GRAND CANAL'S PALACES' FACADE MAPS BASED ON MOBILE SCANNING DATA ACQUIRED BY BOAT

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Abstract:

During the last few years, mobile laser scanning operated from land and water vehicles has rapidly become established for various areas of application, such as the surveying of roads, trackage, and coasts. This is based on the continuous technological advancement of the individual components, the combination of which now makes it possible to deliver highly accurate 3D point clouds at very high measurement rates.

The RIEGL VMX®-250 [1] provides a compact, flexible and high-performance system for mobile laser scanning. The seamless integration of the modular camera system into the hard- and software complements the system.

This report gives an overview of the system concept and demonstrates the high quality of the data, with a project to survey the palaces of Grand Canal in Venice as an example. The ideal workflow for recording, as well as the newly developed automatic adjustment of scan data are described as well as analysis resulting in facade plans is outlined.

The following statements have already been presented partly at the "Oldenburger 3D Tage" 2011 [2] and at Geosiberia 2011 [3] and will be elaborated in more detail here.

1. INTRODUCTION

1.1 The project

In 2010 *RIEGL* carried out a sensational project in cooperation with Università di Venezia [4]: The VMX-250 was employed to capture the century-old facades of the palaces along Grand Canal, as depicted in figure 1, using mobile laser scanning. Results were exemplarily processed based on a few buildings. In this course, the new modular camera system VMX-250-CS6 could be tested in a large project for the first time. The combined processing of the photogrammetric and the laser scan data [5] resulted in colored point clouds, 2D CAD plans, and 3D CAD models using the monoplotting method.

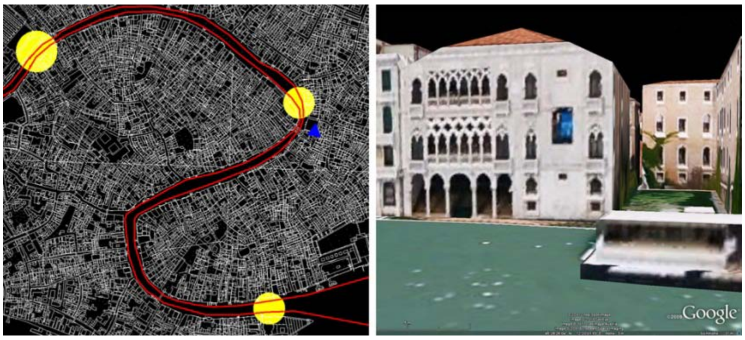

Figure 1: (left) CAD plan of Venice, red: planned trajectory, yellow: areas with planned control points and (right) Facade of the Palazzo "Casa d'Oro" in Google Earth with swimming Vaporetto stop.

2. DATA ACQUISITION

Before arrival on the 9th of November 2010, the weather was a mainly unknown factor. Disregarding advice from the Venetians, who were struggling with high water, rain and fog, the project commenced as planned. Theoretically, a single day of data acquisition would have sufficed, but due to the bad weather, the canal was scanned and photographed on three days under varying conditions, however mainly without precipitation.

2.2 Description of the *RIEGL* VMX-250

The hardware of the VMX-250 consists of two *RIEGL* VQ-250 laser scanners, a camera system, a portable control unit box, and an INS/GNSS-unit which comprises the electronics for real-time kinematic (RTK) and three sensors: the sensor of the inertial navigation system (INS), a global satellite navigation system (GNSS) receiver including antenna, and a wheel sensor (distance measuring indicator, DMI). This last sensor is deactivated when the system is used on a boat. The modular camera system VMX-250-CS6 described in the next section is also part of the hardware.

The *RIEGL* VQ-250 scanners and the INS/GNSS-unit are rigidly attached to a stable mounting platform which can, for example, be mounted on a boat. A single cable connects this measuring head to the control unit box. It is housed in a compact case and contains the power supply, an embedded computer running the RiACQUIRE software package for data acquisition, removable hard drives, and a handy touch-screen providing a convenient control interface for the operator. During acquisition, both laser scanners are operated synchronously, thus taking 3D measurements at the double measurement rate of a single scanner. Key data of the system can be found in table 1.

