APPLICATION OF TLS TO SUPPORT LANDSLIDES STUDY: SURVEY PLANNING, OPERATIONAL ISSUES AND DATA PROCESSING

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ABSTRACT:

Terrestrial laser scanning (TLS) technology has recently increased its interest in the geological community for the geometric survey of slopes involved in landslides and for the acquisition of a DSM of rock wall, that can be used for predicting possible paths of falling dawn stones. In particular, the paper deals with this last application, focusing on some open aspects which have devised to be accurately studied.

Firstly, a method for the survey planning is proposed, which is particularly devoted to the application to rock wall survey. Secondly, operational issues such as the selection of ground constraint, the materialization and the measurement of ground control points (GCP) are proposed, as well as a solution for the positioning of GCPs. Finally, some concerns about data collection and processing are afforded.

1. INTRODUCTION

Since the appearance of long range terrestrial laser scanners (TLS), application of this surveying technique has increased the interest in the international communities of surveyors and geologists.

Despite the high powerfulness of current available TLSs, which allow the acquisition of very dense and accurate point-clouds in a fast and simple way, the management of the large amount of data is the real problem to cope with. However, applications for landslides monitoring would allow to obtain some products that were not available or were available only with a strong effort by applying classical surveying methods.

First of all, a georeferenced DSM of slopes interested by possible movements can be easily obtained by TLS. The derived DSM offers an accurate geometric description of the surface, that can be used for predicting possible paths of falling dawn rocks. For the sake of completness, each DSM can be compared to other DSMs acquired at different times in order to evaluate displacements, changes of volumes and modeling the possible landslide behaviour.

In the opinion of the authors, this kind of application is that highly exploiting the capabilities of TLS instruments and techniques in the geological field. As consequence, this paper will focus on the geometric survey of rock walls, a part some general considerations which may concern other kinds of application as well.

1.1 Surveying of a rock wall by TLS techniques

The subject presented in this paper is currently of very high interest. Indeed, in the last months Italian newspapers have reported about different cases of landslides, cracks and damages of rocks interesting important mountain tops in the Alpine Area, with a higher frequence in the Dolomitic Region (North-Eastern Italy). Similar problems can be registered each day in all sites where instable rock walls threaten roads or human settlements which have been built up in their nearby.

Currently the stability analysis of rock walls is carried out by applying a set of different investigation techniques, concerning geological, geotechnical and geophisical aspects. In almost all studies, the geometric survey is a fundamental pre-requisite, this consisting in a primary data acquisition stage (e.g. the images in a photogrammetric survey), in their processing to get a sparse point-cloud describing the surface, and finally an interpolation/regularization method to obtain a regular grid of points (DSM-Digital Surface Model). According to the specific method applied, one of these stages could be avoided.

The state-of-the-art of surveying techniques offer different possibilities to acquire the geometric description of a rock wall, which will be analysed in more detail at par. 1.3. Among these methods, the recent appearance of long-range TLS overwhelmed this field of application, leaving to other methods only the role of integrating possible missing data.

The practical application of TLS to the geometric survey of rock walls has been experienced by different research groups; among these, the IC&T Laboratory's group of the Politecnico di Milano – Polo Regionale di Lecco, which operates in an area (Pre-Alpine Area) affected by a very huge number of geological problems. Experiences leaded so far have shown the advantages of applaying TLS techniques, but have addressed as well some open problems which devise to be studied and solved.

1.2 Open problems in the application of TLS techniques

A wide open problem concerning the use of TLS technique is represented by the *survey planning*. So far, no general standard rules have been established to accomplish each task, especially when operating in the environmental field. In experiences carried out, we have understood that a preliminary planning of laser scanning survey is fundamental for deriving all needed information. On the other hand, the risk of collecting a large abundance of data (3D-views, images, topographic measurements and data from other kinds of sensor) would result in the impossibility of their effective management.

In the paper we propose a workflow for laser scanning survey planning, which is particularly devoted to the application to rock walls.

