RIEGL VMX-250 with modular camera system – combined scan and image data acquisition in mobile laser scanning

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Key Words
Mobile Laser Scanning
Photogrammetry
Surveying
Modeling
Orthoimage

SUMMARY

During the last few years mobile laser scanning operated from land and water vehicles has rapidly been becoming 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 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 the 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 and analysis resulting in facade plans is outlined.

INTRODUCTION

In 2010 *RIEGL* realized a sensational project in cooperation with Università di Venezia: The VMX-250 was employed to capture the century-old facades of the palaces in the Grand Canal 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 resulted in colored point clouds, 2D CAD plans, and 3D CAD models using the monoplotting method.

DATA ACQUISITION

Mission Planning

The speed of data acquisition and the huge amounts of data make it essential to carefully plan the surveying mission and the subsequent processing. "Virtual walks" on Google Earth and videos on YouTube provided an overview of the expected conditions in advance: a heavily frequented waterway with traffic driving on the right, roughly four kilometers long and 40 to 70 meters wide. The view of the facades, which are 20 meters high at most, is unobstructed with only occasional Vaporetto stops as an obstacle.

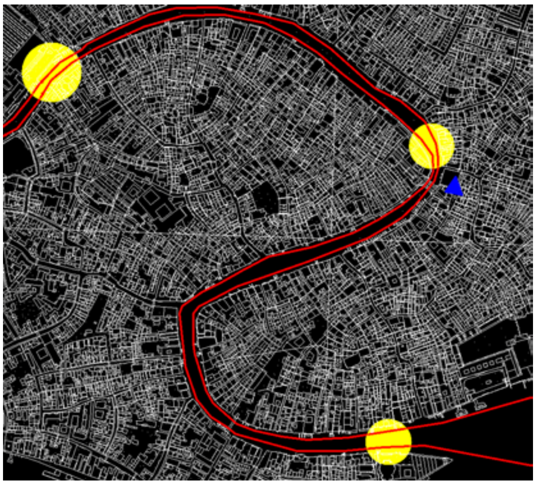


fig. 1: CAD plan of Venice
red: planned trajectory
yellow: areas with planned control points

fig. 2:
facade of the Palazzo “Casa d’Oro” in Google Earth with swimming Vaporetto stop

Good open sky guarantees sight to as many satellites as possible. Forecasts for the days in question predicted signal reception from between 7 and 10 satellites. A great number of satellites, spread as evenly over the sky as possible, is the most essential requirement for measuring an accurate trajectory of the boat and hence for the accuracy of the data. A 20-meter long Venetian workboat equipped with a crane and a crew was organized. The problem posed by visual obstruction of the facades by the Vaporetto stops was reduced to a minimum by mounting the laser scanning system on a scaffold three meters high (figure 6). The height clearance of the bridges of approximately seven meters and the travelling speed of 5 km/h would not impose any restrictions. The ability to perform rapid changes in direction in the canal was not given, which would have contributed to increase the accuracy of the yaw angle. Before departure, two camera positions were chosen such that the cameras were aimed to the right of the boat (due to traffic) for image acquisition. The national reference system "Gauss Boaga", an orthophoto, and a 1:2000 2D CAD plan (figure 1) of Venice served as additional sources of information.

Before arrival on 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.

Description of the *RIEGL* VMX-250

The hardware of the VMX-250 consists of two *RIEGL* VQ-250 2D laser scanners, a camera system, an INS-GNSS-unit and an on-board computer fitted into a portable case. The INS-GNSS-unit comprises the electronics for real-time kinematic (RTK) and three sensors: the sensor of the inertial navigation system (INS), a global satellite navigation system-receiver (GNSS) including antenna, and a wheel sensor (distance measuring indicator, DMI). This last sensor is deactivated when used on a boat. The modular camera system VMX-250-CS6 which is described in the next section is also part of the hardware.

