# COMPARISON OF TECHNIQUES FOR TERRESTRIAL LASER SCANNING DATA GEOREFERENCING APPLIED TO 3-D MODELLING OF CULTURAL HERITAGE

M. Alba, M. Scaioni

Politecnico di Milano – Dept. I.I.A.R., p.za L. da Vinci 32, 20133 Milano, Italy
e-mail: {mario.alba; marco.scaioni}@polimi.it

**KEY WORDS:** Cultural Heritage Documentation, Georeferencing, Visualization, Terrestrial Laser Scanning

## ABSTRACT:

The paper is deals with the application of terrestrial laser scanning for the generation of a 3D model of the historical settlement of San Pietro al Monte in Civate (Lombardia, Italy). In the first part we would like to give a presentation of existing georeferencing techniques that have been applied, and to make a comparison between them. In particular, techniques which allow a reduction of the ground constraints are analized here, i.e. direct georeferencing (in case of either stationing on already known points, and by using the TLS for the determination of stand-point coordinate as well), and surface matching algorithms. The corresponding achievable accuracies have been evaluated before during a testing stage in lab, and then at San Pietro al Monte. Moreover, some operational aspects involved in the application of different techniques in real projects are addressed.

In the second part of paper the essential steps of the 3D object modelling (surface triangulation, editing, texture mapping and visualization) are reported with a presentation of the main problem: difficulties of data-transfer between different processing softwares; simplification of the model and errors due to file formats; memory request by softwares usually exceeds the physical memory which is currently available on computers.

## 1. INTRODUCTION

In the proposed paper we would like to give a presentation of existing georeferencing techniques for *terrestrial laser scanning* (TLS) 3D-views, and to make a comparison between them. This is based on general considerations as well as on results of a test application carried out at the ancient romanic church of San Pietro al Monte in Civate (Lombardia, Italy).

The most part of current applications of TLS require the georeferencing of each 3D-view, which is normally performed by means of targets (or natural features) as GCPs. In literature some alternative methods are proposed to accomplish this task, all featuring the possibility of reducing the GCPs' number to the minimum configuration needed to insert the whole point cloud into the ground reference system. A first group collects all algorithms for *surface matching* (see Grün & Akca, 2006 for a review), allowing the pairwise co-registration of scans on the basis of a shared portion of the captured point clouds. Starting from a scan assumed as reference, all the others are joined up as far as the whole point cloud is co-registered. Finally, some GCPs are used to define the *Ground Reference System* (GRS). The main drawback of this approach is that scans must share large portions featuring a texture rich of details recognizable by *surface matching* algorithms. To exploit the higher accuracy of target measurement, a method based on the *simultaneous block adjustment* of all scans has been also proposed by Scaioni & Forlani (2003). In Ullrich *et al.* (2003) a *hibrid multi-station adjustment* comprehending either 3D-views and digital images captured by a camera co-registered to the TLS has been presented. In some case the use of images might help in measurements of GCPs (tie points in case of triangulation), because the most TLS instruments require special retro-reflective targets as ground constrains. By the knowledge of the camera orientation into the *Intrinsic Reference System* (IRS) of the adopted instrument, it is possible to derive georeferencing parameters from exterior orientation parameters, and vice versa. However this option has not been tested yet in the example presented in the paper. Advantages of such methods are those typical of photogrammetric block triangulation, resulting in a strong reduction of GCPs' numbers, which are replaced by *tie points*.

Limitations are: scans should share enough tie points; an accurate project of scans is required to guarantee a stable geometry to the block; a highly-experienced operator is needed to plan ground and tie point positions. Finally we would like to focus on a third solution, which is usually addressed to in literature as *direct georeferencing* (DG) - see Lichti & Gordon (2004). By this approach a TLS becomes very close to a *robotic total station*: it can be mounted over a tribrach provided of optical plummet and of a level bubble, allowing the centering over a known point and levelling. Thanks to a telescope or by back-sighting a target, the orientation in the horizontal plane can be carried out. The interest of instruments vendors in DG is quickly increasing, as proved by the fact the most part of latest laser scanners have been equipped to be directly georeferenced in the standard configuration. On the contrary, many TLS produced in past years could allow DG, but they required to be integrated by dedicated tools.

The selection of the georeferencing method to adopt depends on two characteristics: the object shape and the required accuracy of measurements. On the other hand, there are some applications where the use of specific georeferencing methods is not completely suitable because of technical, economical or operational reasons. To understand the final use of laser scanning survey with the end-users of acquired data (geologists, geotechnical or structural engineers, architects) is very important. The TLS survey is used in different fields and the requirements can be different from classical topographic map productions. The indoor mine survey for structural studies is a typical example where low resolutions (5-10 cm) and environmental conditions (illumination, temperature, humidity) can cause problem in elementary survey operations. The use of GCP-based georeferencing method is not completely suitable because mine tunnels feature a prevalent dimension that does not allow to establish a stable set of GCPs, and where the large overlap needed between adjacent scans would make too expensive the use of *surface matching* techniques. In this case the use of DG is highly suitable to be successfully applied (see Alba *et al.*, 2006 for more information). Also in other fields, as in Cultural Heritage Documentation, the selection of the most suitable georeferencing method allows to obtain valid results as well as to shorten the time needed by the data processing stage.

