Displacement and surface pathology monitoring of former Tejo Power Station building by combining terrestrial laser scanning, micro-geodesy, photogrammetry and GIS

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Abstract

The old Tejo Power Station (known as Central Tejo) is a very good example of industrial and architectural heritage from the first half of the 20th century, comprising an impressive iron structure covered in brick. Its production ended in 1972 and in 1986 it was classified as an Asset of Public Interest due to its Industrial Archaeological heritage importance. More recently it was renovated and integrated on the new *Campus Fundação EDP* as the Electricity Museum, in Belém neighbourhood, Lisbon. In 2010, EDP foundation decided to build a modern piece of architecture, the new Museum of Art, Architecture and Technology, (MAAT), just on the adjacent east side of the Electricity Museum.

Heritage buildings can be severely affected by nearby construction works and in the case of the Tejo Power Station, structural monitoring is paramount. During the construction of the new MAAT Museum, the nearby Tejo Power Station's buildings required an adequate monitoring system that could both estimate spatial displacements and map the evolution of other type of deteriorations.

This paper describes a combined monitoring system for the Tejo Power Station buildings, including terrestrial laser scanning, micro-geodesy, photogrammetry and GIS technologies. This system accomplishes on the one hand for a detailed characterization of the geometric changes and on the other hand allows for the mapping of the pathology on a spatial database along specific dates, thus from an evolutive point of view. In conclusion, an innovative monitoring system of a heritage building complex is presented, allowing for an integrated analysis of the different events that affect the structure under study, along its lifespan.

Key words: Terrestrial laser scanning, photogrammetry, geographic information system, deformation monitoring, structural monitoring, assisted visual inspection, heritage building

1 INTRODUCTION

Built heritage or architectural heritage conventional preservation activities includes specific types of intervention measures, such as maintenance; repair and stabilization; rehabilitation and modernization; reconstruction and relocation (Petzet, M. 2004). When external phenomena (e.g. construction works nearby, excessive traffic in nearby roads or railways or natural erosion) can influence the stability or the integrity of a heritage building, the establishment of a monitoring tool is paramount. On the one hand deformation monitoring is needed to assess spatial displacements that can put to risk the stability of the building and on the other hand visual inspection is needed to detect surface pathologies and monitor its evolutions.

The old Tejo Power Station (known as Central Tejo) was classified in 1986 as an Asset of Public Interest due to its Industrial Archaeological heritage importance. It is composed of a cluster of buildings with an impressive iron structure covered in brick, from the first half of the 20th century, located in Belém, Lisbon. Its main building has walls as high as 28 m. At the south side, Central Tejo is limited by the Tagus River and at north side by an important road and railway that links to the city centre, both with high traffic. At the east side, EDP foundation decided to build a modern piece of architecture, the new Museum of Art, Architecture and Technology, (MAAT). Due to the proximity of the construction works of the MAAT Museum, the nearby Central Tejo's buildings required a monitoring system that could estimate spatial displacements and detect other type of deteriorations caused by these works. On the other hand, because of maintenance and repairing interventions in the walls surface, a tool to identify, quantify and map the façade pathologies evolution was need. To address the requirements specified above, an innovative monitoring system for heritage buildings, combining different technologies, was stablished, aiming an integrated analysis of the different events that affect the structure under study, along its lifespan. Between 2013 and 2017, 5 monitoring campaigns were made (C0 to C4).

Traditional monitoring, using micro-geodesy and levelling methods, were used, initially to observe and adjust a reference network, and afterwards for the determination of displacements at different epochs of object points strategically located, representative of the geometric behaviour of the buildings and materialized by targets. Laser scanning technology was used aiming for a high-density geometric monitoring of the building walls, thus providing accurate surface models that can be considered continuous, in practical terms. The 3D point clouds of each epoch were compared to the reference epoch ones, and displacement maps were produced, thus providing a more dense and detailed information about the structure behaviour. Photogrammetry was applied to obtain high resolution orthoimages of the building walls. The photogrammetric coverage used a digital camera mounted and calibrated to the laser scanning system, providing directly referenced images. The derived orthoimages were inserted on a Geographic Information System as a base map. Other attributes were associated to each vector representing specific pathologies and organized on a spatial database. In this way, an assisted visual inspection spatial information system for façade pathologies was created. The application allows, for instance, to spatially record any visible anomaly detected on the building façade, to classify it within predefined attributes and to produce analysis of pathology evolution within time.

