An assessment on morphological survey calibration and the automation of digital drawing for the reliable documentation and conservation analysis of out-of-scale buildings

Raffaella De Marco[1], Alessia Miceli[1], Sandro Parrinello[1]

[1] DICAr Department of Civil Engineering and Architecture, via Ferrata 3 27100 Pavia,
raffaella.demarco@unipv.it, alessia.miceli@unipv.it, sandro.parrinello@unipv.it

Abstract – **The application of digital survey practices on Built Heritage has to face in different cases with singular typologies of architectural systems that have an out-of-scale proportion (as tower bells, minarets, civil towers), facing also with uncommon phenomena of structural instability and decay, due to their specific geometry. Their study shows intrinsic instability systems related to their singular structural form, the unusual dimension and the low frequency of ordinary maintenance and restoration, which tend to increase throughout the lifecycle of the building and the exposition to agents of its construction materials.**
In this cases, the aim to monitor the conditions of conservation influences the methodological purposes and pipeline of survey, bridging the practices of range-based and image-based survey through new standards of density, resolution and reliability of data necessary to assess the analysis of such type of monuments. A reflection on the quality of morphological databases to derive digital elaborations and maps for the analysis of instabilities and the monitoring of risks in out-of-scale buildings is presented.

I. INTRODUCTION (SP)

The cognitive representation of the historical architectural structures constitutes a fundamental reading key to the planning of preventive conservation processes on buildings and cities [1] [2]. This purpose is intended both in terms of post-intervention on a built context already damaged, and for the preservation of Built Heritage by future phenomena of risk, induced by natural, seismic or even anthropic events [3].

The graphic transposition is thus necessary not only to define the image and the form of mechanically shaped structures [4] [5]. It is also intended in relation to dynamic phenomena that can characterize a static structure over time and its overall built environment, evolving kinematic behaviours and mutual damages able to reach the urban aggregate [6]. The disposition of a valid representation support is thus conceived as the preliminary operation to a conscious computing action. This action will be not limited to the qualitative data, but it will also extend to quantitative factors that influence the static and dynamic mechanical apparatus. If provided with appropriate experimental characters, the documentation can be configured as a non-invasive protocol for both monitoring and assessment of intervention [7].

This scientific framework contextualizes the reflections conducted on info-graphic qualities obtainable from digital documentation protocols in the case of singular proportioned structural blocks, with respect to the uniformity of the construction fabric. These elements, such as civil or bell towers identifiable in different cultural contexts of architectural heritage, can be characterized by out-of-scale proportions with a clear prevalence of vertical development, and they are also subjected to more marked instabilities, conditioned by the specific formal typology. Through the amplification of degradation and risk factors due to the size, their proportion is also a critical factor for digital acquisition practices, which prevent the guarantee of resolution and correct referencing of the collected data.

Digitization procedures are now a widespread protocol in terms of documentation, with the wide-ranging arrangement of sensors and tools useful for the metric and photographic transposition of the conservation conditions of buildings (such as LiDAR, optical cameras and UAVs). Although, in the case of out-of-scale structures, the conditions of management and interpretation of collected data requires continuous refinements and testing of post-production processing to reach reliable drawings [8] [9].

The development of their graphic-structural product is then articulated not only through the technical requirements of the instrumentation adopted in the field, but also considering the specific calibrations applied during on-site campaigns. The objective is to ensure, in addition to the reliability of the measurement, also an adequate quality of resolution of the expected data. The goal is to maintain a uniform metric tolerance in data approximation over the entire structural surface, supporting both a timeliness analysis and its replicability.

Fig. 1. Some case studies of out-of-scale buildings between west and east Europe: medieval towers in Italy (Pavia), Bell tower in Russia (Solikamsk).

