3D MODELLING OF TRAM TUNNEL FROM TLS POINT CLOUDS FOR TECHNICAL DOCUMENTATION AND EXTRACTION OF CHARACTERISTIC LINES

Mathieu KOEHL[1,*], Delphine SCHUELLER[1], Olivier BARROT[2], Samuel GUILLEMIN[1]
[1] Université de Strasbourg, CNRS, INSA Strasbourg, ICube Laboratory UMR 7357, Photogrammetry and Geomatics Group, 67000, Strasbourg, France – mathieu.koehl, delphine.schueller, samuel.guillemin@insa-strasbourg.fr
[2] Compagnie des Transports Strasbourgeois, CTS, 67000 Strasbourg, France – obarrot@cts-strasbourg.fr

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ABSTRACT:

The Strasbourg tramway has only one tunnel 1400 m long built in 1994. It grants the operation of two lines of the transportation network. It also houses the only underground station "Gare centrale" and is the only tunnel operated by the CTS (Compagnie des Transports Strasbourgeois). Due to new guidelines for georeferencing of underground networks, the CTS had to know the precise planimetric and altimetric position of the tunnel, considered as a sensitive network located in urban areas. The regulations also set the criteria for precision which for this specific case requires an accuracy of less than 40 cm. This project on behalf of and in partnership with the CTS therefore aims to set up a method allowing the 3D survey of the tunnel considering the specific constraints of urban transport networks and then to propose different 2D or 3D deliverables allowing the management of the tunnel. Initially, the project focused on extracting the shape of the tunnel characteristic lines, which corresponds to the line tangent to the points of higher altitude and the extreme points of each cross-section, along the axis of the tunnel. In a second step, a 2D plan containing all the technical elements present in the tunnel was realized, as well as a 3D modelling of a significative part of the infrastructure. A video was also derived from the point cloud to inspect the entire tunnel from different points of views. In the future, more advanced 3D models or BIM models could be considered. This would require information on the structure of the walls, the construction materials, or the links between the different elements. A project to survey and model the underground station will make it possible in the future to perfect the acquisition and knowledge of the underground infrastructures belonging to the transport company.

1. INTRODUCTION

1.1 Project context

The Strasbourg tramway has only one tunnel 1400 m long built in 1994. It grants the operation of two lines of the transportation network. It also houses the only underground station "Gare centrale" and is the only tunnel operated by the CTS (Compagnie des Transports Strasbourgeois).
Due to new guidelines for georeferencing of underground networks, the CTS had to know the precise planimetric and altimetric position of the tunnel, considered as a sensitive network located in urban areas. The regulations also set the criteria for precision which for this specific case requires an accuracy of less than 40 cm.
This project on behalf of the CTS and in partnership with the latter aims to set up a method allowing the 3D survey of the tunnel considering the specific constraints of urban transport networks and then to propose different 2D or 3D deliverables allowing the CTS to precisely position the tunnel. These deliverables consist of a precise characterization of the contours of the tunnel, a survey plan to reference all the elements present within the tunnel providing an accurate inventory of the infrastructure, a 3D model of a section opening perspectives on new modes of 3D representation.
In the first part of this paper, different types of modeling and existing automation techniques applied to tunnels will be explained. They will be analyzed to determine the method that seems most appropriate to the specific case of the survey and modelling of the CTS tunnel. Methods of automatic extraction of tunnel components such as rails, power lines will also be exposed. The principle of BIM (Building Information Modeling) applied to the tunnel and renamed to TIM (Tunnel Information Modeling) will also be developed to present this mode of representation of 3D data from tunnels.
In this project two methods were put in place for the automatic extraction of the tunnel structural lines, i.e. the extreme lines laterally and the highest line of the structure. The two methods could then be compared. For the realization of the survey plan listing the elements of the tunnel, an automatic method of transferring elements from the segmented point cloud of each element was developed. The methods used for the 3D modelling of the tunnel section will also be detailed. In addition to these achievements, other visuals, including a video presenting an overview of the tunnel as well as a route through the structure from one end to the other, were made.

1.2 State of art

Tunnels are part of the infrastructure that is attracting increasing interest in terms of 3D modeling. Indeed, to carry out a structural inspection of the structure, lasergrammetric acquisition techniques are often used. (Wang et al., 2014) describe a collection of the different geodetic surveying techniques that can be used both during the construction of a tunnel and on an already existing tunnel. This state of the art will only concern the techniques applicable to tunnels already built.
Thus, two applications of terrestrial lasergrammetry are evoked. The first is the measurement of deformation in the context of

[*] Corresponding author

tunnel inspections. Indeed, the main source of 3D modeling needs is the structural control of the tunnel. The laser scanner then replaces traditional inspection techniques which consisted of the traditional geodetic measurement of permanent control points placed along an excavation profile. A disadvantage of this method was that it did not provide an overall analysis of the deformations, but only that it showed specific deviations. Lasergrammetry allows global monitoring. In addition, this inspection technique does not require the installation of permanent control points and takes place without contact, which has no impact on the structure of the tunnel. Deformations can be easily extracted from a point cloud, especially if a reference point cloud was acquired directly after the initial construction of the tunnel or if there is theoretical modelling of the tunnel. The main disadvantage of this method of measuring deformation is that the accuracy of the points is of the same order of scale as the first detectable deformations.

