# USING HYBRID MULTI-STATION ADJUSTMENT FOR AN INTEGRATED CAMERA LASER-SCANNER SYSTEM

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## ABSTRACT

A hybrid multi-station adjustment for processing 2D (photographic) and 3D (laser scanning) data in an integrated environment is presented. The composite sensor being used is made up of a long-range high-performance RIEGL laser scanner, based on “time-of-flight” ranging , and a commercial high-resolution CCD camera. The data acquisition and adjustment is performed by means of a dedicated software package. Questions of sensor calibration and advantages of such a combined approach are addressed.

## 1 INTRODUCTION

### 1.1 Laser Scanning

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 (Ullrich et al., 2001) 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.

### 1.2 Photogrammetry

Close range photogrammetry has a long tradition in reconstructing objects from photographs starting with a photo-triangulation (bundle block adjustment) and culminating in the production of three-dimensional photo-models which are object models with texture information taken from photographs (Kraus, 1997), (ORIENT, 2003).

### 1.3 Integration

Recently RIEGL started to offer the 3D imaging laser sensors with an optional high-resolution digital camera firmly mounted to the scanner. The camera is calibrated and has known orientation with respect to the sensors coordinate system. By taking a number of images, the whole field-of-view of up to 90 x 360 deg can be covered by 2D photographic images in addition to the 3D scanner data (Studnicka et al., 2003).
The hybrid sensor system is connected to a controlling computer (usually a laptop) by (Ethernet) cabling or a wireless LAN module. All measurement data is stored within a single project structure on the computer, thereby enforcing their strong interrelationship. The extrinsic camera parameters for the images are related to the extrinsic scanner parameters in a simple way by means of a set of mounting parameters, and as such allows for straightforward manipulation of both data sets without a separate alignment procedure.

# 2 SOFTWARE PACKAGE RISCAN PRO

## 2.1 Project Structure

An entire data acquisition campaign is usually performed by taking 3D scans from a number of different positions. These positions are chosen to give an almost complete covering of the objects of interest. Care must be taken to avoid or at least to consider occlusions that would not show up from any position. It is essential to get an almost real-time overview of the entire scan process to decide when all objects are captured sufficiently. To accomplish this, all scans taken are organized within a single project structure supported by the software package RiSCAN PRO. This project structure bundles scanner data, camera data and the transformations. All project information is accessible by means of a published data structure in order to allow for independent software developers to make full use of the data. (See e.g. PHIDIAS from PHOCAD ( PHOCAD, 2003)) The emerging XML (text based) data description format is used to physically represent project information on permanent media, and thus enables post-processing software packages to make full use of the RiSCAN PRO data. Within this structure all raw sensor data is organized as an easy to access tree structure. The 3D (scanner) as well as 2D (photographic) data uses the same hierarchical structure of coordinate systems. Besides this, the software package is designed to aid in sensor configuration, data acquisition, data visualization and archiving. The package also performs sensor configuration and is used for various calibration tasks.

## 2.2 Coordinate Systems

All scans and photographs are interrelated by hierarchically structured coordinate systems. Their interrelations are described by 4x4 matrices. Although usually only 6 degrees of freedom are used, in principle it would be possible to extend on this to incorporate scale manipulations too.

### 2.2.1 Scanners Own Coordinate System (SOCS)

The SOCS is the coordinate system in which the scanner delivers its raw data. Figure 1 shows the coordinate system of an LMS-Z series instrument. The data of every RIEGL 3D laser imaging sensor comprises geometry information (Cartesian x,y,z or Spherical r,ϑ,φ coordinates) and additional properties (at least intensity, optional color information). Thus the output of a RIEGL 3D laser imaging sensor can be addressed as an organized point cloud in the scanners own coordinate system with additional vertex properties.

### 2.2.2 PRoject Coordinate System (PRCS)

The PRCS is a coordinate system which is defined by the user. For example, PRCS might be an already existing coordinate system native to 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). I.e. if millimeter accuracy is required, the largest figure of coordinates should not excess 10 km.

