# VERY HIGH-RESOLUTION 3D SURVEYING AND MODELLING EXPERIENCES IN CIVIL ENGINEERING APPLICATIONS

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**ABSTRACT:**

In this paper some experiences in 3D modelling of objects with very high-resolution are described, carried out by the DICAM Geomatics group of the University of Bologna in multi-disciplinary contexts within the field of the Civil Engineering. In all the addressed case studies the main aim is the generation of a 3D model of the surface at a sub-millimetric scale, allowing a very accurate characterization of the surface geometry, useful for different purposes. 3D scanning and Structure from Motion photogrammetry have been used to generate the 3D models. In the paper the encountered problems and the adopted solutions in data surveying and processing are underlined, also discussing the added value of very high-resolution 3D modelling in multi-disciplinary activities.

## 1. INTRODUCTION

Starting from the last decade and more and more nowadays, the modern geomatic technologies for 3D modelling are changing the scenery of the construction engineering (Muthuminal, 2020).
In the field of civil infrastructures, the availability of 3D models offers many benefits at every phase of a project lifecycle: before construction to calculate costs; to estimate the opera impact on the surrounding landscape and simulate the effects of particular weather conditions; during construction to check the work progresses and to share data and reports to external stakeholders; after construction to support the design of any possible changes and for archiving uses. The development of Building Information Modelling (BIM) encompasses all these aspects (Ullah et al., 2019).
Laser scanner systems, static or mobile, and Multi-View Structure from Motion photogrammetry, terrestrial and by UAV, have become a standard for 3D surveying of buildings, bridges, roads, etc., also in integration with each other and with other geomatics techniques (Fawzy, 2019). Point clouds and models obtained by these surveying techniques constitute the base also for restoration purposes, HBIM applications, structural monitoring, finite element analysis (Barazzetti et al., 2015; Girelli at al., 2019).
Thanks to the improvements in electronics, sensors, software and methodological approaches for data processing and interpretation, next to the classical surveys of buildings and structures, other applications with very high resolution and accuracy requirements are nowadays emerging in the field of civil engineering, specifically oriented to the three-dimensional geometrical characterization of surfaces and elements.
For these particular cases, Triangulating and Structured-Light Projection Scanners have been proven to be the most reliable and accurate instruments for the surveying phase (Wissmann, 2011, Kersten at al., 2016). The choice of the device among the ones available in the market depends on several factors: the size and complexity of the surface to be acquired, its characteristics in terms of colour, shininess and material, the dimension of the smallest details to be measured, the desired accuracy and resolution.
Digital Photogrammetry and Macro-Photogrammetry is also a surveying method that can be used for this type of applications, especially where the characteristics of the surface to be surveyed, or the particular situation, make it impossible the use of scanning devices (Fraser 2013, Luhmann, 2010, Yanagi & Chikatsu, 2010).
In this paper some experiences in 3D surveying and modelling of objects with very high-resolution are described, carried out by the DICAM Geomatics group of the University of Bologna in multi-disciplinary contexts.
In all the addressed case studies the main aim is the generation of a three-dimensional model of the surface of objects in the field of Civil Engineering. These 3D models allow a very accurate characterization of the surface geometry at a sub-millimetric scale and are useful for different purposes, showing how the very-high resolution 3D modelling can open up new applications in different fields. The single elaborations and the used software, or the parameters adopted in the processing, will not be described in detail, the attention is in fact focused on the different applications.

## 2. APPLICATIONS FOR TRASPORTATION INFRASTRUCTURES

In collaboration with the Roads, Railways and Airports group of DICAM Dept., the use of high precision 3D surveying techniques has been tested to obtain some three-dimensional descriptive parameters of the asphalt texture, in this way expanding the range of the indicators used for its characterization (Bitelli et al., 2012).
In particular, the studies have been focused on the macro-texture indicators, related to the inter-granular roughness, essentially depending on the mixture composition and the type

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of paving. The macro-texture of the pavement plays in fact a fundamental role in the drainage and in safety when the vehicles go at high speed.
Current legislation defines the profilometer as measuring instrument for determining geometric asphalt indicators; the 2D information associated to individual profiles, however, have the disadvantage of a low representativeness of the geometry. The availability of an accurate 3D model opens up to the possibility to extract "volumetric" indicators descriptive of the entire 3D surface of the asphalt, also extending the range of parameters of interest in this type of applications. This approach can provide greater reliability, coherence and representativeness.
To this aim the efficacy of different surveying techniques (Triangulating Laser Scanning, Structured-Light Projection Scanning and Digital Photogrammetry) has been tested, and different approaches for the extraction of the indicators have been experimented. The activity has been performed on various types of asphalt, both *in situ* and on specimens in laboratory (Figure 1 and Figure 2).