The analysis of the deformations of a tunnel surveyed with a terrestrial laser scanner can be carried out by comparing two point clouds acquired at two different periods or by comparing it with a theoretical reference 3D model of the tunnel. For example, inspection maps can be produced by applying color scales to the different values of the deviations between the two entities compared.

The second application of the use of lasergrammetry in the study of tunnels is the extraction of geometries. Whether for inspection or only to map a tunnel, many operators want to know the geometries. The most common of them are cross-sections, longitudinal sections, tunnel axis, installations such as rails, pipes, cable networks. As with complete point clouds, these geometries can be compared to a reference model of the tunnel to determine the gaps between the theoretical plane and the constructed reality. Cross-sections are the subject of numerous publications as their use is so useful. Indeed, many people want to automate and simplify the extraction of these sections. This is the case of (Argüelles et al., 2013), (Kang et al., 2014), (Cheng et al., 2016), (Xu et al., 2019) or (Cao et al., 2019). In their research, (Argüelles et al., 2013) present an approach that optimizes the quality of cross-sections resulting from lasergrammetric acquisition by considering the dimensions of the tunnel, the density of the scan, the size of the laser spot size, the angle of incidence and the position of the scanner. They then expose the influence of the different parameters and advise the user on the parameters of the survey to obtain data of the best possible quality according to the configurations. Thus, in order to obtain the best results, the terrestrial laser scanner must be positioned as close as possible to the center of the tunnel so that the laser beam has the best angles of incidence. A too high angle of incidence will lead to a deterioration in the quality of the data acquired. A lasergrammetric acquisition must be carefully planned to define the most suitable parameters for the measurement of the geometry of the observed tunnel.

(Kang et al., 2014) propose an efficient method of continuous extraction of cross-sections from a point cloud. This method involves the extraction of the central axis of the tunnel using a 2D projection of the point cloud as well as an adjustment of the curvatures using the RANSAC algorithm. The sections are then made according to a predefined interval. The section plane is extracted orthogonally to the center axis for each interval. The points are obtained by intersecting a straight line that rotates around the center axis and the section plane. An interpolation using the BaySAC algorithm is performed to calculate the points of the section that could not be acquired by the scanner, especially because of the presence of masks. This interpolation is carried out from a theoretical section previously adjusted on the point cloud. The use of BaySAC algorithm is then compared to that of RANSAC and it is thus demonstrated that BaySAC provides a result much faster than RANSAC algorithm does.

(Cheng et al., 2016) propose another method of automatic section extraction. This performs a combination of 2D projection and an angle criterion to extract the points of the point cloud boundary in the X, Y plane. The extraction algorithm uses a regular grid superimposed on the projected cloud. Grid boxes with boundary points are extracted by examining whether there are points in the eight neighboring boxes. The angle criterion is then applied to the points in these boxes to determine the points of the boundary. The cutting plane is then defined as being orthogonal to one of the two boundary lines. The points in the vicinity of the plane are projected onto it to create the tunnel section. The extraction method proposed by (Cao et al., 2019) is also based on the extraction of the central axis of the tunnel to carry out the sections. The principle of extracting the points from the section is based on that proposed by (Kang et al., 2014). By adding a step to simplify the tunnel axis, this new method generates a more densified and refined section. (Xu et al., 2019) propose a robust and automatic method of section modeling that is based on the removal of isolated points and the processing of data holes that tend to alter the modeling. The robustness of the method is present in their use of the B-spline algorithm which ignore the isolated points for the calculation of the geometry of the section.

Other 3D geometries can be made based on a point cloud acquired by lasergrammetry. (Loriot, 2009) presents the different methods of 3D modeling including the mesh and texturing of the point cloud by evoking the different methods of improving the rendering. (Gikas, 2012) applies these different modelling methods to the case of a motorway tunnel being excavated in order to document the operation. More and more methods for processing data acquired by mobile laser scanner are also being developed. Indeed, for tunnels dedicated to the circulation of vehicles on rails or automobiles, it is interesting to exploit the facilities to carry out the 3D survey of the tunnel. (Zhou et al., 2017) propose a processing method for inspecting a railway tunnel from data acquired by a mobile laser scanner. Based on the extraction of the rails from a segmentation, a modeling of the alignment of the rails is carried out. From this modeling, a dynamic coordinate system is created. Sections are then extracted at a regular interval according to the local coordinates created earlier.