2.3 Description of the *RIEGL* VMX-250-CS6

The VMX-250-CS6 camera system complements acquisition of laser scan data with the recording of high-resolution color images [5]. Up to six individually selectable, fully calibrated digital color cameras with electronic shutters can be integrated. Each of these industrial cameras is encased in a robust aluminum housing allowing reliable operation under adverse conditions. Image triggering can be parameterized

Table 1: Mobile Laser Scanning System *RIEGL* VMX-250 Specifications.

Effective measurement rate	Up to 2 × 300,000 measurements/sec
Max. measurement range	500 m @ ρ > 80% and 100 kHz 75m @ ρ > 10% and 600 kHz
Accuracy / Precision	10 mm / 5 mm
Scanning rate (selectable)	Up to 2 × 100 lines/sec
Laser Class	1 (eyesafe)
Multi target capability	yes
Range-independent reflectance [6], [7]	yes
INS/GNSS performance	
Position (absolute)	typ. 20-50 mm
Position (relative)	typ. 10 mm
Roll, Pitch, Yaw	0.005°, 0.005°, 0.015°
Camera System	
Resolution	2 MPx (1080p HDTV) / 5 MPx [1)]
Lens / FOV	5 mm / 80° × 60° [2)]

1) Higher resolutions on request. External cameras (e.g. DSLR or IR cameras) from other manufacturers can be integrated.

2) 12mm lenses with a field of view of approx. 40° × 30° were used for the Grand Canal project.

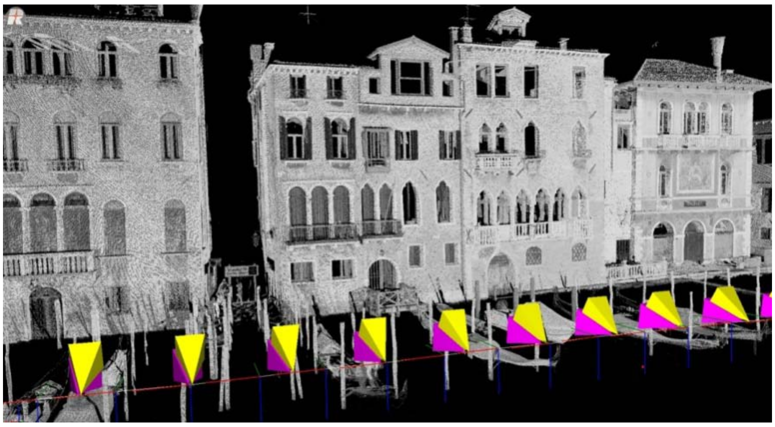

Figure 2: Illustration of the camera positions and fields of view at the moment of their synchronous trigger. Yellow and pink cones represent the fields of view of camera 1 and 2, respectively. The thin red line describes the trajectory. Scan data is displayed colored with the gray-scaled relative reflectance.

individually for each camera either time-based or distance-based. When the picture is captured, the camera sends a strobe signal which is precisely time-stamped by the electronics of the camera system. In conjunction with the known mounting parameters, precise position and orientation of the cameras are defined over time as shown in figure 2. Camera control and image data recording is completely managed by the acquisition software embedding the pictures into the project structure together with the scan data. The accurately time-stamped images can be used to color the scan data, but are also the basis for photogrammetric processing. Additionally, it is possible to record 1080p HDTV videos with precise time information.

The cameras can be attached to the mounting frame and oriented individually to meet the requirements of the current application. A single cable connects the camera system to the VMX-250 measuring head. A robust mechanical connection between these two components guarantees a stable mounting of the camera system with respect to the laser scanners while maintaining the modularity and portability of the whole system at the same time. An additional PC embedded in the control unit is responsible for acquiring image data and storing it on three more hard disks. Although the camera system is designed for use with the cameras offered by *RIEGL*, also models from other manufacturers, for example digital single-lens reflex (DSLR) cameras and infrared cameras or “360°” camera solutions, can be integrated.

2.4 Default camera model

The camera model used is based on a Cartesian coordinate system (CaMera Coordinate System, CMCS). The origin is coincident with that of an equivalent pinhole camera. The x-axis of the right-handed coordinate system is aligned from left to right in the images, whereas the y-axis is aligned from top to bottom. Thus, the z-axis corresponds to the direction of camera’s view.