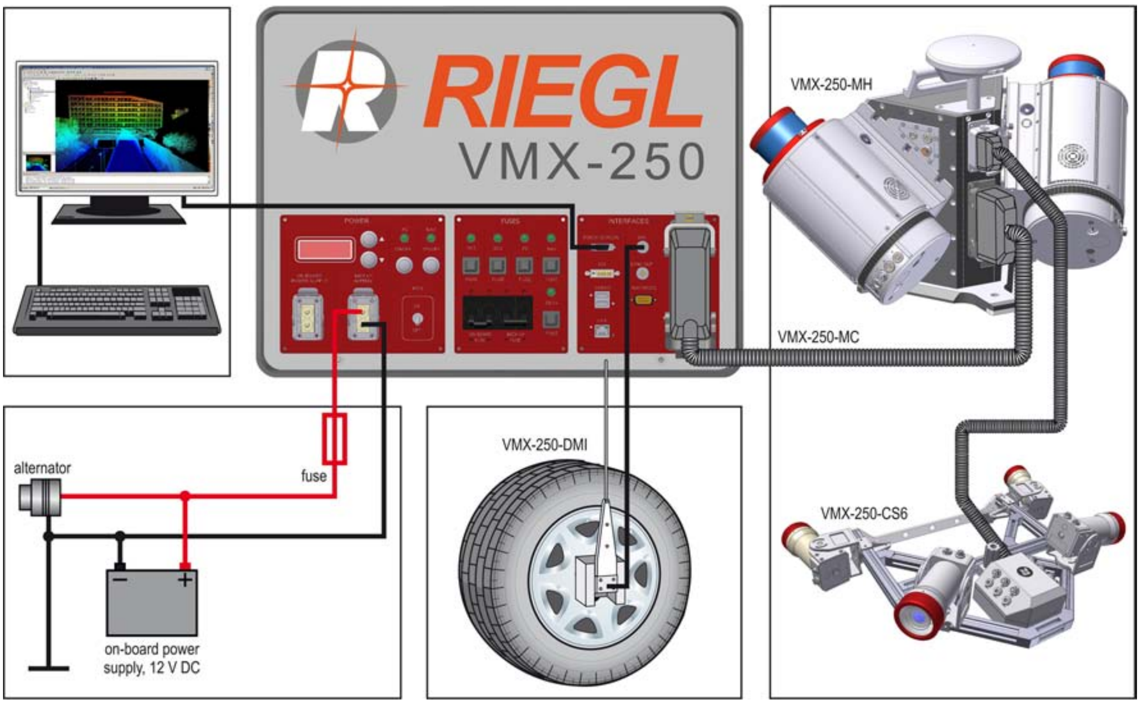


Fig. 3: Block diagram of the Mobile Laser Scanning system *RIEGL* VMX-250 in combination with the modular camera system VMX-250-CS6. In Venice, the DMI sensor was deactivated for data acquisition by boat and only two cameras were used.

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 case and contains the power supply, a 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.

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. 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 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. 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 FullHD videos with precise time information.

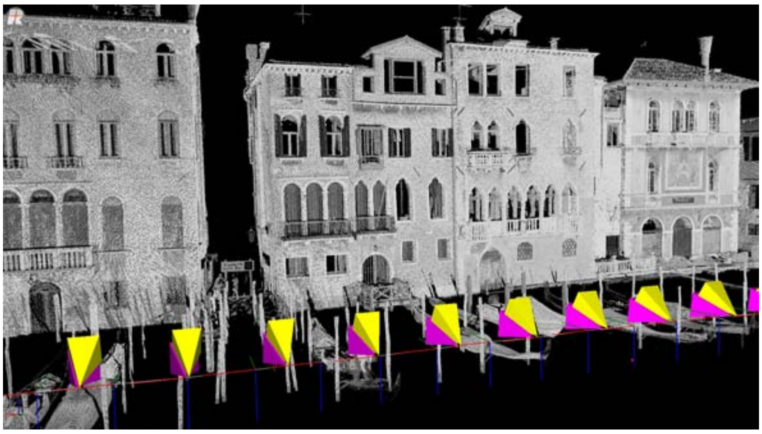


Fig. 4: Illustration of the camera positions and fields of view at the moment of their synchronous triggering. Yellow and pink cones represent the fields of view of camera 1 and 2 respec¬tively.
The red line describes the trajectory.
Scan data is displayed colored with the gray scaled relative reflectance [Rieger (2010)].

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*, models from other manufacturers can be integrated, for example, digital single-lens reflex (DSLR) cameras, and infrared cameras or “360°” camera solutions.

Fig. 5: mobile laser scanning system *RIEGL* VMX-250 with the modular camera system VMX-250-CS6

Fig. 6: VMX-250 laser scanning system mounted on the workboat "Sante" while scanning the Grand Canal in Venice

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.

