TERRESTRIAL WAVEFORM LASER SCANNING FOR DOCUMENTATION OF CULTURAL HERITAGE

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ABSTRACT:

Due to the fact that terrestrial laser scanning is able to rapidly create a detailed and accurate representation of complex building structures, it is becoming a standard procedure for documentation of cultural heritage. Especially hybrid systems, which combine laser scanning with digital photogrammetry, have become a valuable tool, since they combine the advantages of both photogrammetrical worlds: detailed and accurate recording of surfaces as well as texture plus accurate measurement of edges and corners.

Vegetated areas, however, still pose problems to conventional terrestrial laser scanners. Due to the fact that they only record single range measurements, they are not suitable for recording structures hidden in a forest, or overgrown with different kind of vegetation. A new generation of terrestrial laser scanners based on the pulsed time-of-flight technology could help to solve this problem. They are so called “echo digitization scanners”, which are prepared for the online waveform analysis of the entire echo waveform coming back from an emitted single laser pulse. Already during the scanning process, the waveform is processed and multiple echoes discriminated. Therefore, it is possible to detect various objects along the path of the laser beam. Using the last echo and distinguishing between vegetation and solid structures, this technology could help to get better and more detailed information on e.g. buildings within vegetated areas.

Using a case study of a ruined castle, the paper will present the possible implications of this new generation of terrestrial laser scanners for the documentation of cultural heritage.

1. INTRODUCTION

Terrestrial laser scanning has revolutionized documentation of any kind of cultural heritage. In combination with digital photogrammetry, it is becoming a standard procedure especially for recording architectural remains, rock art and archaeological excavations.

When documenting for cultural heritage in woodland environments, one is faced with the problem of more or less dense vegetation surrounding or overgrowing the site of interest. Under these conditions, “conventional” terrestrial laser scanners prove a disadvantage: They only record single range measurements, which usually represent the objects closest to the scanning position. Vegetation obstructing the structures to be recorded will therefore have a negative impact on the documentation: It will drastically reduce the density of points being reflected from the structures of the sites.

A new generation of terrestrial laser scanners based on the pulsed time-of-flight technology could help to solve this problem: *RIEGL*’s new V-Line instruments employing echo digitization and online waveform processing combine the advantages of analogue detection systems (immediate availability of scan result without the need for further post-processing), with those of airborne echo digitizing systems (multi target capability and high precision).

Waveform digitization, as applied in airborne laser scanning, has already proved its high value for detecting archaeological sites under vegetation (Doneus and Briese, 2006). Its application with terrestrial laser scanning could therefore likewise be of benefit for archaeologists and conservationists.

In this paper a brief introduction on the new technology and features of the V-Line is given, elaborating the concepts of online waveform processing, multi-target capability, and calibrated amplitude. Some measurement results are presented to exemplify the capability of the new technology.

2. ONLINE WAVEFORM PROCESSING AND MULTI-TARGET CAPABILITY

The instruments of *RIEGL’s* new V-Line® of laser scanners rely on the principle of pulsed time-of-flight measurement. A short laser pulse is emitted and the time it takes the light to travel from the instrument to the target and the reflected echo signal back to the instrument is measured. From this time and the group velocity of light (according to the actual atmospheric conditions during the measurements), the distance between the origin of the scanner’s own coordinate system and the target is calculated.

2.1 Online waveform processing

In order to determine the time of flight, the echo signals detected by the receiver frontend are digitized and analyzed in real-time within the instrument. Echo digitization enables full waveform analysis and multi-target detection previously not available with terrestrial laser scanners employing analogue signal detection (Pfennigbauer and Ullrich, 2009b). Echo digitization has been used in airborne laser scanners for several years (Ullrich and Reichert, 2005). However, there the digitized

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** Parts of this paper are taken from (Pfennigbauer and Ullrich, 2009)

echo signals are stored during the flight and have to be post-processed subsequently. Although this enables so-called "full waveform analysis", used for sophisticated object classification and reflectance calibration (Briese et al., 2008), the additional time-consuming step in the work-flow is not acceptable for terrestrial laser scanning, especially for applications where the data is required immediately.

For the new series of laser scanners, *RIEGL* developed a new approach to online waveform processing, where the received signals are nearly immediately analyzed. Whenever an echo pulse is identified, a highly accurate estimate of its amplitude and time-of-arrival is performed in real-time. Through the efficient and hardware-oriented implementation of the corresponding algorithm, the instruments are capable of performing about 1.5 million range and amplitude measurements per second. With a laser pulse repetition rate of 100 kHz (42,000 measurements per second on average for the *RIEGL* VZ-400 in long range mode) and 300 kHz (125,000 measurements per second on average for the *RIEGL* VZ-400 in high speed mode), this corresponds to 10 and 5 targets per laser shot, respectively (*RIEGL*, 2009).

