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Digital documentation of fortified urban routes in Pavia (Italy): territorial databases and structural models for the preservation of military ruins

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Abstract

The analysis of the fortified routes in the city of Pavia (Italy) clarifies the adaptation of the medieval capital in the historical politics of the Mediterranean, where the evolution of the defensive system till the Spanish bastioned walls (sixteenth century) identifies the updating of the Lombard tradition to the practices of modern military architecture. Their defensive structures survive in the urban design of the contemporary city, in the configuration of infrastructures and urban aggregates, reflecting the consequences of the great processes of their dismantling (from 1905). The comparison between historical investigations and the current ruins, fragmented into disconnected portions between the historical bastions and the monumental gates, shows a picture of abandonment of the military structures that generates repeated collapses and emerging risk factors towards the surrounding densified urban context. The experimentation of military architectural approaches of documentation at the urban scale, developed by the research laboratory DAda Lab. of University of Pavia, defines an analysis process through the digital representation of the urban remains that is suitable for the preservation of the survived city walls and the enhancement of their fortified identity. The application of different 3D LiDAR systems for morphological acquisition promotes an integrated digitation process of *scansets* on the fortified system controlled at the urban metric scale: the experimentation applies the use of a mobile *real time* scanner for the digital tracking of historical routes, on which to implement the georeferencing of detailed static *scanworlds*, integrated in correspondence of Bastions and Monumental Gates. The optimization of architectural data density and the integration between data contribute to finalize a 3D territorial database predisposed to the architectural modelling of volumes and scenarios of structural instability of the military ruins, defining a virtual framework of widespread knowledge for the historical conservation and urban prevention of the fortified system.

Keywords: LiDAR survey, mobile LiDAR, urban fortification, Pavia.

1. Introduction

The strategic position of the city of Pavia, fluvial crossroad in Lombardy on the route from Milan to Europe, on the one hand, and Central Italy, on the other, has characterized the evolution of its historic center with a corresponding architectural project of military fortification, parallel to a constant expansion of the defensive walls and to the updating of the construction practices of European military engineering. Thus, the fortified project has followed the growth of the city and the location of its urban monuments, developing different borders of defensive walls concentrically to the historical settlement, to include its historical expansion, and each of them has deeply affected the territorial planning of both the defensive walls and the city gates.

From the foundation of the colony[1], four different fortified perimeters have succeeded, the first of Roman age, enlarged in the fifth century AD to include the palace of Theodoric, and then the double expansion of the Gothic walls and the subsequent replacement with the Spanish fortification from the mid-sixteenth century[2]. The sixteenth century walls, built during the Spanish occupation and then maintained by the Austrian Empire, have remained until the Italian unification as the last bastioned defence of the city. Their dismantling and demolition, for the reorganization of the urban fabric, officially entered in the city planning policy from 1903.

Fig. 1. Historical maps of evolution of military fortification in Pavia. On the top the Roman, the Gothic and the Spanish walls (G. B. Claricio, 1585); below, the bastioned city boundary (O. Ballada, 1654).

The Spanish military walls of Pavia follow and extend the layout of last medieval fortification, establishing new pentagonal bastions in correspondence of the previous towers. The first renewal of the fortification is recognized to the French occupation in 1506, with earthworks supported by wooden structures and gabions to protect the gates; however, the strategic project of the entire defensive system is due to the Spanish dominion. From 1546 to 1569, on initiative of Ferrante Gonzaga, governor of the city under the reign of Charles V[3], new military walls are raised, reinforced at the corners by 8 bastions. The new perimeter recovered the planimetry established in the historic center of Pavia and it planned to expand the defence area, widening the border on three sides, except for the river boundary to the south, even preserving the main routes of the city (Gianani, 1983). With the emperor's death in 1558, the fortified project continues its completion under the reign of Philip II, with massive interventions on the existing urban fabric and the destruction of buildings, orchards and gardens to give space to the wider walls.

