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An Automated Surveying and Marking System for Continuous Setting-out of Tunnels

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Abstract: *Setting-out is a crucial and frequently repeated process in construction and civil engineering. It is carried out by qualified operators who, making use of surveying stations, identify reference points to guide workers in their tasks. In this paper we focus on the particular case of setting-out road/train tunnels and propose a system that automatically performs the setting-out operation of the tunnel section to be perforated. The presented system, called Tunnel Continuous Setout (TCS), integrates a scanning device that surveys the excavation front and a laser projector that continuously displays the actual tunnel section computed as the intersection between the surveyed terrain and the planned tunnel section. Thus, the topographer intervention is only required for the precise positioning of the TCS device at the beginning of each working stretch, which depends on the operational range of its components (limited to 25 meters in the current implementation). A prototype of the TCS system has been employed in a real construction site proving its benefits and advantages with respect to the traditional setting-out techniques.*

1 MOTIVATION

One of the most important and frequent tasks in civil constructions is the setting-out operation, also known as “laying-out”, that consists of correctly reifying the projected construction from plans and technical documentation to the working site. Also, through setting-out operations the actual progress of the construction is surveyed and compared to the planned project in order to ensure the correctness and successful execution of the work.

Setting-out becomes even more crucial in certain civil constructions like road/train tunnels whose execution is commonly speeded up by perforating simultaneously from both sides. A minimal deviation from the planned project could stray one part of the tunnel from the other with the subsequent delay and cost increase. Thus, setting-out is carefully and regularly carried out for this type of works (Ichikawa et al., 1990; Barpi and Peila, 2012; Špačková and Straub, 2013; Deshpande, 2013).

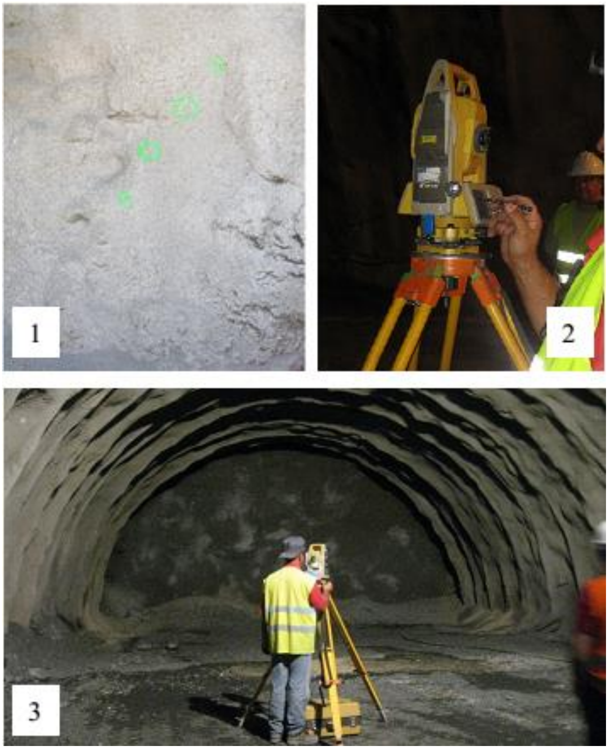

Figure 1: (1) Painted marks used as reference points for a tunnel excavation. (2) These points are calculated through total stations. (3) View of the working area during a setting-out task.

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When excavating a tunnel, the setting out process materializes reference points of the tunnel vault, the gable ends and the ground level to accurately guide the drilling operation. For that, topographers normally employ metallic nails or paint marks to indicate such reference points on the excavation front, which apart from being a time-consuming procedure, rapidly disappear from the surface with the drilling or blasting of the terrain (see figure 1). Hence, that setup process must be repeated on a regular, shortly basis, slowing down the excavation progress.

The system presented in this paper, called Tunnel Continuous Setout (TCS), has been conceived as a tool to improve and speed up the setting out operation of tunnel excavations. The performance of a working prototype[2], shown in figure 2, has been validated in real excavations carried out by the SACYR S.A.U. company, in Spain. This new topographic tool brings up the following advantages with respect to the conventional manual procedure:

1. It reduces the construction time (and consequently costs) by minimizing the stop times required for the topographers to materialize the reference points.
2. The work of the topography operators becomes safer since their participation at the excavation site is reduced.
3. It provides workers with a clearer view of the areas to be drilled. The TCS system draws the complete tunnel section instead of a few reference points.
4. Alphanumeric information can be also projected to inform workers, for instance, about the current kilometer point.

Additionally to these advantages it is worth to mention the small projection errors yielded by the system, lower than 3 cm RMSE, which fulfils the precision requirements needed for this kind of work.

The structure of the paper is as follows. Next, some related works are outlined. Section 3 provides an overview of the TCS system while section 4 details its components. Section 5 presents the calibration of the TCS components carried out during the construction of the prototype. Section 6 details the setup of the TCS in the workplace. Finally, section 7 presents the experiences of using the TCS during the construction of two tunnels and section 8 presents the conclusions.

