Virtual Reconstruction of no longer Existing Archaeological Structures in Highly Urbanized Areas

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This paper presents a methodology for the virtual reconstruction of no longer existing archaeological structures, focusing on cases where the remains are concealed within contemporary urban environments. This approach is exemplified through the digital 3D reconstruction of the ancient Roman circus of Milan, a monumental building largely demolished at the end of the Roman Empire, with most of its remaining vestiges hidden beneath the modern urban fabric of Milan. Central to this approach is the comprehensive collection of historical research data, archival sources, and field inspections. This data is integrated with state-of-the-art surveying technologies, such as terrestrial and mobile laser scanning for underground data collection, photogrammetry for stratigraphic data extraction, and accurate georeferencing using differential GNSS. Thanks to accurate georeferencing, these data sets are then merged with preexisting cartographic and historical data in GIS. The subsequent digital reconstruction process draws upon this georeferenced corpus of sources and comparisons with similar circuses. Refined through interdisciplinary collaboration, this process yields precise and, in some cases, innovative archaeological hypotheses.

Keywords:
Virtual Reconstruction, Roman Circus, Interdisciplinary Data Integration, 3D Survey, Mobile Mapping, Laser Scanning, Photogrammetry, GNSS, GIS, Architectural CAD Modeling.

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1. INTRODUCTION

The 3D reconstruction of a non-extant building is not a new challenge, and established principles exist on how to approach the issue in terms of scientific reliability of sources, interpretative coherence, and methods of presenting information in the form of a virtual model [Denard 2009;

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Grande and Lopez-Menchero 2011; Bendicho 2013; Denard 2013]. Since the late 1990s, those involved in digital archaeology have grappled with the inherent multidisciplinarity of the problem. The creation of a virtual reconstruction in archaeology demands a diverse range of skills, from the ability to generate a 3D model based on known geometric elements, typical of 3D content designers with a strong technical background, to the expertise in philological analysis using available artifacts and historical context necessary for the process of anastylosis, inherent in archaeology and humanities disciplines in general [Reilly 1991; Barceló et al. 2000; Kuroczyński 2017].

The key to striking a proper balance between these two components lies in the seamless integration of realistic 3D model production based on existing conditions—typically obtained through a process of 3D digitization—and the reconstructive hypotheses suggested by archaeology specialists and implemented by digital modeling experts. It is through continuous interaction and balance between these two components that the process can maximize the likelihood of the reconstructive hypothesis aligning with the original structure [Guidi and Russo 2012].

However, despite the methodology being fairly established, each specific case necessitates adaptation to the surrounding conditions, involving varying choices and processes. In particular, the work presented here proposes a methodology tailored to extreme cases where the artifact to be reconstructed is situated in a highly urbanized city context, with the majority of the artifact being completely concealed by the current urban fabric.

The specific case study used to validate our methodological approach pertains to the ancient Roman circus of Milan, a vast structure erected at the end of the third century CE, during Milan's tenure as the capital of the Western Roman Empire. This monumental building was largely dismantled following the decline of the Roman Empire, with its materials repurposed for the construction of new edifices. However, as the cost-effectiveness of dismantling waned, remains were left in situ and repurposed as foundational elements for subsequent constructions. Consequently, the few surviving remains have reached us through their incorporation into modern buildings in various ways. In many instances, these vestiges comprise the foundations of modern structures. Therefore, it is not uncommon, in the area of Milan formerly occupied by the circus, to find elegant apartment buildings in whose basement part of the walls consist of remains of the circus foundations. In other cases, the few extant built elements have been repurposed as structural components, such as one of the two circus towers, which was 'recycled' during the Middle Ages as a bell tower for a church constructed nearby.

In a case like this, the integration of sophisticated 3D surveying techniques facilitating efficient alignment between subterranean and surface-level remains represents an initial non-trivial novelty. This allows for the creation of a realistic model of the existing structure, undoubtedly more accurate than any previously hypothesized approximation, thanks to the capabilities of the technologies employed. In particular, mobile mapping-based underground digitization is integrated with ground-based laser scanning to align the underground structures with those above ground, and differential GNSS is used for georeferencing the ensemble and aligning it with existing cartographic sources.

Moreover, the process proposed in this work underscores the necessity of employing a multitude of sources that individually are insufficient for reconstructive hypotheses but, when integrated, resolve hitherto unresolved interpretative ambiguities. In this regard, the collaboration of the Milan

Superintendency of Archaeology, Fine Arts and Landscape (in the rest of the paper addressed just as “the Superintendency”) was crucial, as it provided a vast number of archival sources without which the access to remains in the basements of Milan's city center or the interpretation of elements emerging from the monument surveys would have been impossible.

This paper presents the latest research on this nearly vanished ancient construction, encompassing updated three-dimensional surveys of all extant circus-related structures both above and below ground. Through the compilation of acquired data and analogies with contemporaneous buildings, a hypothetical three-dimensional model of the monument has been proposed, laying the groundwork for a more comprehensive understanding of Milan's circus and providing essential resources for future research endeavors. The work presented here is structured as follows: the first section is dedicated to a historical description of the monument and how it has arrived at its current state; a section is devoted to specific archival research and the information gleaned from it; a section deals with the technologies and methodologies used for the three-dimensional digitization of the monument's current state and the alignment of the different documental sources with the different explored locations; a section is dedicated to the 3D reconstruction process from various available sources; and a final section is dedicated to the conclusions.