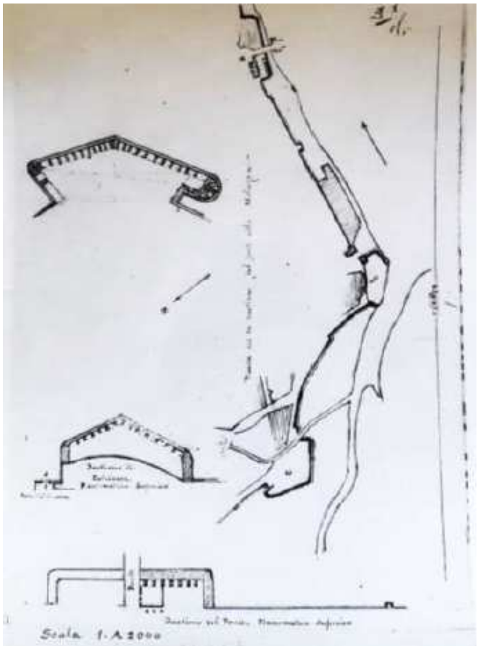


Fig. 2. Project drawings of bastioned fortified walls in Pavia (seventeenth century).

The construction of the renewed fortified perimeter constituted an update of the defense system to modern military engineering, providing pentagonal bastions for the "grazing fire" defence with cannons, and with the reinforcement of bastions' masonry layers to resist artillery compared to the previous crenelated walls. The bastioned system, initially consisting in an embankment and only later reinforced, supplemented the existing structures since the battle of 1525, completing the boundary on all city sides. Only later, in the seventeenth century, this system was extended beyond the riverside for the urban portion of Borgo Ticino.

From the eighteenth century, with the transition to Austrian occupation in 1730, the Spanish walls of Pavia began to be characterized by dismantling events. The first case, after 1783, devolved part of the fortresses and external forts to public benefit by decree of the emperor Joseph II. In 1866 the same Municipality of Pavia presented a petition for the suppression of the military walls, already abandoned, and it obtained from the military administration the full faculty to apply any modification. Subsequent interventions have concerned the "levelling" of the fortified walls, transformed into urban terraced gardens as in the case of *Bastione Borgoratto*, *Bastione del Brollo*, *Bastione Santa Maria in Pertica*, which were later replaced by the realization of the urban ring road (from 1897) and of the east railway line (1906-1915). Only in some punctual cases, the bastions found a new function that has preserved their demolition, as for *Bastione Sant'Epifanio*, converted in the 1950s into a bus parking area.

Fig. 3. Urban demolition of Spanish boundary since nineteenth century: on the top, east side of Bastione del Ponte, (Tollini, 1901); below, demolishment of Bastione Santa Giustina (1892).

2. The architectural documentation of the fortified ruins: objectives and strategies of digitation in the urban area

Actually, the objective of preservation of the city walls in the urban context of Pavia is mainly condensed around the Spanish walls, while few traces remained of previous perimeters, almost entirely destroyed or incorporated in the built fabric of the historical center. The ruins' route includes the monumental historic gates, such as *Porta Calcinara*, from the Gothic fortification, *Porta Nuova*, originally Gothic with the name of *Porta Damiani*, and *Porta Milano*, renewed in the nineteenth century[4]. These remains are linked to the larger perimeter of the conserved portions of Spanish fortification survived to infrastructural demolitions at the beginning of the twentieth century, which led both to the dismantling of the urban suburbs and to their levelling for the main road ring. The infrastructural intervention was planned at the urban level without including an architectural preservation of the monumental nature and historical value of the city walls, and it seriously compromised the cultural sign left by the fortified system on the city, altering the recognizability of the historical urban military form. In parallel, the absence of conservation monitoring applied to the walled ruins has led, today, to a picture of amplified abandonment and instability, with frequent collapses and risks for both population and urban infrastructures, the last repeated in 2016 and January 2019.

Fig. 4. State of conservation of ruins of Spanish fortification in Pavia, particular of Bastione Santo Stefano, incorporated in private residential areas by the urban plan (De Marco, 2017).

Fig. 5. Survey activities in 2019: on the top, mobile LiDAR survey, below static LiDAR survey.

In this context, the coordination of a documentation action developed by the University of Pavia[5] promotes a first analysis of the fortified walls aimed at a double objective: to trace and map the historical fortified ruins in relation to the urban context, in a scale of territorial control; to document the architectural value of the monument itself and of its critic features of stability and conservation, with an attention to the constructive aspect and to the structural analysis conditions related to the prevention of urban and infrastructural stability.

The research, started in 2017, has continued into 2019 with a territorial extension, experimenting the integration of LiDAR survey systems in order to manage, in terms of both *Territorial Scale* and *Big Data*, a georeferenced digital database of points from the urban complexity to reach the overall documentation of the entire fortified system. This database, virtualized in a 3D environment, has been oriented to develop a digital morphological quality of data for reaching a reliable information level on the conservation conditions of the fortified portions.