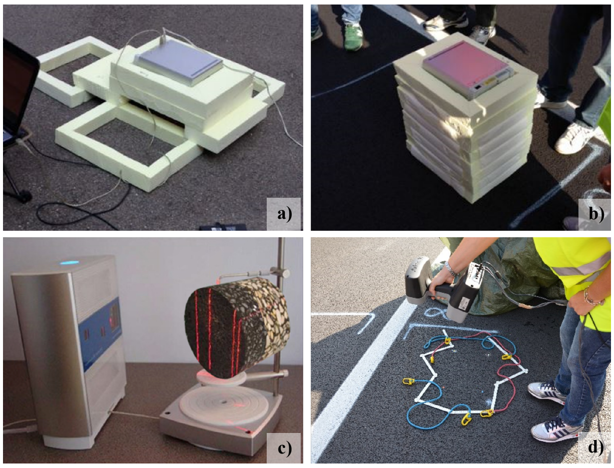


**Figure 1.** Some examples of asphalt surface surveying by different scanner systems: a) and b) Triangulation Laser Scanner used *in situ*, with an *ad hoc* equipment to put the instrument horizontal at the correct working distance (on the left macro mode; on the right wide mode, see Table 1); c) the same instrument used on a specimen in laboratory; d) Structured-Light Projection Scanning.

Table 1 shows the specifications of the used instruments as declared by the producers.

| Name | Next Engine | | Artec MHT |
|---|---|---|---|
| **Technology** | Multi-Stripe Triangulation Laser Scanner | | Structured-Light Projection Scanner |
| | Macro mode | Wide mode | |
| **Accuracy** | 0.127 mm | 0.381 mm | 0.1 mm |
| **Resolution** | 200 dpi | 75 dpi | 130 dpi |
| **Field of View** | 13×10 cm | 35×25 cm | 54×37 cm |
| **Working range** | 12-23 cm | 35-56 cm | 40-100 cm |
| **Acquisition speed** | 50000 points/sec | | 288000 points/sec |

**Table 1.** Instruments specifications.

As regards the photogrammetric survey, a compact Panasonic Lumix DMC-TZ60 camera was used, acquiring for each test a set of images characterized by high redundancy from a distance of about 50 cm, resulting in a 1:100 photo scale (Figure 2).
The list of indicators and the calculation method are analysed in Bitelli et al., 2012. In this context we want to highlight some aspects related to the acquisition and processing of data and also to show further investigation possibilities offered by 3D modelling.

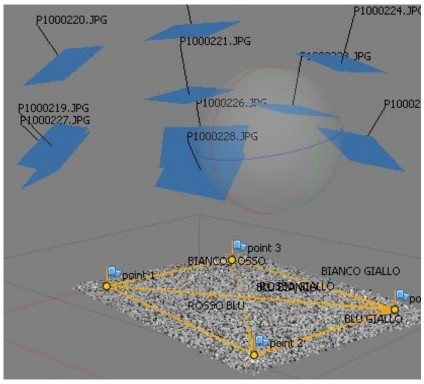


**Figure 2.** Photogrammetric *in situ* survey of an asphalt area.

To choose the best surveying techniques for this application, many tests and comparisons were performed.
For a road area test identified *in situ*, a 3D model was obtained by each technique (Figure 3).