2. HISTORICAL BACKGROUND

The Roman circus, a venue dedicated to horse racing competitions and various spectacles, derives its name from the Latin word "circus," meaning circle, reflecting the shape of the oval track around which races were held. Consisting of two straight stretches connected by two 180-degree bends, the circus featured a central structure known as the "spina" or backbone, with "metae" or turning posts positioned at each end. One short side of the circus housed the "carceres," stalls from which chariots commenced their races, while the opposite side, typically semicircular, often featured a monumental gateway leading to the center. The long sides of the structure featured the "cavea," tiers of seating for spectators, while the "pulvinar" or grandstand—a raised wooden platform sheltered by an awning, strategically positioned along one of the straight stretches—allowed the emperor to observe the races discreetly, unseen by the crowd [Humphrey 1986].

Milan's circus, which is believed to have been constructed concurrently with the Imperial Palace, was situated on the western periphery of the city following the relocation of Emperor Maximianus's court, marking Milan's ascension to imperial capital in the late 3rd to early 4th century [Roberto 2018; Sacchi and Rossignani 2012]. The construction of this complex necessitated a significant urban overhaul: Several noble residences made way for palace annexes, while the city walls were extended westward to accommodate the monumental edifice [Caporusso 2017; Ceresa Mori 2018]. Serving not only as a venue for races and games but also as a site for the celebration of imperial power and grandeur, the circus remained integral to Milan's civic life until the Lombard era, witnessing significant events such as the coronation of King Adaloaldo [the Deacon 1974].

Despite its considerable dimensions—measuring approximately 470 by 80 meters—the Milanese circus, like many Roman monuments, underwent gradual dismantling over the centuries, and was eventually reduced to its foundations.

The entire area once occupied by the circus has undergone significant transformations over the centuries. During the Early Middle Ages (8th-9th century), the Benedictine monastery of "Maggiore" was established, incorporating and preserving some of the existing structures. Among these were large segments of walls, including a polygonal tower dating back to the late 3rd century, and a quadrangular tower believed to have been part of the original carceres of the circus. Over time, the monastery expanded to become one of Milan's most prominent female monasteries, generously supported by affluent families. This prosperity spurred further construction, including the Saint Maurizio church, decorated by the impressive cycle of frescoes by Bernardino Luini, whose bell tower was fashioned by repurposing the quadrangular tower from the circus.

The monastery was dissolved in 1789, after which time the area saw various uses, including as barracks, schools, police stations, and a military hospital. The northern section of the former circus, encompassing the monastery complex, underwent significant alterations, notably between 1865 and 1872, when two new streets — Via Luini and Via Ansperto — were carved out, leading to the fragmentation of the urban landscape.

The circus area suffered extensive damage during the bombings of 1943 in World War II, followed by further demolitions and urban renewal during postwar reconstruction efforts. As a result of these changes, only three sites within the contemporary city preserve remains of the circus structures. A portion of the curved wall, corresponding to a bend in the racetrack, still stands on Via Circo 9-11, reaching a height of approximately 12 meters due to its dual function as part of both the circus and of the defensive walls. Further north, a section of the eastern perimeter wall stretches for about 30 meters along Via Vigna 1, featuring six arches of the podium support vaults. However, the most notable surviving relic is the western tower of the carceres, located within the Maggiore Monastery complex and now part of the Civic Archaeological Museum [Fedeli 2015; Frova 1990; Mirabella Roberti 1984].

Despite the sparse visible remains, historical sources and characteristic place names such as "Via Circo" (Circus Street) and the medieval church of Santa Maria Maddalena "ad Circulum" attest to the presence of the monument in this area of the city. The first systematic investigation into the circus's remains was undertaken by Alberto De Capitani d'Arzago in 1937-38, which yielded detailed surveys of numerous sections of the foundation [De Capitani d'Arzago 1939].

Subsequent discoveries and studies have provided additional insights into the structure, but many aspects remain unresolved. Key questions include the location of entrances for the emperor and the public, the configuration and function of the carceres and eastern tower, and the appearance of the building's facade. Moreover, crucial details such as the spine and the track floor level, as well as the arena, have yet to be definitively identified, despite recent excavations at two sites within the circus area [Fedeli and Frontori 2020].

3. ARCHIVAL INVESTIGATION AND FIELD INSPECTIONS

The digital restoration of a monumental structure that no longer exists typically involves an iterative process, culminating in the creation of a final 3D model. This effort requires a multidisciplinary approach, wherein various technical and philological considerations contribute to formulating the most plausible reconstruction hypothesis.

Central to this endeavor is the exhaustive examination of all available documentary sources. Consequently, meticulous scrutiny of existing remains, combined with the collection and analysis of historical documents pertaining to the site—including previously published research works, historical maps, archival photographs, archaeological reports, ancient artworks, and textual records—formed the foundation of our investigative efforts.

Given the scarcity of visible remains, our research on the circus commenced with a comprehensive philological inquiry into historical and archival data, meticulously curated and interpreted by diverse experts collaborating within this project.