3. Integrated static and mobile survey systems for a digital metric mapping of the fragmented fortified route

With the aim of tracing the shape of the fortified route, the documentation was developed with an acquisition project along the Spanish wall perimeter, also in the partially dismantled portions, to identify all the existing sections and ruins and to transpose them into the reconstruction of the fortified path. The digital acquisition strategy has provided for a fast LiDAR integrated survey processed for *Scansets*[6] through static and mobile laser scanners, calibrated on the type and scale of information to be acquired.

In the first case, the more specific metric acquisition concerned the historic gates, such as *Porta Calcinara* and *Porta Nuova*, and the portions of bastions that are easily accessible and in good condition, such as *Bastione della Darsena*, *Bastardo del Terzago* along Ticino river and *Bastione Sant'Epifanio* in the west side of the city. The mobile survey, instead, has been applied in continuous tracking along urban roads that could underline, in addition to the preserved ruins, the no longer existing or inaccessible walls' sections, developing a metric base of connection for data between the main preserved sites along the historic route. The experimentation of mobile LiDAR has allowed a scanning phase conducted at the urban scale, resulting in an extensive territorial control of data suitable for providing, in a shorter time of acquisition and processing, a metric network of mapping for the entire fortified boundary.

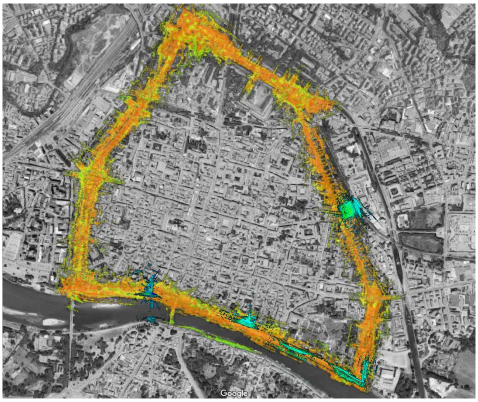
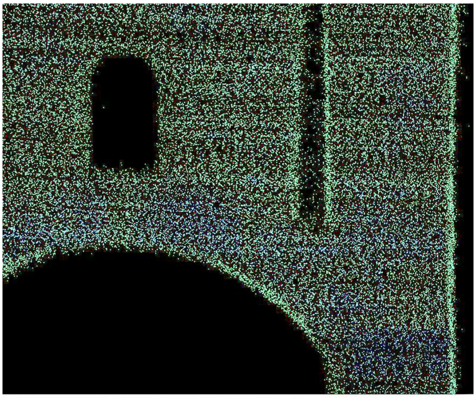


Fig. 6. Integrated LiDAR database of the fortified system of Pavia: reconstruction of the perimeter of Spanish fortification (orange), static integration of detail (blue) on gates and bastions (survey 2019).

The mobile LiDAR acquisition system, with KAARTA Stencil 2 scanner, has allowed, in the first phase, to identify the relationships between the single monumental, visible and accessible portions and the global layout of the fortified system, preserving the shape analysis within the urban fabric. The adoption of Mobile SLAM technology has achieved a continuous metric data in *real time* during the movement of the operator, guaranteeing an automatic registration of the generated points clouds in about 5 minutes for portions of 500 m, with a *laser spot spacing* contained in 20 mm at a distance of 10 m. The survey campaign has been organized with a plan of the scanning sections, developed in a continuous path within the urban area, avoiding closed or inaccessible roads in the acquisition trajectory, and always centered on the fortified element, often with a double parallel path on the top and at the base of the levelled fortified masonry. The documentation provided for the subdivision of the total path into shorter segments, allowing the instrument to elaborate a limited amount of data (Scanset of maximum 1.5 Gb) in a total database of 70 Scansets, for a total archive of 110 Gb developed on 4,6 km. The on-site control of the measured data has found some problems related to the acquisition of the instrument, with the automatic creation of discrete multi-surfaces duplicated within the same scan. These critical issues resulted in the excessive rotation of the instrument during the survey and to the solar glare suffered by the associated RGB camera, necessary for the recognition of dynamic targets used by the LiDAR for mobile tracking. These features have been corrected during the survey campaign.



