GEOMATIC METHODOLOGIES FOR THE STUDY OF *TEATRO MASSIMO* IN PALERMO (ITALY)

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ABSTRACT:

This work illustrates the use of geomatics techniques for the documentation of *Teatro Massimo* in Palermo (Italy), one of the most important and big in Italy and in Europe. The theatre is characterized by a very complex structure and is realized also using innovative solution, studied at the time of the project specifically for this building; for example, an original system was realized for a natural air-conditioning system of the auditorium.
Due to his complexity, the documentation of the *Teatro Massimo* requires studying specific survey solutions for the different parts of the building. In this paper, some studies on two of the most representative parts of the building were described. In particular, a 3D survey of the auditorium was carried out to obtain a first 3D model of the most important internal part; a very accurate monitoring of structure inside the dome of the theatre was also carried out.
The survey of the auditorium was realized by a Terrestrial Laser Scanning (TLS), that has allowed the creation of a digital archive of point clouds, showing, however, the some level of criticality due to the complex shapes of building and of architectural details. The work has highlighted that specific strategy to optimize the number of acquisitions needed for the complete documentation of the auditorium.
The monitoring of the structure inside the dome was carried out by topographic and photogrammetric techniques. The monitoring was aimed at measuring the displacements of the support devices connecting the iron structure of the dome. The monitoring has allowed to understand and to test the proper functionality of this complex system. Some tests were carried out also by a thermal camera to correlate the displacements of the support devices with the dilatations produced by steel thermal gradients.

1. INTRODUCTION

In recent years, the documentation and the preservation of complex cultural heritages can be carried out through the use of modern geomatics methodologies (as topographic, photogrammetric and laser scanning methodologies). These techniques are able to perform analysis that can be directed at both the single structural elements (as beams, columns, decorations) and the complex architectural elements (as façades, floors, roofs, external framework).
Many studies were conducted in last years with geomatics integrated methodologies for the cultural heritages 3D survey (Grussenmeyer et al., 2008; Rinaudo et al., 2010; Dominici et al., 2013).
The geomatics methodologies have been used for documentation (Lo Brutto and Spera, 2012; Tucci et al., 2016), for augmented reality issues (D'Urso et al., 2014, D'Agnano et al., 2015) and to investigate the potentiality as geometric reference to the BIM methodology (Santagati and Turco, 2016; 2016; Rodríguez-Moreno et al. 2016; Angelini et al., 2017).
This study, conducted in collaboration between the DICAM of University of Palermo, the DICEA of Sapienza University of Rome and the C.G.T. s.r.l. in Palermo was aimed to apply geomatics techniques to study and to document the *Teatro Massimo* in Palermo (Italy). The *Teatro Massimo* is the third biggest theatre in Europe, after the Paris Opera and the Wien Staatsoper, and is one of the most important and complex monuments in Palermo. His geometric and architectural complexity need for a strict and complete planning of surveys, which can only be done through technical operations to be included in a comprehensive project of documentation and preservation. These operations could be very costly in computational and economic terms.
At the present it's very difficult to support such a project, so only some preliminary study were conducted for the documentation of the theatre. Therefore, it was considered useful to limit the work to some elements with a particular architectural relevance or interesting for the structural-constructive point of view.
The work was divided into two phases: the first has involved to the Terrestrial Laser Scanning (TLS) survey and the 3D modelling of the auditorium; the second regarded the study of the dome and the analysis of his mechanical systems.
The dome is, in fact, a very important part of the structure of the *Teatro Massimo* both from an architectural point of view and for the ingenious natural air-conditioning system of the auditorium. The structure overlooking the auditorium looks like a flower with some petals that can open up to let the hot air out and ventilate the hall, through a complex system of cables and ropes; this system it is also managed via carriages which work for the opening of the radial arcs of coverage of the hall. The work was aimed to monitoring support devices by topographic

and photogrammetric techniques as describe in a preliminary study carried by Dardanelli et. al. (2012). Some tests were also carried out by a thermal camera to correlate the displacements of the support devices with the dilatations produced by steel thermal gradients.

2. THE *TEATRO MASSIMO*

The full name of Palermo's opera house is *Teatro Massimo Vittorio Emanuele*, but the theatre is usually known as *Teatro Massimo* (Figure 1). The theatre was designed by Giovan Battista Filippo Basile in 1875 and completed by his son Ernesto in 1897.