The second topic aspect of this kind of survey is that involving operational issues such as the selection of ground constraint, and the materialization and measurement of ground control points (GCP).

Finally, the data processing task represent the most complex stage of the whole process, being softwares for laser scanner data management still in a development stage (commercial SWs as well!).

1.3 Comparison with other techniques

Topographic and photogrammetric methods for the measurement of surfaces can basically are mainly three:

- measurement by total station;
- DSM generation from digital images by photogrammetric methods;
- TLS techniques.

The first method is based on the use of a total station equipped by a laser range-finder able to measure distances without any reflective prism. An operator manually performs the collimation of each points by the theodolite lens, and measured coordinates of points are stored in the internal memory.

Digital photogrammetric methods are based on the acquisition of a block of images covering the whole are to survey. Currently several commercial models of high-resolution digital cameras are available, which can be used for this kind of applications after their calibration (Grün & Huang, 2001). The photogrammetric survey must be completed by the topographic measurements of GCP coordinates. The topic stage is however the data processing, which is performed by means of a SW implementing algorithms of digital photogrammetry for orientation and DSM generation. The orientation stage is usually performed by manually measurement of tie and GCPs on the images. Derivation of points describing the surface may be carried out by interactive or automatic methods. In both cases, image coordinates of corresponding points must be measured on at least two images covering the same area. Although automatic methods could be potentially the most suitable because are more productive and less time-consuming, the typical pattern of a rock wall surface does not help image matching algorithms, resulting in several errors and in many areas without points. Concerning manual methods, the use of stereo-images is fundamental, because for an operator finding and measuring corresponding points could be very difficult. Nevertheless, the use of stereo-images changes the structure of the photogrammetric block, because the whole surface of the rock wall must be covered by enough stereo-pairs.

The laser scanning approach can be considered as the technical evolution of the method based on the total station. A long-range TLS (LRTLS) allow the acquisition of points belonging to a surface at a distance of several hundreds metres from the stationing position. Upgraded technical features of current available instruments can be found at websites of producers.

The common measurement principle of all TLS is the *time-of-flight* method, the unique which permits long range measurement in a fast time. More recent instruments are equipped by a digital camera as well, which may collect images to be used for generating orthophotos or realistic Virtual Reality models.

Almost all current LRTLSs present some facilities which can be very helpful in practical surveys, such as the possibility of controlling the acquisition process by means of a laptop or a palm PC, also via remote wireless connection.

From a logistic point of view, in geological surveys the transportability of the instrument and its accessories (tripod, energy unit, PC) is fundamental, because might easily happen that arduous stand-points have to be reached. However, many efforts are required in the future to reduce weight and dimensions of LRTLSs.

2. SURVEY PLANNING

The planning of a laser scanning survey usually suffers from the typical problems involved in the traditional photogrammetric approach: several aspects must be considered, so that a standard design method is not so easy to be established. Nevertheless, a limited effort has been produced so far in order to give at least some basic addresses for a correct survey planning. However, in the following some fundamental guidelines for designing a TLS application to a typical rock wall context are given.

First of all, the extension of the area to be surveyed as well as the expected resolution and accuracy of the point-cloud must be defined, according to the topographic products that must be derived. For example, if a DSM of a rock wall featuring a density of 1 point per 100 cm^2 (meaning 1 point per 10 cm in both horizontal and vertical directions) is required, the resolution of the surveyed point-cloud should be slightly higher, e.g. 1 point per 25 cm^2. This data redundancy is required to guarantee a proper interpolation of the surface.

Assumed as given the instrument to be used (the possibility of selecting between more than one instruments is a chance that seldom happens!), a geometric layout of TLS stand-points must be setup. On the other hand, all the pre-requisite of the survey must be verified, according to the planned scheme and to the metrological parameters of the scanner itself. In case this check is not satisfied, the survey layout has to be properly modified. The following metrological parameters of a given TLS may affect the result of the survey (for their definitions see Iavarone & Martin, 2003):

- horizontal and vertical *field of views (*FoVs);
- range measurement *accuracy*;
- horizontal and vertical scan *resolutions*;
- *size of beam-spot* in the range of involved distances.