II. SENSORS, SURVEY PROCEDURES AND RANGE PARAMETERS TO ASSESS THE QUALITY OF DIGITAL MORPHOLOGICAL DATA (RDM)

The opportunities for digital architectural documentation are increasingly oriented towards the automation and vector management of survey data, mainly consisting of geometric and photographic data from on-site campaigns. The interest is in the shortening of the processing times (in parallel with the costs) together with the possibility of concentrating the work of the surveyor on the analysis of the data obtained from the graphic transposition, rather than their manual processing [10].

The specific case of out-of-scale buildings adds further requirements to the management and calibration of instrumental documentation practices, considered under multiple factors of influence. The main problem is represented by the altered proportions of the monument with respect to the radius of acquisition of the instruments. The prevalence of the vertical dimension (in the range of 30-50 meters) is compared to the planimetric size (between 5-10 meters), with a difference of nearly an order of dimension between the base of the monument and its elevation [11] [12]. This factor influences the instrumental detection in the application of terrestrial and aerial sensors, for their manoeuvrability and measurement trajectory, in particular considering the fixed elements (buildings, vegetation) of the surrounding context [13].

In addition to the measurement reliability of the survey, however, it is also worth considered the difficult management of complex point clouds from LiDAR, not only in terms of spatial extension but also of local data intensification [14] [15]. On the contrary, the 3D Structure-from-Motion products from aerial cameras are often more versatile and compatible in the acquisition and management of formal data on the structures, which can be extended to a global coverage of the entire elevation surfaces (up to 100-150 meters only with light UAVs) but also locally incrementable in the millimetric detail of morphology surface and crack damage (thanks to close manoeuvrability and data acquisition) [16].

For pursuing the instrumental control and the achievement of a quality of documented data functional to conservative analysis, particular calibrations are to be considered in the case of survey of out-of-scale buildings:

A. Density control and data referencing in LiDAR data

The quality of data collected through terrestrial LiDAR sensors is more influenced by the specific acquisition radius, with respect to the target surface.

The incidence is influenced by the measurement distance, linked to the elevation of the monument with respect to the height of sensor positioning. Thus, it consists in the relative angle set between the distance of the instrument from the building block and the maximum measurement height required. The case of out-of-scale buildings located within the dense urban area can limit the possibility of distancing from the object of investigation, defining acute triangulation angles (even 5 meters of base radius for 50 surface height).
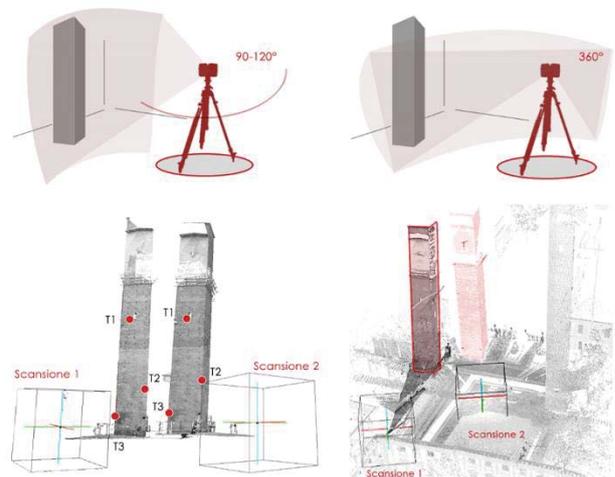

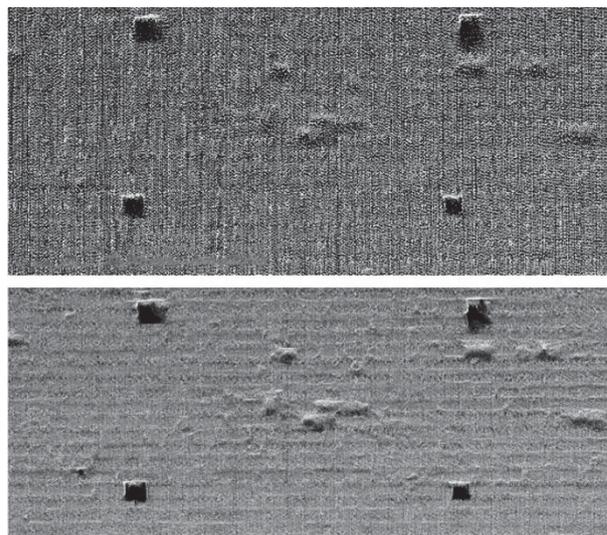Fig. 2. LiDAR scanning, triangulation and overlapping