The investigative process commenced with extensive bibliographic and cartographic research, supplemented by close collaboration with the Milan Superintendency. Their archives yielded a wealth of invaluable resources, including photographs, constrains decrees (whose role is explained in detail in sec. 3.4), and logbooks documenting past physical inspections and excavations.

Below, we delineate the principal activities undertaken during our investigation.

3.1 Bibliographic Research

The initial phase of our investigation involved conducting comprehensive bibliographic research to deepen our understanding of Roman public buildings and circuses, spanning various epochs and geographical regions. Examining examples of contemporaneous works proved indispensable, particularly during the three-dimensional reconstruction phase, to address information gaps regarding the most plausible layout of the Milan circus.

Figure 1. Published first in [De Capitani d'Arzago 1939], this map depicts the area of Milan where the ancient remains of the circus lie, mostly hidden underground.

In this context, a seminal text authored by the English scholar Humphrey emerged as a cornerstone, offering extensive analyses and comparative insights on the subject [Humphrey 1986].

Moreover, we meticulously reviewed all publications pertaining to the circus of Milan, which provided invaluable insights into past studies and archaeological excavations. Among these, the work of archaeologist De Capitani held paramount significance. In the 1930s, De Capitani conducted pioneering research, systematically examining the monument, and delineating its position and overall dimensions through meticulous archaeological excavations. His efforts not only validated his hypotheses but also unearthed remains of parallel walls, foundational elements, and a substantial portion of the curved structure (Fig. 1). Other complementary sources are represented by later studies conducted in the last forty years around the Roman era of Milan and its circus in particular [Caporusso 2017; Ceresa Mori 2018; De Angelis Bertolotti et al. 1988; Fedeli 2015; Fedeli and Frontori 2020; Mirabella Roberti 1984].

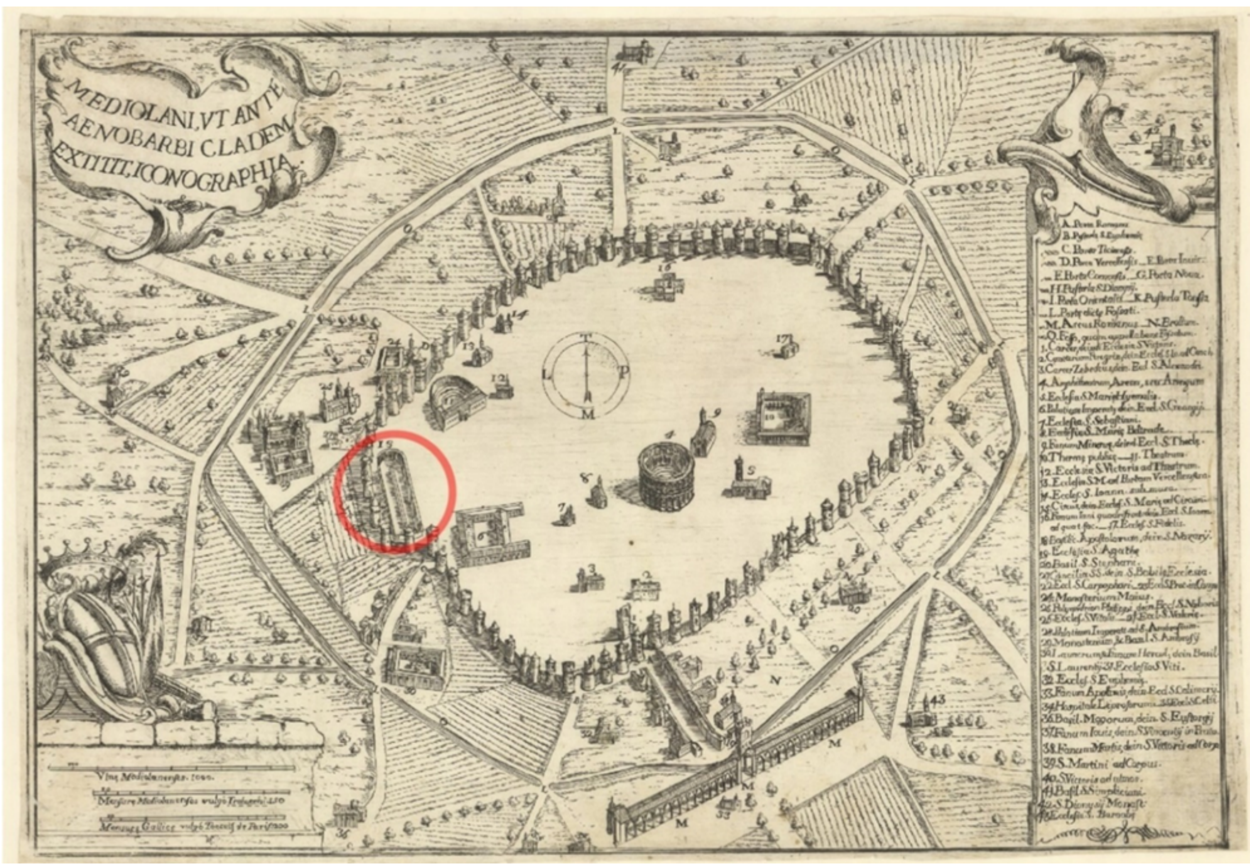


Figure 2. Historical map titled "1735, Mediolani, vi ante aenobarbi cladem extitit", with the Circus highlighted in red. The Circus is depicted upside-down compared to its actual orientation. (Courtesy of Archivio delle Stampe Bertarelli).