By using temporarily stable laser pulses and by carefully matching the sampling rate to the laser pulse duration, a measurement precision better than 2 mm (standard deviation of individual consecutive measurements without any averaging) is achieved for diffusely reflecting targets.

For cultural heritage documentation, the high frequency of measurements combined with the capability of online waveform processing seems to be promising, as it opens the possibility to get a higher penetration rate of obstructing vegetation.

2.2 Multi-target capability

The minimum distance to discriminate two consecutive echoes is determined by the laser's pulse width and the receiver bandwidth. For *RIEGL's* V-Line laser scanners it is about 0.8 m. For shorter distances between scatterers within the same laser shot, the echo signals are superimposed and the instrument cannot discriminate between the echo pulses. The range will be estimated somewhere in between the targets. This will result in a false point.

However, the problem of false points due to close targets can be reduced using the "pulse shape figure". It represents a measure of the distortion of the pulse shape compared to an undistorted pulse for every individual echo. In situations near or below the multiple-target discrimination limit of 0.8 m, the pulse shape figure in that way provides information whether the return echo originates from a single target or from at least two nearby targets. Applying a threshold with respect to the pulse shape information will remove most of "invalid" points and keep only the reliable "real" targets.

In Fig. 1 the scan of a tree is shown from a viewpoint perpendicular to the scanning direction. This side-view is colour-coded according to the pulse shape figure. The red points result from false measurements where echo signals are superimposed and the corresponding range is estimated to be somewhere in between the real targets.

Despite the seemingly high number of false points in Figure 1, one has to acknowledge that all of them represent multiple targets below the range of discrimination. Compared with single-target range measurements, the scan results in a higher number of points due to clearly discernible multiple targets. This can be observed in Figure 1 through the high number of echoes returning from the building structure behind the trees. The multi-target capability could therefore help to get better and more detailed information on buildings within vegetated areas.

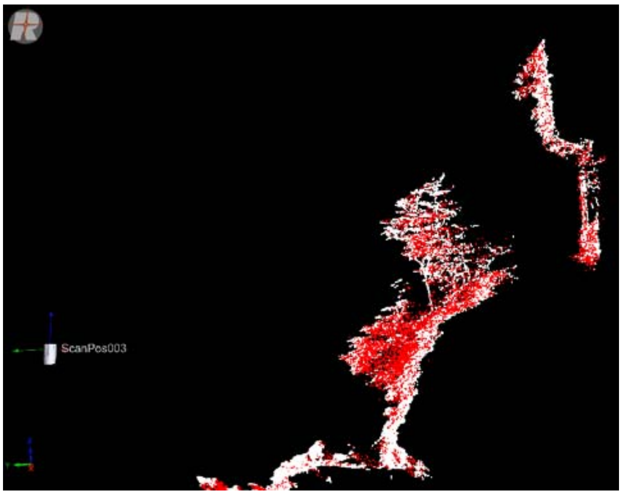

Figure 1. Point cloud of a tree, colour coded according to the pulse shape figure. Red: false points due to close targets.

2.3 Calibrated reflectance reading

Beside geometrical information terrestrial laser scanning additionally delivers amplitude information, whose strength depends on many influencing factors. When calibrated, it could be used for object classification.

RIEGL's V-line provides an amplitude output strictly proportional to a fixed device-specific echo signal power level. Additionally the amplitude information can be provided by means of relative reflectance. This is the ratio of the absolute reflectance of a target to the reflectance of the target the instrument was calibrated with, i.e. a white reflectance standard with 98% reflectance. Thus, white diffuse targets would have assigned about 0 dB, black paper with a reflectance of 10% would give about -10 dB – indifferent to the object's actual distance from the scanner. This applies only for first and single targets not for targets succeeding one or several targets hit by the laser pulse. Figure 2 shows scan results from a forest grey-coded according to the reflectance of the target. Trunks of different species of trees indicate different colours more or less independent of the range to the scanner.

The implication for cultural heritage documentation is clear: Calibrated reflectance reading enables the user to apply at least a simple form of classification, which for example could help to better distinguish between vegetation and solid structures.