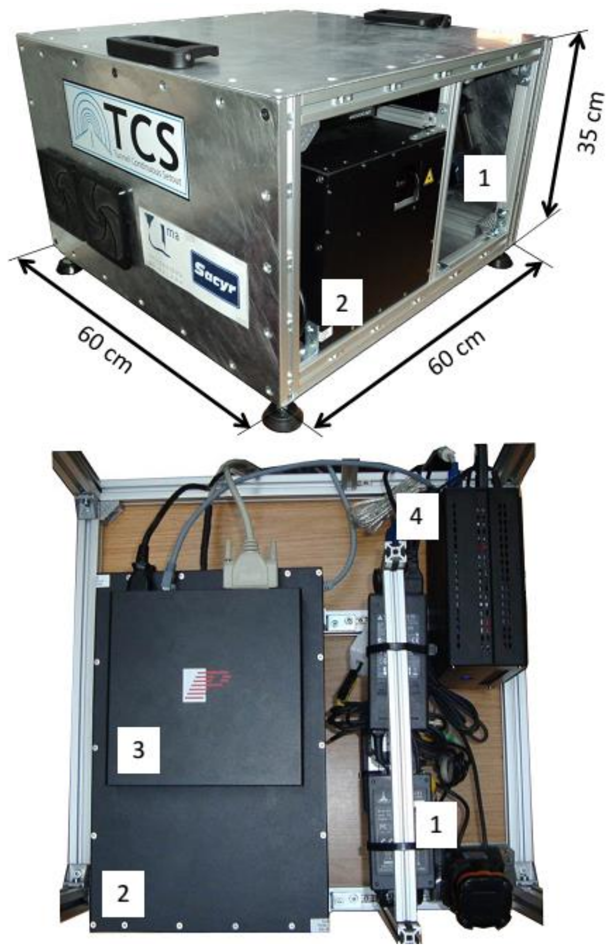


Figure 2: Prototype of the Tunnel Continuous Setout system. It is a compact box that holds (1) a 3D scanning unit, (2) a laser projector, (3) its control unit, and (4) an Intel Atom-based microcomputer.

2 RELATED WORK

Main manufacturers such as Topcon (Topcon, 2013), Leica (Leica, 2013a), or Pentax (Pentax, 2013) offer commercial robotized-total-stations capable of facilitating setout tasks for tunnel excavation by projecting the reference points with visible class 2 laser pointers. Since only one single point is projected at a time, these solutions lack of a helpful complete-view of the tunnel profile, and in many occasions, the projected laser dot on the wall may become unnoticed for the workers.

A recent solution presented by Leica and Amberg Technologies, the TMS Tunnelscan system (Amberg, 2013), introduces a noticeable innovation in this way. It incorporates a 3D scanner Leica HDS4500 (Leica, 2013b) that surveys the tunnel to analyze the advance of the tunnel and the surfaces' deformations. The collected information is used to document and record the excavation task (i.e. as-built

[2] The system has been patented (CCP: ES 2389802 B1, Date: August, 28th, 2013).

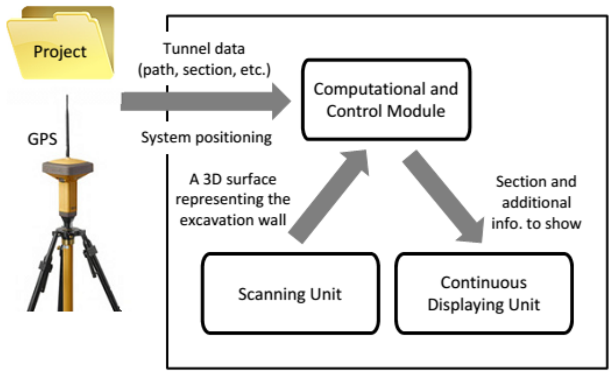


Figure 3: The TCS system. The computational and control module compares the scanning unit measurements with the project data, generating the tunnel profile, as well as additional information of interest for the workers, which will be continuously projected on the front of the excavation by means of the displaying unit.

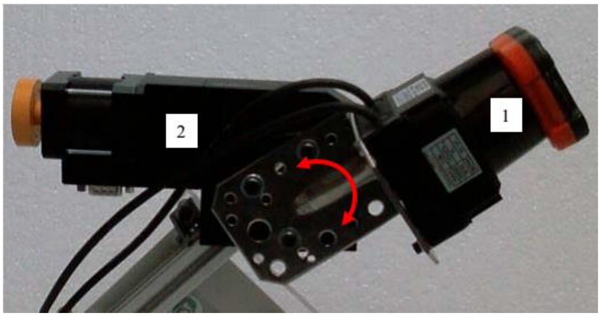


Figure 4: Scanning unit. (1) Hokuyo UTM-30LN laser rangefinder. (2) Micos DT80 rotation stage.

analysis) but not to guide the tunnel excavation (set-out) in a real time.

None of the above-mentioned systems offers a complete solution for automatizing the setout process and for continuously displaying the current section of the planned tunnel on the construction site, which are the main characteristics of the system proposed in this paper. A prototype of such system is being tested by the SACYR S.A.U. Topography department in Andalucía, Spain.

3 OVERVIEW OF THE TCS SYSTEM

The TCS system consists of three subsystems (see figure 3): the *scanning unit*, in charge of accurately surveying the current state of the excavation, the *computational and control module*, that transforms the local measurements into the global coordinate system used in the planned project and calculates the exact location of the current tunnel section, and the *continuous displaying unit* which displays the computed section by means of a laser projector. The procedure to operate with the TCS is as follows:

1. **TCS setup**, which consists of loading the planned tunnel data into the system, including the list of the georeferenced points of the tunnel route, i.e. the tunnel axis, plus its section.

2. **TCS location** in the tunnel, facing the excavation front and computing its global position. The TCS coordinate frame has to be referenced with respect to the coordinate system of the construction. This process requires solving the transformation between a set of control points expressed in both reference frames. Convenient and precise control points are selected as follows:

    (a) First, the tunnel front is scanned, getting the surface point coordinates in the TCS frame, and then a spatially distributed set of them is displayed onto the surface by the laser projector.

