

# GEOREFERENCING OF TERRESTRIAL LASERSCANNER DATA FOR APPLICATIONS IN ARCHITECTURAL MODELLING

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## ABSTRACT:

Commonly several measurements originating from different sensor systems and stations are combined in order to completely model an architectural site. An important step preceding data fusion is the geometric alignment of the measurements with a geodetic coordinate system, or in other words georeferencing the measurements. This paper investigates methods for the georeferencing of terrestrial laserscanning data. Both sensor- and data-driven methods are considered. We propose the integration of a GPS receiver and a digital compass for automated georeferencing. We detail on how virtual city models and aerial LIDAR data can be utilized for georeferencing by point cloud matching. The proposed methods are evaluated in practical experiments and compared to conventional methods. The results obtained are presented and illustrated.

## 1. INTRODUCTION

Any architectural site has multiple aspects, which are of interest when creating a computer model of the site. Typically it is the geometry, which receives most attention, but increasingly spectral properties, reflectance, material, and others are gaining interest as well. These different aspects can rarely be captured with a single sensor system. Furthermore for complex architectures these aspects can never be recorded from a single point of observation. It is therefore common practice to integrate several measurements from different sensors and varying stations in order to model the complete object. This process is also referred to as sensor data fusion. Certain combinations of separate data sources have become standard procedures in the field of photogrammetry, such as the integration of ground plans and digital elevation models for virtual city modeling (Haala and Brenner, 1999) and the integration of multiple terrestrial imagery and CAD building models for facade texturing (Boehm, 2004) and many more are being investigated, such as the combination of aerial and terrestrial laser scanning for improved building modeling and the combination of high resolution panoramic images with city models.

A crucial step preceding the data fusion is the geometric alignment of the separate dataset into a common reference frame. In the case of geodata fusion this is known as georeferencing. Georeferencing has certain advantages in comparison to registration in an arbitrary local coordinate system. Today a large variety of pre-georeferenced geodata is available as standard products, for example digital maps, ground plans, digital terrain models and others. Georeferencing the measurements transforms simple sensor data into geodata and thereby opens the opportunity for an almost unlimited number of combinations with other geodata. The earlier georeferencing is performed the earlier the benefits of data integration can be harvested. If georeferencing can be achieved instantaneous to the measurement, it is possible to check data completeness, coverage and other quality factors in-the-field by comparing it to archived geodata.

### 1.1 Georeferencing in Terrestrial Laserscanning

Terrestrial Laserscanning (TLS) has become popular for the acquisition of architectural scenes, due to the fact that it provides direct, reliable and dense surface measurement in a versatile fashion at independently varying stand-off distance and resolution. However versatile they are, a TLS system is seldom enough for complete scene modeling as indicated earlier. Combining data recorded at multiple stations and integrating independent sensor data and therefore georeferencing of TLS data are essential for the same reasons as given above. The common practice for georeferencing of TLS data, as suggested by the manufacturers, requires three-dimensional control points, preferably provided by specially designed targets. However historically in surveying position and height are recorded separately and therefore three-dimensional control points in a geodetic system are not naturally available. Georeferencing of TLS data typically is achieved by introducing a supporting measurement system, for example a total station, to transfer the geodetic control information onto the special targets. This process is regarded as the most precise way to give a geodetic datum to TLS measurements. The actual steps of the procedure and some practical considerations will be detailed further below. It shall be noted however, that this process does not only cost extra time and effort, it also requires the user to provide a second measurement system and to be able to operate it. It is therefore of great interest to study alternative methods to establish a georeference in TLS data. We will investigate two categories of methods for georeferencing categorizing by the main source of input, either pre-referenced data or sensor measurement.