2.1 Preliminary site investigation

Disregarding all concernes involved in the geological analysis of the site (existing geological maps, evident indications and damages, formulation of ground displacement hypotesis), only aspects interesting the geometric survey are analyzed. available Large scale maps (up to 1:2500 scale) of the rock wall area could be in general very helpful. Unfortunately, this kind of maps seldom presents an accurate geometric description of rock walls, due to the prevalent vertical extension of these sites.

In case of surveys of large areas (some hundreds meter of horizontal length) or in case of sites featuring a complex morphology, a usefull tool for planning the survey layout may be a preliminary low-resolution acquisition, possibly taken from a stand-point presenting a view of the whole rock wall. After the processing of these data, a rough contour map of the site can be derived, to be used in the following planning tasks.

2.2 Positioning of TLS stations

A survey design should be first define the positions of TLS stations, so that the whole object coverage at requested spatial resolution and accuracy could be guaranteed. To this aim it is necessary to compute the ground resolution of each scan, given the TLS stand-point.

Obviously, ground resolution may change inside a same scan, depending on polar coordinates (d, φ, θ) of each measured points and on the horizontal and vertical scan resolution ($\Delta\varphi$, $\Delta\theta$). In a previous paper (Scaioni *et al.*, 2004) two relations were proposed in order to compute horizontal and vertical linear footprints (r_H, r_V) as function of the above mentioned parameters. In order to make a rough simplification of the real configuration of the rock wall, we assumed a simplified terrain model consisting in a plane tilted by a γ angle (*vertical attitude*).

Referring to Figure 1 for the meaning of symbols, *horizontal footprint* r_H can be computed by formula (1), where also the expression as function of the horizontal range d_o is given; during survey planning, the horizontal distance d_0, can be measured from maps instead of the slope distance d.

$$r_H = \frac{d\Delta\varphi}{\cos\varphi} = \frac{d_o\Delta\varphi}{\sin\theta\cos\varphi} \tag{1}$$

According to Figure 1, the *vertical footprint* r_V can be computed as follows (both real and horizontal ranges have been considered):

$$r_V = -\frac{d\,\Delta\theta}{2\cos(\gamma+\theta)} = -\frac{d_o\Delta\theta}{2\sin\theta\cos(\gamma+\theta)} \tag{2}$$

Given formulas (1) and (2), all basic theoretical elements for establishing TLS stand-points are now available.

Now we consider a rough simplification of the rock wall, made up of three horizontal profile:

- the *mean range line*, describing the mean planimetric profile of the rock wall;
- the *max range line*, collecting all the planimetric positions of the rock wall points with the higher distance from possible TLS stand-point area;
- the *min range line*, collecting all the planimetric positions of the rock wall points with the lower distance from possible TLS stand-point area.

Thank to the *mean range line*, a geometric layout of TLS stand-points can be quickly designed; then, the other *range lines* (*max* and *min*) allow to check if the whole object coverage and the required *horizontal* and *vertical footprints* (r_H, r_V) for every point are satisfied.

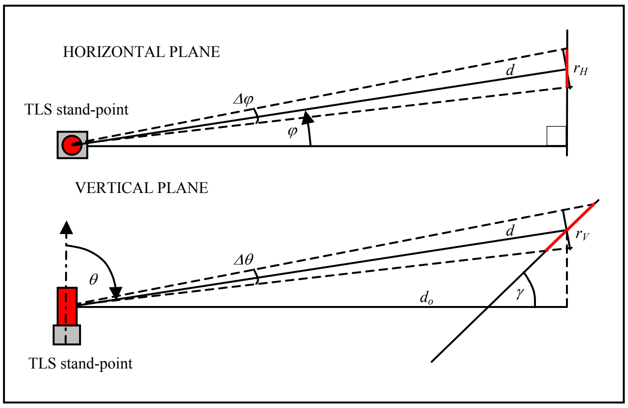

Figure 1: geometric schemes for computing single-ray footprints.