    (b) Then, in order to get their global coordinates, they are manually surveyed with a total station. This process, explained in detail in section 5, has to be done only when the TCS is moved forward to a new operational position. The displacement distance depends on the working range of the system (about 25 m in our prototype).

    Once the TCS is set in the global coordinate frame, subsequent scanned points are easily transformed to such reference system.

3. **TCS operation.** In a continous loop, the TCS performs the following operations:

    (a) Scans the front surface, obtainging a cloud of points.

    (b) Approximates the cloud of points by a triangular mesh.

    (c) Computes the geometrical intersection between the triangular mesh and the planned tunnel profile.

    (d) Projects such intersection on the excavation front, adding any useful textual information about the excavation work, if desired.

4 DESCRIPTION OF THE TCS COMPONENTS

Following subsections describe each component of the TCS in detail.

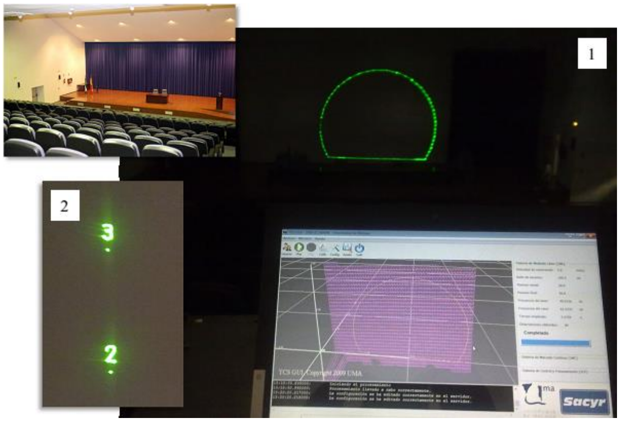


Figure 5: TCS operation example. The TCS system scans the screen of an auditorium, generates a triangular mesh from the surveyed points (see the user interface on the bottom-right of the figure), and intersects the mesh with a simulated planned tunnel. Finally, (1) the resulting profile is projected on the front. During the TCS operation, (2) any desired text can be also projected on the excavation wall.

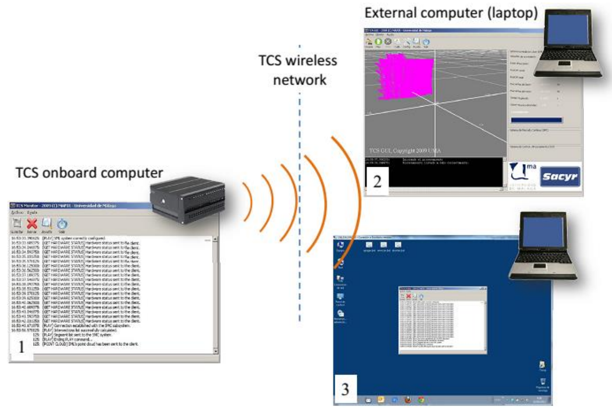


Figure 6: TCS software components. (1) Server-like monitor. (2) User graphic interface. (3) Remote desktop software. Communications between applications have been implemented over a virtual ad-hoc Wi-Fi network mounted on the onboard computer. Remote connections to the TCS system are only needed for maintenance tasks.

4.1 The Scanning Unit

The scanning unit comprises a Hokuyo UTM-30LN 2D laser rangefinder (Hokuyo, 2013) mounted on a rotating unit to accurately survey 3D surfaces (see figure 4). In this prototype a terrestrial laser scanning (TLS) unit (Park et al. 2007) was initially considered, but it was finally discarded due to its high price and difficulty to be integrated into the system (closed communication protocols, excessive size, etc.).

The Hokuyo UTM-30LN is a compact and lightweight rangefinder that scans in a plane with an angular resolution of 0.25º and a 270º field-of-view. Thus, working at the range of 25 m, the scanned points are separated ~11 cm, which gives us sufficient sampling density for our purpose. According to the manufacturer, its maximum range may reach up to 60 m. highly reflective targets and 30 m. range for non-black surfaces. At this maximum distance the specified accuracy is ±3 cm.

In order to scan a surface (i.e. to achieve a two-degree field-of-view) the Hokuyo laser scanner has been mounted on a DT80 Micos rotating unit (Micos, 2013), which can tilt it at angular increments of 0.001º (see figure 4), providing an extremely high resolution along the rotating direction (of about 0.05 cm at a distance of 25 m). Since such resolution is not really necessary, we have set it to a lower value of 0.1º, which still produces samples every 4.3 cm. at 25 m. This way, the whole scanning system delivers a point cloud with a similar spatial resolution along the two scanning axes.

This unit requires a calibration process to relate the reference systems of both the laser rangefinder and the rotation stage, which is described in detail in subsection 5.1.

4.2 The Continuous Displaying Unit

The continuous displaying unit is in charge of projecting the computed tunnel profile onto the excavation surface, as well as additional textual information under demand such as the world coordinate system, the current length of the tunnel, the kilometer point, etc. Such projection is carried out by a laser projector, similar to those employed in light shows. This kind of devices can display almost any shape at large-scale and with a high refresh rate.