The building develops on two plans with a central body corresponding to the auditorium, surmounted by a dome and two vestibules circular to the sides (Figure 2). The theatre, 89 meters wide and 129 long, occupies an area of 7,730 square meters including the room with its outbuildings and 2,765 square meters related to the back the scene and its annexes. The stage is the greatest in Europe and guarantees a perfect vision from every point of view of the theatre.

Figure 1. The *Teatro Massimo*

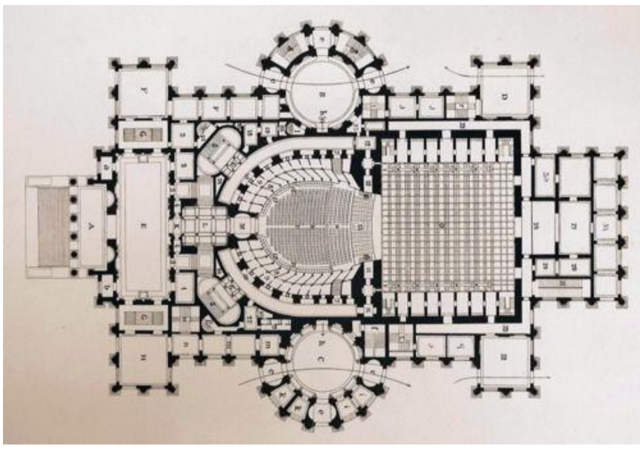

Figure 2. The plan of the *Teatro Massimo*

The auditorium was elegantly decorated according to the project by Ernesto Basile; it has the shape of a horseshoe and it has five floors of boxes and a gallery (Figure 3). The gallery is entirely decorated with gilded stucco. The auditorium hosts up to up to 1300 people and has a dimension of about 26 meters x 20 meters.

Giovan Battista Filippo Basile and his son Ernesto have planned the ceiling of the auditorium as a wheel with eleven "petals", frescoed wooden panels that, through a system of ropes, can be opened upward for natural ventilation of the auditorium. Each panel is part of the original cooling system of the theatre, as they can be opened to let the hot air flow out.

Figure 3. The auditorium

The dome is a wonderful example of engineering design; it has an outer diameter of about 28 m (Figure 4); it has been realized with sixteen radial arches, five polygonal rings, and one hundred twenty-eight diagonal braces that intersect each other (Di Paola et. al. 2016) (Figure 5).

Figure 4. View of the exterior of the dome

Figure 5. The internal structure of the dome

In the lower part of the radial arches, there are support devices that allow the opening of the structure. Each support device has five rollers of cylindrical shape with a diameter of 90 mm. The rollers are placed at 26 mm distance from each other and are connected through an iron frame. The movement develops place inside a cast iron body connected to the arches by a horizontal plate and a cast steel slab (Basile, 1876). This system was realized to oppose the expansions of steel, caused by the constant daily and seasonal temperature ranges that characterize the structure, as well as to avoid tensions in the arches (Figure 6).

Figure 6. Places carriages on the perimeter wall and detail of support device

3. GEOMATIC SURVEY

3.1 Laser scanner survey

The TLS survey was aimed at the acquisition of a 3D model of the auditorium and of the stage. The survey was realized by Trimble Tx8 time-of-flight laser scanner; this device has a maximum range of 120 m on most surface, a field of view of 360° in the horizontal direction and 317° in the vertical direction, a scanning speed of 1 million of points per second. The laser scanner has a range noise <2 mm in standard mode and <1 mm in precision mode; it is also integrated with an HDR camera for acquisition of 10-megapixel image resolution.
In order to have a complete and accurate documentation of the auditorium and of the stage a careful planning was performed; eleven measuring sessions were planned from different positions, three stations were carried out from the floor, two on the stage, three from the second floor of boxes, one from the royal box and three from the fourth floor of boxes.
The survey was carried out to produce a point cloud with an average sampling step of about 5 mm.
The point clouds acquired by each scan station were constituted of about 8÷10 million points for each one; at the end of the survey about 100÷110 million points were measured (Figure 7).

Figure 7. Detail of the point cloud of the stage

In order to allow an automatic merge of the several points cloud, some spherical targets were placed in the auditorium and in the stage.
The processing of raw point clouds was performed by the Trimble *RealWorks* software package. The first processing step was the automatic filtering process to reduce the instrumental noise; then, an automatic registration and merge of the point clouds were executed (Figure 8). A first 3D model of the auditorium and of the stage was then obtained.