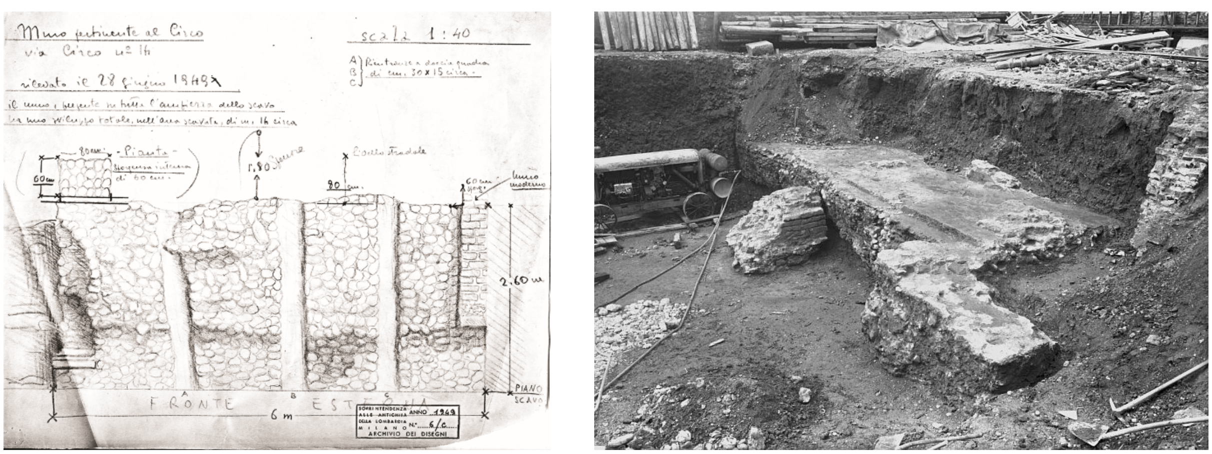
3.2 Cartographic Research

The Bertarelli Prints Archive, housing an extensive collection of ancient Milan maps, served as a valuable resource for conducting cartographic research aimed at comprehending the evolution of the expansive urban area upon which the circus was situated [Alberti 2024].

Within this archive, hundreds of maps spanning various periods of Milan's history were meticulously gathered, enabling the tracing of developmental changes over the centuries. Particularly intriguing among the multitude of maps consulted was an erroneous eighteenth-century depiction. In this rendition, the ancient monument was depicted as it was believed to have appeared based on the knowledge available at the time. Notably, the circus was positioned approximately to the city's east; however, it was depicted in an inverted orientation, with the carceres situated to the south and the curve to the north (Fig. 2). This significant misrepresentation suggests that by the eighteenth century, despite some vague recollections of the monument persisting, likely transmitted through oral tradition, most of the precise topographical details had faded from collective memory.

3.3 Historical Photographs

Extensive scrutiny was applied to the photographic archive housed within the superintendency's office, with a specific focus on uncovering insights into the Circus area. From approximately one thousand images examined, one hundred were meticulously chosen, encompassing artifacts documented during superintendency inspections or captured within construction project records (such as those pertaining to the subway, street developments, and new buildings). These selected images hold particular significance for several reasons. In instances where remains are still extant and visible, these images facilitate an assessment of potential fluctuations in the artifacts' state of preservation over time.



a) b)

Figure 3. a) Drawing depicting an archaeological excavation conducted at via Circo 14 in 1949, after WWII, showcasing remains that no longer exist; b) Photograph taken during the excavation of private building reconstruction in 1951, showing the remains in via Brisa, which are no longer visible (courtesy of Milan Superintendency of Archaeology, Fine Arts and Landscape).

Conversely, if the remains have since become obscured by modern structures or have been permanently removed, these photographs serve as invaluable documentary resources, aiding in the formulation of virtual restoration hypotheses (Fig. 3).

3.4 Archaeological Constraint Decrees

According to Italian law, heritage assets are deemed national treasures and are thus safeguarded by the state, even if situated within privately owned properties. The national government maintains detailed registries of sites of artistic, historical, archaeological, landscape, and architectural significance. It possesses the authority to prevent owners or custodians from undertaking actions that may compromise the integrity of these assets, such as destruction, modification, or alteration.

The responsibility for enforcing this protection lies with the Italian Ministry of Cultural Heritage, which delegates operational tasks to local superintendencies specializing in various types of cultural property (e.g., archaeological, artistic). These local offices issue legal decrees, known as "constraint decrees," designating specific assets as nationally significant cultural heritage sites and prohibiting owners from making alterations without authorization. Each superintendency oversees such decrees within its jurisdiction. In this case the Milan Superintendency of Archaeology, Fine Arts and Landscape was the one with jurisdiction over entire city of Milan, including the circus area.