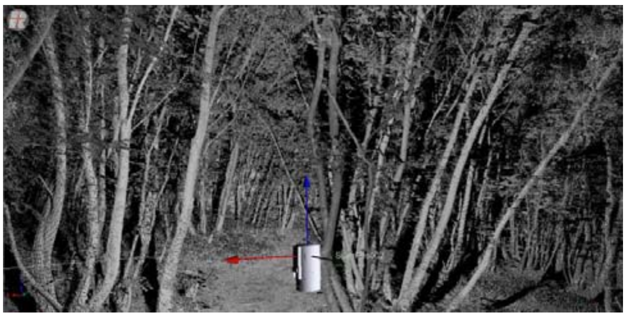

Figure 2. Grey scale encoding of point cloud according to reflectance of target. Range of encoding is -20 dB to 5 dB with respect to white diffuse target. Note that brightness is nearly independent from distance.

3. CASE STUDY: THE RUINED CASTLE OF SCHARFENECK

In a recent paper Pfennigbauer and Ulrich have demonstrated that a vehicle hidden in dense forest could be detected in the point cloud measured from 4 scan positions. Most of the 7.012 points defining the vehicle were not derived from first or single echo signals, but belonged to laser shots where multiple targets had been detected (Pfennigbauer and Ulrich, 2009).

The features of the V-line, as described in chapter 2, therefore seem to be promising to help with the problem of documenting heritage sites in densely vegetated environments. To test and quantify this assumption, a case study was defined at the site of the ruined castle of Scharfeneck.

The ruined castle of Scharfeneck is located near the village "Mannersdorf am Leithaberge" some 30 km south of Vienna in the so called Leitha-mountain-range ("Leithagebirge"), which rises some 280 m above the surrounding river valleys. It was constructed on top of a prehistoric hillfort (Melzer 1980, 77). The castle was first mentioned in 1417 and was abandoned in the 16th century AD (W. Antl-Weiser 1995, 27-31). It was recently subject to investigations using airborne laser scanning (Doneus et al., 2008).

The test was conceived to record an object under extreme conditions:

- The castle is situated within a dense oak/beech mixed woodland and varying degrees of understorey. Large parts of the castle are overgrown by evergreen vegetation (Fig. 3 and 4).
- The test scans were performed when vegetation was most intense.

For the test, a *RIEGL* VZ-400 (see Table 1 for key specifications) combined with a calibrated camera (D200 with 14-mm lens) as a hybrid system was used. Altogether, 15 scan positions covering the northern part of the castle were realized by a single operator on 13th July 2009 within 5 hours (Fig. 5). For each scan position a "panoramascan" (0.08 deg resolution, long range mode for good penetration of the forest, 2'15" scan time, about 5.6 mio. measurements per scan) and 7 calibrated photographs were taken. The registration of the point clouds was realized by fine scanning of retro-reflecting targets (50 mm diameter).

instrument type	*RIEGL* VZ-400
application	terrestrial
measurement range	up to 500 m (80%)
repeatability and accuracy	3 / 5 mm
effective measurement rate	up to 125,000 meas./sec
field of view	100 deg x 360 deg

Table 1. Specifications of *RIEGL*'s new VZ-400 laser scanner.

Figure 3. Vertical aerial photograph (June 2000) of the ruined castle of Scharfeneck, situated in dense vegetation (© Österreichisches Bundesheer, Fliegerhorst Langenlebarn)