A further constraint is represented by the local morphology, which bounds the positioning of the scanner only to the so called *available area*. In the practical applications carried out by the authors, this is resulted as one of the most critical aspects to be considered, especially in mountain areas.

Referring to Figure 2, all the planimetric geometric features described so far are drawn in a CAD or GIS environment, so that all points are referenced in a topographic reference system.

In a second stage, a first planimetric positioning of TLS stand-points has to be drawn, following the profile of the *mean range line*. Each scan should result in an effective horizontal *FoV* avoiding the acquisition of points featuring a too large angle with respect to the normal to the *mean range line* itself.

From an operational point of view, from each stand-point, the effective *FoV* is drawn; in case the distance of the rock wall from the scanner would be so large that the range measurement accuracy may result not enough for the application, also an arc limiting the acquisition area in planimetry can be add up to the planning design. The resulting circular sector defines the *survey area* of the *i*-th TLS stand-point.

Two checks must carried out to assess if the planned layout can be accepted:

1. the whole planimetric area of the rock wall must be inside the *survey area* of at least one TLS position; this check can be done by considering the *min* and *max range lines*;
2. for each scan, the vertical *FoV* of the instrument must guarantee the vertical coverage of the rock wall; to check this, we consider the *most critical possible profile*, defined by the following two points:

    - the first point is that at the lowest distance from the stand-point; to this point is assigned the minimum height inside the *survey area* of the *i*-th scan;
    - the second point is that at the largest distance from the stand-point; to this point is assigned the maximum height inside the *survey area* of the *i*-th scan.

    The vertical profile of the *i*-th scan is reported in Figure 3, where also the TLS stand-point has been drawn. Thank to the knowledge of the vertical *FoV*, the coverage of the profile can be checked up. In case this check is not verified, the *i*-th scan must be divided into two scans with different elevation angles.

Once the coverage of the whole rock wall has been checked, the planned footprints r_H and r_V must be verified as well. This is reduced the analysis of the simplified model of the rock wall defined by the horizontal *survey area* (Figure 2) and the *most critical possible profile* (Figure 3).

The horizontal footprint r_H is checked first by means of formula (1), where the largest range d_{max} and the horizontal angle φ_{max} are considered:

$$d_{max} = \max(d_1, d_2) \tag{3}$$

$$\varphi_{max} = \max(|\varphi_1|, |\varphi_2|) \tag{4}$$

$$r_H = \frac{d_{\max}\Delta\varphi}{\cos\varphi_{\max}} \leq r_{H\max} \tag{5}$$