Constraint decrees served as invaluable sources of information regarding archaeological remains associated with the Roman circus, scattered throughout the basements of apartment buildings in the Milan area once occupied by this monumental structure. These documents contain details of previous excavations, including field diaries, sketches, technical data, and photographic surveys. While this wealth of information proved generally beneficial for accessible remains, it became particularly crucial for elements hidden underground and rendered inaccessible due to subsequent urban development. For instance, many buildings were demolished and reconstructed during the post-war period, with excavated remains often documented, removed, or covered over in public areas.

In addition to archival research, we conducted thorough on-site inspections of the remains. With permission from the superintendency and cooperation from residents, we surveyed all buildings and their basements within the monument's vicinity. This comprehensive fieldwork allowed us to verify the presence of remains, assess their condition, and determine the feasibility of conducting three-dimensional surveys.

4. 3D SURVEY AND GEOREFERENCING

The research conducted on the documents mentioned earlier resulted in the planning and execution of a survey campaign aimed at recording all accessible remains of the circus, covering a substantial area of Milan's city center (Fig. 4), extending approximately 500 meters north to south and 200 meters east to west. The aim was to gather geometric, dimensional, and visual data on each segment and accurately map their spatial positions. Ultimately, the objective was to compile this information into a comprehensive digital model representing the current state of the monument, facilitating its analysis and eventually its digital restoration, as done previously in other projects [Guidi et al. 2014].

Figure 4. Map illustrating the areas where remains of the Roman circus are still present. Various colors denote zones surveyed using integrated 3D digital technologies to create an updated structural model: red for completed surveys, blue for areas with no significant findings, and beige for zones that were inaccessible due to logistical reasons.

To achieve this goal, a combination of techniques was employed. These methods allowed for meticulous documentation by capturing dense 3D point clouds accurately describing the geometry and, in some cases, the color of each surviving trace of the circus. The choice of technology depended on factors such as the condition of the remains and the specific objectives of the survey.

4.1 Terrestrial Laser Scanning

Terrestrial laser scanners (TLS) operate based on two primary techniques: Time of Flight (TOF) and Phase Shift (PS). TOF scanners measure distances by calculating the time taken for a short laser pulse to travel to an object and back. Conversely, PS scanners utilize sinusoidally modulated laser light and determine distance by measuring the phase difference between emitted and reflected laser light. This method offers high precision and resolution, making it suitable for mapping archaeological features. In addition to optically gathered distance data, the scanner collects the other two angular coordinates electromechanically using digital encoders. These encoders read the horizontal and vertical angles associated with each measured distance during the scanning process. Each triplet <horizontal angle, vertical angle, distance> is then converted into a Cartesian triplet <x, y, z>, expressed in meters and referenced to a Cartesian system where the z-axis represents the vertical direction, the xy-plane represents the horizontal plane, and the origin is situated at the optical center of the laser scanner. To ensure the system functions properly, it must remain fixed in one position throughout the entire scanning process. Typically, it is mounted on a tripod and leveled to align with the vertical direction in the real world, ensuring that the z-coordinate captured by the instrument accurately reflects the true vertical orientation [Calders et al. 2020].

a) b)

Figure 5. Leica HDS 7000 Terrestrial Laser Scanner (TLS) capturing archaeological structures in the backyard of the archaeological museums, including San Maurizio's bell tower, derived as a superelevation of one of the original circus towers: a) scanner operating in the field, right in front of the bell tower; b) resulting point cloud.

In this work different PS devices were used, a Faro Focus 3D and a Leica HDS 7000 (Fig. 5), set at least at 1 cm resolution on the digitized surface. The scans taken with these devices were of two categories:

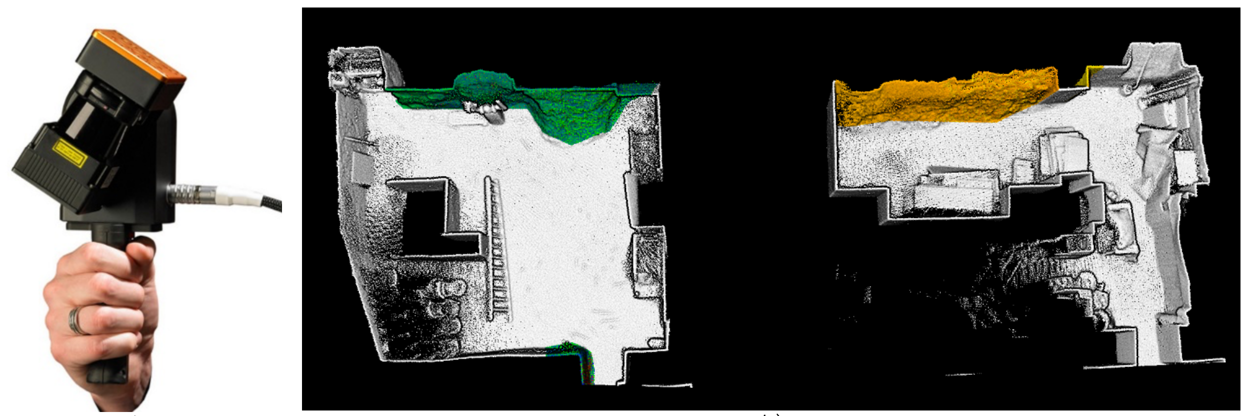
- in some cases, Roman remains either in the basements of modern buildings or in the outdoors;
- in most of the cases this technique was used for the larger spaces like squares, roads and large structures that were used as "connectors" between the outdoor and the indoor spaces.