The sensor-driven approach to georeferencing has established itself for quite some time in aerial photogrammetry, where it is known as direct georeferencing. Sensors for the direct measurement of position, typically GPS sensors, and sensors for the measurement of attitude angles - inertial measurement units - are integrated with the image measurements. This integration is either considered the final result, or it is seen as an initial value for further iterative refinement including additional control in-

formation. Considering the high dynamic characteristics of in-flight measurement, typically high-end components are used in aerial photogrammetry. For ground-based applications the price of these high-end components will often exceed the total budget for the sensor. Therefore low-cost components receive attention in many terrestrial applications. The direct orientation of TLS systems has been investigated mainly for mobile mapping applications, an example is the work by Talaya et. al. (2004). In contrast the applications we are investigating in this work are concerned with stationary measurements, and therefore the system design is closer related to the approach described by Fritsch and Klinec (2000). We describe the integration of a GPS receiver and a simple digital compass for the direct orientation of a TLS system.

Data-driven approaches for the georeferencing of TLS data are based on reference data sets, which already have been georeferenced, such as digital surface models or virtual city models. The point clouds obtained by TLS measurements are matched to these data sets and thereby are brought into alignment with the reference system. The algorithm considered for this matching process is the iterative closest point algorithm introduced by Besl and McKay (1992) and improved by various other authors. For an overview see for example Eggert et al. (1998). Feature-based or local methods for point cloud matching, described for example by Johnson (1997), are not considered at this point.

The alternative approaches for georeferencing of TLS data greatly vary in their properties. They require different levels of extra effort during measurements on-site, such as signaling points or additional measurements. The effort for processing of the data also varies across the different methods. The less manual interaction is required the better and methods which have the potential for full automation shall be preferred. Furthermore the prerequisites, such as availability of certain data sources or sensor measurements are other criteria we use for comparing alternative methods. One of the most interesting criteria of course is the accuracy of the georeferencing procedure. The results obtained in our practical experiments may vary to other cases depending on individual conditions and configurations. However the results shall serve as a rough guideline when several methods are considered with respect to certain application demands.

## **2. METHODS FOR GEOREFERENCING OF TERRESTRIAL LASERSCANNER DATA**

### **2.1 Conventional Georeferencing**

Conventionally, registration and georeferencing are carried out in a combined procedure. Registration of laserdata is performed by measuring at least three tie points in every scan. Georeferencing requires at least three known 3D control points in all scans. Due to historically reasons 3D control points in a geodetic global system usually do not exist. The control information is separated into a horizontal and a vertical control network. This requires the transfer of the control information onto the targets using a total station. In a first step, the global horizontal coordinates of the total station are determined using the existing horizontal control points. The leveling is performed by transferring the height difference from the vertical control points to the total station. In a following step, the coordinates of the tie points can be measured with the known three-dimensional position of the total station. With the knowledge of the global positions of the tie points the georeferencing of the

TLS is determined by aligning the scans with a rigid body transformation.

The advantage of using three-dimensional control points is that it is not necessary to center the laserscanner over a known control point. Arbitrary laserscanner stations can be applied for the measurement because the three-dimensional control information is given by the targets. A further advantage is that the user is not required to measure the instrument height or exactly level the laserscanner. Probably the most important advantage is the outstanding accuracy that can be achieved as shown in section 3.1.2.

One of the disadvantages of this conventional method is the need for a second instrument. The necessity for existing control points is a further restriction. Additional equipment has to be brought into the field, further measurements have to be carried out and tie points have to be placed around the object. It is for these reasons that the method is very time-consuming and costly.

### **2.2 Sensor-driven approaches**

The advantage of sensor-driven methods for georeferencing laserscanner data is the possibility to save time and cost due to direct measurement and automation in determining the global position and orientation of every station. Compared to the conventional method of georeferencing with the use of a total station, the sensor-driven approaches require less additional equipment and are not in need of existing control points around the scene.

A simple and inexpensive possibility for directly determining the global position of the laserscanner is to use a low-cost GPS. The GPS receiver is centered close to the laserscanner's rotation axis. During the scanning process, the GPS position is simultaneously recorded. The results are available in real time. The expected accuracy of this absolute positioning is about 10 m. An improvement of the measured positions of the stations can be reached by using high-end GPS. After the laserscanning process the GPS receiver is placed on a tripod centered over the marked point of the station. The data is post-processed with the use of correction data from a reference station. The analysis of phase information and the use of differential GPS offer a theoretical accuracy of 1 cm in static measurement modus. The acquired GPS positions are given in the global WGS 84 system. These positions have to be converted from WGS 84 to the German reference system Gauss-Krüger.