A number of features have been pondered for the selection of the laser projector. On the one hand, dimensions and weight are crucial for a system that has to be transported and, most importantly, displaced within the tunnel on a regular basis. Single color projectors are then preferable since they are lighter and smaller than multi-color ones. On the other hand, the usually high laser power of this devices has to be limited to guarantee workers' safety. For this reason, a single color (green), low powered laser projector has been the choice.

More precisely, the TCS system integrates a Medium Series Green laser projector (Lasyspain, 2013) that offers high visibility and versatility to display visual data generated by a computer in real-time (see figure 2). This projector mounts a regulated 4.5 watts green laser with a low ray divergence and a long life time. It also characterized by a reasonable weight (16.5 Kg) and dimensions ($364 \times 237 \times 215$ mm). The communication between the laser projector and the computer is accomplished through an external control unit, which connects to the computer by Ethernet and to the projector itself via the ILDA standard (Laserist, 2013). Figure 5 shows an example of the shapes

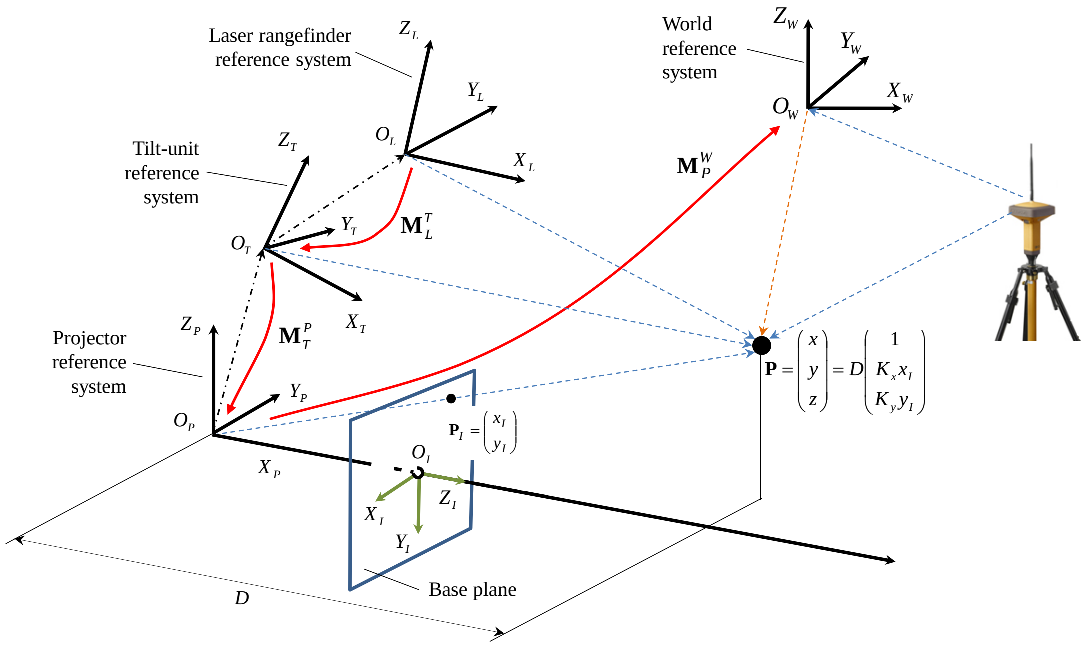


Figure 7: Different reference systems involved in the TCS system: the laser rangefinder (denoted as ’L’); the tilting unit (denoted as ’T’); the laser projector (denoted as ’P’); and the tunnel –world– (denoted as ‘W’).

and data drawn by the continuous displaying unit on a large auditorium where primary tests were made.

4.3 The Computational and Control Module

The software that manages the TCS system comprises two applications: a monitor program running on the TCS onboard computer, and a user interface running on an external computer (typically a rugged laptop) (see figure 6). The TCS monitor is a server-like application that controls the rotation stage and the laser scanner of the scanning unit and processes the gathered data as follows. First, the points are transformed to a global coordinate system and simplified by a triangular mesh. Then, it computes the intersection points between the scanned excavation front (triangular mesh) and the longitudinal point profile of the planned tunnel, as illustrated in figure 5. The resultant setout points are then transmitted to the continuous displaying unit to be projected on the tunnel front.

The laser projector is controlled through a low-level software library supplied by the manufacturer (Lasyspain, 2013), called LD2000. Upon this basic API, the TCS monitor implements some additional functionalities, including:

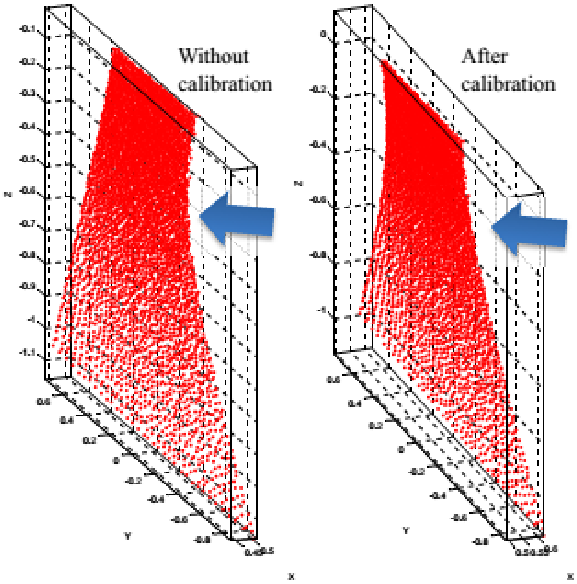
- Initialization and status query functions for the continuous displaying unit.
- Methods for displaying and deleting points, lines and text.
- Multi-image handling and animation functions.
- General displaying functions, including beam intensity regulation, sample rate configuration, etc.

