3D imaging laser sensor and a high-resolution digital camera. We demonstrate the performance capabilities of the system by presenting an example and we describe the software package used for data acquisition, data merging and visualisation, RiSCAN PRO. Addressing the camera model and the data structure provides an insight into the well-organized, published and well-documented project format used by RiSCAN PRO.

1 Introduction

RIEGL Laser Measurement Systems GmbH is well known for developing, manufacturing, and marketing state-of-the-art 3D imaging laser sensors based on the time-of-flight measurement technique with near-infrared pulses. The sensors are unique with respect to the outstanding combination of high measurement accuracy, a very wide field-of-view, a wide measurement range, high data acquisition speed, and proven robustness and compactness.

Recently, *RIEGL* started to offer the 3D imaging laser sensors with an optional high-resolution digital camera firmly mounted to the scanner. The camera used is calibrated and the orientation of the camera is known with respect to the sensor's coordinate system. By taking a number of images, the whole wide field-of-view of the scanner of up to 90 x 360 deg can be covered. The combination of high-resolution calibrated and registered images and high-quality scan data provides a clearly improved usefulness of the acquired data by combining the advantages of laser scanning and photogrammetry.

We describe in the subsequent sections our companion software package RiSCAN PRO. The data structure used by RiSCAN PRO to store all data is published in order to allow software developers to make full use of the data acquired and processed with RiSCAN PRO, e.g., in PHIDIAS from PHOCAD (PHOCAD 2003). We address the calibration tasks necessary to make use of the digital images in combination of the scan data. The capabilities of RiSCAN PRO and the RIEGL LMS-Z360 instrument with the camera option are demonstrated by an example.

2 Software Package RiSCAN PRO

RiSCAN PRO is the companion software package to the RIEGL 3D laser imaging sensors of the *RIEGL* LMS-Z series. RiSCAN PRO supports also the instrument with the camera option. It allows the operator of the 3D imaging sensor to perform a large number of tasks including sensor configuration, data acquisition, data visualization, data manipulation, and data archiving.

RiSCAN PRO is project oriented. A project is stored within a single directory structure containing all scan data, registration information, additional descriptors, and processing outputs. RiSCAN PRO reflects thus a data acquisition campaign in the field. The structure of the project is stored in a text based and documented project file making use of the XML format enabling post-processing software packages to make full use of the RiSCAN PRO data. Within RiSCAN PRO all data are organized in a tree structure for comfortable access and clarity. In the subsequent subsection we describe the key elements of the tree structure and address some background information useful for understanding data handling and data interpretation.

RiSCAN PRO makes use of the following different coordinate systems:

Scanner's Own Coordinate System (SOCS) is the coordinate system in which the scanner delivers it's raw data. Figure1 shows the coordinate system of an LMS-Z210. The data of every RIEGL 3D laser imaging sensor contains for every laser measurement geometry information (Cartesian x, y, z coordinates or polar r, θ, ϕ coordinates) and additional descriptors (at least intensity, optionally color information). Thus the output of a RIEGL 3D laser imaging sensor can be addressed as an organized point cloud with additional vertex descriptors in the scanner's own coordinate system.

Figure1: Definition of the coordinate system of a *RIEGL* LMS-Z360 Laser Scanner (above). Scanner equipped with digital camera mounted on top (below).

Project Coordinate System (PRCS) is the major coordinate system used within RiSCAN PRO. For example, PRCS can be an already existing coordinate system at the scan site, e.g., a facility coordinate system. RiSCAN PRO requires that all geometry data within this project coordinate system can be represented by single precision numbers (7 significant digits). For example, is mm accuracy is required, the maximum coordinates should be less than 10 km.

Global Coordinate System (GLCS) is the coordinate system into which the project coordinate system is embedded. Usually, coordinates in the global system may contain very large numbers.

Camera Coordinate System (CMCS) is the coordinate system of the camera mounted on top of the scanner system providing high-resolution images.

Figure 2 shows an example for the coordinate systems GLCS, PRCS, and SOCS. The object is a building seen from a bird's view. A project coordinate system is defined with the y_{pr} – axis being parallel to the long side of the building and the origin of the PRCS coinciding with one corner of the building. PRCS has to be a right-handed system. GLCS in the example is a left-handed system, e.g., northing, easting and elevation. A number of scan positions are indicated by sp_i, where the scanner has been set up for data acquisition (see the detailed description on scan positions below). Each scan position has it's own local coordinate system (SOCS) sketched by the axes x_{sp1}, y_{sp1}, z_{sp1}.