The GPS receiver only measures the position of the stations. The orientation has to be determined by an additional procedure. One possibility is to use a digital compass and tilt sensor. The compass is co-located with the low-cost GPS. The whole construction is illustrated in Figure 1. Alternatively, tie points can be placed around the scene. In a first step, the scans are aligned in a local coordinate system using the measured positions of the tie points in every point cloud. After that, the laser-scanner data is georeferenced over a rigid-body transformation that aligns the relatively registered dataset onto the measured absolute GPS positions of the stations.

### **2.3 Data-driven approaches**

Unlike the formerly described sensor-driven methods, data-driven approaches for georeferencing terrestrial laserscanner



Figure 1. Laserscanner with low-cost GPS and digital compass.

data are based on pre-referenced datasets. This offers the possibility of georeferencing terrestrial laserscanner data without the knowledge of coordinates of control or tie points or the use of additional equipment like a total station or a GPS receiver. Every acquired point cloud is brought into alignment with the reference system by applying the Iterative Closest Point (ICP) algorithm. This algorithm determines the best match of the measured laserscanner data to the existing georeferenced dataset by minimizing a distance-function.

An example of available georeferenced data are virtual 3D city models. These models contain the facades and the shapes of the roofs of buildings composed of polyhedral structures. The alignment of the laserscanner data to the model is performed by a pointcloud to surface matching. The advantage of using virtual city models for georeferencing laserscanner data is the availability of the facade structures in the model. These vertical structures are also the primary structures measured by the terrestrial laserscanner. The disadvantage of 3d city models is that they generally do not contain ground data. This results in less stabilization of the ICP algorithm. The application of georeferencing with a virtual city model is limited by the availability of such a model. They typically exist only for inner city areas.

Other georeferenced datasets, available for larger areas than those covered by virtual city models, are digital surface models derived from airborne laserscanning. Aerial LIDAR data is 2½D point data. It contains ground and roof information but does not contain measurements of vertical structures. The ICP algorithm matches the scans onto the meshed LIDAR data. In this mesh, the facades appear tilted. This causes a problem when applying the ICP with terrestrial laserscanner data of facades of buildings or other vertical structures. The advantage when compared to the use of virtual city models is the availability of ground information which stabilizes the alignment.

A problem of data-driven approaches is the use of an iterative algorithm. The initial approximate values for the transformation between the two datasets have to be determined manually. The data-driven approaches can be improved by automatically measuring these approximate values. One possibility to determine the initial values with little additional effort is using a sensor-driven approach as introduced in section 2.2.

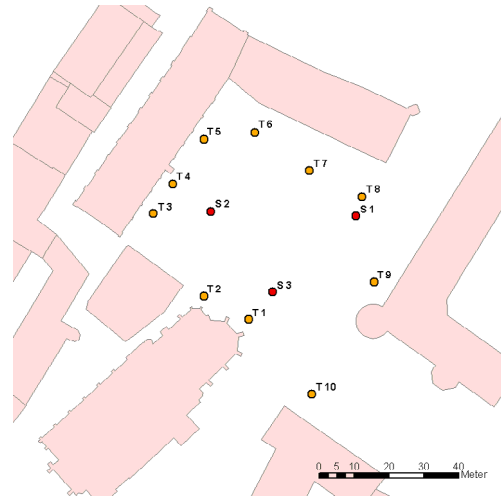


Figure 2. Configuration of the measurement, standpoints S 1 to S 3 and tie points T 1 to T 10