Figure 3: (left) *RIEGL* VMX-250 mobile laser scanning system with the modular camera system and (right) mounting of the system on the workboat “Sante” during scanning.

The internal camera calibration describes the ideal pinhole camera represented by the focal length and the equivalent center of the pinhole projected orthogonally onto the chip surface. The x and y axes use separate focal lengths f_x and f_y which are normalized by the respective pixel spreads d_x and d_y, so that, for example, $f_{x,n} = f_x/d_x$. The center of the image in relation to the CMCS is defined by the parameters C_x and C_y, given in pixel units. For lenses with negligible distortion, usually $C_x \approx N_x/2$ and $C_y \approx N_y/2$ can be assumed, whereas N_x and N_y are the pixel counts in either direction. Deviations from this rule indicate a lens not centered to the sensor.

The lens distortion is modeled by at least two radial and two tangential coefficients: k_1, k_2 and p_1, p_2 respectively. In case the radial coefficients of higher order equal 0, the camera model is identical to the one described in OpenCV (http://opencvlibrary.sourceforge.net/).

2.5 Parameterization of the camera

The two 5-megapixel-cameras were mounted side by side for photos in portrait format, aiming to the right with a vertical overlap in the field of view as shown in figure 3. The 12mm lenses have a vertical field of view of approx. 40° and the overlap of approx. 10° resulted in an effective field of view of approx. 70° taking both cameras into account, which corresponds to a pixel pitch of 14mm at a target distance of 20m.

White balance was performed using a gray card. Exposure time was set to 8ms and gain to 8dB for acquisition. The cameras were triggered periodically every 1.5s yielding generous overlap between two consecutive pictures.

2.6 Parameterization of the scanner

In order to be able to subsequently draw a 2D plan with 1:100 scale from the scan data, a point spacing of one centimeter should be aimed at. This results in a point spacing of 0.1mm for printouts which can just be distinguished by the human eye.

The acquisition software RiACQUIRE calculates the optimal scan parameters. Speed and distance from the target have to be provided. At a speed of 5km/h and 20m from the target a horizontal point spacing of 2.3cm (approx. 2,000 points/m^2) per pass and scanner can be achieved.

To achieve the necessary point spacing for an "orthoscan" (orthogonal projection of a surface generated from a point cloud) at least three scan passes have to be overlaid. These passes have to be optimally aligned to each other. Ideally a point spacing of 10,000 points per square meter could be achieved in a single pass. However, this would require even higher measurement rates, lower travelling speeds, and a shorter distance to the target, all of which was not possible in practice.

Before the actual surveying, the entire system had been initialized. For that purpose it was necessary to perform a quick static alignment procedure and a few minutes of dynamic movements. As soon as the INS/GNSS had reached the required position accuracy, data acquisition began. In the meantime, the white balance of the cameras could be performed.

3. PROCESSING OF DATA

3.1 Quality check and workflow

Even during data acquisition the project was divided into four sectors corresponding to the water sections between the main bridges of Grand Canal. At the end of every day of acquisition, scan and trajectory data were processed into a 3D point cloud using the software package for mobile and airborne applications, RiPROCESS. Computing time equals the time necessary for data acquisition.

This way a first quality check could be carried out directly in the field and the scan parameters and camera settings could be verified. The focus of post-processing was on section 3 between the Rialto and Scalzi bridges. For scan data adjustment, the records of all three days, containing passes both up and down the canal, were used. Selected parts of planar surfaces in the scanned facades of section 3 served to define so-called “tie planes” (TPLs). The automatic adjustment feature in RiPROCESS then allows for correcting position and attitude values of the trajectory.

3.2 Trajectory correction method

Each manually created set of linked TPLs describes a number of observations as input for the scan data adjustment algorithm. A set of N linked TPLs results in $\binom{N}{2}$ pair-wisely calculated distances between two planes' centers of gravity [8] to be minimized by the adjustment tool in a least-square means.

As known well from adjusting point clouds obtained by terrestrial scanners or airborne scanners, usually small correction values for position and/or attitude are applied to each scan record or strip. Thanks to the pre-calibrated mobile scanning system, the residual source of uncertainties to be considered remains the trajectory including the attitude angles in general.