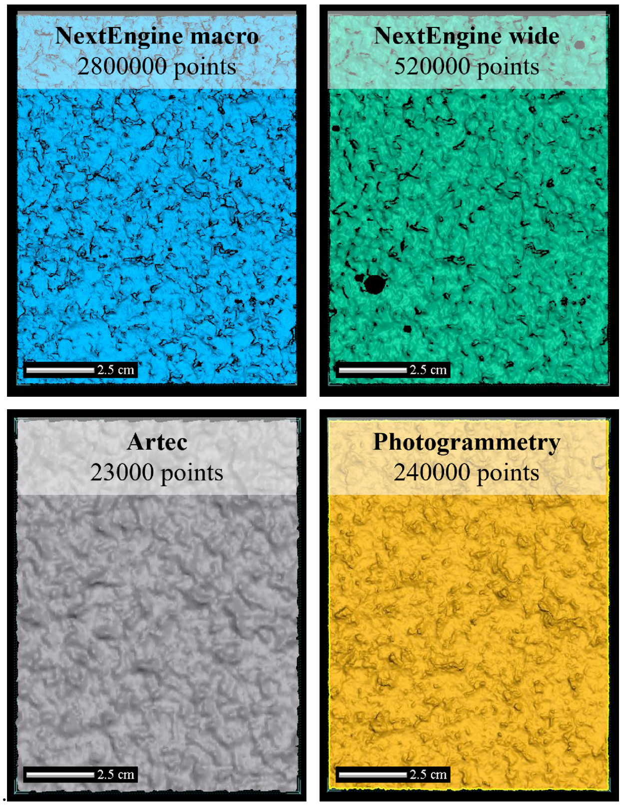


**Figure 3.** 3D models of the same asphalt area acquired *in situ* experimenting different surveying techniques.

Already at the surveying stage, the Structured-Light Projection Scanner used in that experience showed considerable problems, probably because of the material and colour characteristics of asphalts, acquiring surfaces with a low resolution and many holes, difficult to process.
All generated 3D models were then compared with the model obtained from the laser triangulator in macro mode, as the most detailed and complete.
In addition, 2D and 3D indicators were extracted: the first by profiles obtained sectioning each 3D model following the same procedure used for data by profilometer, the second applying the new volumetric indicators on the entire area of each 3D model, as described in Bitelli et al., 2012.
Then the indicators were compared with each other and with those derived from the classic experimental tests, such as for example the sand equivalent test for the determination of the roughness.
The comparisons highlighted the greater effectiveness of the triangulation laser scanning in this particular application.
The 3D model by Photogrammetry was characterized by a lower resolution and a smoothing surface compared to that obtained by Laser Scanner, with effects on the numerical values of the indicators, although 86% of the points are within the accepted tolerance, evaluated equal to 0.5 mm on the basis of the estimated accuracy for the photogrammetric survey. (Figure 4).
As regards the two acquisition modalities of NextEngine laser scanner, obviously the macro mode allowed to obtain an extremely detailed 3D model, but requiring many partial surveys of small areas, extending the processing times and the risk of a residual alignment error in the data. Wide mode permits *de facto* the immediate survey of the surface, that is an aspect very important for the analysis *in situ*, with an accuracy however adequate for this application.

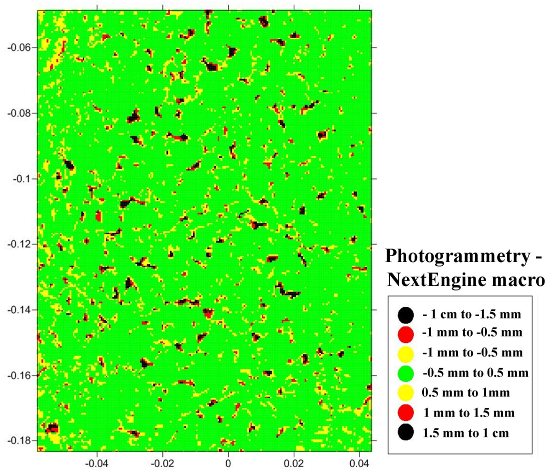


**Figure 4.** Quantitative comparison between the 3D models of the same asphalt area obtained by Laser Scanner survey (macro mode) and by Photogrammetry. The values demonstrate that in this test the photogrammetric approach induced a smoothing effect on the “peaks and valleys” of the surface; green points are within the accepted tolerance.

The possibility offered by the described techniques to repeat at different epochs the survey of the surface morphology permits the monitoring of degradation phenomena, for example comparing the indicators extracted *in situ* in the same test area at different epochs. In this case it is crucial the establishment of the same reference system for all the repeated survey, for example using stable markers ad hoc located in the area.
The data processing was oriented to the search for almost totally automatic procedures in the extraction of indicators from the 3D models, minimizing operator intervention. The process followed in these experiences are similar to those used in GIS in the calculation of geomorphological parameters. Two examples are shown in Figure 5: the peaks and valleys automatically extracted in the same area test of Figure 3, useful for the determination of some volumetric indicators, and a flood simulation on a specimen, by calculating the percentage area of asphalt that emerges for a certain volume of stored water (Bitelli et al., 2010).