In almost all applications data acquisition is based on taking scans from different locations in order to get a more or less complete data set of the object's surface without gaps or "scan shadows". The different scan locations are addressed as **Scan Positions**. When starting a new project, i.e., starting a new data acquisition campaign, the user initialises a new scan position before acquiring data from the scanner. This scan position will hold all data acquired at that specific setting up of the scanner.

A scan position is characterized by it's own local coordinate system (SOCS), i.e., the position and the orientation of the scanner within the project coordinate system. Position and orientation can generally be described by 6 parameters (3 for position, 3 for rotation) or by a transformation matrix. RiSCAN PRO makes use of a 4 x 4 matrix (M_{SOP}) addressed as **SOP** information (SOP for **s**ensor's **o**rientation and **p**osition). The matrix consists of 9 parameters reflecting the rotation (r_{11} to r_{33}) and 3 parameters for the translation (t_1 to t_3). The use of homogeneous coordinates allows computation of rotation and translation in a single matrix multiplication. The translation vector is the scanners position and the column vectors $(r_{1i}\ r_{2i}\ r_{3i})^T$ are the directions of the local coordinate axes in PRCS.

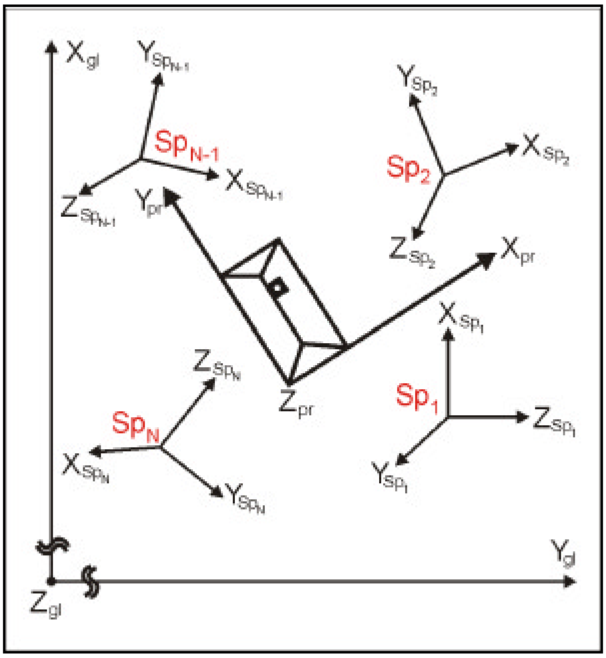

Figure 2: Example for the PRCS, GLCS, and a number of SOCS at a site for scanning a building.

Each scan position holds the scan data taken at this scan position, stored in the scanner's binary data format with extension **3dd**. Furthermore, each scan position holds it's SOP information. In order to transform data from SOCS into PRCS the data points are simply multiplied with the SOP matrix (M_{SOP}) of the scan position.

In case a data point P have to be transformed from a specific scan position into GLCS, a sequential multiplication has to be carried out, first with the M_{SOP} matrix of the scan position to get into PRCS, then M_{POP} which transforms from PRCS into the GLCS.

The process of registration of the various scan positions in the PRCS is basically the determination of the respective M_{SOP}. This process is based usually on tie points within RiSCAN PRO. Tie points are managed by **tie point lists** (TPL). Tie points are usually defined by retro-reflective targets showing up clearly in the intensity data of the scan data and which can also be accurately localized by the use of total stations. The tie point itself is commonly the center of a reflective target.

Every project can hold one tie point list in the project coordinate system **TPL (PRCS)**. Usually the data are gained by measuring the position of the tie points with a total station or by other means, e.g., DGPS. If the tie point coordinates are available in global coordinates, they are entered into the global tie point list, **TPL (GLCS)**, and are subsequently transferred into the TPL (PRCS) by defining an appropriate matrix M_{POP} to fulfil the requirement of single precision representation.

In order to register a single scan position into the project coordinate system, a tie point list in the SOCS system have to be acquired, which is done by fine-scanning the retro-reflective targets visible from the specific scan position. RiSCAN PRO extracts retro-reflective targets from a so-called overview scan or panorama scan and supports the automatic subsequent sequential fine scan of the targets. Once sufficient tie points have been gained M_{SOP} can be determined automatically and the scan data is transferred into the project coordinate system as well as into the global coordinate system.