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 fx and fy which are normalized by the respective pixel spreads dx and dy, so that, for example, fx,n = fx/dx. The center of the image in relation to the CMCS is defined by the parameters Cx and Cy, given in pixel units. For lenses with negligible distortion, usually Cx ~ Nx/2 and Cy ~ Ny/2, whereas Nx and Ny are the pixel offsets 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: k1, k2 and p1, p2 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/).

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

2 × *RIEGL* VQ-250 Laser Scanner	
Effective measurement rate	up to 2 × 300.000 measurements/sec.
Max. measurement range	500 m @ □□□ 80% & 100 kHz 75 m @ □□□ 10% & 600 kHz
Accuracy	10 mm
Precision	5 mm
Scanning rate (selectable)	up to 2 × 100 lines/sec.
Laser Class	1 (eyesafe)
Multi target capability	yes
Range-dependent reflectivity	yes
INS/GNSS properties (trajectory)	
Position (absolute)	typ. 20-50 mm
Position (relative)	typ. 10 mm
Roll, Pitch, Yaw	0.005°, 0.005°, 0.015°
Camera System	
Numbers of cameras	up to 6
Resolution	2 MPx FullHD / 5MPx 1)
lens / FOV	5mm / 80° × 60° 2)

1) Higher resolutions on request. External cameras (e.g. reflex 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.

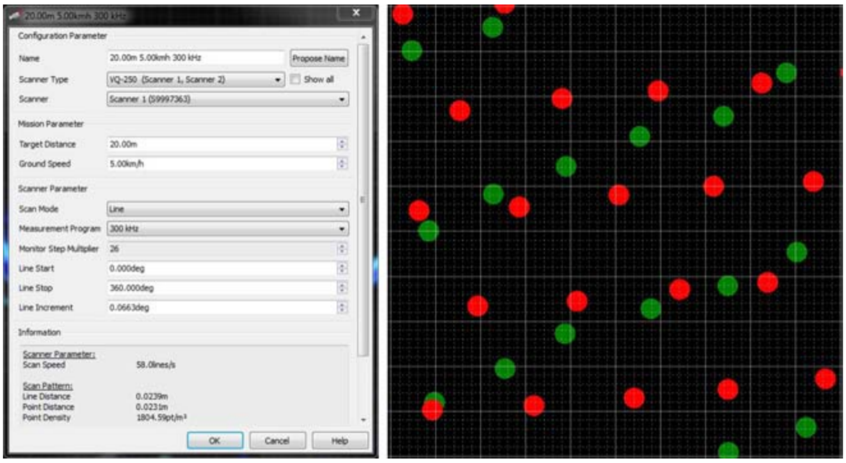
Parameterization of the camera

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. 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 20 meters.
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 1.5 seconds yielding generous overlap between two consecutive pictures.

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 (ca. 2000 points/m2) per pass and scanner can be achieved.



20.00m 5.00kmh 300 kHz

Configuration Parameter

Name: 20.00m 5.00kmh 300 kHz

Scanner Type: VQ-250 (Scanner 1, Scanner 2)

☐ Show all

Scanner: Scanner 1 (S9997363)

Mission Parameter

Target Distance: 20.00m

Ground Speed: 5.00km/h

Scanner Parameter

Scan Mode: Line

Measurement Program: 300 kHz

Monitor Step Multiplier: 26

Line Start: 0.000deg

Line Stop: 360.000deg

Line Increment: 0.0663deg

Information

Scanner Parameter:

Scan Speed: 58.0lines/s

Scan Pattern:

Line Distance: 0.0239m

Point Distance: 0.0231m

Point Density: 1804.59pt/m^2

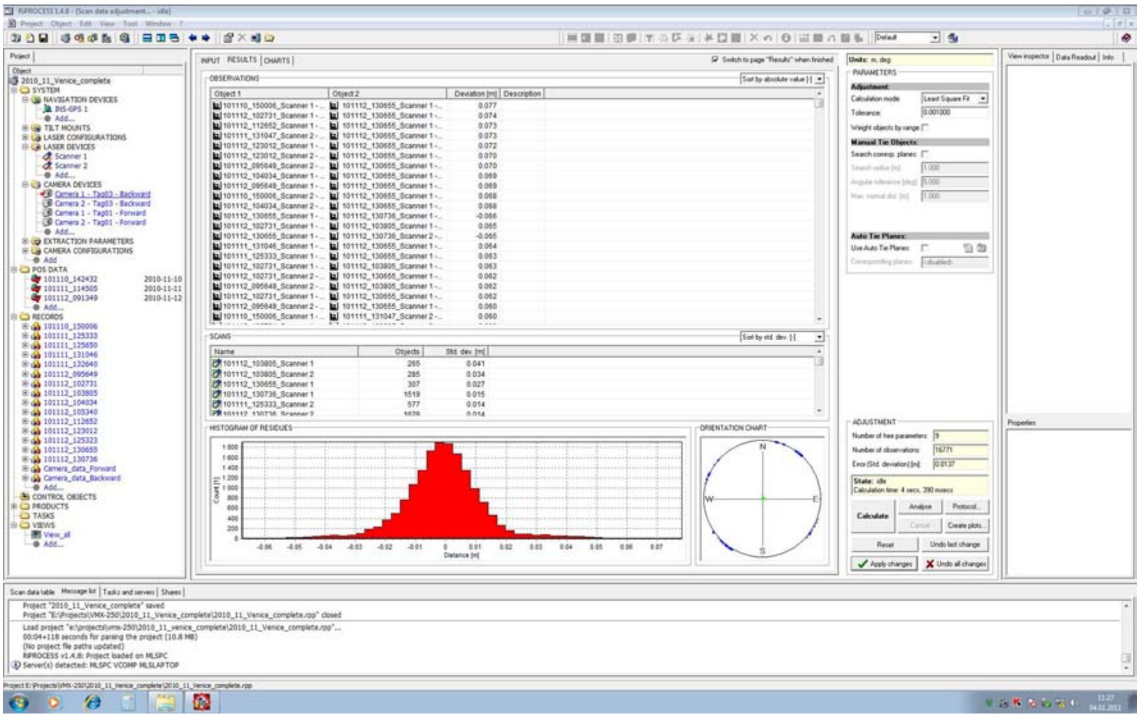
Fig. 7: left: scan parameters applied to a *RIEGL* VQ-250: 58 scan lines per second with an angular resolution of 0.0663° between laser shots, resulting in a point spacing of ca. 2.3cm per scanner and scan.
right: point pattern on the facade (red = left scanner 1, green = right scanner 2), achieves 3,500 points per m2 on the facade (1cm grid spacing)

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 less distance to the target, all of which was not possible in practice.

Before the actual surveying, the entire system had been initialized. For 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.

PROCESSING OF DATA

Even during data acquisition the project was divided into four sectors corresponding to the water sections between the main bridges of the 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 the section three 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. Before the actual adjustment, the yaw angle had to be optimized due the slow acquisition speed in conjunction with the lack of changes in direction within the “linear shape” of the water channel. For this purpose selected parts of planar surfaces in the scanned facades of section three were defined, so called “tie planes”. The automatic adjustment feature in RiPROCESS then provided yaw correction values for all scans in this section.



☑ Switch to page "Results" when finished

Sort by absolute value [-]

Object 1	Object 2	Deviation [m]	Description
101110_150006_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.077	
101112_102731_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.074	
101112_112652_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.073	
101111_131047_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.073	
101112_123012_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.072	
101112_123012_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.070	
101112_095649_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.070	
101112_104034_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.069	
101112_095649_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.069	
101110_150006_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.068	
101112_104034_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.068	
101112_130655_Scanner 1 - ...	101112_130736_Scanner 1 -...	-0.066	
101112_102731_Scanner 1 - ...	101112_103805_Scanner 1 -...	0.065	
101112_130655_Scanner 1 - ...	101112_130736_Scanner 2 -...	-0.065	
101111_131046_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.064	
101111_125333_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.063	
101112_102731_Scanner 1 - ...	101112_103805_Scanner 1 -...	0.063	
101112_102731_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.062	
101112_095649_Scanner 2 - ...	101112_103805_Scanner 1 -...	0.062	
101112_102731_Scanner 1 - ...	101112_130655_Scanner 1 -...	0.062	
101112_095649_Scanner 2 - ...	101112_130655_Scanner 1 -...	0.060	
101110_150006_Scanner 1 - ...	101111_131047_Scanner 2 -...	0.060	

Sort by std. dev. [-]