### 2.2.3 GLobal Coordinate System (GLCS)

The GLCS is the embedding coordinate system which usually is constituted by external bodies. This coordinate system is capable of handling large coordinates.

### 2.2.4 CaMera Coordinate System (CMCS)

The CMCS is the coordinate system of the digital camera used. It is defined by the camera's image sensor.

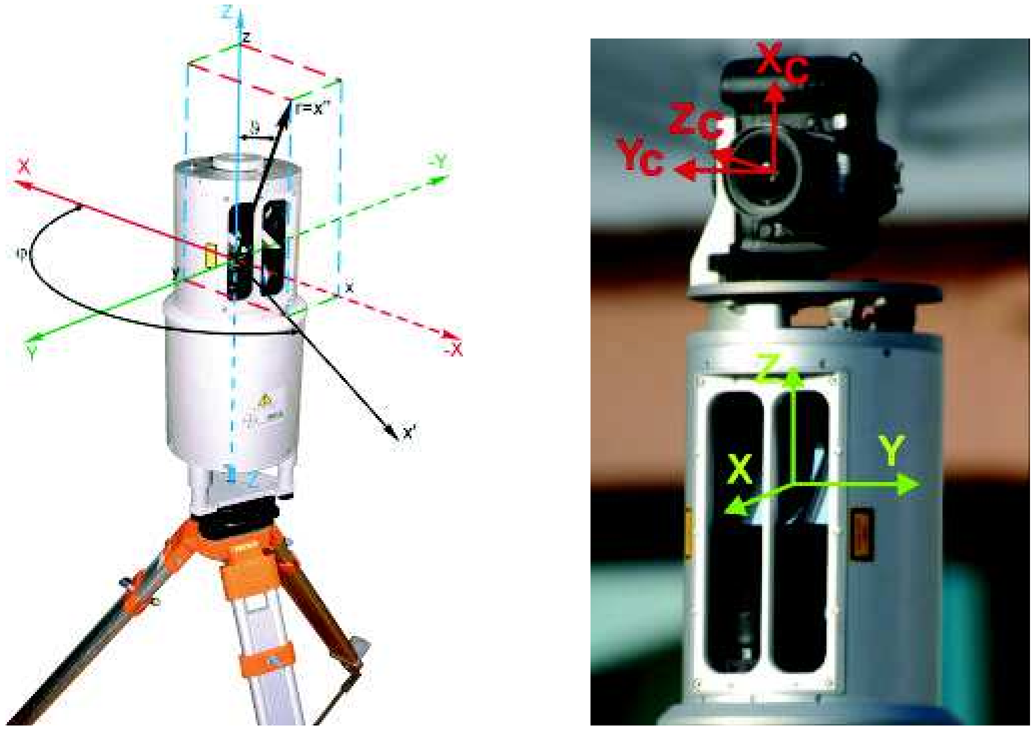

Figure 1: Definition of the coordinate system of a RIEGL LMS-Z series instrument (left) and RIEGL LMS-Z360 with a digital camera mounted on top of the laser instrument (right).

## 2.3 Orientation

Figure 2 shows an example of coordinate systems GLCS, PRCS and SOCS. The object is a building seen in birds view. A project coordinate system is defined with the $y_{pr}$ axis being parallel to the longer side of the building and the origin of the PRCS coinciding with one corner of the building. PRCS must 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 $SOCS_i$, where the scanner has been set up for data acquisition (see detailed description on scan positions below). Each scan position has its own local coordinate system (SOCS) sketched by the axes $x_{socsi}$, $y_{socsi}$, $z_{socsi}$. 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 objects 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 initializes a new scan position before performing the measurement. This scan position will hold all data belonging to this specific setting of the instrument. Part of this data is a transformation $\mathbf{M}_{\mathbf{SOP}N}$ (scanner orientation and position) which describes the SOCS of location $SOCS_N$ with respect to the PRCS. Although the transformation is stored as a 4x4 matrix, only 6 degrees of freedom (3 rotations, and 3 translations) are actually used, since no affine distortions need to be applied to the scans.