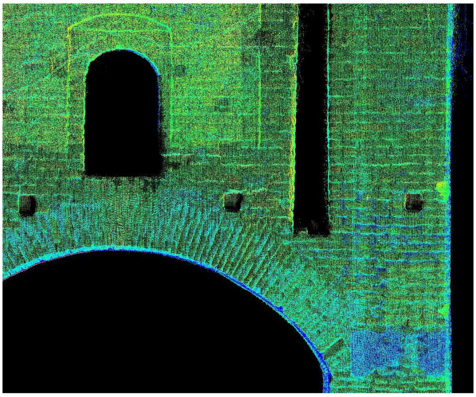


Fig. 7. *Porta Calcinara*: comparison in data quality of morphological description of masonry between mobile LiDAR (above), and static LiDAR (below).

For the LiDAR survey from static laser scanner, with FARO CAM2 Focus S150, data acquisition has focused both on the monumental context of the elements, to reconnect the scanworlds to the territorial system already digitized in the mobile phase, and on the deepening of the specific conformation of the monumental portions, evaluating the singularities of morphological detail to the planning of scan stations. This action aimed at completing the database with a densification of the morphological data suitable for the analysis of structural vulnerabilities and conditions of conservation of wall surfaces. The acquisition of monumental gates, *Porta Calcinara* and *Porta Nuova*, including their entire planimetric and altimetric development, with environments and wall masonries, both external and internal to the fornix, till the wooden structures of the roof. The polygonal routes of scanning have been developed in a closed path around the monuments and through the fornix; respectively, the acquisition included 14 Scanset each one, with a data density of 1 mm *laser spot spacing* for the portions on the ground and of 3 mm for the upper parts of walls.

The same acquisition strategy was conducted for Spanish bastions, conformed as architectural elements extended in linear development but morphologically more complex in the planimetric articulation. In particular, the documentation of *Bastione Sant'Epifanio*, preserved in full height, provided for a scan planning both on the urban façade, developing the detail of the interior of each fornix, and towards the countryside side, still including the perimeter of the highly degraded moat, with a total of 59 Scanset. The recording of the entire structural geometry in a single three-dimensional Scanworld allowed to digitally manage the structural configuration of the walled portion.

4. Management and georeferenced elaboration of morphological data for the development of the territorial model

The acquired scans included selection, filtering and processing of partial 3D point clouds, through different softwares[7] of optimization of static and mobile data, finalized to the database registration at the territorial scale.

In the alignment of Mobile LiDAR data, scans have been subdivided in relation to the layout of the urban context, considering the relationship of the fortified route with urban roads, infrastructural junctions, and with the disposition of walled ruins on a double level, on the main road and at the base of moat level. The division of acquired areas has guaranteed a better control, facilitating the management of the databases during registration. The interaction between the different scans, developed in *cloud-to-cloud* mode with the support of manual referenced targets, was optimal with overlapping sections of 100 m between Scansets, with an average error of 20 mm acceptable on the overall urban scale. The global database obtained by Mobile LiDAR has been extended to the territorial scale with an architectural shape detail. The alignment of static LiDAR data has been more effective and faster, thanks to the automation in the alignment of scansets allowed by the acquisition paths and by GPS information of each scan. The denser quality of data and the control of the closed polygons adopted on the sites of the monumental gates allowed to compensate the error on the scale of millimetre, maintaining a *cloud-to-cloud* recording mode. At the same time, the recording of the metric data on the bastions has presented criticalities due to the linearity of the acquisition paths, rarely connected in closed polygonals due to the lack of connections between road surface and basement perimeter. Cloud-to-cloud alignment supported by manual targets has contained the registration error and the metric reliability. The comparison between the two types of LiDAR data has showed differences in terms of quality and technical format. Morphological discrepancies are found near the edges of the walls and in proximity of the construction details, with more linear and defined geometries in the point clouds from static LiDAR respect to Mobile KAARTA data, more approximate and with rounded profiles in relation to the dynamic acquisition of the metric points. However, Mobile survey has achieved the arrangement of a 3D ScanWorld of the entire urban layout with an architectural quality in fast times, both of acquisition and of alignment in function of the greater extension of the single Scansets (up to 1 km) in comparison to the distance of static laser scanning (150 m).

The finalization of the overall territorial database has been possible with the registered integration of ScanWorlds from LiDAR systems, with manual insertion of control targets. The integration between databases, in terms of both extensive (mobile) and punctual (static) survey, has increased the quantity and quality of information that can be managed in terms of fast documentation of the extended ruins of the city walls, functional to the analysis of wall sections. The instrumental complementarity and reliability control in the alignment of metric data allowed to focus on the morphology of the fortified system, supporting possibilities of analysis of the architectural context at the different scales of investigation. It has also defined a basic metric network as an organic system of information adaptable to multiple and subsequent actions of discretization and integration.