Figure 4. The ruined castle as seen from the ground during the dormant period

Figure 5. Photograph of *RIEGL* VZ-400 on scan position 3

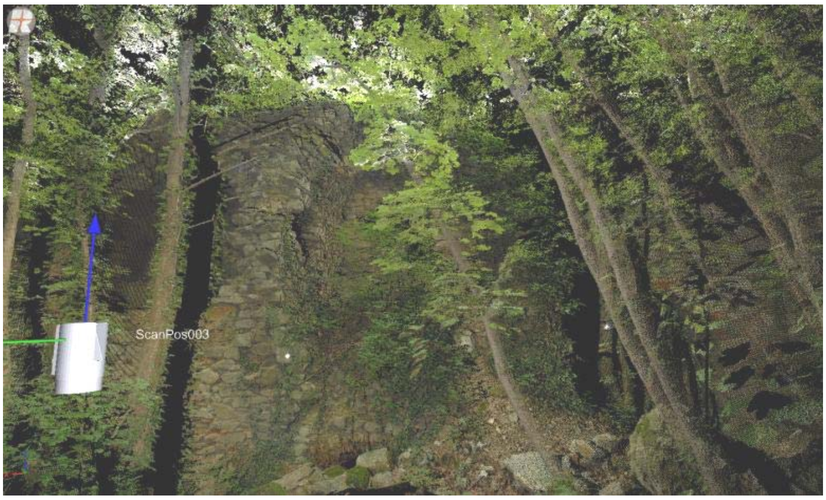

Figure 6. True coloured point cloud of scan position 3

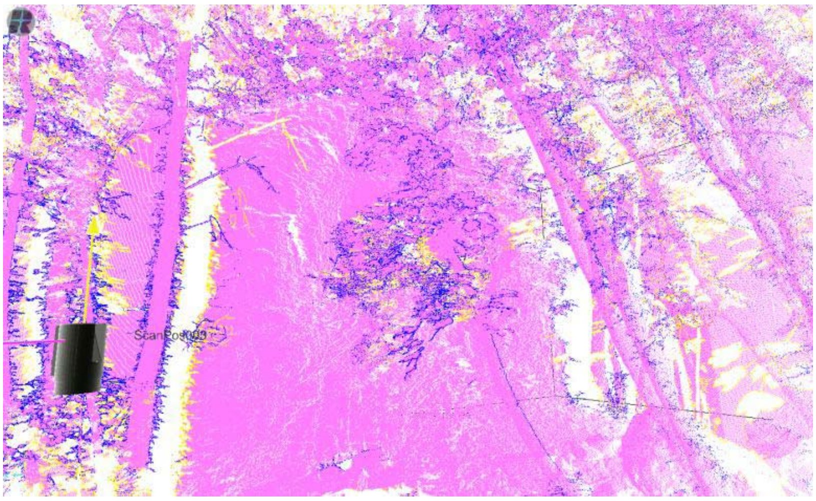

Figure 7. Coloured Scan, pink: single target, blue: first target, yellow: last or other target

Figure 8. Grey scale encoding according to relative reflectance showing a range from -20dB and +5dB