In the application described in this paper, i.e. the survey of the Basilica of San Pietro al Monte in Civate to achieve a 3D model for VR visualization, two different orders of accuracy are required. Outside the church, the simple geometric shapes and the absence of complex artefacts call for an accuracy of about ±5 cm, enabling the use of different georeferencing methods. On the others hand, the indoor of the Basilica presents a lot of frescos and bas-reliefs, requiring a higher accuracy that can be achieved only by the GCP-based approach.

In this paper we would make a comparison finalized to define the achievable accuracy in 3D point measurement according to different existing georeferencing techniques, firstly by a laboratory test, and finally by using as case study the surveying of the Basilica of San Pietro al Monte.

Figure 1: View of the basilica of San Pietro al Monte in Civate (Lomardia, Italy), and the Oratory of San Benedetto.

## 2. BACKGROUND ON 3D-VIEW GEOREFERENCING

The problem of scan registration is usually addressed through the definition of 2 reference systems (RS): the *intrinsic* and the *ground* RS.

Usually a laser scanner performs the measurement of a large point cloud in a very short time (up to 12k points per second in case of the fastest existing ToF or phase-shift TLSs, and even more in case of close-range triangulation instruments). For each laser point a range measurement ($\rho_m$) and an intensity value (I) are collected; these data may be integrated by RGB information in case a digital camera is co-registered to the scanner. Furthermore, the horizontal rotation angle ($\alpha_m$) and the vertical attitude angle ($\theta_m$) are registered for each measured point, allowing its determination in the *intrinsic reference system* (IRS) of a given scan position. In practice, if more than one scan are captured from the same stand-point without altering the TLS position and attitude, all resulting 3D-views will be referred into the same IRS.

By construction, the laser scanner axes are not perfectly aligned, so that these differences have to be corrected in order to transfer the measured spherical coordinates ($\rho_m,\alpha_m,\theta_m$) into the IRS ($\rho,\alpha,\theta$). The geometric model adopted to perform this correction should be given by TLS technical documentation, but this does not happen for all instruments. On the other hand, each laser scanner model is usually provided by its own software for data acquisition control, which directly performs the trasformation of 3D point coordinates into the IRS.

The *ground reference system* (GRS) is shared between more than one scan. To trasform each scan from its own IRS into a GRS a 3D roto-translation is to be computed on the basis of common control points (or features). This operation is called *scan co-registration*. Given the vector $X$ storing coordinates of a point in the GRS, and the vector $x$ with the corresponding coordinates in the IRS, the trasformation between both reference systems can be expressed by introducing the *rotation matrix* **R** and the vector $O_1$ expressing the origin of the IRS with respect to the GRS:

$$X = \mathbf{R}x + O_1 \qquad (1)$$

The rotation matrix **R** can be parameterized by *cardanic angles* ($\omega,\varphi,\kappa$) as commonly done in photogrammetry. Concerning materialization of a GRS, this can be done by a set of control points with known coordinates, or by considering a scan as reference for co-registering all the others that overlap to it. In this paragraph we would like to give a presentation of different georeferencing techniques.

### 2.1 GCP-based georeferencing

The widespread adopted technique for scan georeferencing is based on registering each 3D-view to the GRS by means of a set of GCPs materialized by *targets* or natural features. Thanks to the knowledge of a minimum of 3 GCPs that can be measured in the scan to be georeferenced, all 6 parameters of the rototranslation can be computed by a resection technique. In practice, the GCPs' number should be increased in order to improve the global redundancy of the observations. Being this problem not linear, usually an algorithm which does not require any approximations for the unknowns is applied; in literature a large variety of these methods are reported (see Beinat & Crosilla, 2001). To cope with possible outliers and to automatically find corresponding points on the scan and the ground, the RANSAC algorithm is widely used (Fischer & Bolles, 1981). Finally, once a set of valid GCPs has been established, a *least squares* algorithm is applied to exploit the data redundancy and to evaluate the precision of the estimated solution. However, this technique can be used either for the georeferencing of a block of scans to a common GRS, and for the pairwise registration of them. In the last case, GCPs are replaced by control points (or features) which are shared between two near 3D-views.

### 2.2 Direct georeferencing

The second strategy to perform the scan georeferencing is that based on the so called *direct* method. The most part of existing TLS can be *directly georeferenced*, meaning that the sensor can be optically centered over a known point and levelled, while the remaining DoFs can be fixed by orienting the IRS system toward a known point. The basic geometric model describing a TLS which can be oriented by a telescope is similar to that describing a classical theodolite. The scanner is stationed over a known point in a given GRS, while the z axis of its own IRS is put vertical. Being known the vector *H* from the stationing point to the origin $O_1$ of the IRS (from calibration or from mechanical drawings) coordinates of $O_1$ in the GRS can be easily derived (see Fig. 2)

The azimuth orientation is carried out by the alignement of the scanner head along a known direction thank to a pointing device (telescope or backsighting target measurement). By collimating a point $O_2$ having planimetric known coordinates in the GRS ($X_{O2}$,$Y_{O2}$) also the direction of the x axis of the IRS can be fixed and then the horizontal angle κ constrained. The IRS will result rotated around the z axis of an angle κ with respect to the GRS; for this reason, we refer to a generic point n the IRS by vector $x_\kappa$. The transformation from IRS to the GRS is given by the expression:

$$X = R_\kappa x_\kappa + O_1 \qquad (2)$$

where the rotation matrix $R_\kappa$ will define the rotation κ around the *z* axis.