Upstream of the application of these modeling or extraction methods, the pre-processing of point clouds must be carried out. Pre-processing refers to cloud consolidation, georeferencing and segmentation. Although these steps may seem relatively simple, the application of these steps to a linear structure such as the tunnel can pose some difficulties, especially for consolidation. Even if many acquisitions are made without recalibration spheres, this is not possible for the case of the tunnel. Its geometry, which has many similarities from one section to another, makes the consolidation stage more difficult despite the use of recalibration spheres. For georeferencing, tunnels being underground infrastructures traditional geodetic surveying methods must be implemented in order to carry out this step. The software is also adapting to the development of the use of the laser scanner in tunnel modeling. This is particularly the case of the *3DReshaper* software which offers many functions applicable to tunnels such as the calculation of the axis, the realization of profiles or sections, etc. For inspection, comparison functions are also available such as polyline comparisons to compare several sections, or profile comparison tools. The guide published by *3DReshaper* presents many examples of how to use these functions in the case of a tunnel.

Once the tunnel envelope has been modelled, it is possible to focus on different components of a tunnel assigned to the circulation of a tram. Indeed, different elements are common to different types of tunnels. Among them, we find in the first place the rails. These are present in many tunnels, especially those used for rail transport. The need for rail modeling comes mainly from the knowledge of their deformations. The main method used for data acquisition on rails is mobile mapping system (MMS). (Lou et al., 2018), (Yang and Fang, 2014), (Elberink et al., 2013) and (Elberink and Khoshelham, 2015) all describe methods of extracting rails based on the geometry of rails from data acquired from the MMS. The first method exploits the shape, geometric properties, and intensity of reflection of the rails to detect them. This semi-automatic method quickly provides rail extraction results with 99.7% accuracy based on the tests performed. The method of (Yang and Fang, 2014) is quite close to the previous method. It also relies on the geometry and intensity of the rails to provide extraction and model the rails. (Oude Elberink et al., 2013) present a method of classifying points based on the properties of rails such as their relative height, linearity, or relative position with other objects. The modeling is then carried out by matching the points classified as "rails" with a parametric model of rail. This model is then refined using the interpolation of a Fourier curve. Interpolation parameters are used to reconstruct a mesh model of the rails. The method of (Oude Elberink and Khoshelham, 2015) makes it possible to extract the central line from the railway tracks. It consists of the detection of the points of the cloud reflected by the rails. Two approaches are then used. The first generates the points of the center line by projecting the points of a rail onto the parallel rail and taking the midpoint. The second models the rails by matching a model of two parallel rails to the point cloud. The correspondence is smoothed through Fourier series interpolation. The center line is then determined by the geometric center of the two parallel rails. However, these methods can only be used in the case of rails not embedded in the roadway. However, the tram rails present in the tunnel of the study are gauge rails (Broca type), recessed. It is therefore not possible to use similar methods of geometry detection. Rather, the rail situation involves groove detection that can be compared to fingerprint path detection explained by (Xufang et al., 2013).
Power lines that provide power to vehicles running on the rails are another important point in the modelling of tunnel elements. Again, a MMS can be used to speed up the acquisition process. (Sánchez-Rodríguez et al., 2019) and (Pastucha, 2016) present point cloud classification methods to distinguish catenaries, junction cables or structural elements. (Sánchez-Rodríguez et al., 2019) propose a method to carry out the inspection and study of the spire of the power lines of a railway tunnel. This is a first approach to define a railway network inspection methodology. This method can be divided into 3 main steps: (i) The first, as mentioned earlier, is the classification of elements. This consists, from the raw data from the MMS, to roughly classify the cloud into ground, power line, catenaries, rails, and others. This classification is facilitated thanks to the knowledge of the elements present on the test network which is the Spanish rail network. (ii) In the second step, the power line class is subdivided into contact line and suspension cable thanks to an algorithm from RANSAC and Matlab software that make it possible to determine the polynomial of degree 1 closest to the data and to compare the maximum distance between this polynomial and the points of the cloud with the known section of the contact lines. (iii) For the third stage, the portions whose maximum distance corresponds to the radius of the contact line are thus classified as such, the others as suspension cables. The method was tested on 3 tunnels of the Spanish railway network. The results obtained could be compared to the truth on the ground. They are very satisfactory with accuracy above 92% for suspension cables and more than 95% for contact cables.
Even if the method of (Pastucha, 2016) is not originally applied in a tunnel, it can be transposed for use in such infrastructures. It is also based on the high regulation and standardization of railway installations as well as on the geometry of the elements of the power lines and the relations between them, which change very little between the different study regions. This approach has several steps. (i) First, it restricts the search for catenaries relative to the distance to the trajectory of the MMS and then finds the support structures according to the density of points above the tracks. (ii) Next, the method checks for the presence of these structures and classifies the points in the cloud using a RANSAC algorithm. It determines the presence of catenaries as well as masts or structural beams depending on the type of structure detected. The method also makes it possible to determine the coordinates of the objects on the ground that have been identified. (iii) Finally, the classification is refined thanks to a modified DBSCAN (Density Based Spatial Clustering of Applications with Noise) algorithm.