Name	Objects	Std. dev. [m]
101112_103805_Scanner 1	265	0.041
101112_103805_Scanner 2	285	0.034
101112_130655_Scanner 1	307	0.027
101112_130736_Scanner 1	1519	0.015
101111_125333_Scanner 2	577	0.014

Units: m, deg

PARAMETERS

Adjustment:
Calculation mode: Least Square Fit
Tolerance: 0.001000
Weight objects by range ☐

Manual Tie Objects:
Search corresp. planes: ☐
Search radius [m]: 1.000
Angular tolerance [deg]: 5.000
Max. normal dist. [m]: 1.000

Auto Tie Planes:
Use Auto Tie Planes: ☐
Corresponding planes: (disabled)

ADJUSTMENT
Number of free parameters: 9
Number of observations: 16771
Error (Std. deviation) [m]: 0.0137

State: idle
Calculation time: 4 secs, 390 msecs

```
Project "2010_11_Venice_complete" saved
Project "E:\Projects\VMX-250\2010_11_Venice_complete\2010_11_Venice_complete.rpp" closed
Load project "e:\projects\vmx-250\2010_11_venice_complete\2010_11_Venice_complete.rpp"...
00:04+118 seconds for parsing the project (10.8 MB)
(No project file paths updated)
RiPROCESS v1.4.8: Project loaded on MLSPC
Server(s) detected: MLSPC VCOMP MLSLAPTOP
```

Project E:\Projects\VMX-250\2010_11_Venice_complete\2010_11_Venice_complete.rpp

Fig. 8: Screenshot – SDA Analysis Day 1-2-3, section 3

In a second step the software automatically created a table of correction values for orientation, in particular the yaw angle and the positions in addition, which were applied to the trajectory at specific time stamps corresponding to the previously defined tie planes. Adjacent time stamps within a 1-second time window were merged to one single entry. This automated trajectory refinement procedure allows for optimal alignment of the eleven passes from all three days: The result of these adjustment steps shows a residual standard deviation of 0.0137m (figure 8) based on all 16,771 observations (95 tie planes).

After these steps of optimizations and the application of the improved trajectory to the point cloud, image data from both overlapping 5-megapixel cameras was subject to refinements. Only the images from the best pass up and down the canal were used. First, the white balance was optimized and then scan and image data were combined. RiPROCESS offers tools for both optimization steps.

By clicking corresponding points in the images and in the point cloud in RiPROCESS, the exact mounting of the cameras (external calibration) was easily determined. This made exact navigation and measuring in image and scan data possible. After another few clicks, the point cloud was colored from the image data and a photorealistic 3D visualization allowed a first breathtaking trip into the virtual world of the Grand Canal.

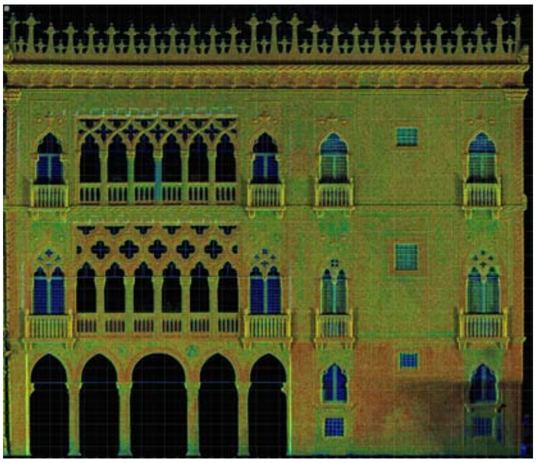
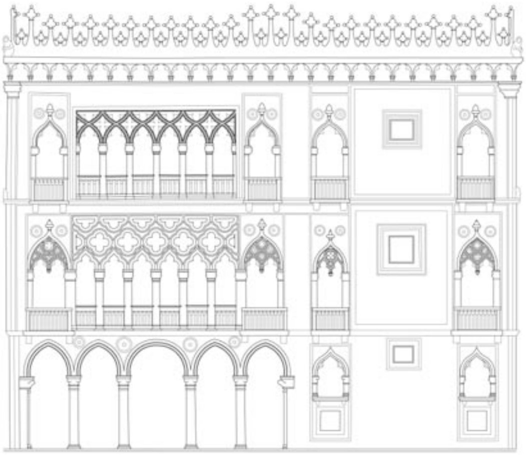
For further processing in the local Italian coordinate system (Monte Mario / Italy Zone 2), the project was transformed accordingly with the *RIEGL* GeoSysManager during export into the proven LAS format. Additionally, it is possible to check the accuracy using externally surveyed control points, which, however, were not yet available at the time of publication.