Therefore, the correction values have to be applied to the trajectory at specific time stamps which are deduced from the TPL observations. As a convention, the time stamp of that point in the point cloud with minimum distance to the TPL's center of gravity is used to link the observations to the trajectory. Corrections can be calculated and applied to only selected or to all trajectory components which are the three dimensions in space for position, resulting in a correction vector, and the three attitude angles.

First, for simplification, let us assume a set of only two TPLs where one is assigned to the time-stamp τ_1 and the second one is considered fixed in terms of a reference plane as shown in figure 4a. The adjustment algorithm will minimize the observed distance between the two planes by calculating correction values for the trajectory at time τ_1. (For the simple case of two TPLs only, the resulting distance will always be zero.) In general, the applied positional correction vectors do not equal the initial difference vectors between the centers of two defined planes because the planes can be oriented arbitrarily in space. This might become more evident in case only correction values for attitude angles are applied to the trajectory.

In a more general approach, a set of N TPLs will result in N time stamps $\tau_1, \tau_2, \ldots, \tau_N$ for applying corrections at the trajectory, called vertices in the further text. The example in figure 4b shows a set of three planes with corresponding time stamps τ_i, τ_{i+1}, τ_{i+2}. When performing the adjustment, correction values for the trajectory at all three time stamps are calculated minimizing the observed distances of TPLs while also keeping the sum of positional corrections at a minimum. In this way it is ensured that matching of the point clouds of interest is improved while preventing single records from drifting away in space. Furthermore, additional information can be used to weight the allowed correction to be applied at the vertices. It is convenient to consider for instance the position accuracy estimates of the trajectory for weighting, which leads to relatively larger correction values assigned to vertices with poor trajectory quality compared to vertices with good quality.

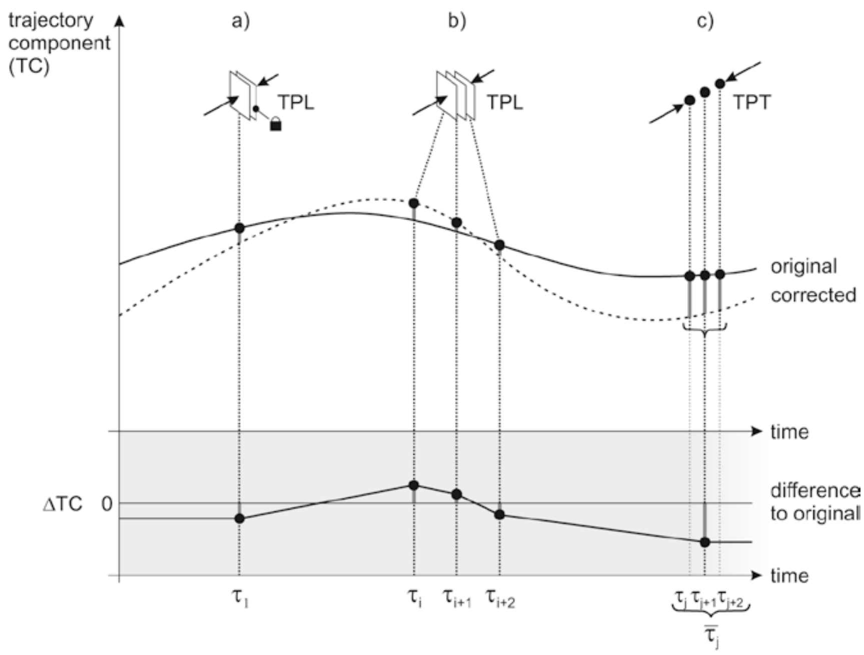

Figure 4: Examples of applied trajectory corrections at specific time-stamps (vertices) based on tie observations in the point cloud.

Since the scan data adjustment tool allows to create both plane and point observations, it is also possible to use “tie points” (TPTs) as depicted in figure 4c (or a combination of both) for establishing the necessary input of the adjustment tool. In order to reduce the number of free parameters, it is reasonable to merge adjacent time stamps τ_j, τ_{j+1}, τ_{j+2}, which are within fractions of seconds, to a common vertex at $\overline{\tau_j}$ where a correction value will be applied. Since time stamps can be subject to be merged to only one and, additionally, observations of different sets of linked TPLs can have an impact on one and the same time stamp, contradictive conditions in general for calculating the corrections are introduced. Consequently, the adjustment tool will calculate corrections which minimize the residuals, but cannot force them to zero.