In most tunnels, fire prevention devices are in place like dry columns. These pipes, like others, also need to be modeled. (Lee et al., 2013) propose a method based on pipe skeletons to recreate geometry. It is no longer limited to a portion of pipe but makes it possible to model a set of pipes including straight pipes, angled pipes and tees acquired using a laser scanner. Once the skeletons of the pipes are extracted, they can be segmented into components and the parameters of the pipes can be calculated (position and orientation of the central axis, radius). The models of each pipe can then be generated from this data. This method is easily usable in the case of acquisitions that can be made all around the pipes and even has a robustness when confronted with incomplete data. In the case of a tunnel, part of the pipes is inaccessible because it is placed against the wall. This can therefore complicate the operation of this method because too large a portion of pipes has a lack of data and therefore the calculation of parameters can be distorted. Some parts of the tunnel need to be modelled but are not necessarily part of elements common to other tunnels. Thus, the extraction of characteristic rows can be useful. In this sense, (Zhang et al., 2016) and (Ni et al., 2016) propose methods for detecting and extracting these lines. (Zhang et al., 2016) based their method on a statistical approach using a Poisson distribution as a tool for the detection and extraction of characteristic points in a point cloud. This technique makes it possible to set different thresholds according to the properties of the local surfaces. An analysis of the regions makes it possible to group the edge points as well as the corners and to acquire information on the relationships between the different characteristic elements. The characteristic lines are then reconstructed based on the geometry of the edge points by applying a search for local midpoints that are then smoothed and linked together to create the lines. (Ni et al., 2016) present a method for detecting edges and plotting characteristic lines in a 3D point cloud based on an analysis of the geometric properties of the neighborhoods of points. This method called AGPN (Analysis of Geometric Properties of Neighborhoods) includes 2 main steps: (i) edge detection by analyzing the neighborhood of each point by combining a RANSAC algorithm and angular analysis, (ii) and a characteristic line drawing step using a hybrid method based on region growth and model adjustment on edge detection.

Other methods are used to extract and model information about the structure of the tunnel. Like (Yi et al., 2019) who present a method giving the possibility of detecting the different types of voussoirs that were used to build the walls of the tunnel. They are based for this on the fact that the types of voussoirs are limited and that they are always arranged according to known patterns. The point cloud is then compared to images of the different patterns to determine which one is used. The parts composing the schematics are then modeled and then placed as in the intended order. Global methods of decomposing tunnels according to the different elements also exist. (Sánchez-Rodríguez et al., 2018) and (Cheng et al., 2019) propose methods based on point clouds from MMS surveys, applied to railway tunnels. They make it possible to isolate the different components of these tunnels. The first aims to automate the inspection of railway tunnels by providing classified data essential to the examination of structures. It is divided into three main stages: (i) the pre-treatment of the point cloud, (ii) the classification between soil and oversoil and (iii) finally the detection of the elements present in each group. The second method implemented by (Cheng et al., 2019) simplifies the creation of elements in the creation process of a BIM (Building Information Modeling) model. The first step of this method is the implementation of a classification of the tunnel point cloud to allow the identification of the different elements. Then according to the classes created the parameters of the models of each component are estimated to finally create an as built BIM model.

The development of BIM for buildings has led to the application of this system to tunnels, renaming it TIM (Tunnel Information Modeling). (Henglmüller, 2021) outlines the potential benefits of using TIM as well as its relevance. Indeed, infrastructures such as tunnels require regular checks to guarantee the good condition of the installations and thus the safety of the structure. A TIM model facilitates these control operations by listing all the elements present in the tunnel as well as providing structural information, on the materials and on the relationships between the different elements.

2. APPLIED SURVEYING METHODS

The aim of this project being the extraction of the tunnel structural lines as well as the modelling of the structure, the realization of a TLS survey quickly became obvious. We used the Faro Focus 3D X330 TLS. As the chosen device does not allow direct precise underground geolocation, it was necessary to prepare the georeferencing of the point cloud upstream of the 3D survey by the realization of a polygonal path along the tunnel attached to the GNSS at its two ends and by the installation and survey of flat targets distributed throughout the tunnel.

2.1 Geodetic survey

This survey consists of the realization of a polygonal network crossing the entire tunnel and the installation of checkerboard targets allowing the georeferencing of the TLS survey. An unavoidable constraint of the exercise lies in the fact that the tunnel is in operation and that it is therefore necessary to carry out the measurements at night, outside the operating hours of the network and in one go to allow to proceed by forced centering. During the investigation of the tunnel, four samples of checkered targets were attached in order to test their resistance to the passage of trams. Indeed, the time slots allowing to carry out the surveys being very short, it is impossible to carry out the two stages of acquisition during the same intervention. It is therefore essential to ensure that the targets can remain inside the tunnel without being moved or taken off by the many trams running during the day. The choice was made to space the stations by about a hundred meters, in order to obtain a dense network while limiting the number of stations. As the tunnel is not straight from one end to the other, but curves in places, this interval sometimes had to be reduced to allow for maintaining intervisibility between stations. 24 stations were used, two outside the tunnel at each end and 20 in the tunnel. The two stations present at each end allow for one of them the descent inside the hopper and for the other to measure on references determined by GNSS and therefore known in coordinates. 4 checkerboard targets were set near each of the 20 indoor stations. The path was observed with the Trimble S9 High Precision Tacheometer, in forced centering and by performing the measurements in double turning. The planimetric closure is of the order of 4.3 cm and altimetric closure of 2.2 cm with an angular closure of 0.0056 gon.