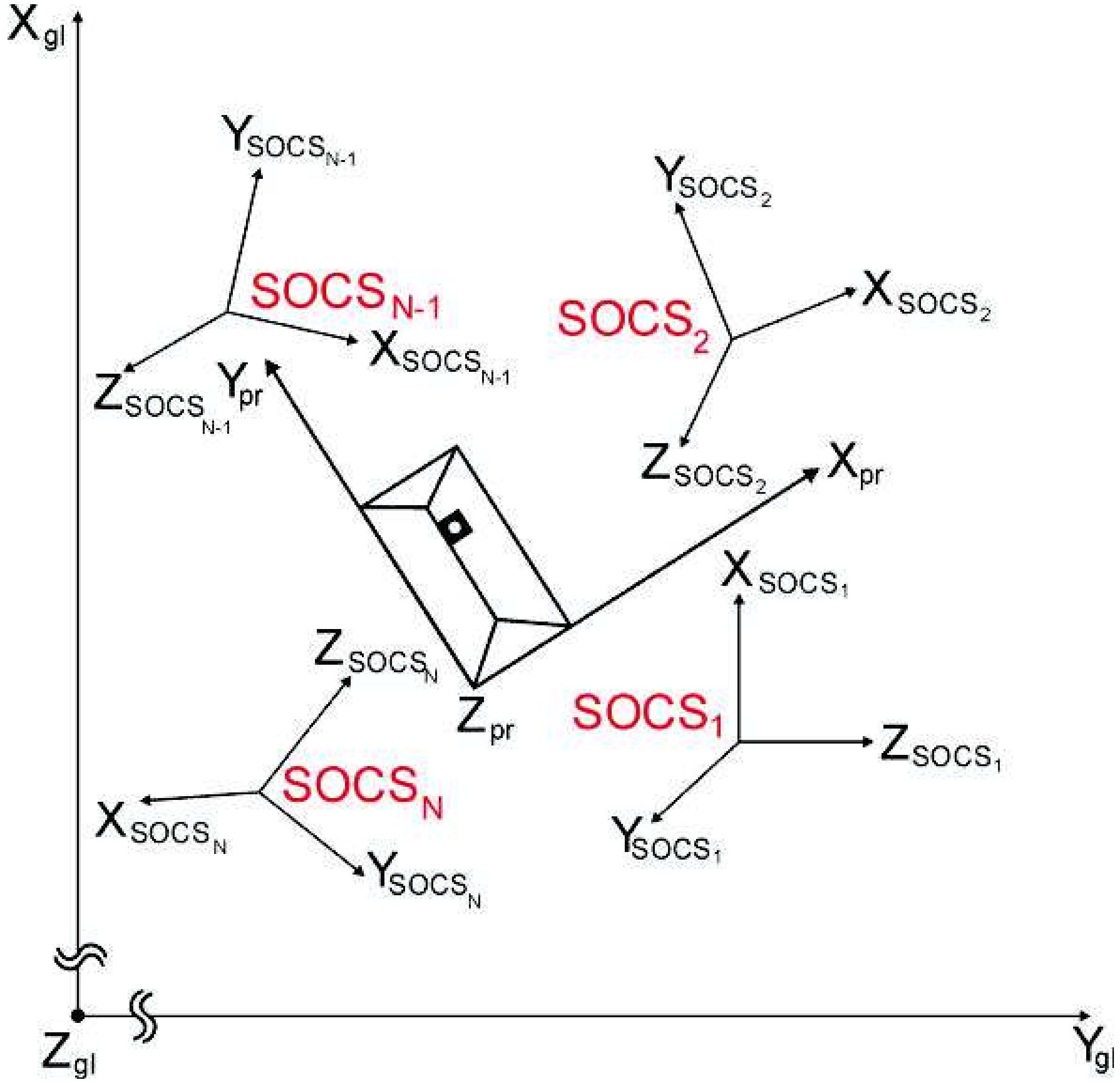

Figure 2: Example of PRCS, GLCS, and a number of SOCS at a site for scanning of a building