On the other hand, the TCS interface runs on an external computer and communicates to the TCS monitor over a virtual ad-hoc Wi-Fi network mounted on the TCS onboard computer. This application provides the user with functionalities for visualization of the scanned data, setting up the system configuration, monitoring and controlling the components of the system, modification and saving of the system parameters, etc. The communication between both applications is implemented over TCP-IP. It is worth to mention that the remote connections between the monitor and the interface are only needed for configuration and monitoring purposes.

The software developed for the TCS is written in C++ and relies extensively on the Mobile Robot Programming Toolkit (MRPT, 2013) for geometrical operations and 3D visualization.

5 CALIBRATION OF THE TCS SUBSYSTEMS

Figure 7 shows the different coordinate frames involved in the TCS system. The scanning unit entails two reference frames: one attached to the laser scanner (denoted as ’L’) and another one at the tilting unit (denoted as ’T’), which is taken as the reference system of the overall scanning unit. On the other hand, we consider a reference system attached to the laser projector (denoted as ’P’). This section describes the



a) b)

Figure 8: Point clouds surveyed by the TCS from a wall. a) Before calibrating the scanning unit, and b) after its calibration. In the first case, because the parameters of the transformation between the laser scanner and the rotating unit are not correct, the points' cloud is not planar.

two calibration procedures carried out to determine the geometrical transformations between these reference systems, which comprise a translation vector and a rotation matrix, that is, six degrees-of-freedom. For convenience, we will make use of homogeneous coordinates and, therefore, such transformations consist of 4×4 matrices. More information on the calibration of scanning units in the context of topography can be found in (Moreno et al., 2013). The reader can also refer to (Park et al., 2015) for a similar procedure aimed to calibrate a camera-based motion capture system (MCS) and (Fernandez-Moral et al., 2015a; Fernandez-Moral et al., 2015b) for calibration of laser range finders.

5.1 Calibration of the scanning unit

The objective of this calibration is to compute the geometric transformation, $\mathbf{M}_L^T$, that transforms a 3D point in the laser rangefinder reference system, $\mathbf{P}_L = (x_L, y_L, z_L, 1)^\mathsf{T}$, into the tilting unit frame, $\mathbf{P}_T = (x_T, y_T, z_T, 1)^\mathsf{T}$, that is:

$$\mathbf{P}_T = \mathbf{M}_L^T \mathbf{P}_L \tag{1}$$

where

$$\mathbf{M}_L^T = \begin{pmatrix} \mathbf{R}_L^T & \mathbf{t}_L^T \\ \mathbf{0} & 1 \end{pmatrix} \tag{2}$$

being $\mathbf{R}_L^T$ the rotation matrix given by the composition of three rotations (r degrees in the x-axis, p degrees in the y-axis, and w degrees in the z-axis) and $\mathbf{t}_L^T$ the translation vector between the two frames.

For estimating the homogeneous transformation $\mathbf{M}_L^T$ we rely on the transformation of points scanned from a planar surface. Figure 8-a shows a points' cloud obtained while assuming $\mathbf{M}_L^T$ is the identity. We can notice that the point cloud conforms a blended surface, when it should be planar. The calibration process aims at computing the transformation that minimizes the distances of the surveyed 3D points to the 3D plane π representing the wall.

Next, we outline the procedure followed for calibrating the scanning unit:

1. The TCS is placed in front of a planar surface, as for example, a wall.

2. This surface is then surveyed with the scanning unit at pitch increments of 0.01°, yielding a cloud of 3D points $\{\mathbf{P}_{L_i} = (x_L, y_L, z_L, 1)^\mathsf{T}, i = 1,\dots,n\}$, where n is the number of pitch increments.

3. Finally, we estimate the transformation $\mathbf{M}_L^T$, which minimizes the distances of the gathered points to the plane π. This is equivalent to minimize the smallest eigenvalue λ of the covariance matrix of the points' matrix, that is:

$$\left(\underbrace{\begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix}}_{\mathbf{P}_{T_2}} \; \underbrace{\begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix}}_{\mathbf{P}_{T_1}} \; \cdots \; \underbrace{\begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix}}_{\mathbf{P}_{T_n}} \right)$$

where each 3D point $\mathbf{P}_{T_i}$ is computed from expression (1). Mathematically,

$$\hat{\mathbf{M}}_L^T = \underbrace{\arg\min}_{\mathbf{M}_L^T} \lambda \tag{3}$$

The optimization stated in equation (3) is carried out by means of the Levenberg-Marquardt algorithm (Levenberg, 1944) and using, as initial estimation of the unknown parameters, the values: $r = p = w = 0^\circ$, and $\mathbf{t}_L^T = (0,0,0)^\mathsf{T}$ m. The optimization algorithm produced the following results: $r = 1.1631^\circ$, $p = -0.0115^\circ$, $w = -0.3323^\circ$, and $\mathbf{t}_L^T = (0.1263, 0, 0.0184)^\mathsf{T}$ m, respectively.

This calibration procedure is only performed ones and in case the attachment system of the laser rangefinder to the tilting unit is modified.

5.2 Calibration of the scanning unit with respect to the laser projector

The laser projector uses a virtual image plane to define and represent the rays emanating from the laser diode (see figure 7).