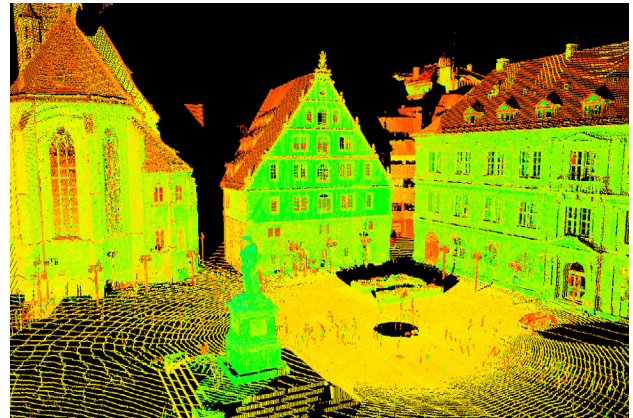


Figure 3. Point cloud rendered in a multi-hue coloring scheme

### 3. PRACTICAL RESULTS

Two measurement campaigns were carried out to verify the approaches described in the previous sections. Several configurations of instruments and data processing were tested and compared. In all cases the Leica HDS 3000 was used to perform the laserscanner measurements. The HDS 3000 is a pulsed laser scanner operating at a wavelength of 532 nm. The scanner is able to acquire a scene with a field of view of up to 360° horizontal und 270° vertical in a single scan. The typical standoff distance is 50 to 100 meters, but measurements of more than 200 meters are possible. The manufacturer specifies the accuracy of a single point measurement with 6 mm. But when using specially designed targets, the accuracy on those targets is below 1 mm, when repeatability is considered. This accuracy, which is achieved at control or tie points, is crucial to the accuracy of registration.

#### 3.1 Schillerplatz

The first experiments were carried out on the Schillerplatz, which is the square in the heart of the old city that has been reconstructed true to the source after its destruction in World War II. The monument of the poet Friedrich Schiller in the center of the square is surrounded by several historically important buildings like the “Altes Schloss”, the “Prinzenbau”, the “Fruchtkas-



Figure 4. Measurement on the “Schillerplatz”

ten”, the “Alte Kanzlei” and the “Stiftskirche”. There is a natural interest to record and to visualize this meaningful place in detail for a virtual 3D city model of Stuttgart. The terrestrial laserscanner offers the possibility to acquire a detailed 3D texture from all facades around the square.

### 3.1.1 Measurements

The primary interest is in the recording of the facades of the historic buildings around the Schillerplatz. The resolution on the facades is chosen to about ten centimeters in order to be able to reconstruct the scene in detail. The monument placed in the center of the square causes considerable occlusions. To prevent holes in the point cloud, the dataset is composed of three separate 360°-scans from varying stations. Figure 2 shows the configuration of the measurement with its three stations in a digital map. It also gives an impression of the size of the square, which has a diagonal of about 100 meters. To be able to register and integrate the dataset, ten tie points were placed around the square. The point clouds are acquired within one day of field work. They consist of about ten million points. Figure 3 shows a portion of the point cloud in a multi-hue coloring scheme.

### 3.1.2 Conventional Georeferencing

The coordinates in position and height of the tie points were determined using a Leica TCR 307 total station. The global accuracy of the total station measurement was 1 cm. With the knowledge of the global position of the point clouds, it is possible to super-impose and to compare the laserscanner measurement with other georeferenced datasets. The excellent accuracy of the total station measurement is shown in Table 1. The numbers shown for the accuracy are the mean errors on the tie points. For the given project, the total accuracy of the georeferencing is about 3 mm.

tie points	control points	positional accuracy	height accuracy
yes	yes	x 0.001 m y 0.002 m	0.002 m

Table 1. Georeferencing using control points and a total station.

### 3.1.3 Sensor-driven approach

About 20 minutes of real-time GPS position data was recorded at every station during the laserscanner measurements. The data was recorded using a low-cost GPS receiver based on the SiRF II chipset in an ASCII protocol. The average of the measurements during each time-interval is computed to obtain a better estimate of the true position. The resulting positional accuracy of the GPS measurement is about 4 meters. This value is to be expected considering the low-cost receiver and the limitations on satellite reception. The corresponding height at the station is measured in an elevation model of Stuttgart. This height is typically more reliable than that of the GPS receiver. The accuracy of the elevation model is about 0.15 m.