A matrix $\mathbf{M}_{\mathbf{POP}}$ is used to transform the data from the PRCS to the GLCS. The total transformation chain to get from local scanner coordinates to the global reference frame then is:

$$\mathbf{x}_{\mathbf{GLCS}} = \mathbf{M}_{\mathbf{POP}} \mathbf{M}_{\mathbf{SOP}\,N} \mathbf{x}_{\mathbf{SOCS}_N} .$$

A similar transformation chain holds for camera coordinates:

$$\mathbf{x}_{\mathbf{GLCS}} = \mathbf{M}_{\mathbf{POP}} \mathbf{M}_{\mathbf{SOP}_N} \mathbf{M}_{\mathbf{COP}_{N,M}} \mathbf{M}^{-1}_{\mathbf{mount}} \mathbf{x}_{\mathbf{CMCS}_{N,M}} ,$$

where N is for the N`th location and M for the M`th photo taken at this location. $\mathbf{M}_{\mathbf{mount}}$ is the camera mounting matrix which is considered constant during a measurement campaign (at least until the camera is detached from the top of the scanner head). It establishes 6 degrees of freedom (3 rotations, and 3 translations). The matrix $\mathbf{M}_{\mathbf{COP}N,M}$ describes a mere rotation about the z-axis of the respective SOCS system at the current location where the image is taken. This rotation angle is a measurement result which is available from the scanner head. The mounting matrix and the rotation matrix together describe the transformation of image coordinates into the scanners own coordinate system. The splitting of this transformation factors out the constant part, allowing a simple mapping of camera images to the scan data. The separate storage of $\mathbf{M}_{\mathbf{mount}}$ also gives rise to two scenarios of usage which are described in 4.1 and 4.2 later in this text.

During the course of measurement it is necessary to find the transformation matrices. One reliable method is to place retro-reflective signals into the scene which may be automatically identified from the intensity image of a scan, i.e an actively acquired image in the near infrared based on the intensity of the echo pulse. These signals are then gathered in a project wide list and are given unique names. A semi-automatic procedure is used then to help the operator find corresponding signals within all scan positions. As a side effect a first coarse relative orientation of the locations is found ($\mathbf{M}_{\mathbf{SOP}1}, \mathbf{M}_{\mathbf{SOP}2}, ..., \mathbf{M}_{\mathbf{SOP}N}$). This usually is sufficient to visualize the data to investigate if enough scans have been taken, and to choose additional scan locations.

If global coordinates of some of the signals are available, it is possible to orient the PRCS with respect to a global reference frame. These signals are addressed as control points then, while all of them are addressed as tie points. If no signals are available, it is still possible to manually mark tie points within the scan images. This might be meaningful if it is unfeasible to apply signals to exposed points, like to the roof of a church or similar.

Since signal coordinates are usually determined from the scans only in a coarse resolution, RiSCAN PRO offers an automatic high resolution scan of the signals, also called fine-scan, resulting in high precision signal coordinates.

The camera images may be used to give a true colored view of the scene at this early stage. Note that the images are directly applicable to the scan data since their transformation matrices are completely known at this point.

The transformation matrices of course need further improvement to achieve higher accuracy. This is done, using a hybrid-adjustment procedure taking into account all scans simultaneously.

## 3 SOFTWARE PACKAGE ORIENT

ORIENT (ORIENT, 2003) is a program system which was mainly intended to do rigorous adjustments in the field of photogrammetric point determination. It was developed at the TU Vienna Institute of Photogrammetry and Remote Sensing (i.p.f.).