2.2 TLS survey

The TLS survey was carried out with the Faro Focus 3D x330 scanner. The resolution used for the scans was set to 1 point every 6 mm at 10 m and the quality was set to x3. The choice of x3 quality was made in line with the texture of the walls and the presence of pollution and dust on the walls. The scans were made with color to ultimately obtain a total scan time of 7’51”. The first TLS station was positioned at a polygonal path station in order to have optimal visibility on the four checkerboard targets measured with a tacheometer from this station. The checkerboards were used for the georeferencing of the cloud and allow to make the link between the two parts of the TLS acquisition campaign. A TLS station was carried out every 30 m. Between the different TLS stations, recalibration spheres have been positioned to allow the consolidation of point clouds between two consecutive stations. Indeed, the spheres are essential in view of the geometry of the tunnel, a linear, smooth and circular section. A cloud-to-cloud consolidation (from commonalities detected on the clouds) or by planes would not have been conclusive because of the resemblance of one scan to another. Thus, a total of sixty-seven scans had to be carried out to complete the acquisition of the tunnel (Figure 1).

Figure 1: TLS data acquisition in low lightning conditions

2.3 Point cloud processing

After acquiring the entire tunnel, it was necessary to start by processing the data.
The first step in processing is the consolidation of the point clouds. The raw point clouds extracted from the laser scanner were imported into the *Faro SCENE* software. Automatic sphere-based consolidation was performed for each portion of the tunnel acquired in one go. The difference in the detection quality of each sphere is due to a greater distance between the scanner and the target, to an angle too sharp during the

acquisition or to a too low detection of the number of pixels belonging to the target. Some scans were assembled to the consolidated group through plan and point consolidation (measured manually). The remaining scans were added one by one to the consolidated group, again by consolidation from the spheres. Several clusters, groups of scans consolidated, had to be used and then consolidated relatively to each other. Georeferencing has also made it possible to simplify the process because it has the effect of fixing the position of the checkerboards present on certain scans. This makes it possible to constrain consolidation. *Faro SCENE* software provided a RMS on the consolidated cloud of 6.8 mm. This value seems quite acceptable and consistent in view of the linear geometry of the point cloud which is conducive to error drift.
To obtain a point cloud that was easier to manipulate during modeling, a resampling was performed on the project. In order to reduce the number of points while maintaining sufficient density to allow good visualization, it was decided to keep one point every 1 cm. As a result, the initial point cloud of 2,420,635,327 points has been reduced to a cloud of only 259,130,807 points. The cloud cleanup was performed on the *CloudCompare* software. A translation had to be applied to the coordinates of the points to be able to maintain the accuracy of the initial cloud and allow a smoother use of the software.
The resampling was carried out directly on *Faro SCENE* when exporting the point clouds thanks to the Uniform Filter application. It is therefore possible to choose the value of the sampling to be applied to the exported files. The final cloud thus obtained is shown in Figure 2. It is displayed in real colors; the color scan setting having been selected during the acquisition. The color effects are due to the position and colors of the lights present inside the tunnel.

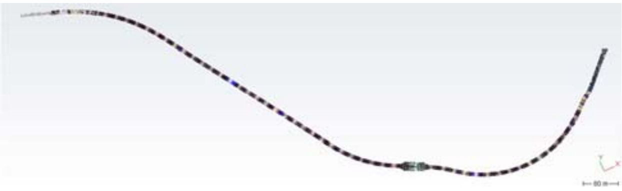

Fig. 2: Whole tunnel point cloud

Once the work of assembly, cleaning and re-sampling was completed, it was possible to model. For this project the modelling first took the form of the tunnel structural lines, which corresponds to the lines tangent to the highest altitude points and the outermost points of the tunnel, along the tunnel axis, as shown in Figure 3.

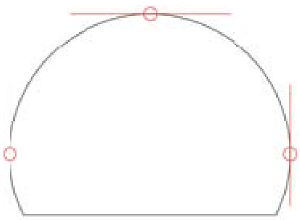

Fig. 3: Simplified section and elements of the structural lines

In a second step, a 2D plan containing all the elements present in the tunnel (fire extinguishers, lights, panels, etc.) was carried out, as well as a 3D modeling of a section of the infrastructure. The tunnel consists of different parts that must be considered separately. It consists first of a hopper which is an uncovered part, then a portion with a rectangular section followed by a long portion with a circular section. The station "Gare centrale" has a particular geometry in the middle of the tunnel. Finally, a smaller portion with a circular section is continued by a new portion with a rectangular section to finish with the exit hopper. In order to be able to model each of the parts at best, the point cloud has been subdivided into sub-clouds corresponding to each of the parts.