The tie points in the scans are used to compute a local registration of the point clouds. The pre-aligned data is then fitted onto the GPS measurements by computing a rigid body transformation minimizing the distances at the stations in a least squares scheme. Table 2 shows the obtained accuracy when comparing the coordinates of the tie points, derived by the method described above, to the total station measurements.

tie points	control points	positional accuracy	height accuracy
yes	no	x 2.8 m y 2.7 m	0.1 m

Table 2. Georeferencing with low-cost GPS and tie points.

### 3.1.4 Data-driven approaches

The city surveying office of Stuttgart provides a 3D virtual city model for the whole of the city. This model has been generated on the basis of the ground data from the “Amtliche Liegenchaftskarte” (ALK) and stereo photogrammetry. A digital elevation model has been determined using the given aerial photographs. Using this height model, the 3D ground data of the buildings have been estimated by intersecting the elevation model with the planar ground data of the ALK. The facades and the shapes of the roofs of the buildings are measured with stereo photogrammetry. The resulting height determination accuracy of the virtual 3D city model is about 0.3 to 0.5 m. The positional accuracy is better than 0.1 m, which is due to the accuracy of the ground data in the ALK (Wolf, 1999).

Using this city model, every measured point cloud is georeferenced individually applying the Iterative Closest Point (ICP) algorithm from manually determined initial transformations. The results after georeferencing the acquired laserscanner data are shown in Table 3. A problem is caused by a systematic error in the height of the city model of about 0.4 m, which could also be verified using aerial LIDAR. The positional accuracy is better than 0.2 m, while the height determination accuracy is influenced by this offset.

tie points	control points	positional accuracy	height accuracy
no	no	x 0.14 m y 0.08 m	0.42 m

Table 3. Georeferencing by point cloud matching with a virtual 3D city model.

In a second computation the initial values for the transformation between the point clouds from terrestrial laserscanning and the city model have been determined by using low-cost GPS measurements to acquire the positional information and tie points to

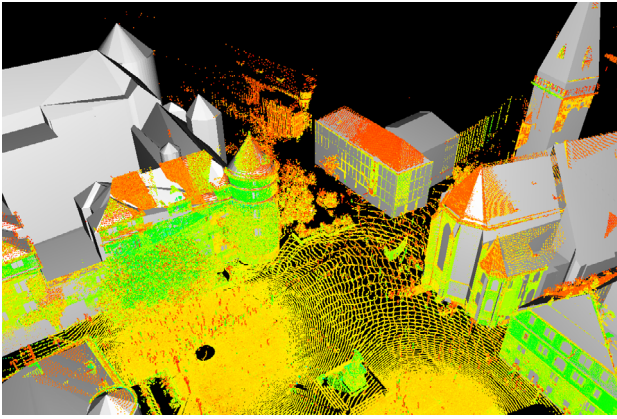


Figure 5. Super-imposition of terrestrial laserscanner data and virtual 3D city model.

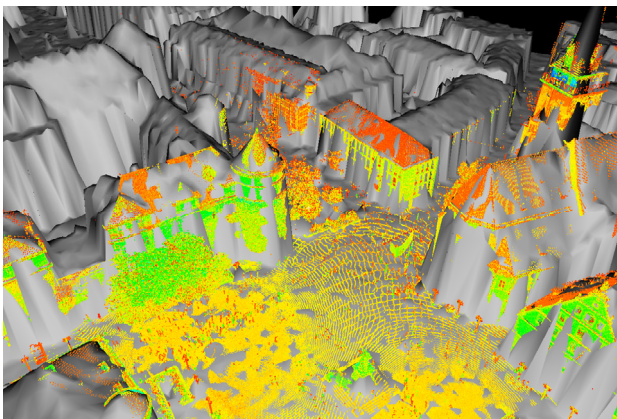


Figure 6. Super-imposition of terrestrial laserscanner data and aerial LIDAR.