A detailed description of DG technique and an evaluation of its precision is reported by Lichti & Gordon (2004), and by Scaioni (2005).

The DG tecnique allows only the goreferencing of 3D-views into an external GRS, and is not used for scan co-registration. Moreover, if more than one scan are directly georeferenced into the same GRS, they will result co-registered as well. Note that, in this case, scans do not required to share nor common points, and overlapping surfaces.

### 2.3 Surface matching

Likewise digital photogrammetry, where *image matching* refers to estimate a geometric 2D transformation mapping a patch extracted from a reference image to one or more slave images, *surface matching* means to compute a 3D transformation (usually a 3D roto-traslation) between corresponding portions of two point-clouds. Obviously, the problem of matching two surfaces is much more complex than the 2D case. Indeed, in case of 2D images, observed data are the intensity values of each image pixel, that can be considered as a function $I= f(i,j)$, where *i* and *j* are row and column of a pixel in the image. In case of 3D surfaces, only the geometry - i.e. the coordinates of points or surfaces (like *triangulation*) computed from the point cloud - is considered, but here not always one coordinate can be expressed as explicit function of the others. This fact result obviously in a complication of the problem.

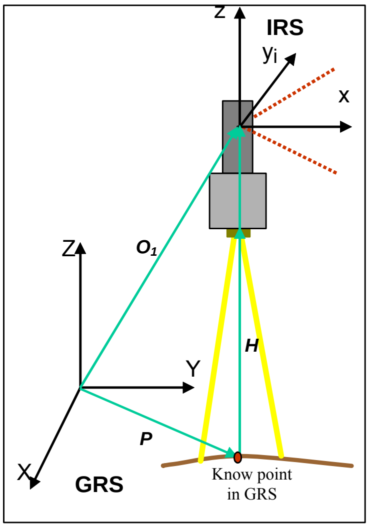


Figura 2: Ground and Intrinsic RS of a scan position adopting the direct method.

Moreover, existing surface matching algorithms can be directly tared on points (for example the ICP - *Iterative Closest Point* - method of Besl and McKay, 1992, and its improvements or modifications) or on triangulated surfaces (for example the algorithms of Acka, 2006, and Bologna *et al.*, 2004). Current research efforts are focused also in developing methods integrating either the geometry and the laser response or the RGB values.

However, in operational packages one of the most popular and efficient surface matching methods is the already mentioned ICP algorithm, which is based on the search of pairs of nearest points in the two sets to register, and on estimating the rigid transformation which aligns them. Then, the rigid transformation is applied to the points of one set, and the procedure is iterated until convergence. The ICP assumes that one point set is a subset of the other. When this assumption is not valid, false matches might occur, that negatively influence the convergence of the ICP to the correct solution (Fusiello *et al.*, 2002).

## 3. DATA ACQUISITION

### 3.1 Site description

The object of this study is an historical settlement named *San Pietro al Monte in Civate*, one of the most important and well organised testimonies of Romanic style in Lombardia, Italy.

The first church was built by Benedictines in 772, probably on a pre-existence paleochristian building or military fortification. The XI century was the period of maximum splendour with the integration of stuccos and frescos of the Benedictine monastic art. Monastery decline began in the XII century and the last chaplain was murdered by brigands in 1611. In 1757 the belfry collapsed and in 1798 Napoleon sold the monastery properties by auction. Only in 1927 Mons. Giuseppe Polvara, from Pescarenico (Lecco), began the first restoration. He was painter, architect and the founder of the religious scholl and family “Beato Angelico” of Milan. The architecture is the result of 13 centuries of alteration. The current structure of the Basilica of San Pietro and the chapel of San Benedetto is in Romanic style and dates back to the end of XI century. Inside the Basilica, the paintings dated XI century are the most important among the paintings of the same age. Very impressive is the one of the back side, inspirited to the Apocalypse.

### 3.2 Instruments

The laser scanning surveying has been carried out by using a Riegl LMS-Z420i instrument equipped by a calibrated digital camera Nikon D100 (6.1 Mpixel) and by a tool for tilt-mounting. This device has been used because the horizontal FoV of this scanner is panoramic (360°), but the vertical one is limited to ±40°. Thanks to the knowledge of the relative transformation between all tilted positions of the scanner head and the vertical one, the georeferencing procedure is quite simple. Once the LMS-Z420i has been georeferenced in vertical position, all tilted positions will result georeferenced as well. In a similar way, also the integrated digital camera is mounted in a known position, so that all acquired images can be oriented in the IRS of the scanner in a straight-forward manner. A detailed description of technical features of this long-range TLS can be found at Riegl website; a good review is reported also by Ingensand (2006).

The data acquision is controlled via a PC. The energy supply of all tools is guaranteed by a Honda EU10i portable electric generator, capable of 0.9 kW allocated power with a total weight about 13 kg.