3 Use of high-resolution images within RiSCAN PRO

RIEGL 3D imaging sensors can be equipped with an optional high-resolution digital camera. The images can be used to assign a color to the vertices of the point cloud data or to apply the images as a texture to the meshed surface generated from scan data. Before being able to apply the image information to the scan data a camera model has to be selected and the camera has to be calibrated.

RiSCAN PRO makes use of an 10-parameter model for the internal camera calibration (Intel 2003). The internal parameters of the camera model can be determined within RiSCAN PRO in different ways and are described below in the calibration tasks section. In order to make use of the image data calibration data holding the internal parameters of the camera have to be available. The calibration data are contained in the calibrations section of the project file. The calibration data have to be determined for every camera to be used and for every setting of the camera's focus and aperture to be used.

In order to utilize the image information also the external orientation of the camera has to be known. The definition of the external orientation differs for the two different kinds of images managed in RiSCAN PRO:

Type 1 Images: Images taken when the camera is mounted on top of the scanner
Type 2 Images: all other images, i.e., when the camera is NOT mounted on the scanner

Type 1 images are stored in the folder corresponding to the scan position at which the images have been taken. As the camera is firmly mounted on top of the scanner and the orientation of the rotational platform is well known, the orientation of the camera within the scanner's coordinate system is well defined after carrying out a calibration procedure after mounting the camera. This calibration routine is described in detail below. As soon as the scan position is registered in the project coordinate system the image information can be completely utilized.

The mounting calibration information specifies the 6 degrees of freedom of the camera's coordinate system with respect to the scanner's coordinate system, i.e., 3 rotational parameters and 3 translation parameters. Within RiSCAN PRO the mounting calibration is stored as a 4 x 4 matrix for convenience of definition and of application. The mounting calibration matrix transforms from the scanner coordinate system into the camera system in case the rotational part of the scanner is at the position of phi equal to 0 deg. The additional rotation at an other angle is modelled by the COP matrix (**c**amera's **o**rientation and **p**osition matrix) stored with every image of Type 1 reflecting the phi angle.

The three translation parameters are well defined and are determined for a specific camera model and lens after final calibration at the manufacturer's premises. Mounting and de-mounting the camera do not change these three parameters. The three parameters describe simply the coordinates of the center of the scanner's coordinate system at phi equal 0 deg within the camera's coordinate system.

4 Calibration tasks

4.1 Laser sensor calibration

The laser sensor itself has not to be calibrated by the user. As the sensor accurately measures all geometrical information, i.e., range and the angles, no calibration tasks with respect to the laser data have to be carried out.

4.2 Calibration of internal camera parameters

For a camera with a wide-angle lens calibration of the camera is done by taking images of a flat regular structure with well-defined dimensions, for example a flat black-and-white image of a check pattern. A series of images are taken covering in total the complete field-of-view of the camera.

For a camera with a telephoto lens the method with the check pattern becomes impractical. In order to get an image in focus the distance of the camera to the check pattern has to be quite large. In this case it is possible to base the camera calibration on identifying tie points in the calibration images which are arbitrarily distributed in 3D with known 3D coordinates. Again, by taking a series of images covering in total the complete field-of-view with a more or less uniform distribution, the parameters can be determined accurately.

4.3 Mounting calibration

The three rotational parameters of the mounting calibration have to be optimised after each mounting of the camera. This can be done directly after mounting the camera and taking both scan data and an image sequence, but can also be done off-line after taking all data of the data acquisition campaign. This calibration task is based on identifying at least two tie points in the images taken at one scan position with well-known 3D coordinates in the scanner's own coordinate system (SOCS).

As the mounting calibration has to be carried out after each mounting of the camera RiSCAN PRO manages a large number of mounting calibrations within a single project, although most projects can be handled with a single mounting calibration.

5 Example project

Data have been acquired with a *RIEGL* LMS-Z360 3D Imaging Sensor combined with a Nikon D100 camera with a Nikkor 14 mm lens. The key features of the instrument are summarized in Table 1.