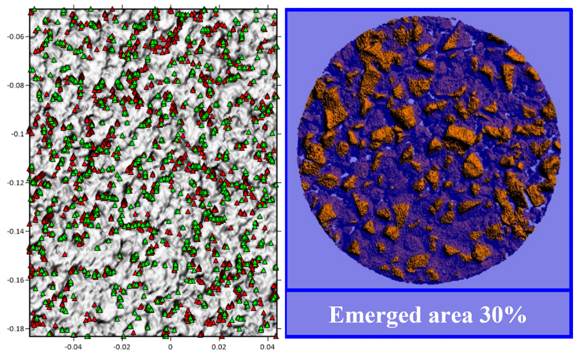


**Figure 5.** Examples of the analysis on the 3D models of an asphalt specimen: on the left, peaks (in red) and valleys (in green) automatically extracted for the determination of texture indicators; on the right, flood simulation on a specimen to calculate the emerged area (right image).

Still in the context of the road pavements analysis, the use of Structure from Motion in combination with Structured-Light Projection scanner has been recently tested by the same research group to evaluate the effects on the asphalt performances of external events that could cause its degradation.
The experimentation is based on the comparison of the asphalt specimen’s characteristics before and after the events. Alongside classic experimental tests such as skid resistance and British Pendulum tests, the procedure provides the comparison f 3D models generated by means of Structure from Motion photogrammetric surveys carried out at different epochs (Figure 6).

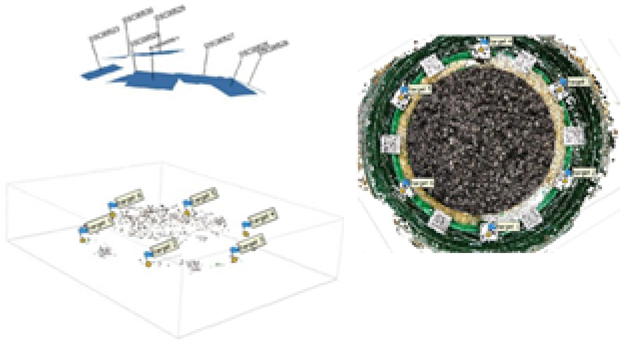

**Figure 6.** Photogrammetric survey of the surface of an asphalt specimen: on the left images acquisition scheme; on the right an example of the obtained dense point cloud (about 20 million points).

## 3. APPLICATIONS FOR STRUCTURES AND MATERIALS ENGINEERING

The characterization and assessment performance of masonry materials are very important in construction sector. Different experiences of sub-millimetric high-resolution geomatic surveys were carried out in collaboration with the colleagues of Structural Engineering and Materials Engineering.

High-resolution scanning for surface monitoring in the field of masonry materials was firstly performed. In particular, it was related to the evaluation of superficial deterioration in brick walls exposed outdoor to weathering and simulating moisture and salt capillary (Bitelli et al., 2015).

The proposed procedure, realized through repeated surveys over time by the triangulation laser scanner NextEngine and the consequent comparison of the obtained 3D models, successfully permitted to extract quantitative information about the material spalling and the surface smoothing.

The survey was performed during the night or protecting the work area with curtains, to avoid negative effects of the sunlight on the acquired data. These are as for example a poor RGB texture and a noisy surface, because of a reduced contrast between the laser line and the background colour of the surface (Figure 7).

**Figure 7**. A phase of survey by triangulation laser scanner

Two vertical areas, respectively on the front and back wall surface, were surveyed in 2010 and 2011 (Figure 8).

Regarding the problems of this kind of test, where the object is essentially almost plane and elongated in one direction, it is necessary to pay close attention to the alignment phase between the many acquired scans, in order not to degrade the final data with residual alignment errors that can lead to incorrect interpretations of the investigated phenomena.

The obtained photo-textured 3D models were compared in different ways. A visual comparison was performed by analysing products as shaded relief maps of the surfaces and orthophotos derived by the RGB images acquired by laser contextually to the metric survey, to identify those areas most affected by degradation phenomena. A comparison of the profiles obtained sectioning the generated surfaces at the two epochs produced maps showing the differences between the two surfaces, to recognise areas with apparent material gain and loss.