3. EXTRACTION OF STRUCTURAL LINES

To model the structural lines representing the planimetric footprint of the tunnel, i.e. the contours of the tunnel seen from above, two methods were defined, applied and then compared. The first uses the *3DReshaper* software and its feature contour function. The second is a Python script that allows you to directly extract the extreme points of a cross-section from a point cloud in ASCII format and an axis of the tunnel. Only this second method makes it possible to realize the structural line that corresponds to the summit tangent of the tunnel.

3.1 Contour line extraction methods

The first step is to generate a mesh of each of the portions of the point cloud after having carried out a regular re-sampling while keeping only the outer edges. In *3DReshaper*, software used for these treatments, the parameter of the average distance between the points can be changed. To determine the most suitable value for this point cloud, tests were carried out with the values 0.56 - which is the default value, 0.1 and 0.01. The mesh made with a value of 0.01 is the most faithful. It is possible to distinguish the holes allowing the assembly of the tunnel voussoirs between them. The mesh now available it is necessary to carry out a smoothing of its surface. Indeed, the objective is to obtain the contour of the mesh, but it must be as smooth as possible so that the contour also has the least possible roughness. *3DReshaper* makes it possible to smooth the noise of a mesh by choosing the intensity. The entire mesh has been smoothed by applying an intensity to smooth the assembly holes of the voussoirs. From the resulting mesh, it is possible to apply the external contour extraction function. As the goal is to obtain the planimetric position of the tunnel, it is sufficient to extract a 2D outline. It is then necessary to define the direction of projection of the point cloud which is here the Z axis because only the coordinates (X, Y) of the contour of the cloud must be preserved. The projection plane is the plane defined by the X axis and the Y axis. The software therefore produces the contour of the projected point cloud by assigning the altitude value to the contour points the value of the minimum altitude of the treated tunnel portion.
This method therefore does not make it possible to obtain the geometry of the maximum altitude line. But the *3DReshaper* software nevertheless makes it possible to extract characteristic lines. By applying this function on the portions with a rectangular section, it is possible to extract the edges between the walls and the ceiling of the tunnel. These lines are not straight because they follow the edges of the triangles of the mesh to connect the two selected vertices.

3.2 Python scripts

This method consists of writing a Python script that uses as input a cloud in ASCII format and a directional line following the tunnel. It makes it possible to extract successive sections of the point cloud in order to extract from each of them the maximum altitude point, and the two points located outermost of the tunnel, the tangency points defined above. The point clouds of the different parts of the tunnel are those that have already been worked on (assembled, cleaned and sampled). To

limit calculation times, the circular portions have been subdivided into several sections. Exports in ASCII format can be made directly from the *3DReshaper* software. The software also has a function to extract the neutral axis from a tubular shape. This axis corresponds to the line passing through the geometric centers of gravity of the sections. The function determines a first help line roughly passing through the centers of the point cloud sections. This line can then be worked to remove aberrant sections.
The neutral axis is then calculated from this line, portion by portion by selecting the appropriate type of section, namely circular or rectangular. A smoothing can also be applied to the created axis. Before launching the algorithm, it is necessary to enter a certain amount of data to the program: (i) the ASCII file containing the points of the neutral axis of the tunnel, (ii) the ASCII file of the point cloud to be processed (iii) the half thickness of a section, (iv) the verticality or not of the cross sections. The first step of the script consists of the realization of cross-sections of the tunnel. These sections are defined by normal vectors calculated from the coordinates of the points composing the neutral axis of the tunnel. A cross-section defined by a normal vector as calculated above follows the slope of the tunnel as it plunges. Figure 4 shows a vertical cross-section and conversely a a cross-section according to the slope of the tunnel.

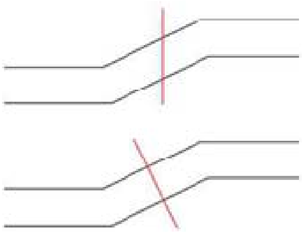

Fig. 4: Orientation of the section plane

To study the impact of choosing vertical or depending on the slope of the tunnel, both options were coded. To follow up on the first tests, it seemed interesting to add a smoothing function to the Python script to eliminate the points of the structural lines that are too far from the general trend line.

Analysis of the results: A version of the extraction of the same section was carried out by choosing the "option" vertical section in order to highlight a possible impact of the choice to make the sections vertically or according to the slope of the tunnel. To compare the results, the distance is calculated between each point in the point cloud in non-vertical section and its closest neighbor to that in vertical section. Some compared points have a significant difference. This is due to the difference in altitude of the extracted points. The planimetric deviation between two points extracted by a vertical section and its counterpart in the section orthogonal to the axis is of the order of one centimeter, depending on the inclination of the tunnel. However, this gap remains in the axis of the line. This therefore has no influence on the extracted contour. The choice is therefore made to extract sections only orthogonal to the axis of the tunnel. Once the lines of all the portions obtained and smoothed, the polylines connecting these points were created. The summit lines of the station and hopper portions are of no interest because they do not have a clearly defined summit.