The technical specifications of the two units used during our work are reported in Table I.

4.2 Mobile Laser Scanning

Unlike a terrestrial laser scanner, which typically remains stationary during the scanning process, a mobile mapping device, such as a handheld mobile LiDAR system, enables the operator to capture 3D data while in motion. The device used in this project, the Geoslam Zeb-Revo, incorporates a laser scanner that captures a single scan line at a time over a 270° angular field, excluding the portion of the scanline below the scanning point. Additionally, it features an Inertial Measurement Unit (IMU) that provides the device's angular orientation. The device is designed as a wearable unit capable of acquiring spatial data while the operator walks, holding the scanning unit in front, and connected to a backpack containing the battery and a data-logger unit for real-time data storage [Nocerino et al. 2017].

Since the scanner operates on a single scanline, the coordinates are calculated in 2D using optically measured distance and electromechanically calculated angles. These data are then rotated into a local 3D reference frame using the angular information provided by the IMU. The IMU also provides accelerations in the three spatial directions, enabling estimation of the unit's trajectory in space.



a) b)

Figure 6. Geoslam Zeb-Revo handheld mobile LiDAR: a) unit being carried out by the operator during scanning (the battery and acquisition device carried out in the operator's backpack are not shown here); b) example of point clouds obtained underground.

This allows real-time alignment of the single scanlines using an algorithm known as 3D Simultaneous Localization and Mapping (3D SLAM) [Keitaanniemi et al. 2023]. While terrestrial laser scanners excel at capturing detailed information from a fixed vantage point, mobile mapping devices offer the advantage of rapid data collection along routes or through tunnels (Fig. 6). This capability proved particularly beneficial in our case, where a major challenge was aligning the 3D digitization of a small section of a Roman wall in a building's basement with a large-scale 3D scan of a nearby square. To swiftly address this challenge, we chose to scan the Roman remains underground and continue scanning along the tunnel/basement to the stairs leading to ground level, the path to the door connecting to the road, and finally the road itself leading to the previously scanned square.

Table I – Technical specifications of the laser scanning devices used in the project

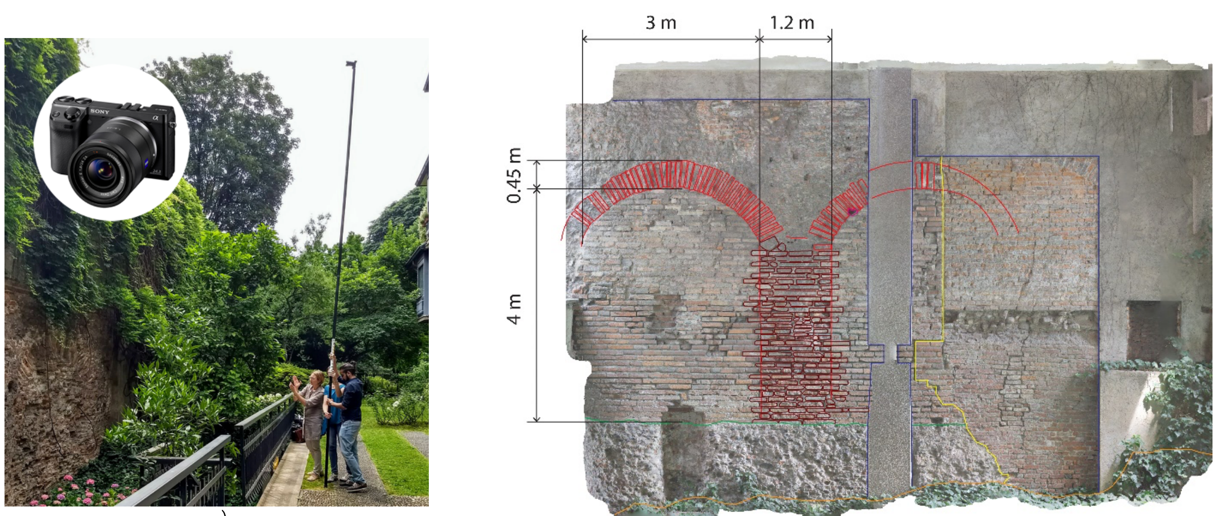
	Faro Focus 3D	**Leica HDS 7000**	**Geoslam Zeb-Revo**
Measuring principle	Phase Shift	Phase Shift	Time of Flight
Wavelength	905 nm	1500 nm	905 nm
Max angular resolution	0.009° (40960 points on 360°)		0.65°(416 points on 270°)
Beam divergence	0.19 mrad	< 0.3 mrad	NA
Range noise	1.2 mm (10% reflect.)	0.6 mm (0.14% reflect.)	6 mm
Spot size @10m	5.7 mm	6.8 mm	NA
Scan Rate max	976k pt/s	1016k pt/s	43 k pt/s
Angular field of view	360° x 305°	360° x 320°	360° x 270°
Max operating distance	120 m	187 m	30 m (indoor) 15 m (outdoor)

Although TLS could have been used for scanning tunnels [Argüelles-Fraga et al. 2013], we found the mobile mapping approach for the interior/underground sections swifter and more effective. By employing both static and mobile scanning devices, the square/large area served as a connection between the above and below-ground components of the 3D scan. This approach was repeated along different routes to ensure redundancy of information, essential for the final global optimization of the relative orientation of the various components. The technical specifications of the mobile devices used for this work are detailed in Table I.