MODELING AND EVALUATION OF MEASUREMENT RESULTS

In cooperation with EKG Baukultur and PHOCAD, 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 (EKG 2011) drew exemplary 2D CAD plans. Using the "Phidias" software, PHOCAD created an orthophoto and a 3D CAD model based on the RiPROCESS project (fig. 9-16).

Casa d’Oro

The Palazzo Casa d'Oro is probably the most familiar example of Gothic architecture along the Canal Grande. 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 used as a museum (Venedig 2011).

	
Fig. 9: Photo (*RIEGL*)	Fig. 10: “Orthoscan” orthogonal depiction of the point cloud (*RIEGL* RiPROCESS/RiSCANPRO)
	
Fig. 11: Orthophoto (Phocad/Phidias)	Fig. 12: 2D CAD drawing (EKG)

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 façade. Today the palace is state property and used as museum for modern art and hosts a famous collection of oriental art (Venedig 2011).

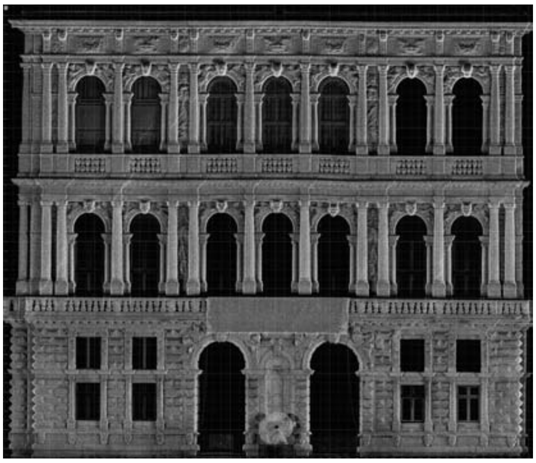
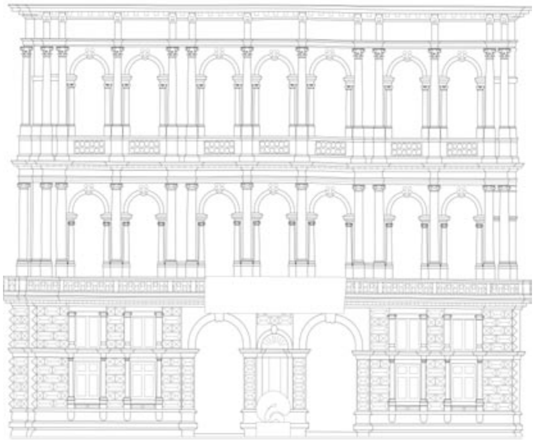
	

Fig. 13: “Orthoscan” orthogonal depiction of the point cloud (*RIEGL* RiPROCESS/RiSCANPRO)	Fig. 14: 2D CAD drawing (EKG)

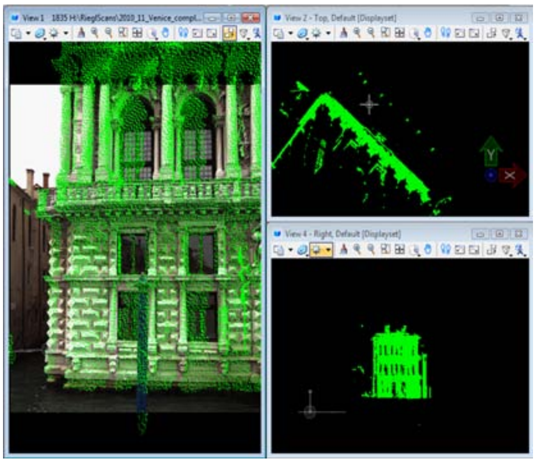



Fig. 15: Monoplotting (Phocad/Phidias)	Fig. 16: 3D CAD drawing (Phocad)

PERSPECTIVES

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

Data acquisition	**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:

- Even higher point resolutions will probably be possible soon through higher measurement and scan rates.
- Measurements of reflectance can provide additional information especially for moist facades.
- 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.

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