determine the orientation. The registration of the scans is computed by a rigid transformation with the scanned tie points. Thereafter the scans are transformed on the measured GPS positions. As the last step, the final georeferencing is performed by using the ICP algorithm and transforming the point clouds on the virtual 3D city model. The algorithm converges to approximately the same final result. Therefore there is no improvement in the resulting accuracy, but an important improvement in the automation of the method. Table 4 lists the results for this second case.

tie points	control points	positional accuracy	height accuracy
yes	no	x 0.13 m y 0.08 m	0.46 m

Table 4. Georeferencing by point cloud matching with a virtual 3D city model and pre-alignment using tie points. The initial approximation is derived from low-cost GPS measurements.

Another georeferenced dataset, available for the whole area of Baden-Württemberg, is the digital surface model. This model was determined using airborne laserscanning. The measurement was made by TopScan with the system ALTM 1225 from Optech. The ground resolution is 1.5 m, the resulting height determination accuracy about 0.15 m (Schleyer, 2001).

Using the same method described earlier, the terrestrial laserscanner data are georeferenced applying the ICP algorithm, now

using the aerial LIDAR data. The initial transformation in-between the two datasets is determined manually as well. The results are described in Table 5. The resulting total accuracy of 26 cm is two times better than the result achieved using the city model. The main reason for this improvement is the height offset within the virtual city model.

tie points	control points	positional accuracy	height accuracy
no	no	x 0.02 m y 0.25 m	0.08 m

Table 5. Georeferencing by point cloud matching with aerial LIDAR.

Obviously this method can also be automated by using GPS measurements and tie points. The results are presented in Table 6. The total accuracy of the georeferenced point clouds has been improved compared to the results without the use of an additional low cost GPS receiver. The reason for this fact is based in the different approach. In the first case, every single scan is separately transformed on the aerial LIDAR data. In the overlapping areas of the different transformed point clouds a clear deviation is identifiable. The accuracy of the georeferencing of the scans depends on the accuracy of the aerial LIDAR data used. In the second case, the three scans are first registered with the use of the additional measured tie points. This relative orientation is very stable because of the better accuracy of the acquired positions of the tie points. After transforming these joined scans into the aerial LIDAR data, the result will be improved by the use of the precisely measured tie points.

tie points	control points	positional accuracy	height accuracy
yes	no	x 0.05 m y 0.10 m	0.06 m

Table 6. Georeferencing by point cloud matching with aerial LIDAR and pre-alignment using tie points. The initial approximation is derived from low-cost GPS measurements

### 3.2 Schloss Rosenstein

A second experiment was performed at Schloss Rosenstein. The palace was built from 1822 to 1830 by King Wilhelm I. It is located on a small hill in a park just outside the city center and gives a beautiful view over the Neckar valley. The main goal was to acquire dense range data of the facades on all sides of the palace. Five stations were selected around the palace. A view from the second station is given in Figure 7.

At every station low-cost GPS and digital compass measurements were made during the scans as described previously. In addition geodetic GPS measurements were made using a high-end GPS receiver. The Trimble 4700 was used as a rover station in the field, while data at a reference station was recorded simultaneously. The geodetic GPS measurements were post-processed using Trimble's Total Control software package. The post-processing process derived a final accuracy of the GPS measurements just below 1 cm. These measurements serve as a reference for this experiment.

Since the GPS antenna is equipped with the same adaptor to the tribach, it can be placed on the same tripod as the laser scanner. Using two tripods, one at the current station and one at the previous station, GPS and laserscanner measurements were carried out in parallel, dramatically speeding up the process.



Figure 7. Terrestrial Laserscanning at Schloss Rosenstein.

Combining the low-cost GPS and the digital compass measurements gives a global orientation of the scanner head in WGS 84. Thereby the laserscanner data is directly georeferenced instantaneous to the measurement itself. The data can immediately be super-imposed with other geodata as shown in Figure 8. Since the HDS 3000 has to be leveled for operation, the tilt measurements of the compass are ignored for these experiments.