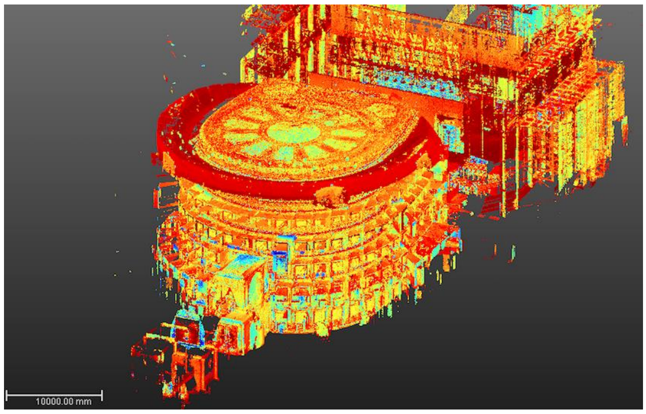

Figure 8. Extraction of the 3D model

3.2 Topographic Monitoring

Robotic total station is the technological evolution of electronic theodolites; it is an innovative instrument in which the robotic components move automatically the alidade in the horizontally way and the telescope vertically. The easy maintenance and the rapid installation allow the use in various fields of engineering applications, such as structural monitoring.
The monitoring system used in the topographic control was composed of two Trimble S8 robotic total stations with an angular accuracy of ±1” and a distance accuracy down to sub-millimetre using a prism (±[2 mm+2ppm]).
Several daily measurements were made to highlight correlations with the thermal changes of the structure.

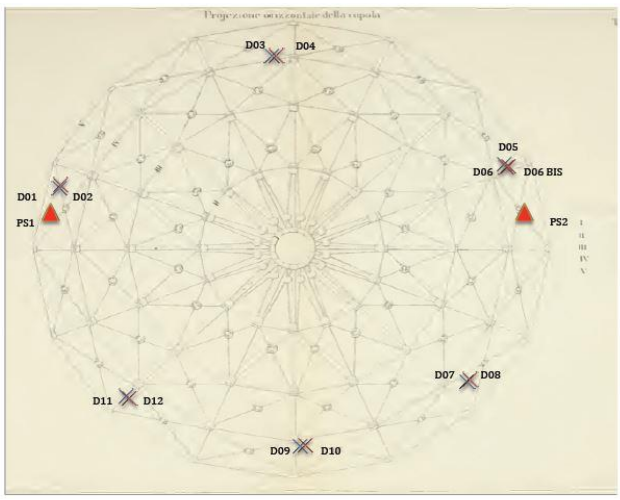

Figure 9. Horizontal projection of the Dome (from the original Basile’s drawings) with station points (PS1, PS2) and measured points (D01-D12)

The two total stations were set-up over two static supports (called PS1 and PS2) to increase the accuracy of the measurements, whereas some mini prisms were positioned both in the strategical points subject to movement and on some control points. The two total stations were controlled and monitored by a PC over WLAN.

The monitoring was conducted through backwards intersection method only for 6 support devices (called from C1 to C6); two mini-prisms were located on each device (called from D01 to D12), to enable the observation from both station points (Figure 9). Besides another mini-prism was placed on an outside fixed point, not influenced by the thermal dilatations of the ribbings.

So it was possible to determine the absolute displacements in a local reference system. The six control points on the support devices and the fixed point were determined from each of the two point stations.

Table 1 showed the coordinate X, Y, Z and the differences ΔX, ΔY, ΔZ of the point C1/S1, C3/S1 and C3/S2, for the six series of daily measurements.