Many kinds of observations and/or parameters may be treated simultaneously. The subset of features required in the context of this paper concerns (for math. background see: (Kraus,1997))

- Observations:
    - image points (x,y) stemming from some CMCS: PHOTO
    - polar points (direction φ, zenith angle θ, distance r) in some SOCS: POLAR
    - object control points (X,Y,Z) given in PRCS: CONPOI
    - differences of parameters: for $M_{COP}$ ROTPAR=OBS
- Parameters:
    - object points (X,Y,Z) in PRCS REFSYS
    - transformation (orientation) parameters
        - exterior reference points (origins of SOCS) REFSYS
        - rotations ROTPAR
    - additional parameters ADPAR
        - for image deformation (distortion)
        - for eccentricity of mounting (like a GPS-antenna in aero-triangulation)
        - for rotations of mounting (like an IMU misalignment in LIDAR)

The program system is controlled by a command language which makes it suitable to be run also in batch-mode. ORIENT is linked as DLL (dynamic link library) to RiSCAN PRO using CMD-files as interface. So, adjustment is run as black-box module in a standardized environment. Only few parameters may be controlled by the operator.

Robust estimation is used to detect and eliminate gross errors automatically.

# 4 HYBRID ADJUSTMENT APPROACH

## 4.1 Improved Orientation

Determination of a complete set of $\mathbf{M}_{SOP}$ matrices can be done from laser-measurements alone, or may be the sole result of standard photogrammetric methods. It is a straight forward procedure however, to combine both methods to improve accuracy, or to cut down the total time for measurement.

Taking signal coordinates from a wide angle laser scan usually is done with modest precision only, due to time constraints. While in principle the laser may be programmed to deliver data in high resolution, this would require far too much time and deliver huge amounts of unnecessary data in regions where no signals are seen (which is the case in most areas of the image). One possible remedy is to first estimate coarse signal coordinates from the scan and then conduct a series of high resolution scans of small size, each covering just a single signal. While this cuts down measurement time considerably, even more savings might be achieved by using high resolution camera images instead, to find signal coordinates of sufficient resolution. The coarse coordinate estimate available from the laser scan can be used to narrow the search area within the camera image in this case, so that reliable operation might also be possible without using a flash light, which is mandatory otherwise. This essentially splits the detection and estimation steps between the both technologies.

On the other hand it is possible to improve accuracy without saving measurement time, by simply combining the data of both sub-systems and feeding it to the adjustment algorithm as a single set of inputs.

Both approaches imply that the camera already has been calibrated. It still might be an interesting question whether this is a necessary precondition, or if the camera calibration can be recovered from the data after the measurements have been finished, using a method similar to the one addressed in the sequel.

## 4.2 Camera Calibration from Field data

### 4.2.1 Test-field Calibration

The integrated camera laser-scanner system using the technique of hybrid adjustment also offers the possibility to do camera calibrations independent from other measurements in a self-provided small (some few points) test field.

In traditional photogrammetry installing and maintaining a test-field was a tedious and laborious task. Since we have a laser scanner system with automated detection of retro-signals and fine-scanning capabilities to measure especially the direction to these signals precisely, we have an instrument solving the task of determination of the signal coordinates with sufficient accuracy in a fast way. Since the camera has only a small eccentricity with respect to the laser center, the distance precision is of sub-ordinate importance.

So, the laser scanner determines as well the coordinates of the test-field as well it triggers the taking of photographs in known (i.e. measured) viewing directions. The signals are also automatically determined and identified in the digital images allowing the set-up of a hybrid adjustment by observations with the following unknowns: all the object coordinates of signals, 3 mounting rotations of the camera against the laser head, 3 eccentricity components of the camera mounting (i.e. the relative coordinates of the laser center counted in the CMCS), 3 coordinates of interior orientation, and a set of distortion coefficients. Observations are: polar and image coordinates.

From the adjustment-theoretical point of view this approach is very sound since it avoids the correlations between the points of the test field.

The datum definition (i.e. choice of PRCS) for this local adjustment is simple keeping position and attitude of the SOCS fixed: PRCS:=SOCS. (The datum definition has no influence upon the quality (accuracy) of camera calibration.)