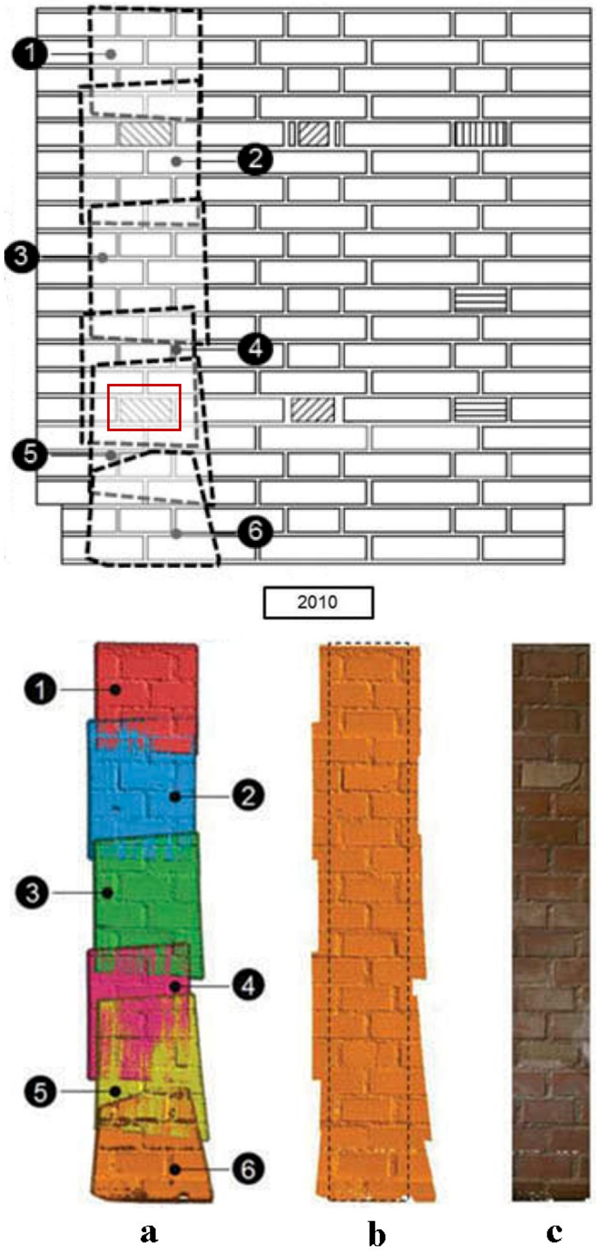


**Figure 8.** On the top: footprints of the scans necessary to survey the front wall area in 2010 (in red the detail shown in Figure 8); on the bottom (a) the aligned scans, (b) the merged mesh and (c) the photo-textured 3D model (Bitelli et al., 2015).

In Figure 9 are shown some examples related to the brick indicated by the red rectangle in Figure 8.

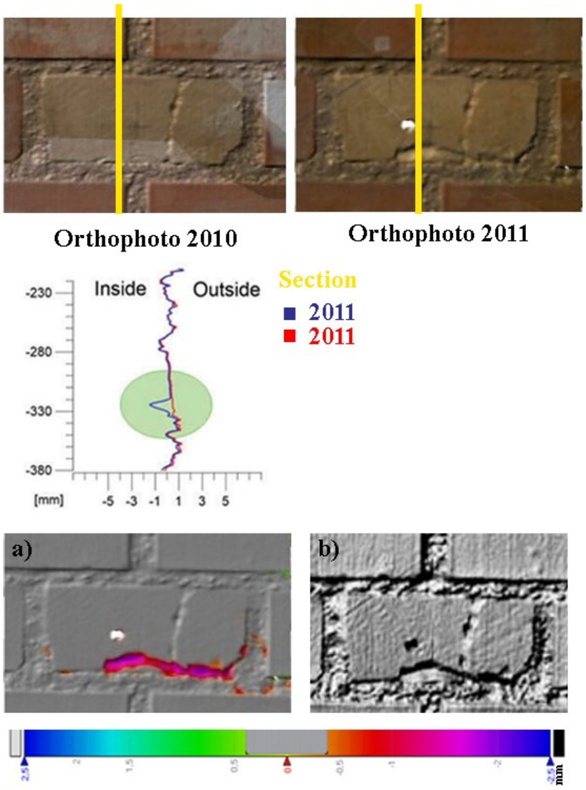


**Figure 9.** Examples of products derived by triangulation laser data useful for the analysis of wall degradation. From the top: orthophotos and profiles of 2010 and 2011 obtained sectioning the 3D models along the direction drawn in yellow. Images below: a) displacement map [mm]; b) shaded relief map of the 2011 surface, with applied a 7.5 × depth magnification factor (modified by Bitelli et al., 2015).