3D Imaging Laser Sensor RIEGL LMS-Z360	
Measuring range	2m up to 200m
Range measurement accuracy	12 mm
Laser	0.9µm/Class 1 (eye safe)/3 mrad beam divergence
Measurement rate	8000 - 24000 points/s
Scanner performance	
Scan range	Up to 90 deg x up to 360 deg
Minimum scan step width	0.004 deg
Angular resolution	0.0025 deg
Physical data	
Main dimensions (LxØ)	490 mm x 210 mm
Weight	approx. 13 kg
Power supply	12 – 28 V DC, 4 A @15 V DC
Temperature range	Operation: -10°C to +50°C, Storage: -20°C to +60°C
High-resolution camera system	
Camera type	Nikon D100
Resolution	3008 x 2000 pixel, pixel size 7.8 µm
Lens	Nikkor 20 mm

Table 1: Key parameters of the data acquisition system used in the example. For a more detailed description of the laser measurement system see www.riegl.com and (ULLRICH 2001).

The object is the arena in Verona, Italy (compare Figure5). Data have been acquired from only four positions. Data acquisition has been done in cooperation with Instituto Universitario di Architettura di Venezia, Prof. F. Guerra. At every scan position at least 9 images have been taken with fixed focus and fixed aperture. For merging the data numerous retro-reflecting targets have been posed in the scene (compare Figure 3 and 4). The coordinates of the reflectors have been measured by a total station providing the data in the tie point list PRCS. A single person has carried out the complete acquisition within 2 hours net time.

Merging the scans and thus registering the scans in the project coordinate system has been done in the field in order to check data coverage immediately. After correcting the mounting calibration of the camera, the image information was ready for being applied already in the field.

Figure 3: RIEGL LMS-Z360 with Nikon camera mounted on top at work scanning the arena in Verona, Italy.

Figure 4: Retro-reflective targets used for merging the scans.

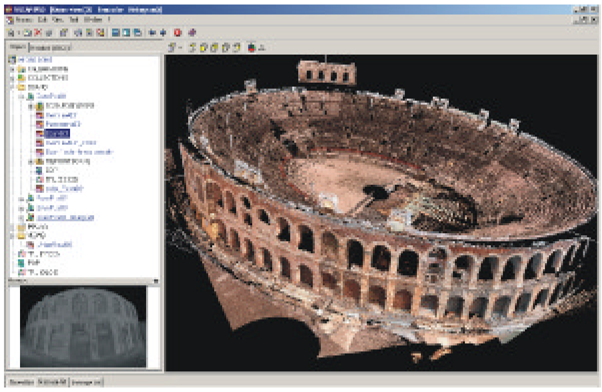

Figure 5: Total view of the online - merged point cloud data from a virtually elevated position (to the right of the image). The color of each point has been taken from the corresponding camera image. To the left the tree structure displays the several scan positions and the files at a single scan position.

6 Summary

The combination of high-performance laser imaging sensors with high-resolution digital cameras, which are calibrated and firmly fixed to the scanner, forms a measurement system providing the advantages of both field of laser scanning and photogrammetry. The software package RiSCAN PRO allows performing all necessary tasks to merge the data of both sensors, the laser sensor and the camera and provides the data in an organized, open and well-documented format for further processing and archiving.

Figure 6: Detail of the scan data showing a part of the point cloud data. The vertex color is again taken from the corresponding image.

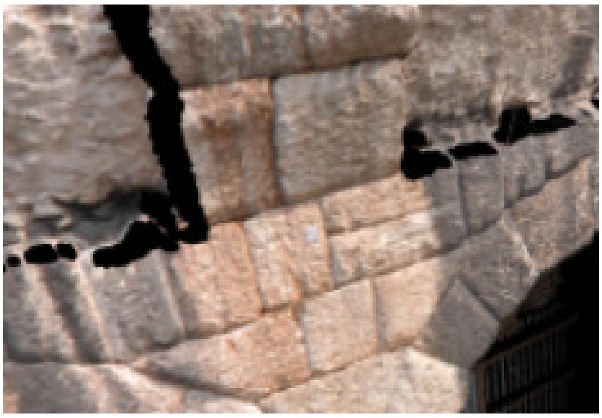

Figure 7: Detail of the scan data showing a part of the meshed surface generated from the scan data. The vertex color is again taken from the corresponding image. Black areas are due to lack of scan and image data as virtual camera position differs clearly from real sensor position. Retro-reflector can be identified in the center of the image.

7 References

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