**Minimal test-field requirements:**
One might establish a test-field as recommended for single pose camera calibrations: a lot of points in different distances (foreground and background) both covering the whole image format. This implies, let's say, 2*(5*5) to 2*(8*8) signals to get also the distortion reliably determined (however, one might save a lot of the near inner points,…).
But we may even save most of these signals: The integrated camera laser-scanner system allows the virtual duplication of retro-signals: assume the scanner being set up with near vertical z-axis of SOCS; then, imagine a vertical plane passing through the origin of SOCS containing one column of near and far signals, let's say, 2*5 to 2*8 signals. We let the laser determine these few points in PRCS=SOCS and take an image yielding an $\mathbf{M}_{\mathbf{COP}}$; then we advance the scanner head by some d$\varphi$ yielding another $\boldsymbol{M}_{COP}(\varphi)$ and take another image. This latter step we repeat until the whole image format is covered with a raster caused by duplication of our single column of signals.
Practically, these signals may be placed on a wall (inner face of wall openings for easier access) in two vertical profiles; the laser scanner device stands near that wall seeing the wall nearly projecting.

**Discussion of time effort**:
In the standard case (raster of e.g. 2*(8*8) signals) we need a lot (e.g. 128) of fine-scans and only one image – in the virtual case (one column of signals) we need only some (e.g. 16) fine-scans but a series of (e.g. 8) images. If we can read out the image partially (the sub-range of image columns needed is easily estimable), processing time can be reduced further.

**Discussion of stability:**
For both approaches the same postulates about stability of the integrated camera laser-scanner system hold true as for normal operation.
It should be emphasized that no additional measurements by theodolite or total station are necessary to determine the coordinates of the control points.

One might argue whether the determination of the mounting parameters in $\mathbf{M}_{\mathbf{mount}}$ belongs also to the task of camera calibration; anyway, these parameters are determinable with the implemented orientation procedure; nevertheless, $\mathbf{M}_{\mathbf{mount}}$ has to be determined after each re-attachment of the camera onto the laser head considering the interior parameters of the camera stable (Studnicka et al., 2003). But in this case, only few targets are necessary to do the mounting alignment which may be restricted to the rotational components only since the eccentricity may be considered constant.

### 4.2.2 On The Job Calibration

The usual notion of a test field is a permanent installation of a lot of signals which have been determined with very high accuracy. So, the coordinates of those signals are usually well known before starting the camera calibration. As we have seen in section 4.2.1, we can use a test field (even a temporary one) whose coordinates are determined "on the fly". The term "on the job calibration" means in photogrammetric triangulation that during the adjustment of some project, the parameters of interior orientation (including distortion) are determined also. Here (see 4.1) we have a quite similar situation: We use the configuration of some project to do also a camera calibration – on the job! Maybe, we haven't calibrated that camera before; maybe, we are in doubt about the quality of the calibration. However, the current configuration may not be sufficient to get a complete calibration yielding even singular parameters. Nevertheless, the adjustment system used can handle even such situations doing a regularization or, even better, using data from an older calibration as "fictitious" observations of the interior camera parameters (Kraus, 1997). So, this "on the job” feature might be restricted to advanced users whereas the standardized approach of 4.2.1 is considered uncritical.

### 4.3 Post Processing

In close -range applications the resolution of the camera images may be significantly higher on the target surface compared to the laser scan data. Some features of the target object only show up in the camera images, e.g., colour pointing, but not in the scan data. Furthermore, the laser scan data tend to have higher noise and thus lower accuracy at edges and structures smaller than the laser footprint.

For example, if an edge of a facade shows up in at least two registered and calibrated images, the edge can be reconstructed in 3D by photogrametrical means with high precision. This reconstructed edge can subsequently be used to modify and thus to improve meshed scan data by inserting the edge as a feature line in the scan data mesh.

As another example, the size of a traffic sign can be accurately determined from the camera image projecting and intersecting the precisely determined silhouette with the traffic sign's plane retrieved from the scan data.

## 5 SUMMARY

So, integrating a digital camera, a laser-scanner, and hybrid multi station adjustment, we have an autarkic system covering the complete processing chain - including calibration – from data acquisition up to topologically structured surface data which is homogeneously adjusted into the project frame.

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