Another more recent example regarded the geometrical characterization of 3D printed steel elements.
The use of CAD/CAM solutions, despite the growth in recent years in many production sectors, remains pioneering in building construction industry. In 2021 the first 3D-printed pedestrian bridge was inaugurated in Amsterdam. It is 12 m long and realized of stainless steel with the so-called Wire and Arc Additive Manufacturing (WAAM) technology by the Dutch company MX3D (www.mx3d.com).
In the research, necessary to fully exploit the potential of this technology, one of the fundamental phases is - together with the mechanical and microstructural ones - the geometrical characterization of the construction elements, usually characterized by very irregular surfaces (Laghi et al., 2020).
The use of 3D scanning can nowadays meet this need and provides data indispensable to assess the geometrical properties of these elements.
Here the case study of one tubular specimen is presented. The Structured-Light Projection scanner Artec Spider was used to acquire the external surface of the tube (Figure 10).
The characteristics of this instrument are the following: acquisition speed of 1 million points/sec, resolution of 100 points/mm$^2$, accuracy of 0.05 mm, field size of 90x70 mm and a working distance of 25 cm.

**Figure 10.** a) Circular tubular elements realized with the WAAM technology; b) 3D scanning of one specimen (Laghi et al., 2020).

Twelve scans were necessary to acquire the entire outer surface. The obtained 3D model consists of around 40 million of triangular elements, with an average size of about 0.1 mm.
This model has been processed and analysed to obtain the geometric characterization of the surface irregularities and of the global geometrical imperfections, also comparing the 3D model of the "real" object with the "ideal" designed tube (Figure 11).

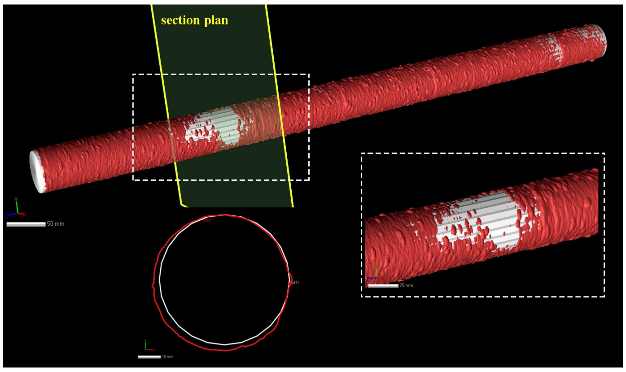


**Figure 11.** 3D model of the tubular specimen, in red, and in white the ideal design cylinder, with a transversal section shown below; in the dashed rectangle a detail of the two surfaces.

Many investigations were performed on the 3D model in order to obtain a detailed characterization of the external surface.
First of all, 40 transversal sections of the tube were extracted and analysed, to find the mean and standard deviation of the diameter along the tubular element and to calculate its relative error with respect to the design model, resulted equal to 2.76%.
Through the sections, the roughness of the surface was calculated, resulting in a non-uniform behaviour both along the length of the element and along the cross-section at each section plane, with an average value of 0.75 mm calculated as the discrepancy between the average value of radius obtained from 3D model and the design model.
Then the centres of each section were plotted to evaluate the lack of straightness of the longitudinal axis of the tube (Figure 12).

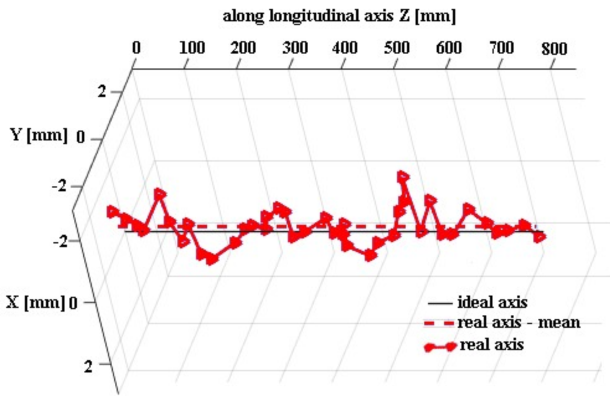


**Figure 12**. Study of straightness of longitudinal axis of the tubular elements (modified by Laghi et al., 2020).

## 4. CONCLUSIONS

Some works conducted in recent years by authors and colleagues from other scientific areas were presented, which show how in various fields of Civil Engineering the use of digital 3D data in very high (sub-millimetric) resolution is becoming increasingly important.
The purpose of the work was above all to show the opportunities and potential of Geomatics in multidisciplinary applications in this area, which can undoubtedly be considered very interesting and promising
The continuous technological evolution of instrumentation - both hardware and software - makes it difficult to state which solutions are absolutely the most appropriate in the different cases, and some of the examples reported, even if made in recent years, could today be faced also with other tools. However, acquisition and processing technologies can be definitely considered mature for every wider adoption, using single or integrated different approaches.

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