5. Conclusions

The action of documentation applied on the ruins of the fortified system of the city of Pavia shows how the extension of the mapping on a fortified system on the territorial scale increa-

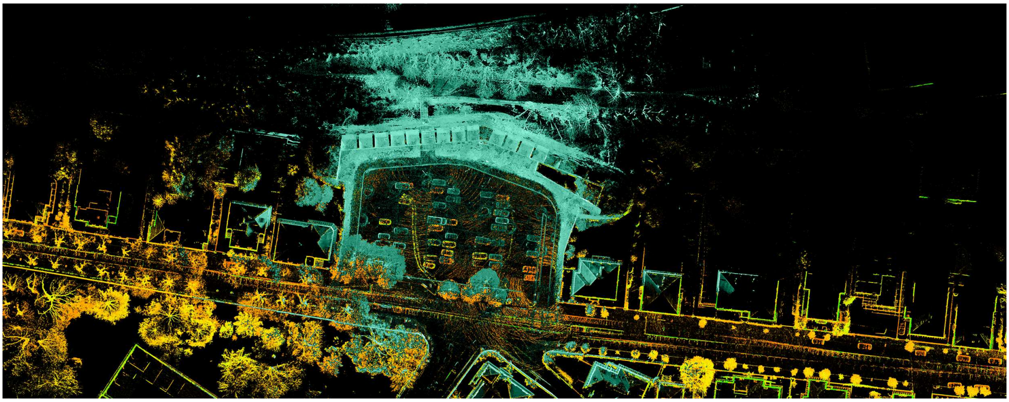


Fig. 8. Integration between Mobile LiDAR survey (yellow), of the overall fortified boundary, and Static LiDAR survey (blue): detail of georeferenced point cloud of *Bastione di Sant'Epifanio* within the urban built context.

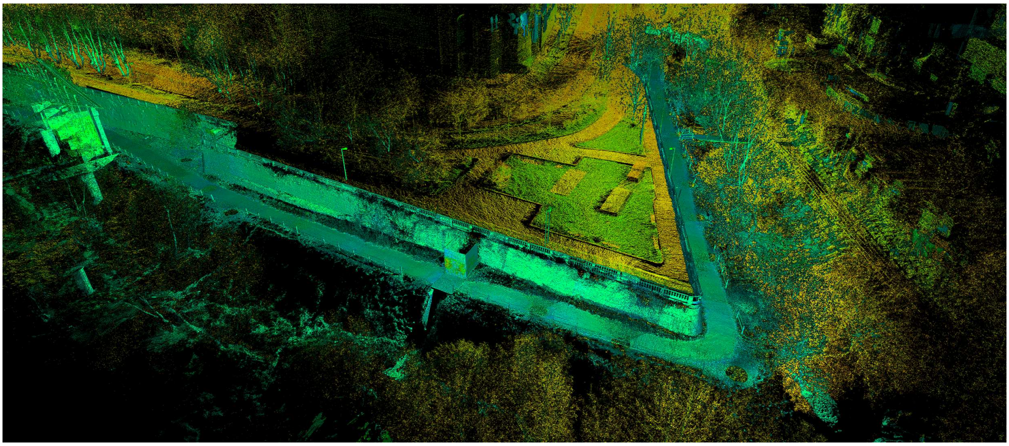


Fig. 9. Quality integration for mobile (yellow) and static (blue) point cloud in the survey of *Bastione della Darsena* ruins for a deeper documentation of masonry and structural quality of the monumental ruins, in fast acquisition times.

singly requires acquisition procedures at the same time reliable and fast. Reliability is considered for the development of adequate and dynamic monitoring and diagnostic operations of walled structures, achieving a 3D territorial database that can be integrated over time, for multiple analyses both historical, geometric and for information modelling. The development of research is for the integration of inaccessible portions of walls, such as those preserved in original height or incorporated in private areas. Thus, an implementation of acquisition is offered by UAV cameras, in particular on the top and countryside of the walls. Another aspect is linked to semantisation of spatial discontinuous data, subdividing the fortified ruins from the urban layers of trees, gardens, roads and built fabric of the city.