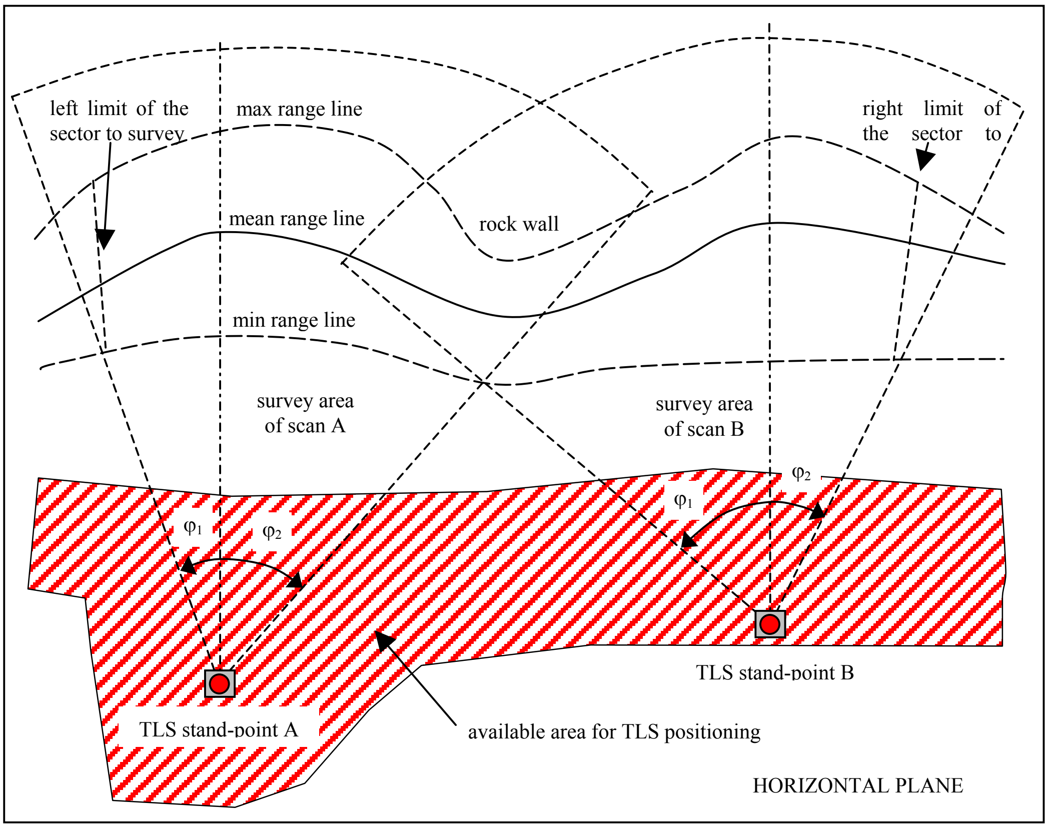

Figure 2: planning layout for the horizontal positioning of TLS stand-points.

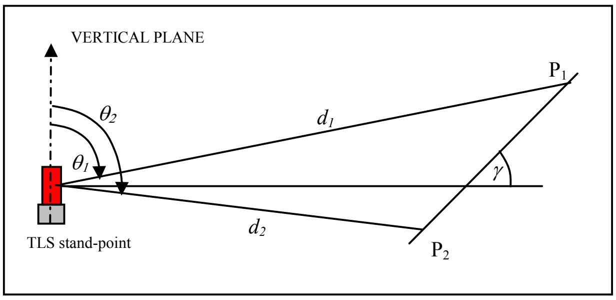

Figure 3: geometric scheme of the vertical most critical possibile profile.

Then the vertical footprint is checked out for both point 1 and 2 of the *most critical possible profile* through the formula (2):

$$r_{Vj} = -\frac{d_j \, \Delta\theta}{2\cos(\gamma + \theta_j)} \le r_{V\max} \qquad j = 1,2 \qquad (6)$$

In case the designed layout is not worthy, a new project must be setup.

2.3 Evaluation of the amount of collected data

Once the coverage of the ground and the required footprints have been checked, a rough prevision of the amount of data to collect has to be done. One of the main open problems in today's laser scanning technique is dealing with a very huge dimension of point-clouds, which gets difficult the data processing. Even though a resampling of each scan could be performed after the acquisition on the field, the best solution would be to directly carry out the data collection at a suitable resolution. This strategy will result in a reduction of the acquisition time as well.

2.4 Registration of 3D-views

Although the widespread diffusion of TLS techniques is almost recent and common theoretical fundamentals and terminology have not been established yet, the problem of 3D-view registration is usually addressed in literature through the definition of 3 kinds of reference systems:

1. the *intrinsic reference system* (IRS) of each scan, defined by the used scanner and thus depending on its diplacement;
2. the *project reference system* (PRS), shared between more than one scan; to trasform each scan from its IRS into a common PRS, all scans must be co-registered; a complete review of co-registration methods is reported by Gruen & Akca (2004);
3. the *ground reference system* (GRS), which is a particular PRS referred into a given topographic reference system; due to the limitation of the rock wall extension to few hundred meter and the accuracies of 3D coordinates of the point-cloud in the order of few cm, a local planar approximation for the geoid can be adopted. The resulting GRS is made up of a 3D reference frame featuring the *z* axis aligned to the vertical direction and the *x-y* plane co-planar to the local plane. Furthermore, the GRS may be referred to a geodetic reference

system, if at least 3 GCPs were available for computing the georeferencing.