Fig. 3. Different point clouds, at 20-meter-high, without (above) and with (down) high density overlapping.

To ensure the quality of transposition of the morphological data to the detail of the wall texture, it is possible to proceed by associating a parallel process of refilling of the point measurement datasets to the standard scan campaign. For each medium quality scan operated with global shooting angle (360° x 320°), a partial dataset (variable angle x 320°) with increased acquisition density is associated. The collimation of the partial scan (not performed by the instrument due to the reduced angle) is guaranteed on the basis of the previous complete reference.

The refilling process is developed in a double-step procedure. Firstly, a scan with global shooting angle (360° x 320°) is performed in a medium quality set (with a range of density between 1:4-1:8 and medium resolution 2x, around 6 minutes of scan). This scan defines a preview panorama to set the refilling action of the instrument, and it also provides a global basis for the measuring of the context space. Then, without changing the scan-station point, a second partial scan (variable angle x 320°) is performed. The decrease of the acquisition angle allows to concentrate a higher density of acquired point in a specific corner of space measurement, optimizing the combination between the performance of the instrument and its time of scanning (with a range of density between 1:1-1:2 and high resolution 4x, around 7 minutes of scan).

It is possible to take advantage of the second partial scan round in order to develop a colorimetric integration of the LiDAR data, concentrating the shooting of the integrated camera on the optical cone aimed focused on the monument (and reducing its operating times from 4 to 1-2 minutes).

These settings allow to obtain a point cloud specifically calibrated for high morpho-metrical quality even for altitudes higher than 20 m (laser spot range under 5mm). The point cloud can be referenced firstly considering the partial scans of structural block, with a controlled selection of homologous targets and, subsequently, with the scans of surrounding context, even also using a cloud-to-cloud visual alignment.

B. Resolution and alignment of data from UAV

The UAV survey activity requires a careful preliminary planning of the shooting strategy to be adopted on site, tested and calibrated for controlled distances of approach to the shooting surface, evaluating the photographic data acquired by the instrument during the hovering [17] [18]. The characteristics to be considered concern the photographic detail required (distinction of the wall texture profiles), the geometry of the on-site acquisition context (radius around the block of the out-of-scale building and the presence of elevation structures in the surrounding area), the number of shots that can be taken with respect to the dimensions and elevations of the surfaces and the autonomy battery times of UAV. The choice is influenced by the acquisition distance from the wall surface (optimizable at 2 meters for a

photographic camera even at 12 Mpixel), ensuring a range of oscillation in hovering not exceeding 30 cm. In this way, the photographic campaign is structured with flight plans according to horizontal and vertical trajectories of overlapping shooting positions for at least 30% of the width/height of the photographic framework. The shooting stations are controlled by setting a metric control grid, generating a mesh of localized coordinates for each shooting position of the UAV. [19]

Fig. 3. UAV mesh quality from survey at 35 high level.

III. GEOMETRICAL AND IMAGE RESOLUTION FOR THE CONSERVATION ANALYSIS (AM)

The integration of range-based and image-based data obtained during the survey allows for an overarching database to be defined, enriched both in terms of specific geometrical characteristics and material/texture mapping of the elevation surfaces. It is central to consider that, in the purpose of a specific documentation protocol for out-of-scale structures, a minimum range of metric reliability (5 mm) and resolution photo quality (1pixel for 2-5 mm) is guaranteed by the presented process on the overall development of the vertical surfaces.