Two kinds of GCPs have been adopted, all consisting of targets covered by retro-reflecting paper. The first type is a simple retro-reflecting paper put on the walls with glue. The second type is a cylinder with diameter $\phi$ = 50 mm and height h = 50 mm. The advantage of these targets is the possibility of putting them directly over known points by a tripod or a pole without a permanent materialization.

A Leica total stations TCRA 1203 has been used for the determination of GCP coordinates and for some detail measurements inside the church. Finally two GPS Leica 1200 has been used to link the local survey to the national mapping frame.

### 3.3 Surveying operations

The aim of the survey of the Basilica di San Pietro was to derive a virtual reality 3D model of the building itself, requiring two different precisions in data acquisition. In outdoor, the simple morphology and construction materials of the object has required a precision about ±5 cm, while the inside the basilica, the presence of a lot of frescos and bas-reliefs have solicited a higher precision in the order of ±2 cm.

For this reasons, different surveying techniques and 3D-view georeferencing methods has been adopted, as shown in the following.

#### 3.3.1 Geodetic network

Two different geodetic networks have been setup and measured to establish the GRS. The measurement of some points which are common to both networks allowed to define a unique reference system. The first network consists in 12 main vertices materialized by topographic nails, whose measurement has been carried out by the TLS itself outside the basilica (see red lines in Fig. 4). In this case, the TLS Riegl LMS-Z420*i* has been used as a total station, so that in this application the point-cloud acquisitions as weel as the determination of the geodetic network have been carried out at the same stage. From every standpoints, the preceding and the following vertices have been measured by using cylindrical retro-reflective targets to materialize the points.

The resulting closed traverse of 280 m total length has presented a planimetric closure error of 3.5 cm. The network's measurements (11 standpoint and 45 targets) have been processed by L.S. and the results show a precision of ±1.7 cm in X-Y and ±2.9 cm in Z. The propose method has allowed to obtain the TLS survey and the network solutions in only one day of work on the field.

Inside the church, the measurement has been carried out by means of a Leica TCRA 1203 total station. The L.S. adjustment of the geodetic network has resulted in the determination of target coordinates with estimated std.dev of ±2 mm in X-Y and ±3 mm in Z. Coordinates of some points belonging to the outside network have been measured in order to join the 2 networks. At the final stage, thank to static GPS measurement, 2 points of the national GPS network IGM95 has been linked to the local network in order to derive mapping coordinates of points in the national grid.

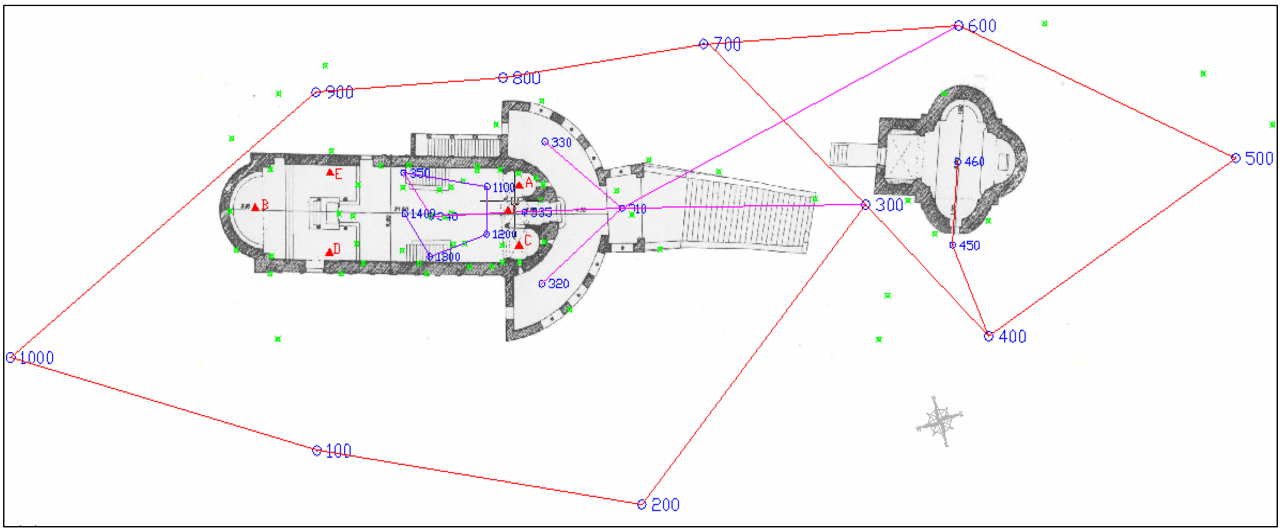


Figure 3: planimetric view of theBasilica di San Pietro al Monte, reporting the layout of the geodetic network and the laser scanning stand-points.

### 3.3.2 Laser scanning data acquisition

All data for the geometric modelling have been acquired during 2 measurement campaigns. The first one lasted 1 day in June 2006, when all external scans of the basilica have been taken, and in a second campaign in September 2006, when the job has been completed. Both georeferencing and point cloud capture have been controlled by the software Riscan Pro licensed by Riegl and installed on a PC linked to the scanner Riegl LMS-Z420*i*.