In general transforming a scan from a reference system to another require the computation of 6 parameters of a 3D roto-translation, meaning the knowledge of at least 3 common points whose coordinates are known in both systems.
Concerning strategies for registering multiple scans, two different approaches can be followed:

- *fully GCP based registration*: if enough GCPs are known to straight-forward register each scan. Moreover, if the TLS features a large horizontal *FoV*, GCPs can be also external to the area to be acquired;
- *pairwise registration*: starting from a 3D-view which is chosen as reference, all the other 3D-views sharing a sufficient number of tie points (TPs) are registered to a common PRS, as far as the whole block is oriented. As TPs, in geological applications retro-reflective targets have to be preferably used, because their measurement can be performed with the higher accuracy either by automatic and manual procedures. Methods based on automatic extraction of not-signalized tie points or directly on matching corrisponding surfaces are very usefull in architectural and mechanical applications, but they do not hold yet in the geological field, where the presence of not coherent terrain and of moveable objects (rocks, vegetations,...) can lead to errors in registration. After the pairwise registration of all 3D-views to the same PRS, thank to a small set of GCPs the point-cloud can be transformed into a GRS.

According to these considerations, the registration method completely based on GCPs appears as the only which may guarantee a sufficient accuracy in surveys for geological investigations. This approach needs the positioning of at least 4-5 control points for each planned scan. Even though the direct topographic measurement of all CPs would be the most reliable way (so that all points would play as GCPs), in practise this approach might be largely time-wasting.
We experimented a solution based on the use as GCP of some special targets made up of a retro-reflective disk mounted on a topographic tripod through a support; this is equipped by a system to fix a prism for total station measurement or a GPS antenna (see Figure 4). The reflective-disk is interchangeable, so that targets of different sizes can be used according to the distances involved. Advantages of this apparatus are both. First, the disk can be rotated in an horizontal plane, because its rotating axis can be put vertically; this chance allows to include the same target in scans from different positions, while the 3D coordinates of its center does not change. Secondly, the geometry of the support is known and the coordinate of the target center can be easily measured in the GRS.
Adoption of such targets together with a TLS featuring an horizontal *FoV* of 360° allows to put some GCPs also behind the stand-points, perhaps in positions far from the surveyed area where topographic measurement can be carried out in easier way. In the case of rock walls, this solution has resulted as very usefull, because very often the positioning of targets directly on the rock itself is really difficult.
Obviously, the geometric distribution of the targets must be carefully planned, in order to avoid the bad determinability of the registration parameters of each scan.

Figure 4: reflective target for TLS applications with GPS antenna mounted

3. DATA ACQUISITION

This stage is the core of the whole process, because the complexity of the context to be surveyed requires to verify all the hypoteses established during the design stage. By positioning the TLS in all planned stand-points, the complete coverage of the object at the wanted ground resolution can be checked; also the acquisition of CPs must be verified. To do this, a really usefull instrumental tool is the preview at low resolution of the whole scan. After this check, possible modification or integration of the survey layout can be carried out during the same measurement campaign.
Another important task is the verification of the registration procedure, resulting from a correct targets' displacement and acquisition in all scans.
Acquisition of *digital images* can be carried out during the range data collection, in order to add up information about the color texture of the objects (Sgrenzaroli & Wolfart, 2002). This possibility is very important in case of rock walls presenting vegetation, which adds up noise to the DSM; color information may help in removing this noise. Digital camera may be fixed to the TLS or may be used independently: in the former case, the image geometry of the camera can be related to that of the scanner, so that a corrispondence between each point of the 3D-view and the image can be established by "on the job calibration", to be carried out only once time before an acquisition session (Ullrich *et al.*, 2003). In the latter case, each image can be oriented with respect to the point-cloud in post-processing by *space resection*. In both cases, image registration to the point cloud is performed by manually measuring well identifiable points on the 3D-view and the images. The *a priori* knowledge of intrinsic camera calibration parameters would reduce the number of control points to adopt.