The digital documentation strategy for the integration of detailed Scanworlds fits the control of a territorial network of the fortified route of Pavia, thus achieving a balanced survey in terms of efficiency and reliability. The goal of fast survey in the connection of the fragmented fortified ruins towards the establishment of adequate architectural-urban models, operating both as dimensional documentation and spatial data for structural diagnostics, enlarges the potentialities of such amount of data and it directs new opportunities of management of territorial databases to understande territorial complexities and rediscover the fortified origin.

Notes

Paragraphs 1, 2, 5 were written by Raffaella De Marco, paragraph 3 by Francesca Galasso, and paragraph 4 by Chiara Malusardi.

[1] The foundation of the Roman city dates to 89 BC, recognizing Ticinum camp by Ius Latii, legal status of urbes. See Fagnani 1959.

[2] For a more extensive focus on the architectural morphology of ruins in the historic fortification of Pavia, see Parrinello, De Marco 2017.

[3] The Spanish conquest of the city was in 1525 with the famous Battle of Pavia between the emperor Charles V and French king Francis I, imprisoned in the city. The battle, decisive for the conquest of Italy, changed the urban fortification with the destruction of the entire north side of Castle's walls, then included in the project of reconstruction of new bastions. Among the fortified project, the activity of Eng. Giovanni Maria Olgiati (1494-1557), director of walls' construction from 1542 to 1555.

[4] *Porta San Vito*, then *Porta Milano*, was renewed during the construction of Naviglio canal, (1816-1818), within a neoclassical reform of urban gates, now destroyed, including *Porta Ponte* and *Porta Borgoratto* (*Porta Cavour*), designed by arch. Carlo Amati (1822) and eng. Carlo Reale (1823).

[5] The research project on digital documentation of the fortified ruins in Pavia is developed by DAda Laboratory (director prof. S. Parrinello) of DICAr - Department of Civil Engineering and Architecture of University of Pavia.

[6] Considering the different types of instrumental data, namely "scans" for static LiDAR and "trajectories" for mobile LiDAR, "Scanset" has been adopted to identify a single metric acquisition set of data by a LiDAR instrument.

[7] Processing with Cloud Compare, for KAARTA scans, and SCENE, for FARO scans; then all data was registered through Cyclone.

Bibliography

Arecchi, A. (1999). *I bastioni di Pavia*, Liutprand Ed., Pavia.

Cerrillo-Cuenca, E.; Bueno-Ramírez, P. (2019). "Counting with the invisible record? The role of LiDAR in the interpretation of megalithic landscapes in south-western Iberia (Extremadura, Alentejo and Beira Baixa)", *Archaeological Prospection*, 26, pp. 251-264.

Galandra, M. (1994). "Le mura spagnole di Pavia (Alcune note storiche)", *Bollettino della Società Pavese di Storia Patria*, XCIV, XLVI, Litografia New Press, Como.

Gianani, F. (1983). *Le mura e le porte di Pavia antica*, Tipolitografia A e C S.r.l., Pavia.

Leydi, S. (1989). *Le cavalcate dell'ingegnero. L'opera di Gianmaria Olgiati ingegnere militare di Carlo V*, ISR, Ferrara.

Pavesi, P. (1897). *Le fortificazioni spagnole di Pavia*, Tipografia popolare, Pavia.

Parrinello, S. (2018). "La documentazione delle porte urbiche veronesi: progetto di analisi per la proposta di piani di recupero sul sistema fortificato", in *L'intreccio dei saperi per rispettare il passato interpretare il presente salvaguardare il futuro*, Italia, pp. 801-812.

Parrinello, S.; Marco, R. De. (2017). "Le mura di Pavia: sistemi digitali di modellazione virtuale per la valorizzazione urbana delle cinte fortificate", in *FORTMED 2017. Defensive Architecture of the Mediterranean XV to XVIII Centuries*, vol. 5, pp. 327-334.

Puente, I.; González-Jorge, H.; Martínez-Sánchez, J.; Arias, P. (2013). "Review of mobilemapping and surveying technologies", *International Measurement Confederation*, 46, pp. 2128-2144.

Sammartano G., Spanò A. (2018). "Point clouds by SLAM-based mobile mapping systems: accuracy and geometric content validation in multi sensor survey and stand-alone acquisition", *Applied Geomatics*, 10, pp. 317-339.

Tolomelli D. (2001). "Le fortificazioni esterne: traccia per uno studio", in Vicini, D., *Museo in Rivista. Notiziario dei Musei Civici di Pavia*, Musei Civici, Edizioni Cardano, Pavia, pp.57-59