To achieve such data, 27 main scan positions have been established; some features of the acquired scans are reported in Table 1.

| Stand-points | Positions | # of scans for each stand-point | Scanning time [min] | # of total measured 3D points (Mil) | Mean point density on the object [points/cm] | Max angular resolution [deg] | type of georeferencing |
|---|---|---|---|---|---|---|---|
| 200 | outside | 3 | 6 | 1.60 | 0.50 | 0.06 | direct |
| 300 | outside | 1 | 4 | 1.99 | 0.40 | 0.12 | direct |
| 400 | outside | 1 | 4 | 1.99 | 0.40 | 0.12 | direct |
| 500 | outside | 2 | 4 | 2.70 | 0.30 | 0.12 | direct |
| 600 | outside | 1 | 4 | 1.99 | 0.40 | 0.12 | direct |
| 700 | outside | 1 | 4 | 1.99 | 0.30 | 0.12 | direct |
| 800 | outside | 2 | 3.5 | 1.50 | 0.40 | 0.04 | direct |
| 900 | outside | 1 | 4 | 1.99 | 0.50 | 0.12 | direct |
| 1000 | outside | 1 | 4 | 1.99 | 0.30 | 0.12 | direct |
| 100 | outside | 1 | 4 | 1.99 | 0.40 | 0.12 | direct |
| 450 | first floor | 1 | 1.5 | 0.70 | 0.50 | 0.20 | direct |
| 460 | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | direct |
| 310 | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | direct |
| 320 | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | direct |
| 330 | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | direct |
| 340 | first floor | 3 | 12 | 5.97 | 1.00 | 0.12 | GCPs |
| 335 | first floor | 2 | 3.00 | 1.40 | 1.00 | 0.20 | GCPs |
| A | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| B | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| C | first floor | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| D | first floor | 2 | 2.50 | 1.30 | 1.00 | 0.11 | GCPs |
| E | first floor | 2 | 2.50 | 1.20 | 1.00 | 0.13 | GCPs |
| 1100 | basement | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| 1200 | basement | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| 1400 | basement | 3 | 4.5 | 2.10 | 1.00 | 0.20 | GCPs |
| F | basement | 4 | 5.00 | 2.60 | 1.00 | 0.10 | GCPs |
| G | basement | 2 | 3.00 | 1.40 | 1.00 | 0.20 | GCPs |
| total | | 60 | 116 | 55.3 | | | |

Table 1: features of scans acquired by Riegl LMS-Z420i at the Basilica di San Pietro al Monte

Figure 4: laser scanner Riegl LMS-Z420i with its integrated camera during scanning of the oratorio di San Benedetto roof.

From each stand-point, apart a few exceptions, 2 or 3 different scans have been acquired according to different inclinations of the Riegl LMS-Z420*i* head (see Table 1). This fact shows somehow the planning of laser data acquisition is a really complex task, requiring an attentive analysis to correctly plan all scans to capture.

Each scan has been integrated by its companion digital image captured by Nikon D100 camera equipped by a 20 mm lens.

## 4. TESTING DIFFERENT METHODS FOR 3D-VIEW GEOREFERENCING

The more and the more commercial softwares make the process of scan georeferencing automatic, the availability of tools for the quality control does not often improve at the same degree. This makes difficult to evaluate the precision and the presence of potential gross errors. In some cases the only viable procedure to check the results it's the visual inspection of scan alignment. On the other hand, a more accurate analysis could be carried out if a set of *Independent Check Points* (IchP) would be available. Here a laboratory test where the available precisions obtained from different georeferencing techniques could be evaluated by using a set of widespread IChPs is presented at par. 4.1. Secondly, methods that have been applied for georeferencing scans taken at the complex of San Pietro al Monte are described and compared (see par. 4.2).

### 4.1 Laboratory test

In the Surveying Lab in Lecco town of Politecnico di Milano university, a first test-field has been setup to make practical tests and comparisons about different georeferencing techniques applied to TLS data and instruments. This is made up of a small geodetic network composed by 6 verteces on the floor, from which the coordinates of 12 retro-reflective targets have been measured.

Coordinates of the network, whose layout is reported in figure 6, have been measured by a total station and, after a L.S. adjustment, have resulted in a std.dev of ± 1.6 mm in planimetry and in ± 2 mm in height. The scanner Riegl LMS-Z420*i* has been positioned on 4 verteces of the network, georeferenced in different ways, and from each position the coordinates of targets have been acquired. Subsequently, by applying the set of georeferencing parameters computed at each station, the residuals on 23 IChPs have been evaluated. All IChPs have been materialized by retro-reflectivie targets as well.

The classical *GCP-based georeferencing* (indirect method) has been carried out by the SW Riscan Pro adopting to control the data acquisition process as well. Here a L.S. procedure is implemented together with a data pre-analysis stage, which is able to perform:

- automatic target recognition and measurement;
- automatic target labelling based on the knowledge of mutual distances between them in each scan and on the ground;
- computation of parameters allowing a minimal check on target measurement, such as their evaluated size, number of points, mean registered laser response.