The efficacy of this method proved indispensable due to the unique characteristics of the remains under survey: i) the majority of the remains were situated within rooms and basements of private properties, often prestigious residences with privacy and security concerns; ii) the necessity of navigating lengthy and intricate paths from the Roman remains to the outdoor areas crucial for data alignment; and iii) the imperative of completing the work swiftly to minimize the time spent within the private residences during the data acquisition phase.

4.3 Photogrammetry

In addition to the two previously mentioned active 3D acquisition systems, the decision was made to employ photogrammetric surveying utilizing the Structure from Motion/Image Matching (SfM/IM) technique [Aicardi et al. 2018].



a) b)

Figure 7. Photogrammetric acquisition: a) example of shooting with the camera mounted on a tall monopod to capture details of one of the few walls of the circus still standing; b) metric orthoimage showing the traces of the structures supporting the seatings.

Two primary considerations drove this decision. Firstly, photogrammetric surveying excels in generating high-resolution two-dimensional metric representations, facilitating the enhanced extraction of traces on walls discernible through wall stratigraphy. This capability proved particularly valuable when examining one of the few remaining intact walls at via Luini 1, where distinct traces of supporting arches for seating steps were clearly discernible [Kassotakis and Sarhosis 2021].

Secondly, the flexibility of sensor movement during acquisition, afforded by photogrammetry, is facilitated by a simple, lightweight camera that can be positioned atop a pole [Kallas and Napolitano 2023]. This allows for access to shooting points that would otherwise be inaccessible with bulkier and heavier 3D scanners. While an alternative could have been a camera mounted on a drone, logistical challenges and the complexity of obtaining flight authorizations make this approach nearly unfeasible in densely urbanized areas like Milan's city center [Colomina and Molina 2014]. Therefore, employing a tall monopod provided a solution to access locations that would have been otherwise unreachable with alternative technologies (Fig. 7).

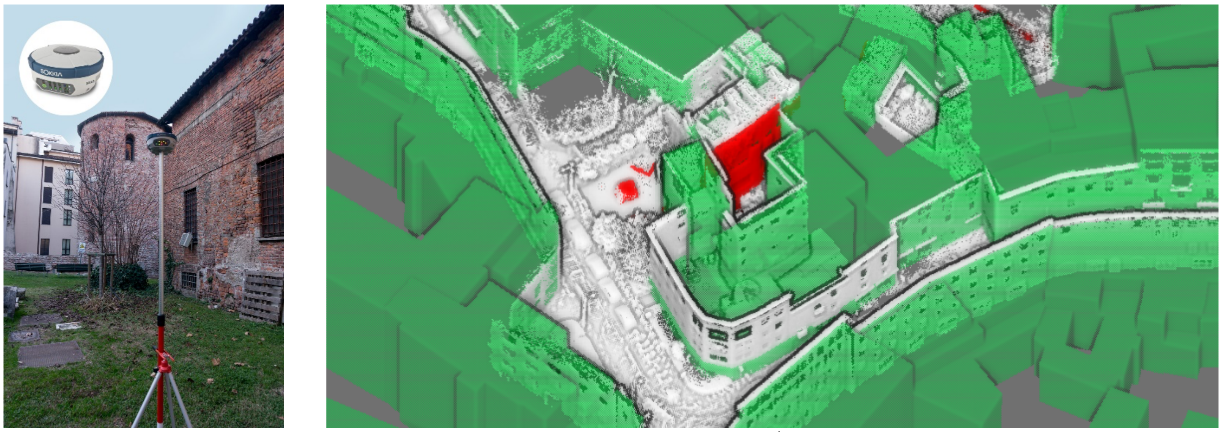
4.4 Differential GNSS

In addition to a relative orientation through Iterative Closest Point (ICP) optimization on partially overlapped 3D datasets, we performed an absolute orientation of selected reference points within the 3D scan data. This involved estimating the absolute georeferenced coordinates of specific ground control points defined by targets. These targets were both scanned during the 3D survey and measured separately using a differential Global Navigation Satellite System (GNSS).

As is well-known, standard GNSS receivers provide location information based on signals received from satellites. The satellite networks available for this purpose include GPS (USA), GLONASS (Russia), Galileo (Europe), and BeiDou (China). However, regardless of the network used, these signals are susceptible to various factors such as atmospheric conditions, signal blockages, and satellite orbit errors, which can introduce inaccuracies in position determination. For this reason, rather than relying solely on direct measurements from satellite signals, a differential Global Navigation Satellite System (GNSS) can be utilized for high-accuracy applications [Odijk et al. 2017].