2 GEODETIC MONITORING

2.1 REFERENCE NETWORK

A monitoring surveying reference network was established to allow for the determination of displacements at different epochs of object points strategically located, representative of the geometric behaviour of the buildings during the construction of MAAT and materialized by targets.

The horizontal reference network was composed by 7 reference stations (E1, E2, E3, ER1, ER2, ER3, ER4) and 22 fixed target points (P1 to P22), strategically located on the buildings façades (Figure 1). The target points were observed from the reference stations with a total station (linear accuracy: ±(0.6mm+1 ppm); angular accuracy: ±0.5”) and a network adjustment was carried out using the program *Epoch Suite*. Accurate coordinates were determined for the whole network for the Reference Campaign with an overall network accuracy better than 2 mm. The vertical reference network was composed by 9 levelling references (N1 to N9) established on the same concrete bases of the horizontal reference stations marks and 20 levelling marks, strategically located on the buildings façades. The levelling observations were made with a digital level (height accuracy: ±0.3mm/km). The accuracy of the levelling network is accomplished at 0.3mm using the appropriated technical procedures and methodologies, as well as the adequate equipment.

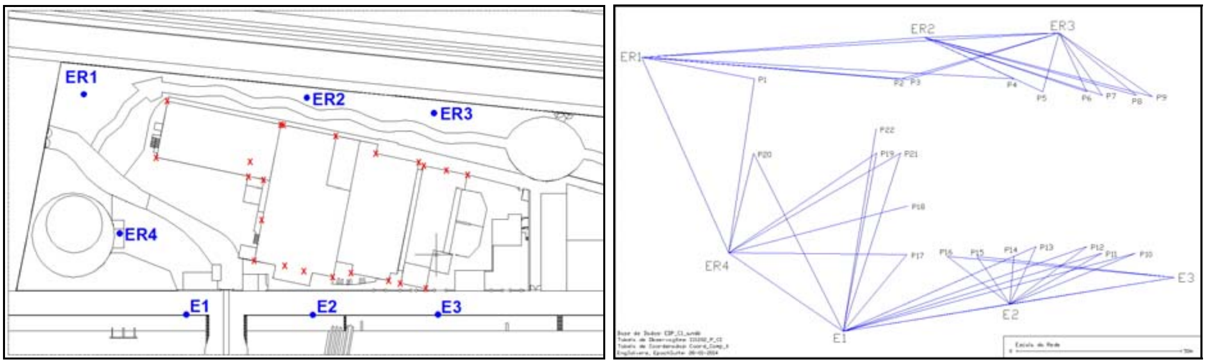


Fig. 1 - Reference Network plan (left) and horizontal observations (right)

2.2 MONITORING OBSERVATIONS

Between 2013 and 2017, besides the reference campaign (C0), another 4 observation campaigns were made (C1 to C4). The same procedures were followed for every campaign. Due to the proximity, at the north side, of a road and railway with excessive traffic during the day, that could influence the stability of the reference stations nearby, all observations were made at night, when the traffic was inexistent or much reduced.

The total station was set up in each of the seven reference stations and all visible points (object targets or reference targets) were observed. For the 22 observed points only 2 were observed from one single station, all others had redundant observations. These data were processed by *Epoch Suite* software to adjust the network, based on the observations. The results were displacements values and error ellipses for each target in relation to the reference network. Some external factors, as earth movements nearby one of the reference station or manual movement on a point target for other purposes besides the monitoring, deteriorated the network and observation conditions from the initial campaign to the last one. Excluding the influence of these factors the displacement vectors were determined with an associated estimated standard deviation of less than 2.5 mm, for the 2 points observed from a single station, and with an associated estimated standard deviation of less than 1.6 mm for all the other 20 points.