After the L.S. estimate of georeferencing parameters, residuals on GCPs are displayed together with the sigma nough of the adjustment. The *direct georeferencing* (DG) has been performed by using coordinates of each TLS stand-point

obtained from the measurement of geodetic network. The angular setup has been accomplished by the employment of a level plummet (sensibility equal to 30″/2 mm), complemented by a back-sighting target measurement for the hazimutal orientation. Also in this case, all available GCPs that have not been used for georeferencing have been adopted as IChPs.
During laboratory testing, one further option has been evaluated. The TLS has been used without exploiting the total station measurements, but it simultaneously has scanned the object and measured the stand-points of geodetic network. In this operation, the TLS has been put on each vertex of the network, but this time considered with unknown coordinates, it has been levelled and hazimutally oriented. Moreover, from each stand-point, range and both horizontal and vertical angles towards the preceeding and the next vertex of the traverse have been measured. Here two cylindric retro-reflective targets have been placed on o tripod just over the monument of the network on the floor. The resulting coordinates of the close traverse's verteces have been calculated by L.S. adjustment. The residuals on IChPs were slightly worse than based on DG with total station measurements (see table 2), but they were however very interesting for those application fields where a lower accuracy is requested.
Finally the *surface matching* method has been analysed. Scans have been processed in Imalign-Polyworks software according to the following scheme: in the first step, scans have been pairwise aligned, then a ICP-based global alignment has been applied to the whole dataset. The target coordinates in every scan have been compared to GCPs determined with total station (see table 2). In figure 5 some results of laboratory tests are shown, where the precision is expressed by 3D-RMS error.

| **Rejection (cm)** | **INDIRECT** | | **DIRECT WITH TS** | | **DIRECT WITHOUT TS** | | **SURFACE MATCHING** | |
|---|---|---|---|---|---|---|---|---|
| | **XY** | **Z** | **XY** | **Z** | **XY** | **Z** | **XY** | **Z** |
| ***sqm*** | 0.5 | 0.3 | 0.9 | 1.6 | 1.1 | 1.5 | 0.9 | 1.1 |
| ***max*** | 1.2 | 0.5 | 3.2 | -4.0 | 3.7 | 3.6 | 2.6 | 3.9 |
| ***media*** | 0.0 | 0.0 | -0.3 | -0.1 | 1.0 | 0.5 | 0.1 | 1.4 |
| ***RMS*** | 0.5 | 0.3 | 0.9 | 1.6 | 1.5 | 1.6 | 0.9 | 1.8 |

Table 2: Results of the analysis of residuals on 23 IChPs according to different georeferencing methods.

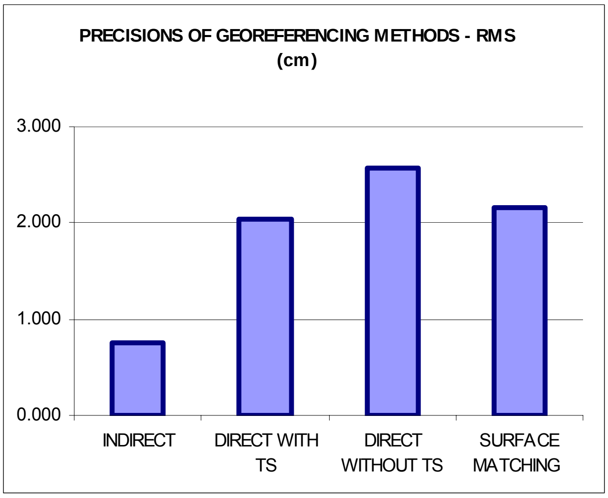


Figure 5: Comparison of RMS of 3D residuals achieved by applying different techniques for terrestrial 3d-view georeferencing in laboratory test.

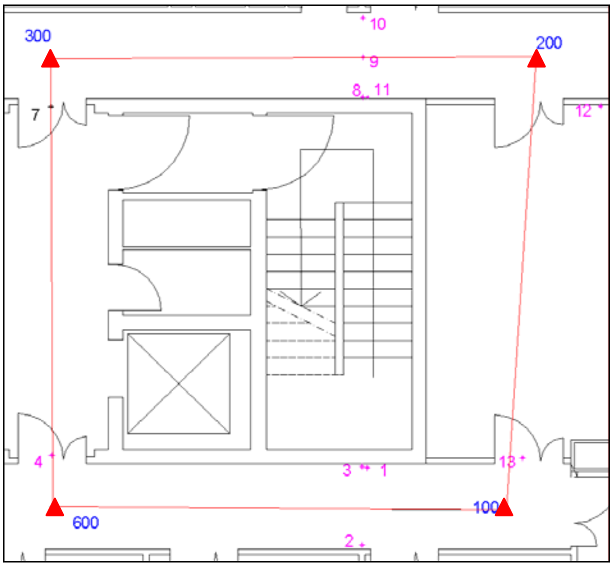


Figure 6: Layout of the geodetic network used in laboratory testing.