The correction values are interpolated between vertices by linear means (or others like spline fitting), whereas before and after the first and last vertex, the correction values are extrapolated by using the first and last known correction value, respectively, as shown by the polyline ΔTC.

Moreover, external control objects, for example points, planes or spheres, can be integrated into the adjustment procedure by creating links to corresponding tie objects, which allows absolute adjustment of the point cloud. Otherwise only relative adjustment is applied to the point cloud between scan records.

3.3 Trajectory adjustment procedure

After having defined a set of 95 user-interactively created TPLs, the correction values were determined in two steps. Before the positional adjustment, the yaw angle had to be optimized due to the slow acquisition speed in conjunction with the lack of changes in direction due to the “linear shape” of the water channel. In a second step the position corrections were carried out. This workflow is completely supported by RiPROCESS based on the method described in the previous section. The outcome is an automatically generated table of corrections for attitude, in particular the yaw angle, and the positions which is applied to the original trajectory.

This automated trajectory refinement procedure allows for optimal alignment of the eleven passes from all three days of data acquisition: The result of both adjustment steps shows a residual standard deviation of 0.0137m based on all 16,771 observations.

4. MODELING AND EVALUATION OF MEASUREMENT RESULTS

4.1 Partners for post-processing

In cooperation with EKG Baukultur [9] and PHOCAD [10], the registered photos and point clouds were assessed regarding their suitability for further processing. Based on the orthoscans of the facades of the palaces "Casa d'Oro" and "Casa Pesaro", EKG Baukultur GmbH drew exemplary 2D CAD plans as shown in figures 5 and 6, respectively. Using "Phidias" software, PHOCAD created an orthophoto and a 3D CAD model based on the RiPROCESS project shown in figure 7.

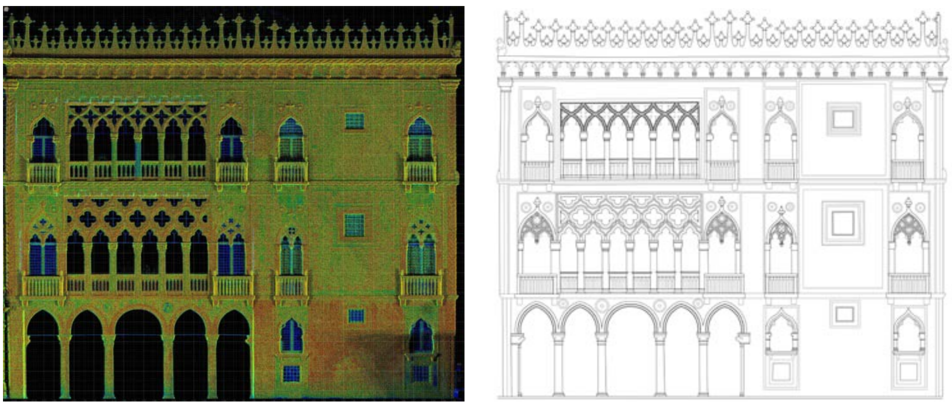

Figure. 5: (left) Orthoscan with color-coded reflectance (*RIEGL* RiPROCESS/RiSCAN PRO) and (right) 2D CAD Drawing (EKG) of “Casa d’Oro”.