Final processing of contour lines: To achieve a 3D usable result, the 3D edges of the rectangular section portion were added to the outline from the Python script. However even if the result is right in terms of position, the first visual obtained can still be worked. An additional data can be integrated on these contours, it is the thickness of the voussoirs (concrete wall of the circular parts). Indeed, this thickness is visible in certain places of the tunnel and can therefore be measured on the point cloud using the *Faro SCENE* software (Figure 5). In order to confirm the value, the thickness was measured several times at different locations. This value was therefore set at 35 cm.

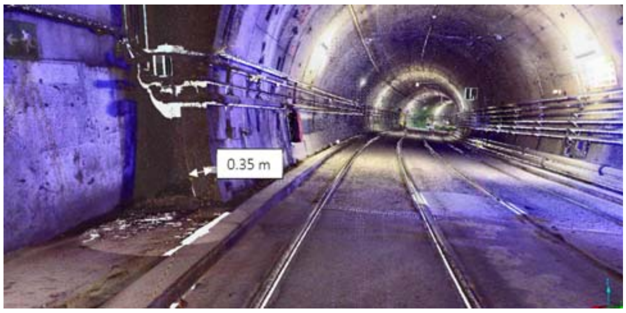

Fig. 5: View of the tunnel and measurement of the thickness of the voussoirs

4. OTHER MODELS

4.1 2D technical plan

The second modeling mode is a 2D plan. The purpose of this plan is to postpone all the elements present in the tunnel. These elements are as follows: (i) The dry column, (ii) Dry column connections, (iii) Fire extinguishers, (iv) Emergency exits, (v) Smoke detectors, (vi) Sanitation buffers, (vii) Air extractors, (viii) Emergency exits signs, (ix) Smoke detectors signs, (x) The lights, (xi) Traffic lights, (xii) Safety optical barriers (xiii) Emergency call stations, (xiv) Speed limit signs, (xv) Lighting controls, (xvi) Safety lights (rectangular), (xvii) Electrical boxes, etc. All of these elements could be placed on a plan manually, but this method is very time-consuming. The goal here was to automate the production of this plan from the tunnel's point cloud (Figure 6).

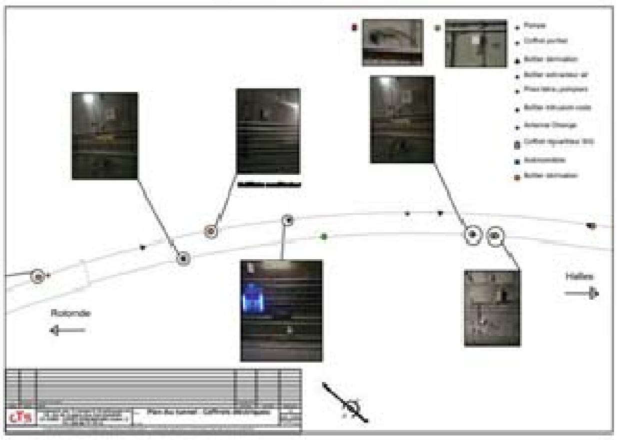

Fig. 6: 2D plan with implantation of technical units

4.2 Map of the LAC (Overhead Contact Line).

To extract the power line from the complete point cloud, it was therefore necessary to define Clipping planes for the rectangular sections. These plans make it possible to deactivate all the elements located above or below this plane and therefore to keep only the area of interest. The power line can then be segmented manually. For the sections with a circular section, the extrusion carried out for the modelling of the 3D section was extended along the entire length of the tunnel. Thanks to a segmentation according to an object, we obtain a point cloud without the tunnel wall, thus leaving the view free on the power line (Figure 7). This could be segmented manually.

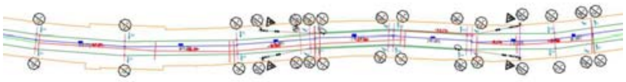

Fig. 7: Detection of area of inconsistency between the LAC of the infrastructure drawings and that of the point cloud

4.3 3D section

For the 3D modelling of a section of the tunnel with a varied panel of elements, we used the tunnel envelope. Since this 3D modeling was only to serve as a test, the different elements, segmented during the creation of the 2D plan, could then be modeled in 3D by proposing two methods: (i) a modeling faithful to reality by meshing extracts of point cloud and (ii) a schematic modeling from geometric primitives (Figure 9).

Fig. 8: Extract of 3D tunnel model

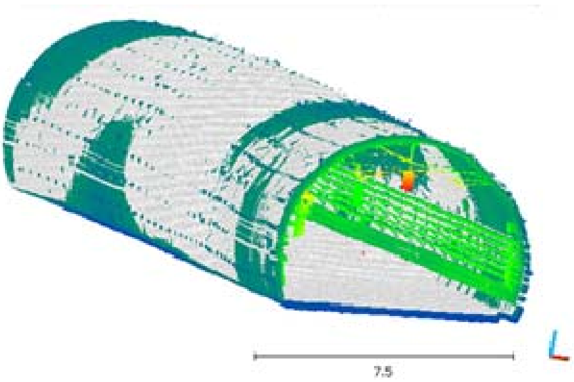

Fig. 9: Colorized point cloud of the comparison between the modeled wall and the point cloud

4.4 Rendering video

In addition to the 2D plans and the 3D section, more realistic renderings can be obtained. Video is certainly the easiest rendering format to share because, unlike modeling or point clouds, it doesn't require any specific software to play. A video can target a non-specialist audience because no technical skills are required for browsing or understanding the file. A video of the entire tunnel was therefore completed (Figure 10).