## 4.2 Georeferencing of scans taken at San Pietro al Monte

### 4.2.1 DG without total station data

The DG technique has been adopted to get georeferenced all scans acquired outside the church of San Pietro al Monte in Civate, accounting for 10 3D-views (see the layout in figure 4). The IRS of the first stand-point (100), therefore termed as $IRS_{100,}$ has been adopted as GRS. The instrumental height has been removed in order to reduce it to the ground plane. After, by using hazimuth orientations and ranges towards the preceeding and the following network vertex from each stand-point, and the instrumental heights, all scans have been georeferenced into the GRS. In a first stage, the acquisition SW Riscan Pro has been used for DG, but this unfortunately does not allow to do any check of the georeferencing data quality. For this reason a different procedure have been used. First, the target measurements from network stations acquired in every scan have been exported, and they have been processed by L.S.. Finally the adjusted target coordinates have been imported in Riscan Pro, and all scans have been georeferenced. The final accuracy has resulted (3D RMS error) of ±1.9 cm in X-Y and ±3.5 cm in Z.
DG with known stationing point coordinates has not been performed because no total stations measurements have been taken for the outdoor geodetic network.

### 4.2.2 Surface matching

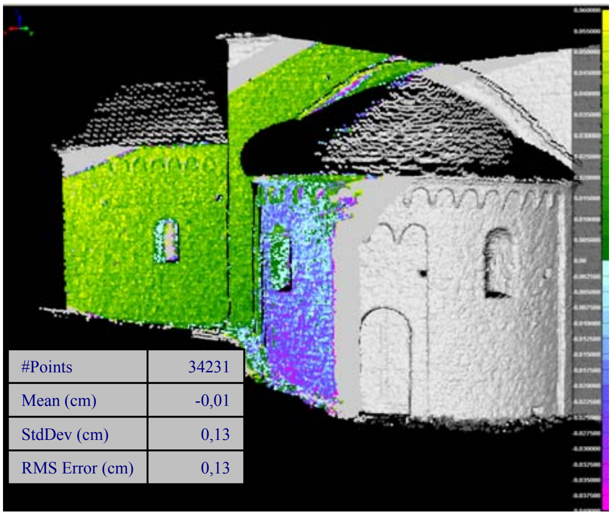
The use of surface matching is faster than DG method presented above, because it does not need to centre the TLS over a known point, nor levelling and azimuth orientation. On the other hand, this method requires large overlaps between adjacent scans and highly textured surfaces of the object to survey. The scans were processed in Imalign-Polyworks software according to the same scheme already described at par. 4.1.
The uncertainty of georeferencing for this solution has been evaluated according to ICP alignment report (see table 2). To value the real precision of surface matching method is very difficult, because this does not use IChPs to check the data quality. Usually, the precision computed from ICP algorithm and evaluated by comparing the differences between two

aligned scans hss resulted worse than the accuracy of 3D point coordinate measurements, as laboratory test showed. While an RMS error of ±0.7 cm is reported by the ICP report, it has been evaluated to ±2.1 cm from IChPs analysis.

To reduce the alignment error, TLS stand-points have been planned to setup a closed polygonal path around the site to survey. This has allowed to compute an adjustement of observations needed to derive coordinate of TLS stations. For example, 5 scans around the oratory of San Benedetto (300,400,500,600,700) has been used to check the alignement error. Scans have been aligned by surface matching, and finally the last and the first scans have been compared.

| # Scan | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Media (cm)** | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | -0.1 | 0.0 | 0.0 | 0.1 |
| **Std. Dev. (cm)** | 1.0 | 1.2 | 1.1 | 1.0 | 1.0 | 1.1 | 1.0 | 0.7 | 0.7 | 1.3 |
| **RMS (cm)** | 1.0 | 1.2 | 1.1 | 1.0 | 1.0 | 1.1 | 1.0 | 0.7 | 0.7 | 1.3 |

Table 3: results of ICP alignment on different scans outside San Pietro al Monte.



| #Points | 34231 |
|---|---|
| Mean (cm) | -0,01 |
| StdDev (cm) | 0,13 |
| RMS Error (cm) | 0,13 |

Figure 7: Error in surface matching methods

## 5 3D MODEL

After the description of different georeferencing techniques which have been applied and compared, we would like to present the workflow of the process to built up the final 3D model from the point clouds. Moreover, different software packages that have been used will be addressed in the sequel.

All the editing procedures have been carry out in RiscanPro Software. The scans have not been merged as one XYZ file because the following operation could not be performed due to limitation of the physical memory of the adopted computer. Each scan has been cropped to include only the area of interest, i.e. deleting the non relevant parts. The surface triangulation has been carried out at the original data resolution, and after the number of triangles has been reduced by “smoot & decimate” function of RiscanPro. This modifies the surface structure of the polydata object by optimizing the point data (*smoothing*), and by reducing the amount of triangles (*decimating*). Processing of 3D model followed by filling the holes and removing of spikes. Finally the triangulated meshes has been joined together with the high resolution images, captured by a calibrate Nikon D100 camera equipped by a 20 mm lens.

In a second step the SW Cinema 4D has been used. The scans have been imported through VRML file format that allows to import a texturized mesh. The SW Cinema 4D is not well optimized to process very dense datasets as those generated from TLS data. For this reason, each single scans has been edited alone and only for the final rendering all 3D-views have been used as a whole. Unfortunately a virtual tour by video has not been created yet because the memory request by softwares exceeded the physical memory which is currently available on computers at the Surveying Lab.