This calibration consists of determining the geometric transformation that relates a 3D point, $\mathbf{P}_T = (x_T, y_T, z_T, 1)^{\mathsf{T}}$, in the scanning unit reference system with the pixel coordinates $\mathbf{P}_I = (x_I, y_I, 1)^{\mathsf{T}}$ in the image plane. This transformation is similar to the calibration matrix of a camera (Hartley & Zisserman, 2004) and results from the composition of the two following ones: the 3D transformation, $\mathbf{M}_T^P$, between the reference systems of the scanning unit and the laser projector, that is:

$$\mathbf{P}_P = \mathbf{M}_T^P \mathbf{P}_T \qquad (4)$$

and the 3D-2D projection in the reference system of the laser projector -in meters- to the image plane of the projector -in pixels-

$$\mathbf{P}_I = [\mathrm{K} \,|\, 0]\mathbf{P}_P \qquad (5)$$

where

$$\mathbf{M}_T^P = \begin{pmatrix} \mathbf{R}_T^P & \mathbf{t}_T^P \\ \mathbf{0} & 1 \end{pmatrix},$$

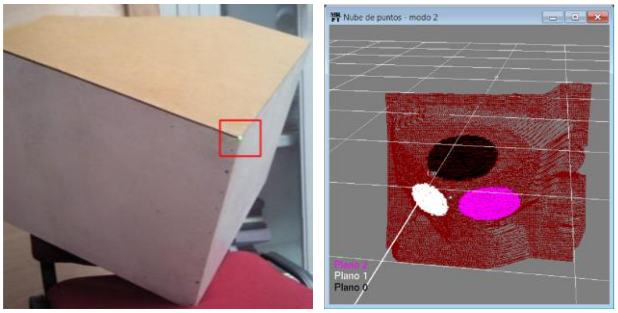
and

$$\mathbf{K} = \begin{pmatrix} 0 & -1/K_y & 0 \\ 0 & 0 & -1/K_x \\ 1 & 0 & 0 \end{pmatrix}$$

being K_x and K_y scale factors in the *x*- and *y*-axis of the image plane, respectively; $\mathbf{R}_T^P$ the composition of three rotations (*r* degrees in the *x*-axis, *p* degrees in the *y*-axis, and *w* degrees in the *z*-axis); and $\mathbf{t}_T^P$ the translation vector.

The value of the six unknowns of $\mathbf{M}_T^P$, that is, *r*, *p*, *w*, $\mathbf{t}_T^P$ and the two scale factors K_x, and K_y can be estimated from three known, non-aligned, test points. However the accuracy in the estimation of these parameters with a small set of test points is compromised, mainly due to the characteristics of the scanning sensor, and is likely far from the design requirements imposed by the company. Therefore, for gaining in robustness, a set of 50 points regularly distributed onto the image plane were selected, which we have experimentally proved that yields the desired results. A reduced number could have been also considered (at the cost of reducing the precision), albeit it is important to note that this process has to be done only once.

For collecting this points' set we employ the calibration structure shown in figure 9-a. This structure consists of three square boards joined together along their edges which itself is conforming a corner. The area of these boards is about 1 m^2, which facilitates the extraction of reliable points from the data surveyed by the scanning unit.



a) b)

Figure 9: Structure used for calibrating the scanning unit with respect to the laser projector. a) Point projected on the structure corner. b) 3D planes recovered from the point cloud surveyed by the laser measurement unit.

The procedure aimed to estimate the abovementioned parameters is as follows:

1. The calibration structure is placed in front of the TCS system.
2. The laser projector displays a point $\mathbf{P}_I = (x_I, y_I)^{\mathsf{T}}$ on the corner of the structure (see figure 9-a). This is done by manually moving the position of the point, using the keyboard arrow keys, until it hits right on the corner.
3. The scanning unit takes a scan of the pattern, providing a point cloud, which is used to extract the 3D coordinates, $\mathbf{P}_T = (x_T, y_T, z_T)^{\mathsf{T}}$, of the corner (see figure 9-b). These coordinates are obtained from the intersection of the three 3D planes that conform the structure, which are otained by a robust fitting procedure as RANSAC (Fischler & Bolles, 1981).
4. We repeat steps 1 to 3 considering new points distributed uniformly on the image plane of the projector, i.e. moving the calibration structure. In our case we consider 50 points, which suffice, in our experiments, to yield an accurate estimation of the parameters involved in this calibration.
5. Finally, once the 50 correspondences have been established, we can estimate the unknown transformation parameters by minimizing the projection errors of the selected points. Mathematically,

$$\left\{\hat{\mathbf{M}}_T^P, \hat{\mathbf{K}}\right\} = \underbrace{\arg\min}_{\left\{\mathbf{M}_T^P, \mathbf{K}\right\}} \sum_{i=1}^{n} \left\| \mathbf{P}_{I_i} - [\mathbf{K} \,|\, 0]\mathbf{M}_T^P \mathbf{P}_{T_i} \right\| \qquad (6)$$

As previously, the minimization formula stated in expression (6) is carried out by a Levenberg-Marquardt

Figure 10: Some projection patterns used in the global positioning procedure of the TCS (dotted lines are not drawn).

algorithm, using as initial estimation of the unknown parameters the values: $r = p = w = 0^\circ$, $\mathbf{t}_T^P = (0,0,0)^\mathsf{T}$, and $K_x = K_x = 1$, and converging to the following ones: $w = -2.8762^o$, $p = -4.1941^o$, $r = -1.7189^o$, $\mathbf{t}_T^P = (-0.0141, 0.1901, -0.0873)^\mathsf{T}$ m, $K_x = 8003.7489$, and $K_y = 8015.6290$.