Comparing the low-cost to the high-end GPS measurements over the five stations, the mean absolute error is about 1 meter in position and 2 meters in height. Table 7 shows the mean absolute errors in position and height on the targets for direct georeferencing, when integrating compass measurements with the low-cost GPS. It is obvious, that the errors in position are larger than the deviations of the low-cost GPS alone, since compass errors are added with a lever of about 50 meters, whereas the height is not influenced by compass measurements.

tie points	control points	positional accuracy	height accuracy
no	no	x 2.3 m y 2.7 m	2.0 m

Table 7. Direct georeferencing with low-cost GPS and digital compass.

#### 4. CONCLUSIONS

We have proposed several alternative methods for georeferencing of terrestrial laserscanning data. The methods have been implemented and tested in two projects. An overview of the total accuracy of each approach is given in Table 8. One can see, that none of the methods can replace georeferencing with a total station in terms of accuracy. However alternative methods are still viable when other factors are considered. These factors include the availability of control data, equipment, personnel and time constraints.

Fully automated direct georeferencing requires the least extra effort and equipment in the field. Not even tie points have to be placed. Further more it acquires no additional time for processing. The currently obtained accuracies will seldom suffice as

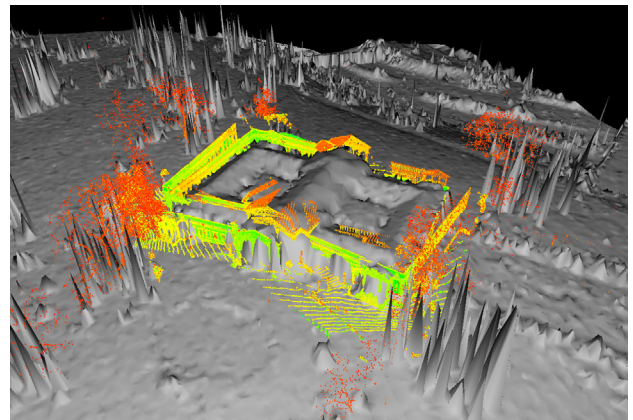
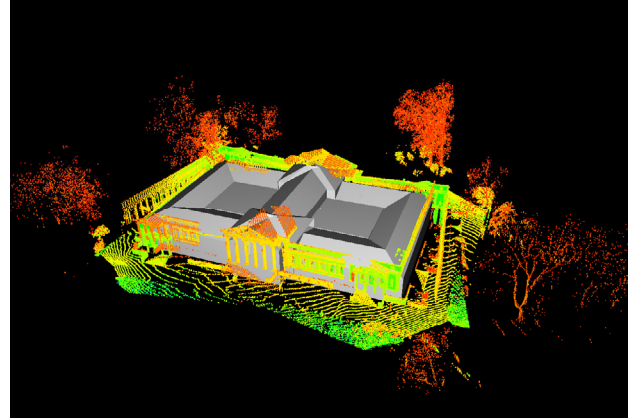


Figure 8. Super-imposition of directly georeferenced terrestrial laserscanner data and virtual city model (top) and aerial LIDAR (bottom).

final result. Still we see some potential with the current hardware by applying more elaborate processing. The results of direct georeferencing are ideally suited as initial values for further automated refinement. In this work we have shown methods employing virtual city models and aerial LIDAR data and applying iterative closest point (ICP) matching. Using these methods we were able to obtain accuracies well suited for many applications in visualization, city modeling and general architectural applications. Given the iterative nature of the ICP algorithm convergence is an issue, as is processing time, which is in the range of a few minutes. For future work we will explore more robust closed-form solutions using object recognition techniques.

method	total accuracy
conventional (total station)	0.003 m
low-cost GPS + tie points	4.3 m
virtual city model	0.45 m
virtual city model + low-cost GPS + tie points	0.48 m
aerial LIDAR	0.27 m
aerial LIDAR + low-cost GPS + tie points	0.13 m
low-cost GPS + digital compass	4.7 m

Table 8. Total accuracy of the tested methods for georeferencing.

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