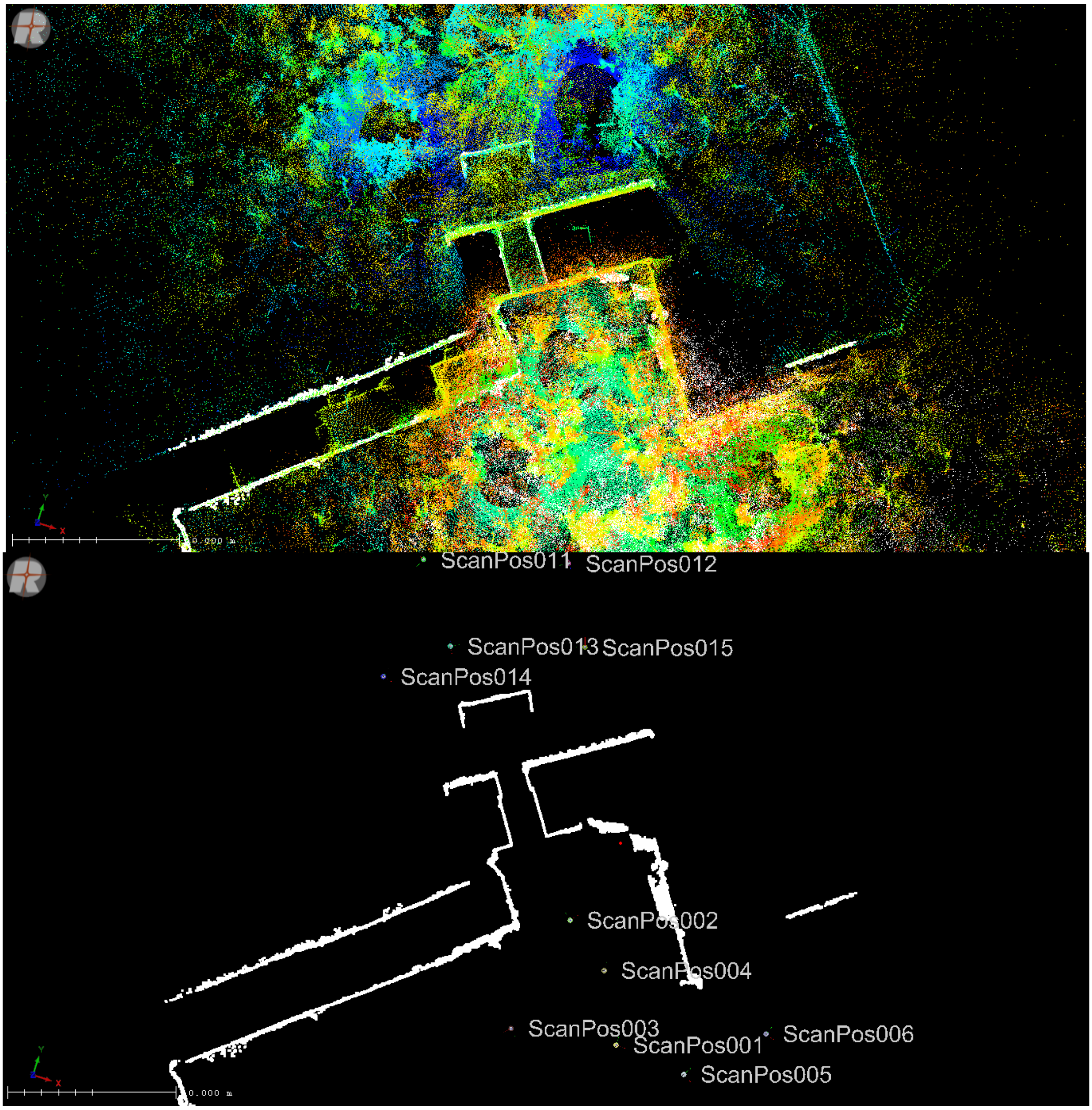

Figure 9. Top view of the scanned part of the ruined castle of Scharfeneck with and without vegetation

Fig. 6-8 show the resulting point cloud of scan position 3 in a 3D-view. All figures are displayed from the same view point. The original scan position is marked by the symbol of a scanner displaying also the rotation axes of the scan. In Fig. 6 the point cloud is coloured using the rgb-values of the digital camera. The shadows on the wall in the background are areas without measurement due to tree trunks obstructing the direct view from the scanner to the wall. Fig. 7 displays the same point cloud encoded according to their multiple target value (see chapter 4). In Fig. 8 the points are grey scale encoded according to their relative reflectance.

The measurements from all scan positions were merged into a single point cloud (Fig. 9, upper image), where the vegetation was removed manually within 8 hours working time (Fig. 9, lower image).

4. DISCUSSION

In all of the scan positions, vegetation was either in between the scanner and the castle or covering the surfaces of the documented walls (Fig. 5). Using the multi-target capability due to the online waveform processing, the number of documented points could be increased. On scan position 1, 5.6 million measurements resulted in 6.3 million targets with up to 6 returns per measurement (Table 2).

This can be also demonstrated on figure 7. It displays the point cloud from scan position 3. The individual points are coloured according to their multi-target value: Most points in this image are pink, i.e. they represent measurements with a single echo. In areas, where leaves and branches obstruct the direct view to the wall in the back, the points become blue (representing a first echo) and yellow (last or intermediate echo).

Targets	Measurements
1	4.955.484
2	598.580
3	58.301
4	4.286
5	239
6	10

TOTAL: Meas. : 5 616 900 Targets: 6 345 946

Table 2. Echo distribution of the first scan position. 5.6 million measurements resulted in 6.3 million targets with up to 6 targets per measurement.

Altogether, the northern wall of the castle could be defined by 4.853.152 points. From these, 4.468.712 points were first or single echoes. This would be the number of points one would get using a "conventional" scanner. This means that due to the multi-target capability of the V-line, the documentation of the wall could be enhanced by 384.440 additional points. This represents roughly 8% of the total measurements defining the wall.

These additional points are not equally distributed. They can be found especially in areas, where dense vegetation would not allow too much information using "conventional" scanners. In that way, detecting multiple targets using online waveform processing has the potential to deliver a more complete documentation of a cultural heritage object in dense vegetation.

The technology of online waveform procession saves the operator from having to store vast amounts of raw data and time-consuming post-processing. However, it also has its limitations with respect to, e.g., multi pulse resolution for close targets, where there are more sophisticated methods like Gaussian decomposition to be applied when processing the data off-line. In this case, the minimum distance to discriminate between two consecutive echoes could be reduced resulting in an even higher number of points relevant for the documentation of the castle.

Filtering of the vegetation was done manually, so far. However, the data coming from the V-line scanners does provide additional information for further processing. Using the calibrated amplitude might help to distinguish between vegetation and solid structures improve filtering of vegetation in future. It also might be used to interpret the scanned surfaces (see for example Challis et al., 2006).

5. CONCLUSIONS

The approach of online waveform processing opens new possibilities for the documentation of cultural heritage sites within vegetated areas. This could be demonstrated by a test scan of the northern part of a ruined castle under extreme conditions (densely vegetated area; walls overgrown with evergreen vegetation; scanning time when vegetation was most intense). Using a *RIEGL* VZ-400 scanner, the vegetation could be partly penetrated resulting in more points measured from the otherwise hidden relevant structures.

Pulse shape figure and calibrated amplitude is important additional information, which is recorded during the scan. This information could be used for a sophisticated automatic filtering of vegetation – a challenge for future research.

6. ACKNOWLEDGMENTS

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