Although this procedure is time consuming, as commented, is only accomplished once. As in the previous calibration, it must be repeated if the physical union of both the scanning unit and the laser projector, is altered.

6 SETUP OF THE TCS SYSTEM AT THE WORKING PLACE

This section describes the calibration procedure followed to correctly frame the TCS with respect to the global reference system. For that, we need to determine the geometric transformation $\mathbf{M}_P^W$ which relates the coordinates of any 3D point $\mathbf{P}$ in the TCS reference system, $\mathbf{P}_P = (x_P, y_P, z_P, 1)^\mathsf{T}$, with its coordinates in the tunnel (world) reference system, $\mathbf{P}_W = (x_W, y_W, z_W, 1)^\mathsf{T}$ (see figure 7).

The global positioning procedure is analogous to the one described in section 5.2, but with different coordinate systems. In practice, this procedure is accomplished as follows:

1. The TCS system is placed, in front of the excavation front, at an initial distance around 5-10 m obtaining a dense cloud of 3D points.

2. Then, a set of uniformly distributed points $\{\mathbf{P}_{P_i} = (x_{P_i}, y_{P_i}, z_{P_i}, 1)^\mathsf{T}, i = 1, \ldots, n\}$, from the cloud are selected and projected on the excavation wall (in our tests $n = 9$). In order to facilitate this task, the TCS software proposes three predefined patterns (see figure 11). The operator can select one of them and arbitrarily move their points to avoid certain parts of the excavation front, like deep holes, or sharp zones.

3. Once the projected pattern fits well to the wall, its points are surveyed with a total station. For precision purposes, it is recommendable that the pattern covers the whole wall.

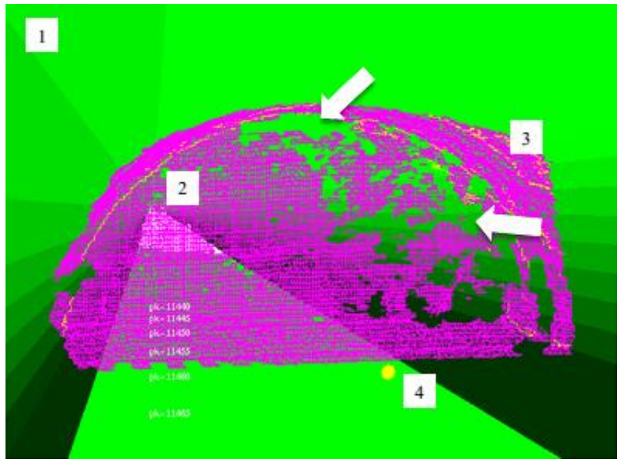


Figure 11: Snapshot of the TCS user interface. (1) Planned tunnel. (2) Mesh created from the scanned points. (3) Intersection of the planned tunnel and the mesh. The arrows point at areas where the scanned points were either lost or very noisy. (4) Position of the TCS system during the operation.

4. Finally, from the established correspondences, we obtain the geometric transformation $\mathbf{M}_P^W$ that minimizes the residues of the n projected points:

$$\left\{ \hat{\mathbf{M}}_P^W \right\} = \underbrace{\arg\min}_{\left\{\mathbf{M}_P^W\right\}} \sum_{i=1}^{n} \left\| \mathbf{P}_{W_i} - \mathbf{M}_P^W \, \mathbf{P}_{P_i} \right\| \qquad (7)$$

This procedure takes about 10 minutes and it has to be repeated each time the TCS is moved as long as the excavation goes forward. The operation distance is limited by the reflectivity of the wall material and the Hokuyo laser scanner, which, according to our tests, provides reliable measurement (±3 cm of accuracy) working up to 25 meters of distance. Thus the TCS system has to be moved when the excavation goes forward 15-20 m (depending on the initial distance considered in the step 1). Note that in this setup operation neither the length nor the profile of the tunnel are involved.

The TCS setup and the above described calibration processes are critical for the optimal operation of the system but also tedious and bored chores, so the TCS software includes *wizards* that facilitate these tasks and allow the operators to verify the accuracy of the whole procedure. Concretely, during the TCS setup, the software interface reports the residual error from the formula (7), warning the operator when it is higher than a pre-established value (5 cm in our case). In these cases the calibration process should be repeated until the error is acceptable.