3 TERRESTRIAL LASER SCANNING - DEFORMATION MONITORING

Terrestrial Laser Scanning provides high density 3D point cloud, which for almost every survey applications might be considered continuous. Spatially continuous deformation monitoring can therefore be applied, allowing for a more complete analysis of the deformation and of its nature. The TLS system used for this task was a Riegl VZ400, for which the main technical specifications can be seen in Table 1.

Table 1

Terrestrial Laser scanner	**Specifications**
Riegl VZ-400	Range up to 600 m @ Laser Class 1; Repeatability 3 mm; Rate up to 122000 measurements/sec; Field of View up to 100º x 360º

Aiming to analyze the Central Tejo building walls possible deformations between campaigns, the TLS was set up in each of the seven reference stations of the reference network and 3D geometric data were acquired. The parametrization of data acquisition allowed obtaining a point density on the walls better than 2 cm (variable between 0.8 cm and 2 cm). Target points used for the geodetic monitoring were covered in retroreflector material so it could be also scanned. Due to the same traffic constraints described for the geodetic monitoring, the TLS survey was made at night, guaranteeing the minimization of the instability effects on the reference stations at north.

To minimize the influences of the uncertainties associated to global registration between all the point clouds, it was decided to analyse independently the data provided by each reference station in one campaign against the data provided by the same reference station on the initial campaign, C0. So, for each campaign C#, where # varies from 1 to the number of campaigns, each reference station E(i), where (i) varies from 1 to 7, is compared to E(i)C0. Indirect referencing, based on retro-reflectors, and shape matching techniques combined, were used to register the acquired point clouds. To allow for a spatially continuous surface comparison it was necessary to create a reference 3D mesh for every E(i) from C0. The comparison was then made along the surface normal, which includes the point to be compared. In past works theoretical accuracies were estimated along several data processing phases (concatenation of point clouds and surface matching) and have shown that point uncertainty can be better than 5 mm and surface uncertainty better than 3mm (Berberan, A. et al 2012). In the present work, equivalent procedures for the estimation of theoretical accuracies confirmed the results of the previous works. In addition, the displacements results were interpreted and compared to the ones obtained from the geodetic observations, having showing coherence within the same order of magnitude.

By using this methodology for each campaign, the point cloud acquired for each reference station was compared to its correspondent in the reference campaign. The differences for each point could be mapped with a RGB value from a color scale. The resulting image is a displacement map that can be exported and analyzed for the interpretation of the nature of the displacement along the entire wall surface and not only in a discrete set of points representing it.