4.5 Virtual tour

Thanks to the *FARO Scene* software another viewing mode is possible. This is a tour of the tunnel's point cloud in virtual reality. Even if the realization of this virtual tour does not require major steps in terms of modifying the point cloud, it is nevertheless essential to have virtual reality equipment. To allow a person to virtually "walk" in the tunnel it is necessary to be equipped with a virtual reality headset as well as control levers.

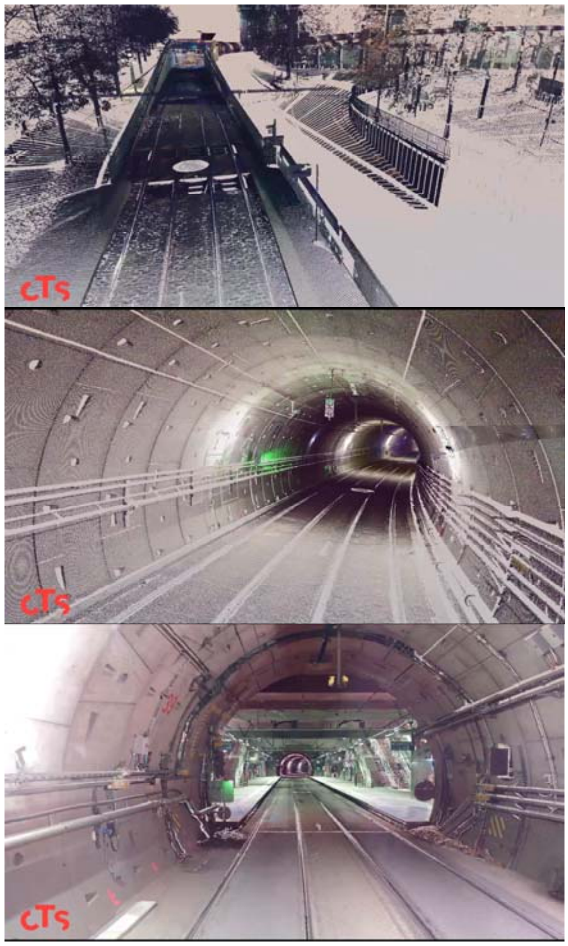

Fig. 10: Video of tunnel (a) Entering the tunnel at Rotonde station, (b) Common section of tunnel, (c) Entering the Gare centrale underground station

5. CONCLUSION

The French regulation of Environmental Code stipulates that all underground networks must be georeferenced by 2026. To comply with this regulatory framework, the CTS asked INSA Strasbourg with the problem: "Positionning and modelling the tram tunnel between Les Halles and Rotondes stations". A state-of-the-art approach has made it possible to study several existing solutions for monitoring, surveying and modelling underground structures as well as the elements composing the tunnel. This study and a reflection on the different types of renderings possible to respond to the problem of the CTS quickly highlighted that it was necessary to carry out a dense 3D survey of the tunnel, in the form of a survey with a 3D laser scanner. A methodology was therefore defined to acquire a georeferenced and accurate point cloud. Following the field measurements, the reflection focused on three main types of rendering to be proposed to the CTS. To obtain the positioning of the tunnel, it was agreed with the CTS that only the tunnel structural lines would be extracted from the point cloud at first. To do this, two methods were put into practice and compared.
The first method consisted of the use of functions of the *3DReshaper* software, which allow the extraction of the

external contours of the tunnel in the form of polylines easily integrated into a GIS software. This method turned out to be fast and offers a relatively smooth result. On the other hand, it does not allow to extract the high line of the tunnel and the external contours are not known in altimetry.

To overcome this limitation, a second method, based on the automatic realization of sections in the point cloud and then the search for characteristic extreme points in each of these sections was developed in the form of Python scripts. The tests applied in this program made it possible to extract the three-dimensional external contours as well as the summit line of the tunnel. A 2D comparison of the results obtained using the two methods revealed average deviations of the order of one millimeter.

The second project involved the creation of 2D plans inventorying the elements present in the tunnel. Starting from the acquired point cloud and segmented by elements, and after creating an adapted codification, different plans could be made. To automate this process, an algorithm has been developed to directly associate, for each extract of the point cloud concerning an element, the insertion point and the symbol corresponding to the component. The generation of the drawing could be carried out automatically, to obtain 2 plans of the tunnel presenting one the safety elements and the other the displays and lights. A plan of the power lines was also made.

For the third project, a 3D model of a section of the tunnel was created. This last modeling allowed the CTS to put a foot in the 3D with a simple model. In the future, more advanced 3D models or BIM or TIM models could be considered. This would require information on the structure of the walls, the materials that make up the tunnel or the links between the different elements.

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