4. DATA PROCESSING

Data processing is based on three main stages, which are performed by devoted SWs (commercial or scientific):

1. pre-editing of each scan, i.e. resampling of scans in case they are too dense and measurement of CPs;
2. registration of all 3D-views to a given GRS; cleaning of points located in not interesting parts, in order to reduce the total amount of data before next stages. Furthermore, after registration, large portions of the point-cloud may be made up by the overlap of more scans. Thank to a filtering method, duplicate data should be eliminated;
3. interpolation of the point-cloud to derive the final DSM. From the registered point-cloud a DSM describing the external surface of the surveyed slope can be derived. Thank to *meshing* techniques, the set of raw 3D points is converted into a continuous surface and thus results in a visually more intuitive representation and in reducing the amount of data. The widespread used meshing technique is *triangulation* of scan data.

The availability of an accurate DSM of a landslide area may be very important for geological investigations, for which usually only rough information read from mid scale maps is used. In particular we would like to focus on some products than can be obtained from the DSM:

- as input data for specific SW simulating possible landslide behaviour;
- simulating the path of possible falling rocks;
- computation of volumes (and their variations if multi-temporal data were available);
- computation of vector field describing movements of the landslide surface.

Furthermore, from the TLS survey also other kinds of topographic products can be derived as well. These are briefly addressed in the following sub-paragraphs.

4.1.1 Cross-sections and countour lines: Very simple products that can be derived from TLS survey are cross-sections and horizontal countour lines. Thank to the high density of points, they give an accurate description of the site, very usefull in planning of works of consolidation and protection.

4.1.2 Orthophotos: The knowledge of a DSM allows to generate orthophotos, that may be very usefull in geological analysis. Indeed, orthoimages offer a detailed view of the slope, which could be intergated by other information (cross-sections, contour lines, positions of different sensors an so on).

4.1.3 Topographic maps: Nevertheless, information described so far can be integrated by a vector map directly derived from the 3D point-cloud. For example, while the DSM and its by-products are the most appropriate methods to represent a slope, concerning building, street, infrastructures, these could be better drawn by extracting their contours.

5. CONCLUSION AND FURTHER DEVELOPMENTS

In the paper some technical aspects concerning the application of TLS to the survey ofrock walls have been presented. In comparison to other topographic and photogrammetric techniques, TLS seems to be the most suitable and fast approach for this kind of application. Some tests leaded by the authors and the information derived from the (still very poor!) published literature have shown that several problems exist and devise to be focused in order to optimize the whole survey process. The paper has concerned with particular enphasis a pair of this aspects: the *survey planning* and the definition of the *ground constraint*.

A simplified method for planning a TLS survey has been proposed, which is really suitable to be applied in a very large case of rock wall surveys, where available information might be very poor (see obseravations at par. 2.1). Nevertheless, the method can be easily extended to the survey of some other kinds of objects. The procedure has been thought as a standard approach that could be easily implemented in a software. Obviously, if more detailed initial data were available (e.g. a rough DSM or contour lines), a more accurate planning could be performed.

Concerning the definition of the ground control, after some introductory definitions, different available strategies have been presented and analyzed. A solution consisting in the use of some special retro-reflective targets mounted on topographic tripods has been proposed. The advantage of this kind of GCP consists in the possibility to put them outside the rock wall, where their positioning and measurement might result very difficult if not impossible.

Several other problems concerning this kind of application should be analyzed in more details, especially those related to the data processing. Even though the main product needed from the survey of a rock wall is merely its DSM and no feature extraction tasks are requested, acquired data may contain very often noise, prevalently due to vegetation. Filtering and removing this kind of noise devises further study. Radiometric information which could be derived from digital images could very helpful to this aim.

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