Support device	Time	X	Y	Z	Δ X	Δ Y	Δ Z
C_1/S_1	9.04.22	100.5065	101.6695	9.8316	0.0000	0.0000	0.0000
	13.17.22	100.5065	101.6692	9.8316	0.0000	-0.0003	0.0000
	17.30.24	100.5065	101.6691	9.8316	0.0000	-0.0004	0.0000
	21.43.26	100.5065	101.6689	9.8316	0.0000	-0.0006	0.0000
	1.56.24	100.5066	101.6693	9.8316	0.0001	-0.0002	0.0000
	7.55.57	100.5064	101.6693	9.8316	-0.0001	-0.0002	0.0000
Support device	**Time**	**X**	**Y**	**Z**	**Δ X**	**Δ Y**	**Δ Z**
C_3/S_1	9.04.22	126.1065	103.1575	9.9093	0.0000	0.0000	0.0000
	13.17.22	126.1066	103.1575	9.9092	0.0001	0.0000	-0.0001
	17.30.24	126.1063	103.1578	9.9092	-0.0002	0.0003	-0.0001
	21.43.26	126.1063	103.1574	9.9092	-0.0002	-0.0001	-0.0001
	1.56.24	126.1062	103.1572	9.9093	-0.0003	-0.0003	0.0000
	7.55.57	126.1063	103.1574	9.9093	-0.0002	-0.0001	0.0000
Support device	**Time**	**X**	**Y**	**Z**	**Δ X**	**Δ Y**	**Δ Z**
C3/S2	9.04.22	126.2273	103.2133	9.9086	0.0000	0.0000	0.0000
	13.17.22	126.2274	103.2131	9.9086	0.0001	-0.0002	0.0000
	17.30.24	126.2272	103.2133	9.9086	-0.0001	0.0000	0.0000
	21.43.26	126.2271	103.2132	9.9086	-0.0002	-0.0001	0.0000
	1.56.24	126.2269	103.2132	9.9086	-0.0004	-0.0001	0.0000

Table 1. Coordinates (in meters) of the control points

The vertical component of displacement ΔZ was quite absent, furthermore was confirmed remarkable concordance between the points belonging to the same support device. Finally, the expected horizontal displacements were in the range ±0.4-0.6 mm, in accordance with the theoretical model provided by structural engineers.

3.3 Photogrammetric Survey

Monitoring by photogrammetric techniques was possible only on two support devices (C1 and C3). A Canon Eos-01 Mark II digital camera with a 50 mm focal length was used. The camera was mounted on a slide bar and the camera axis was directed downwards.

Some circular photogrammetric targets were placed on the upper surface of the support devices (Figure 10). Four stereopairs of the two support devices were taken in a day only, at 10 a.m., at 2 p.m., at 3.30 p.m. and at 6 p.m. Hence established the baseline equal to the maximum range of the slide bar (about 7 cm), the maximum object distance resulted equal to 65 cm. Also, in this case, the analysis of photogrammetric data was directed to determine the trend of the points coordinates during the day and to consider the compliance of the achieved results with the available structural model. Data processing was organized into the following four steps: camera calibration, image orientation, calculation of the points coordinates and analysis of the coordinates trend during the day.

Data processing was carried out through Topcon Image Master software package; this software package is usually used to extract point cloud models from stereopairs and characterized by powerful image-matching algorithms but also by a complete bundle adjustment process suitable to obtain submillimeter accuracy.

The calibration was carried out by means of a planar calibration grid; the images were taken at a distance equal to the one used during the monitoring operations so that were reproduced the same conditions of the survey. Seven unknown camera parameters (principal distance, principal point coordinates, two coefficients related to radial distortion, two coefficients related to tangential distortion) were computed.

Relative and absolute orientation of the stereopairs were carried out using only tie-points and distances to scale the photogrammetric model. The photogrammetric measurements were carried out on circular targets located on the fixed part and on the mobile part of the support device. The centre of targets was identified, through image-matching algorithms in a semi-automatic way.

Figure 10. Frame with control points and tie Ponts disposed on the support device

Tables 2 showed the coordinates and the displacements of the points with regard to the four stereopairs. As it was to be expected, the points located on the fixed part of the roller, had displacements much smaller than points in the mobile part.