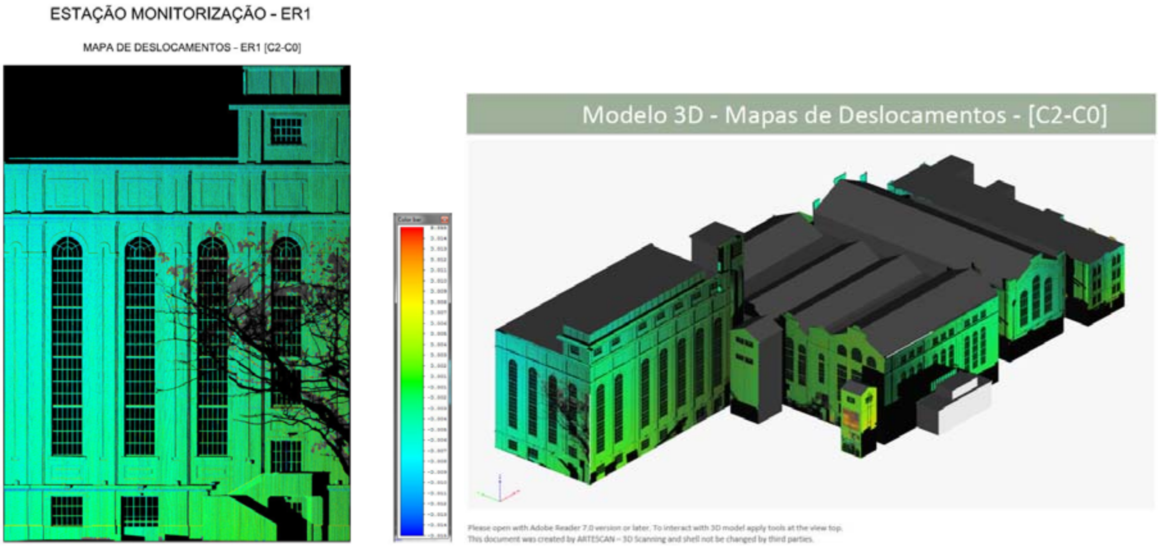


Fig. 2 - Displacement Map (left) and 3D Model of Displacement Maps (right)

4 TERRESTRIAL LASER SCANNING AND DIGITAL PHOTOGRAMMETRY – 3D AND IMAGE SURVEY

A complete TLS survey and photogrammetric coverage was accomplished aiming to provide high density 3D data and imagery of the whole buildings complex. The acquired and processed data was used for record purposes and to support assisted visual inspection.

The laser scanning and photogrammetric system used was a Riegl VZ400 combined with a Nikon D300, for which the main technical specifications can be seen in Table 2. Both sensors are calibrated, so the system provides, besides 3D point clouds, oriented images.

Table 2	
DSLR Camera	**Specifications**
Photographic cameras Nikon D300 and D50	12.3 Million (Effective pixels); 23.6 x 15.8 mm CMOS sensor; 4288 x 2848 Pixels; 5.5 µm (Pixel size)
Lenses	20mm; 85mm

Fig. 3 - TLS and photogrammetric survey acquisition (left) and resulting point cloud (right)

The complete coverage of the buildings complex took 86 laser scanning stations, all around the area under study, as well as on top of the terraces and roofs. For each station, laser data and image were acquired. Point clouds were acquired with a point density on the object of more than 3 cm, and photogrammetric images were acquired with resolution on the object better than 0.8 cm/pixel. The radiometric data acquired by the camera was merged with the geometric data of the TLS, thus providing a coloured point cloud (X, Y, Z, R, G, B).

Point cloud registration was accomplished by using retroreflectors as 3D tie points, distributed around the area and surveyed with a digital total station. A unique 3D coloured point cloud was created with a filtered resolution of 1 point every 3 cm. This point cloud can be visualized, analysed and measured using a point cloud visualization software, as *Artevis*.

Total Length: 19.785 [m]

Visualization	
Visible	☑
Smooth	☐
Size	1
Color	
Mode	Rgb
Rgb	
Select	
Brightness	1
Elevation	
Use	☐
Properties	
Count	18,162,088
Min	
X [m]	85.45
Y [m]	151.015
Z [m]	98.602
Max	
X [m]	224.218
Y [m]	212.233
Z [m]	141.544
Mean	
X [m]	152.845
Y [m]	188.38
Z [m]	113.306
Stdev	
X [m]	39.019461
Y [m]	17.04739
Z [m]	8.696511

	X [m]	Y [m]	Z [m]	dL [
1	88.966	189.666	123.449	0.
2	88.964	189.687	122.311	1.
3	88.961	189.664	121.411	0.
4	88.961	189.491	120.274	1.
5	88.960	189.585	119.347	0.
6	88.958	189.606	118.190	1.
7	88.962	189.669	116.808	1.
8	88.954	189.701	115.086	1.
9	88.955	189.674	114.475	0.
10	88.955	189.654	113.447	1.
11	88.958	189.680	112.006	1.
12	88.959	189.715	110.080	1.
13	88.961	189.706	108.500	1.
14	88.957	189.731	107.153	1.
15	88.962	189.719	105.734	1.
16	88.963	189.733	104.953	0.
17	88.963	189.670	104.283	0.
18	88.969	189.718	103.690	0.

Fig. 4 - 3D Coloured Point Cloud on Artevis, software for the visualization analysis and measurements of point clouds.