Figure 8: North view of the 3D Model.

Figure 9: South-west view of the 3D Model.

## 6 CONCLUSIONS

In the paper a background about 3D georeferencing methods for 3D-views acquired by TLS has been presented. These accounts for the typical technique based on the use of targets as GCPs, for the so called *direct georeferencing*, and for the *surface matching*. In particular the paper would like to stress and to analyze the performances achievable by the direct georeferencing techniques, that are based on the use of a TLS instrument like a theodolite. According to this approach, here two different methods are proposed and tested: the first one exploits information about the TLS stationing point which must be already available from previous measurements; the second allows to derive at the same stage both scanner setup and determination of stand-point coordinates.

These techniques have been applied and compared during surveying of a pair of completely different sites: an indoor test field established in the university lab, and to a real case study, i.e. the ancient church of San Pietro al monte in Civate (Lombardia, Italy). Testing has been carried out in order to evaluate the accuracy in data acquisition according to different techniques. Comparisons have been made on the basis of a common set of independent check points.

Both methods based on direct georeferencing allow to get slightly worse accuracies with respect to other approaches. Obviously, the most critical case occurs when data about stationing points are not available. On the other hand, in case a medium accuracy is enough (i.e. at 2-3 cm level), direct methods are really operational, because they would avoid the most part of the work to be carried out on the field. Furthermore these are applicable disregarding the specific morphology of the surveyed object, because they do not require any particular overlapping between scans or rich textures to successfully apply surface matching techniques.
The last point is very interesting for the reconstruction of Virtual Reality 3D-models of cultural heritage, because in this case it's more important to have a complete modelling of a large site than to achieve the highest accuracy in surveying.

## ACKNOWLEDGEMENTS

This work has been partially funded under the national research program "COFIN 2004" (Prot. 2004080741) leaded by Prof. C. Monti (Politecnico di Milano). Thank go to Don Vincenzo Gatti and to "Associazione amici di San Pietro" (Civate, Italy) for having given the full access to the Basilic and for the friendly cooperation. Finally we would like to thank M. Sala and E. Ambrosini who worked on information extraction from laser scanning data during their degree thesis at Politecnico di Milano, Polo Regionale di Lecco. Authors would like to acknowledge Prof. Alberto Giussani (Politecnico di Milano) for the coordination of this project, and Dr. Fabio Roncoroni for his support during the data acquisition stage.

## REFERENCES

### References from Journals

Fischler, M.A., and R.C. Bolles, 1981. Random Sample Consensus: a Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography. Comm. ACM, n. 24, pp. 381-395.

### References from Proceedings

Alba, M., Giussani, A., Roncoroni, F., and M. Scaioni, 2005. Strategies for Direct Georeferencing of Riegl LMS-Z420i Data. In Proc. of Optical 3D Measurement Techniques VII,Vol. 2, Vienna, Austria, 3-5 Oct, pp. 395-400.

Besl P. J., and N.D. McKay, 1992. A method for registration of 3-D shapes. IEEE Trans. Patt. Anal. Machine Intell., pp. 239–256.

Bologna, R., Guarnieri, A., Minchilli, M., Vettore, A., 2004. Automatic Registration of 3-D Views. IAPRSSIS, Vol. 34(B5), Istambul, Turkey, pp. 315-320.

Beinat, A., and F. Crosilla, 2001. Generalised Procrustes Analysis for Size and Shape 3-D Object Reconstructions. In Proc. of Optical 3D Measurement Techniques V, Vienna, Austria, Vol. 2, 3-5 Oct, pp. 345-353.

Fusiello, A., Castellani, U., Ronchetti, L., and Murino, V., 2002. Model acquisition by registration of multiple acoustic range views. Computer Vision – ECCV 2002, LNCS vol. 2351, Springer, pp. 805-819.

Grün, A., and D. Akca, 2006. Least Squares 3D Surface Matching. IAPRSSIS, Vol. 34(5/WG16), Dresden, Germany, on CDROM.

Ingensand, H. 2006. Metrological Aspects in Laser-Scanning Technology. In: Proc. of 3$^{rd}$ IAG/12th FIG Symp., Baden, Austria, May 22-24, pp. 10, unpaginated CDROM.

Lichti, D.D., and S.J. Gordon, 2004. Error Propagation in Directly Georeferenced Terrestrial Laser Scanner Point Clouds for Cultural Heritage Recording. In Proc. of FIG Working Week, Athens, Greece, May 22-27, pp. 16.

Scaioni M., 2005. Direct Georeferencing of TLS in Surveying of Complex Sites. IAPRSSIS, Vol. 36(5/W17), Mestre (Italy), unpaginated on CDROM.

Scaioni, M., and G. Forlani, 2003. Independent Model Triangulation of Terrestrial Laser Scanner Data. IAPRSSIS, Vol. 34 (5/W12), Ancona Portonovo, Italy, pp. 308-313.

Ullrich, A., Schwarz, R., and H. Kager, 2003. Using Hybrid Multi-Station Adjustment for an Integrated Camera Laser-Scanner System. In Proc. of Optical 3D Meas. Tech. VI, Zurich, Switzerland, pp. 298-304.