The given characteristics are implemented in the post-production phase, in order to obtain two parallel processes to automate the data elaboration: the drawing phase and the diagnostic mapping. The presented automation procedure is fundamental in order to guarantee the efficiency and expeditiousness of the work, otherwise prevented by the large scale of the building:

A. Automation of vectorization from raster data

Obtaining photographic data with appropriate resolution and sharpness (approximately 3968x2976 with 72dpi in 1:1 quality) is a preliminary basis for the generation of rectified photo planes on which to perform an automatic vectorization of the wall texture. High quality of photographic asset allows the operator to automatically

select the mortar joint, based on geometry, area and colour. This step allows for a segmentation of the material two-dimensional output, that generates raster contours highlighting the single elements of the texture, alongside with their peculiarities due to degradation phenomena.

Starting from this segmentation, it is possible to proceed with a semi-automatic mode, in which the obtained contours are vectorized: in this phase, the operator is required to control specific parameters, such as "threshold", "paths" and "noise", that are used by vector-based software to process the given image and generate corresponding paths [20].

The control of the noise variables is therefore refined and standardized, according to a real formal target, with a calibrated evaluation on the specific orthoimages. The "threshold" parameter is adjusted in order to guarantee the level of resolution automatically recognizable by the vectorization process: high levels may cause a union of vectorial borders between cluster areas, while low levels can compromize the recognition of the costructive *formal* shape from the visual *color* shading of surface. The "path" parameter is adjusted in order to underline the linearity of the perimeter in the building block, often solving the noisy reading of irregular mortar joints. Lastly, the "noise" parameter is adjusted in order to better ensure the raster interpretation, also of small empty clusters.
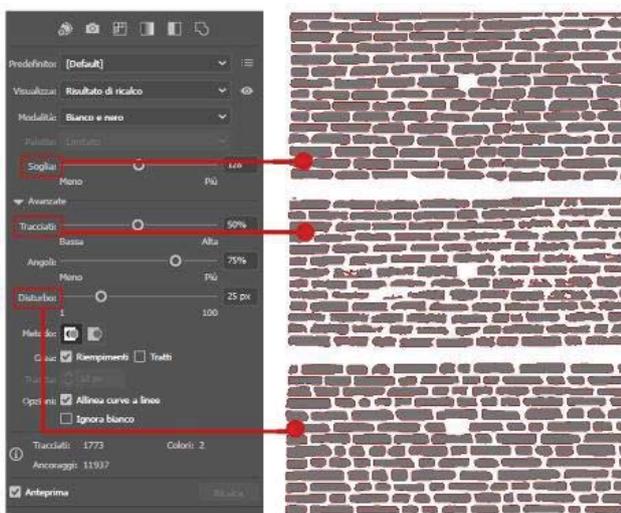

Fig. 4. Semi-automatic vectorialisation of masonry texture at 20 meters high level.

B. *Reference of elevation map to decay conditions*

The quality of transposition of morpho-metrical data, comprehensive of conditions of density and alignment of point clouds obtained from LiDAR and UAV survey, allows to proceed with further analysis in which the distribution of the points is compared to strategically chosen average surfaces.

In this way it is possible to highlight alterations due to decays in the geometrical fabric, expressed as depression - erosion, gaps, cracks or bump areas, patinas, detachments.

The LiDAR outputs, which are metrically reliable, and UAV photogrammetry outputs, morphologically detailed from the base to the top, are subsequently integrated within a controlled procedure, in which the level of detail of the two datasets is uniformed. This allows to obtain a high-resolution material documentation of the entire vertical development of the out-of-scale building.

The resolution of morphological detail achieved in LiDAR/UAV point clouds ensures the analysis of the points' deviation from a defined geometrical plane, set as Reference Plane. The range of deviation is mapped within a colour map, where each colour tone corresponds to a tolerance range of distance from points to the plane. The deviation is interpreted both when positive, as detachment, and negative, as patina, with the representation of a color map ranging from red to blue (with a 3mm of range).