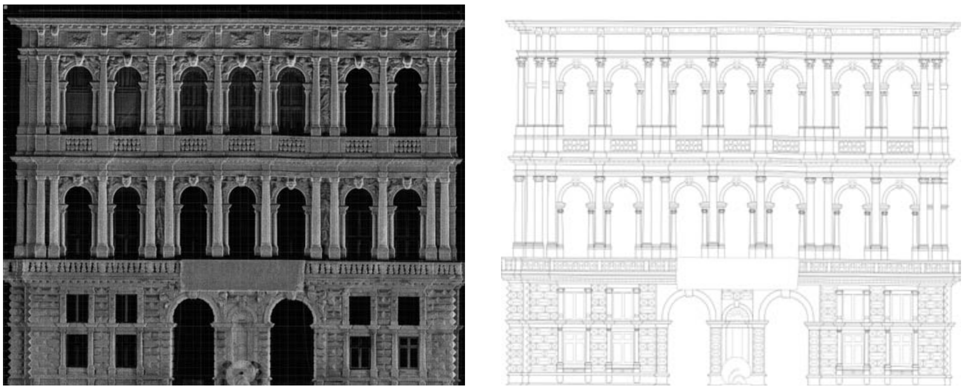

Figure 6: (left) Orthoscan with gray-scale coded reflectance (*RIEGL* RiPROCESS/RiSCAN PRO) and (right) 2D CAD Drawing (EKG) of "Casa Pesaro".

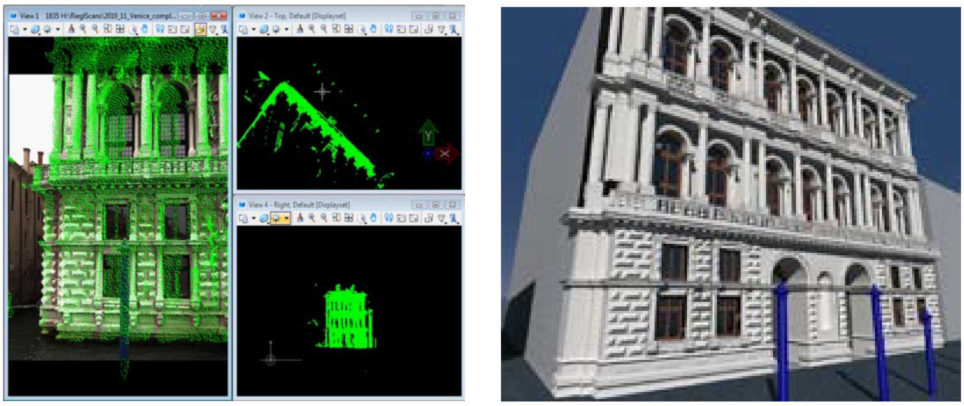

Figure 7: (left) 3D Monoplotting and 3D CAD drawing (Phocad/Phidias) of "Casa Pesaro".

4.2 Casa d'Oro

The Palazzo Casa d'Oro is probably the most familiar example of Gothic architecture along Grand Canal. Constructed from 1421 onwards by order of the wealthy patrician Marino Contarini, it owes its name to the original gilding of the facade. The numerous subsequent owners performed significant building alterations, and the structure suffered considerably during the 19th century. In 1894 Baron Giorgio Franchetti bought the Casa d'Oro and had it reconstructed according to numerous watercolors, lithographs and engravings. He accumulated a large art collection which, together with the casa itself, became state property when he died. Today the Casa d'Oro is home to a museum [11].

4.3 Casa Pesaro

Construction of the palazzo started in 1628 by combination and modification of some already existing buildings by order of the Pesaro family. The distinguished architect Baldassare Longhena started the project. After his death in 1682 it was finished by Gian Antonio Gasparia in 1710. The palazzo is a famous example of Baroque architecture with a sophisticated marble facade. Today the palace is state property and home to a museum for modern art and hosts a famous collection of oriental art [11].

5. PERSPECTIVES

It has been demonstrated that the mobile scanning system *RIEGL* VMX-250 is able to both scan and photograph the facades of Grand Canal with high resolutions in a short time. Table 2 gives a very brief executive summary. The quality of the acquired data is more than sufficient for CAD drawings on a scale of 1:100.

Table 2: Necessary workflow and time required.

Workflow	Time
Data acquisition	3 days + journey
Georeferencing of point cloud and images	Approx. 1 man-week (depending on the degree of optimization)
Creation of CAD drawings	1 day per facade (2D) 2 days per facade (3D)

Further processing options:

1. Even higher point resolutions will probably be possible soon through higher measurement and scan rates.
2. Measurements of reflectance can provide additional information especially for moist facades.
3. The high point density enables graphic representations of irregularities of the facade (for statistical purposes). Deformations, vertical declines, and other structural damage can be made clearly recognizable and visualized to scale.

8. REFERENCES

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