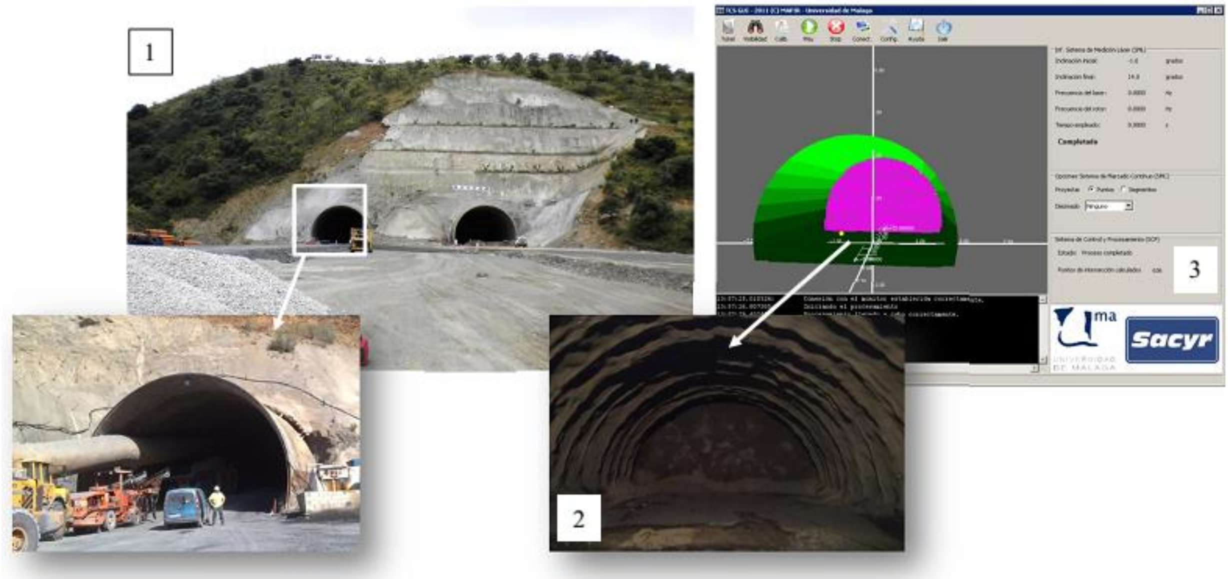


Figure 12: (1) Highway AP-46 of Las Pedrizas, Malaga (Spain). (2) Excavation wall covered with shotcrete. (3) Snapshot of the TCS user interface (intersection of the planned tunnel and the triangular mesh generated from the scanned points).

7 EXPERIMENTS

The TCS system has been tested in two tunnels under construction as well as in more controlled environments in order to evaluate both the usability of the prototype (software and hardware) , and the achieved precision by the system (including the calibrations and setup procedure). The performed tests consisted of placing the TCS system at different distances from the sensed surface (from 5 to 20 m) and evaluate its precision by measuring the residues (i.e., the projection errors) of a set of control points randomly selected by means of a total station (approximately 25 control points per trial).

The tests performed in the tunnel yielded a root mean square error (RMSE) of 0.65 cm, increasing up to 2.8 cm for distances about 25 meters (i.e., the maximum working distance). These results were confirmed by the tests carried out in the auditorium (figure 5). The RMSE obtained there were slightly lower, ranging from 0.45 cm, for a distance of 5 meters, to 2.5 cm when the system was placed at the maximum working distance. We attribute this difference to the physical properties of the sensed surface (almost plane with uniform color) in this controlled scenario.

The performance of the system was also analyzed under diverse types of surfaces: from building facades to the real tunnels, showing, in most of cases, a good behavior. Figure 10 shows, however, a snapshot of the user interface where the laser rangefinder failed in some areas. The very low reflexivity of some materials (i.e. too dark, absorbing most of the incident laser light) that occasionally we encountered at the excavation front caused noisy measurements, and even lost echoes. Certainly, this issue may limit the use of the TCS system in those cases since the triangular mesh created from very sparse scanned points are not precise enough or may even fail to cover the entire excavation front (as the case in figure 10). Notice, however, that this is not a problem of the TCS itself, but of the laser scanning technology, which may be overcome to some extend using a more powerful laser scanner.

Another possibility to cope with this issue is to reduce the working distance or artificially modifying the surface reflectivity. For the latter, a possible solution consists of spreading shotcrete[3] on the excavation front when needed (see figure 12). The time needed for covering the excavation front with shotcrete is not significant in the whole process while the reliability of the measurements is greatly improved.

Regarding the time improvement achieved by the TCS, it is difficult to quantify it mainly due to two reasons. First, the overall excavation depends on many other tasks and circumstances, not just this particular set-out operation carried out by the topography team. Secondly, the usage of the prototype was restricted to some portions of the two tunnels that the company was building in Spain (see figure 12), and unfortunately, it was not intensively used in the excavation because, as it is understandable, introducing a new operational procedure is not straightforward and entails

[3] It is worthy to mention that spreading shotcrete onto the surface is a common step after each blasting away, so it is not an additional requirement imposed by the TCS system.

some minimum training and operational adjustment of the workers in the field (not just the topographers).

In any case, we gathered feedback from two sides: the topography team (which actually promoted the project) which were really positive and keen on exploiting it as much as possible (there is a patent of this device hold by the company SACYR S.A.U.), and engineers in charge of the excavation, who mostly highlighted the gain in security, the potential for speeding up the excavation, and also the usefulness of the information (i.e. tunnel profile and auxiliary data) which was continuously projected on excavation wall.

8 CONCLUSIONS

This paper has presented a system, called TCS, which has proved to be useful for the task of guiding the tunnel perforation. The TCS system projects the complete profile of the tunnel on the work front, instead of a number of reference points, which is continuously refreshed, showing additional data if demanded, like the current kilometer point. We can stress not only the economic benefit of the system, but also the reduction of risks for the topography team, since they can operate the system from the distance.

Regarding the precision achieved by the system, the tests carried out in both controlled environments and road tunnels under construction prove the suitability of the developed system, yielding residues under 3 cm, and thus fulfilling the precision demanded by the construction company.

On other hand, it is worthy to mention that, given the priorities of the construction company, we could only test the system in some isolate portions of two tunnels, and thus, no general, quantified data was obtained. However, the experienced operators that used the prototype substantiated both the precision achieved and the convenience of its use, remarking specifically the increment in the ease of use as well as an important reduction of the excavation time.

Finally, the paper also contributes with the formulation of the calibration of the different coordinate systems involved in the whole process, which can be applied to a number of similar problems that we encounter in topography.

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