The Reference Plane, considering the specific geometry of the surface, can be set as a perfectly vertical plane or it can be aligned to the structural front. In the first case, macroscopic deformations of the entire block are highlighted, corresponding to drifts or deformations caused by stress influences and structural mechanisms. In the second case, local damages and surface pathologies can be shown, calibrating their map reading and interpretation through the selection of different possible ranges of tolerance. In this way, it is possible to highlight alterations such as depressions, erosion, gaps, cracks, patinas, detachments, with a preliminary automatic mapping based on the query of parameters related to the depth of irregularities of the masonry surface [21].

The documentation process is, therefore, possible even in high-altitude areas (over 20m) generally not accessible due to the height limitation of ground-level cameras.

The quality of detail allows to develop detailed abacus of degradation pathologies, as well as crack maps in which each crack can be clearly observed both in material photo planes and in the photographic dataset obtained during the high-altitude survey operations.
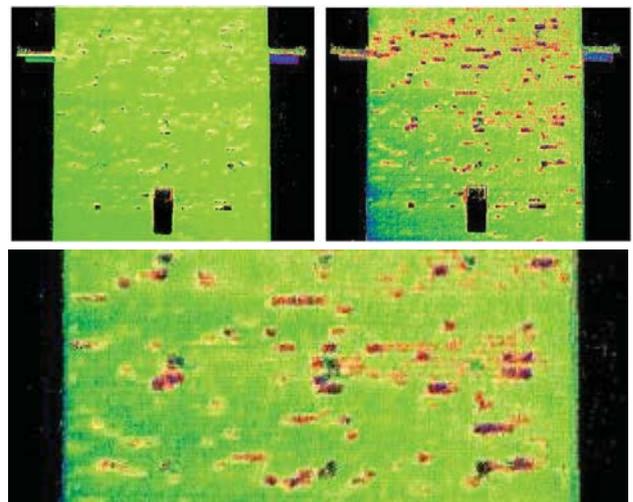

Fig. 5. Morphological ranges of decay at 30-meter-high, highlighting erosions (red) and patinas (blue) areas.
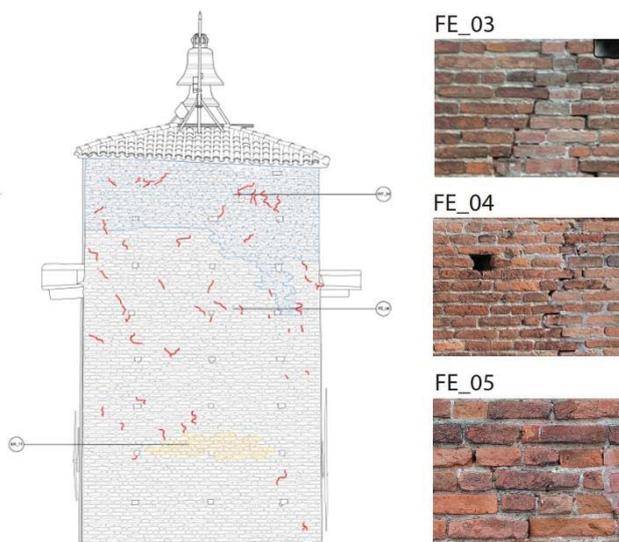
FE_03

FE_04

FE_05

Fig. 6. Cracks mapping at 38 level high in the case study of the Clocktower in Pavia.

IV. CONCLUSIONS (RDM)

Digital survey processes nowadays allow to respond to specific requests about the documentation of architectural elements, especially considering non-ordinary ones, as out-of-scale buildings. The result is a typologically unified product, namely the three-dimensional morphological database, in which the ability of interaction can offer different possibilities of knowledge.