Artevis is a software developed by Artescan which allows for the handling of large data sets of 3D point cloud data in an efficient and user friendly way. Within this application it is possible to manage and explore multiple 3D point clouds by conventional 3D controls (move, pan, rotate etc.), to measure coordinate data as well as partial and total distances, to create 3D vectors and to enhance the visualization of the point cloud by using multiple visualization modes (e.g. colouring by elevation or direction).

5 ASSISTED VISUAL INSPECTION FOR BUILDING FAÇADES

As described before the Tejo Power Station building is constructed of an iron structure covered with brick. Several maintenance and repairing interventions are often executed in the walls surface, mainly on the bricks, whenever a visual inspection detects any new issue. With the aim to create a complete identification of all the visible deteriorations on the wall surface at a specific time, to quantify and classify these deteriorations and, finally, to analyse its evolution in time, an application was developed and implemented. To serve as the base for the identification and mapping of the façade deteriorations, orthoimages were produced from the photogrammetric data. For the storing, management and inquiry of the spatial information a Geographic Information System (GIS) tool was considered.

5.1 ORTHOIMAGERY

Unlike conventional photos orthoimages provide metric quality, particularly useful in surveying and modelling applications. Specifically, when orthoimages are imported into a CAD environment, they can be used to register and model architectural structures that, for example, may need restoration and recovery of pathologies (Oliveira, A. et al. 2012).

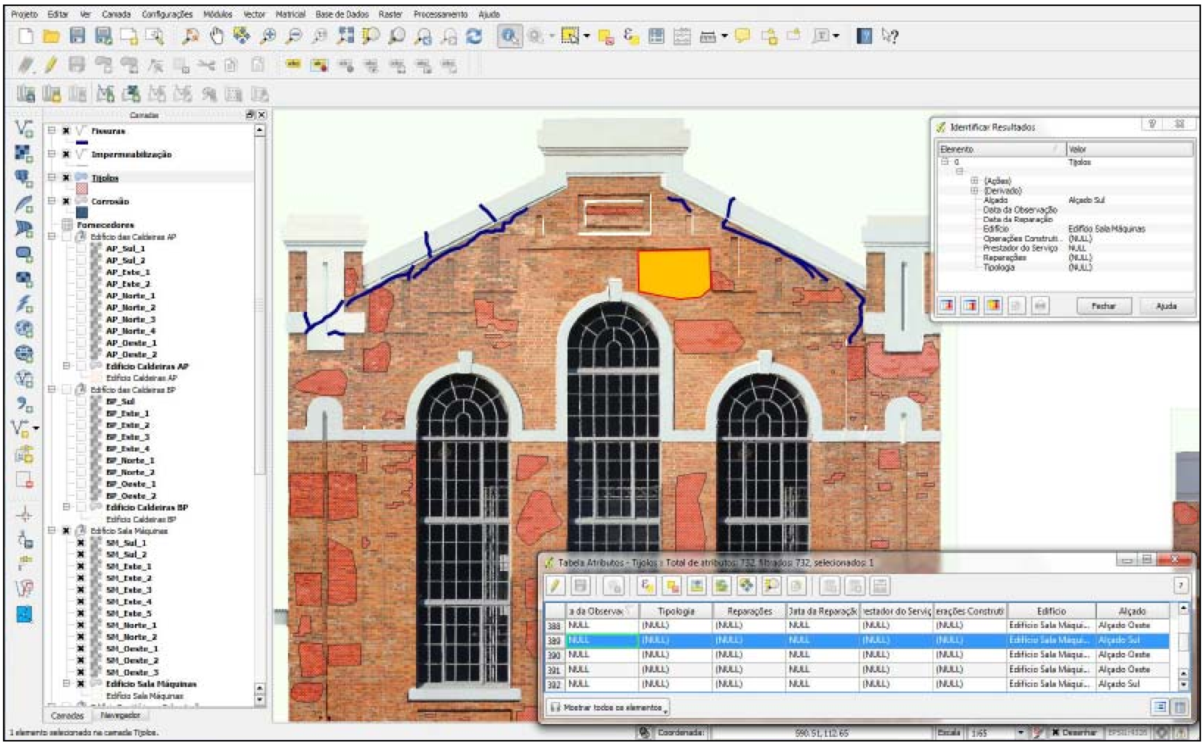
Building façade orthoimages are images who were corrected from their deformation in relation to an orthogonal view to a vertical plane aligned with the façade. They are metric images that can be imported into CAD or GIS applications and where it's possible to measure distances and areas correctly. These orthoimages were produced for all visible façades, including elevated terraces, in a total of 52 images. The image resolution on the object used for the orthoimages was 0.8 cm/pixel.