	D01 Coordinates			**D06** **Coordinates**		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
2 p.m.	0.0945	0.3417	0.0598	0.0549	0.3497	0.0136
6 p.m.	0.0945	0.3413	0.0600	0.0549	0.3495	0.0138
10 a.m.	0.0941	0.3406	0.0621	0.0547	0.3492	0.0144
3.30 p.m.	0.0943	0.3407	0.0619	0.0548	0.3493	0.0139
Time frame	Displacements			Displacements		
	ΔX (mm)	ΔY (mm)	ΔZ (mm)	ΔX (mm)	ΔY (mm)	ΔZ (mm)
2-6 p.m.	0.011	-0.457	0.174	0.036	-0.16	0.148
6-10 a.m.	-0.431	-0.667	2.098	-0.188	-0.294	0.659
10-3.30 p.m.	0.271	0.152	-0.155	0.118	0.082	-0.529

Table 2. Coordinates and displacements of the points

3.4 Thermographic inspection

In order to correlate the displacements of the support devices with the dilatations produced by steel thermal gradients, three thermal testing were acquired by Flucke TiR 32 thermal imaging camera at the same time as a topographic and photogrammetric survey, and precisely at 10 a.m., at 3.30 p.m. and at 6 p.m.. Thermal images show for the support devices that during the day steel is subject to thermal gradients of about 6°C (Figure 11 and 12), instead for the dome was about 2°C. This data, used as input for the theoretical structural model, is enabled to verify the accordance of the measured displacements with the ones expected, considering that the theoretical model, for each degree of thermal variation, expected displacements equal to 0.12 mm.

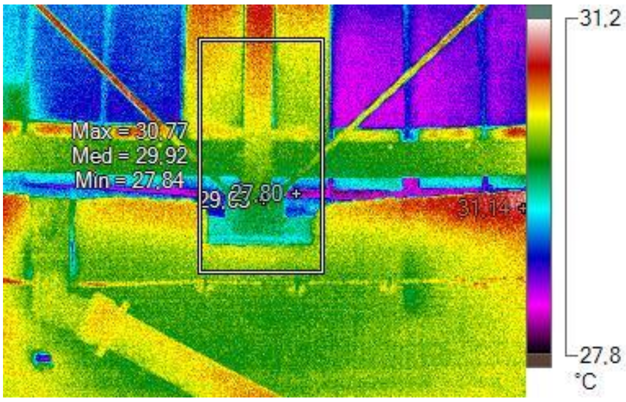

Figure 11. Thermal images of the roller C3

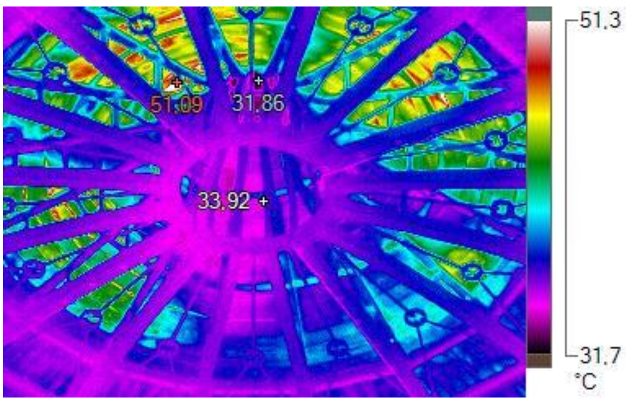

Figure 12. Thermal images of the dome

4. CONCLUSIONS

The TLS survey allowed to obtain a first 3D model of the auditorium, with a precision of a few centimeters. The TLS survey shows, however, some critical issues due to the complex shapes of the building and of the architectural details. The work has highlighted that specific strategy to optimize the number of acquisitions needed for the complete documentation of the auditorium. Furthermore, a topographic network is essential for the correct registration of different scans.

The results obtained for the monitoring outline almost exclusively the horizontal component of the displacements; as it was expected, the vertical component is practically equal to zero. Displacements determined by topographic techniques, besides, are of the same order of the ones determined by photogrammetric techniques. For both methods, the mean value of the absolute displacements of the support devices results practically identical, equal to about 0.8 mm. This result, quite in accordance with previsions of the theoretical model, demonstrates, that until today the support devices accomplish its task very well. Moreover, both techniques, topographic and photogrammetric, obviously if used in the proper way, are absolutely suitable to determine sub-millimeter displacements.

Topographic methods have two substantial advantages over the photogrammetric ones. The former consists in a complete automation of the measurements acquisition, apart from the initial cycle which requires necessarily manual intervention, the latter in the rapidity of data processing; in fact, the robotic instrument is usually equipped with a software able to provide quickly coordinates, statistical parameters of the measurements and displacements. Instead, the strong point of the photogrammetric techniques is connected especially with the cost of instrumentation, considerably lower than the one necessary for the topographic survey. On the other side, data processing (orientation and restitution of the coordinates) requires longer time and greater experience.

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