Considering the different survey methodologies and sensors for 3D morpho-metrical database, the possibilities of technical calibration of tools and acquisition modes lead to a necessary reflection of the parameters that affects the metrical quality and formal and material detail of digitization applied in the case of out-of-scale buildings.

On the other hand, the querying of conservation qualities needs to be developed in terms of localization of static phenomena (influences in the plane, deflections, rotations…), related to the overall system (composed and cinematic mechanisms) and its degradation phenomena (surface and material) that have ended or are still ongoing; alongside, the specialization of sensitivity and orientation of data arises, in order to convey the obtained data in a structure-ordered database, which better expresses the relations between not only 2D but also 3D measurements [22] [23].

The objectives of the morpho-metrical quality of integrated databases in out-of-scale buildings combine methods and outputs of digital documentation and focus on the detail of acquired data (density and resolution) and its referencing to the geometrical proportion context.

Therefore, it is possible to develop considerations about the calibration of a structural-focused digital survey applied in non-ordinary spatial and dimensional conditions: updating the qualitative judgements on the

documentation pipeline is a key to improve the specificness and expeditiousness of the acquisition approach, the planification and post-production, within the view of a possible replication for planned monitoring operations [24] [25].

REFERENCES

[1] S. Della Torre, "Preventiva, integrata, programmata: le logiche coevolutive della conservazione." Pensare la prevenzione. Manufatti, usi, ambienti: atti del XXVI convegno Scienza e Beni culturali, Bressanone, 2010, pp. 13-16.

[2] S. Bertocci, "Il contributo del rilievo urbano dei centri storici italiani per il recupero e la prevenzione della vulnerabilità sismica: alcuni casi studi in Abruzzo, Toscana ed Emilia". In A. Marotta, G. Novello, Disegno & Città. Cultura, Arte, Scienza, Informazione, Gangemi Editore, Roma, 2015, pp. 397-405.

[3] L. Di Lodovico, L. Iagnemma, "Rischio e Pianificazione. Tutela, prevenzione e sicurezza nella programmazione urbanistica." The Journal of Urbanism, 25, 2/2012, pp. 1-6.

[4] A. Giuffrè, "Il rilievo nella scienza delle costruzioni". XY Dimensioni del disegno, vol. V, n. 11-12, 1989, pp. 50-52.

[5] A. Giuffrè, C. F. Carocci, "Restauro strutturale. Il rilievo quale indispensabile preliminare dell'analisi meccanica". XY Dimensioni del disegno, vol. VII, n. 17-19, 1993, pp. 34-33.

[6] A. Giuffrè, "Lettura sulla meccanica delle murature storiche, Roma, Kappa, 1990.

[7] G. Minutoli, "Percorsi di conoscenza per la salvaguardia della città storica", didapress, Firenze, 2017.

[8] S. Caprili, F. Mangini, S. Paci, W. Salvatore, M. G. Bevilacqua, E. Karwacka, N. Squeglia, R. Barsotti, S. Bennati, G. Scarpelli, P. Iannelli "A knowledge-based approach for the structural assessment of cultural heritage". Bulletin of Earthquake Engineering 2017, 15/11, pp. 4851- 4886.

[9] A. Guarnieri, F. Pirotti, M. Pontin, A. Vettore, "Combined 3D Surveying Techniques for Structural Analysis Applications". International Symposium on Photogrammetry and Remote Sensing (ISPRS), 2005, vol. XXXVI-5/W1, pp. 22-24.

[10] M. Pieraccini, D. Dei, M. Betti, G. Bartoli, G. Tucci, N. Guardini, "Dynamic identification of historic masonry towers through an expeditious and no-contact approach: Application to the "Torre del Mangia" in Siena (Italy)". Journal of Cultural Heritage, 15, 2014, pp. 275–282.