5.2 GIS TOOL FOR BUILDING FAÇADES

The vectorization of façade deterioration, based on orthoimages, can be done in a CAD environment and then imported onto a GIS tool or it can be done directly in the GIS. A structured database was defined along with the specialists on the deteriorations, so all the possible events (feature classes) and associated attributes to be classified are pre-defined. The GIS tool establishes the link between the graphic representation of a specific event to its attribute. On the other hand, after this link is created, it allows the information to be queried on both ways. Meaning that one can select a specific line that represent a deterioration and consult its associated attributes. Or one can select from the database a specific record and visualize its graphic location (Figure 5). Safety assessment is based not only in information at a given point in time but on the evolutionary analysis of the collected information so, concerning assisted visual inspections, the way this information is produced facilitates a chronological comparison of the information (Berberan, A. et al 2012).

The application allows, for instance, to spatially represent any visible anomaly detected on the building façade, to classify it within predefined attributes and to produce analysis of its evolution within time. The implemented tool is capable of:

i) importing orthoimages as base maps for the analysis;
ii) mapping of visible deteriorations as graphical elements;
iii) classify the attributes of each graphical element on the associated database (e.g. for a brick deterioration one can define the probable cause, the date of observation, the dimensions, if there has been any intervention or restoration of that element, the name of the service provider and date, etc.);
iv) associate external documents to a graphic element;
v) query both graphically or by attribute;
vi) statistical analysis of the anomalies (e.g. by type, façade orientation or dimension);
vii) change detection within time, by analysing the evolution of the anomalies.



Identificar Resultados

Elemento	Valor
0	Tijolos
(Ações)	
(Derivado)	
Alçado	Alçado Sul
Data da Observação	
Data da Reparação	
Edifício	Edifício Sala Máquinas
Operações Construti...	(NULL)
Prestador do Serviço	NULL
Reparações	(NULL)
Tipologia	(NULL)

Tabela Atributos - Tijolos :: Total de atributos: 732, filtrados: 732, selecionados: 1

	a da Observa	Tipologia	Reparações	Data da Reparaçã	estador do Servi	erações Construti	Edifício	Alçado
388	NULL	(NULL)	(NULL)	NULL	(NULL)	(NULL)	Edifício Sala Máqui...	Alçado Oeste
389	NULL	(NULL)	(NULL)	NULL	(NULL)	(NULL)	Edifício Sala Máqui...	Alçado Sul
390	NULL	(NULL)	(NULL)	NULL	(NULL)	(NULL)	Edifício Sala Máqui...	Alçado Oeste
391	NULL	(NULL)	(NULL)	NULL	(NULL)	(NULL)	Edifício Sala Máqui...	Alçado Oeste
392	NULL	(NULL)	(NULL)	NULL	(NULL)	(NULL)	Edifício Sala Máqui...	Alçado Sul

Fig. 5 - GIS tool for Assisted Visual Inspection. Orthoimage, graphic elements and attributes.

6 CONCLUSION

The combination of different monitoring technologies and methodologies into one holistic monitoring system for heritage buildings, allowed both for a better comprehension of the relation between the different phenomena that affects the object under study, and for the compilation of critical information, dated in time, about the conditions and anomalies of the building. Although this broader monitoring approach can still be improved and optimized, is irrefutable its capacity for detailed detection and characterization of geometry surface deformations and pathologies, as well as for record and maintenance management of highly valuable heritage buildings.

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