[11] A. Anzani, L. Binda, G. Cardani, P. Condoleo, A. Saisi, "Damage evaluation of historic towers: a procedure for their integrity assessment." Proceedings 2nd Canadian Conference on Effective Design of Structures, McMaster University Hamilton, Ontario, Canada, 2008, pp. 1-10.

[12] G. Tucci, V. Bonora, "Towers in San Gimignano: metric survey approach". Journal of performance of constructed facilities, 31(6), 2017.

[13] E. Candigliota, F. Immordino, "Low Altitude Remote Sensing by UAV for monitoring and emergency management on historical heritage." ANIDIS Congress, vol. 30, Padova, 2013.

[14] R. De Marco, "Morpho-metric documentation for the structuring of city shape. Calibration and optimization of Laser Scanner survey for the development of a reliable database on Bethlehem urban system." In S. Parrinello (edited by). 3D Bethlehem. Management and control of urban growth for the development of heritage and improvement of life in the city of Bethlehem. Volume 1., Edifir, Firenze, pp. 57-84.

[15] G. Pancani, "Il centro storico di Poppi: analisi a livello urbano per la valutazione del rischio sismico". DisegnareCon, vol. 10, n. 18, 2017, pp. 9.1-9.10.

[16] A. Friz, T. Kattenborn, B. Koch, "UAV-Based photogrammetric point clouds. Tree stem mapping in open standards in comparison to terrestrial laser scanner point clouds." International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XL-1/W2, 2013, pp.141-146.

[17] C. Achille, A. Adami, S. Chiarini, S. Cremonesi, F. Fassi, L. Fregonese, L. Taffurelli, "UAV-based photogrammetry and integrated technologies for architectural applications - Methodological strategies for the after-quake survey of vertical structures in Mantua (Italy)". Sensors, 15(7), 2015, pp. 15520-15539.

[18] N. Kerle, F. Nex, M. Gerke, D. Duarte, A. Vetrivel, "UAV-Based Structural Damage Mapping: A Review". ISPRS international journal of geo-information, 9(1), 14, 2020.

[19] R. De Marco, "Mapping solutions and reliability control in UAV's photogrammetry for structural emergency. The multi-instrumental survey of the Clock Tower in the historical complex of University of Pavia". In: S. Barba, S. Parrinello, M. Limongiello, A. Dell'Amico, "D-SITE Drones - Systems of Information on culTural hEritage. For a spatial and social investigation." Pavia University Press, Paviam 2020, pp. 238-247.

[20] S. La Placa, S. Parrinello, "Vectorialisation practices of the image drawing of the floor mosaics of the Basilica of Nativity in Bethlehem." SCIRES-IT-SCIentific RESearch and Information Technology 9.2 (2019): 95-104.

[21] B. J. Smith, M. Gomez-Heras, S. McCabe, "Understanding the decay of stone-built cultural heritage". Progress in Physical Geography, n. 32 (4), 2008, pp. 439-461.

[22] S. Parrinello, R. De Marco. "From survey to the model: the graphic transposition of an earthquake." Disegnare Idee Immagini, 2018, vol. 57, pp. 70-81.

[23] A. Miceli, M. Morandotti, S. Parrinello, "3D survey and semantic analysis for the documentation of built heritage. The case study of Palazzo Centrale of Pavia University". VITRUVIO - International Journal of Architectural Technology and Sustainability, vol. 5, n. 1, 2020, pp. 65-80.

[24] S. Parrinello, R. De Marco, "Integration and modelling of 3D data as strategy for structural diagnosis in Endangered Sites. The study case of Church of the Annunciation in Pokcha (Russia)." IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage, IMEKO, 2019, pp. 223-228.

[25] S. Parrinello, F. Picchio, R. De Marco, "New generations of Digital Databases for the development of Architectural Urban Risk Management." Le Vie dei Mercanti XV Forum Internazionale World Heritage and Disaster. Fabbrica Della Conoscenza, La scuola di Pitagora editrice, vol. 71, 2017, pp. 1-10.
.