The differential GNSS system consists of a mobile unit, known as the "rover," and a second receiver situated in a fixed position, referred to as the "base station." The base station's position is determined with high accuracy using traditional survey methods integrated with GNSS measurements averaged over extended periods of time (several hours or more) to minimize measurement uncertainty. During real-time survey operations, the base station estimates its position using a specific set of instantaneous satellite pulses and compares it with the previously known reliable position estimation. This comparison allows for the estimation of a set of corrections, which are then transmitted to the rover unit. The rover, operating in a different but nearby location, applies these corrections to its own GNSS estimated position at the same instant, resulting in an improved estimation accuracy in the order of few centimeters [Chen et al. 2018]. During the survey of the circus remains, a differential GNSS survey over 13 points uniformly distributed across the surveyed area was performed. Such absolute coordinates were used for a final alignment and georeferencing of the 3D data collected above the ground level, previously aligned with the underground scans. The survey was carried out by identifying certain areas, typically squares, large courtyards, or private terraces, to maximize the visibility of satellite constellations while simultaneously limiting the multipath effect.

The receivers were positioned on 2.20 m high survey poles for reduced multipath and greater satellite visibility, whose verticality was ensured by bubble leveling. They were left stationary acquiring satellite signals at a measurement frequency of one per second for an average time window of 22 minutes to improve the estimation accuracy. As a result, the standard deviation of positioning error was below 2 cm in all cases except one (see station S05 in table III).



a) b)

Figure 8. GNSS data acquisition: a) GNSS receiver during the 20 minutes data acquisition phase in front of the roman towers, in the Archaeological Museum backyard; b) 3D scans georeferenced through the GNSS data.

This step proved to be crucial for establishing the most reliable survey ever made on the Roman circus of Milan remains, that was used as a starting point for the reconstruction process. Additionally, it allowed for the proper alignment with previously existing geographical data and the correction of certain details about the monument that remained uncertain after previous research efforts.

a) b)

Figure 9. Locations of the data acquisition sites referenced in Tables II and III: a) regions where the handheld laser scanning took place; b) specific points where the geographical coordinates of targets were acquired using a differential GNSS device.

Table II – Geographical locations, visualized in Fig. 9a, where the absolute coordinates of targets were acquired using the differential GNSS device.

	Longitude	Latitude
Via Cappuccio 15	45.46331	9.17924
Via Cappuccio 17	45.46345	9.17927
Via Cappuccio 21	45.46392	9.17912
Via Circo 4	45.46180	9.18078
Via Circo 9	45.46113	9.18012
Via Circo 10	45.46159	9.17949
Via Circo 11	45.46103	9.17987
Via Torchio 12	45.46079	9.18034
Via Medici 9	45.46112	9.18091
Via Morigi 7	45.46321	9.18044
Via Morigi 13	45.46399	9.18056
Via Morigi 15	45.46417	9.18040
Via Vigna 1	45.46412	9.18010
Torri romane	45.46506	9.17847
Via Ansperto 7	45.46480	9.17912

Table III – Geographical locations, visualized in Fig. 9b, where underground 3D scanning was conducted using the handheld mobile Lidar. The third column shows the standard deviation of each position in mm.

	Longitude	Latitude	Std Dev (mm)
S01	45.46501	9.17869	6
S02	45.46499	9.17884	17
S03	45.46495	9.17898	4
S04	45.46489	9.17868	10
S05	45.46485	9.17946	32
S06	45.46479	9.17925	6
S07	45.46427	9.18061	3
S08	45.46416	9.18071	6
S09	45.46198	9.18185	9
S10	45.46188	9.18191	18
S11	45.46102	9.18018	1
S12	45.46080	9.17960	13

4.5 3D Data Integration

A differential GNSS with centimeter-level accuracy was used to georeference large point clouds of squares and large spaces gathered with a terrestrial laser scanner mounted on a tripod. This generated a set of fixed dense clouds at different spots of the entire circus area locked in by the GNSS control points, covering approximately a rectangle 500 meters long and 100 meters wide. Each georeferenced point cloud was used to align with Iterative Closest Point (ICP) the point clouds originated by a handheld mobile mapping device.

The ICP process exhibited a standard deviation of error in the order of few centimeters in all the cases considered.

Figure 10 displays the alignment of TLS and mobile mapping system data, mutually aligned with ICP and georeferenced using differential GNSS, overlaid on the city's provided georeferenced plan. The 3D scanned component (depicted in gray) seamlessly integrates with the underlying map (illustrated in green), serving as an initial visual validation of the process's efficacy.

Additionally, the figure illustrates the path traversed by the mobile lidar operator while scanning the outdoor areas.

Figure 10. Integration between the mobile lidar data with the terrestrial laser scans mutually aligned with ICP and georeferenced using differential GNSS. Such data, here represented in gray, are overlaid on the city's provided georeferenced plan (green). The figure also illustrates the path traversed by the mobile lidar operator while scanning the outdoor areas (red).

4.6 Geographical Information System (GIS)

Since all collected data are pivotal in hypothesizing and reconstructing the ancient Roman circus, we integrated all gathered information from various research strands into a Geographic Information System (GIS), linking them to specific locations within the area. This enabled us to organize existing elements conducive to developing virtual reconstruction hypotheses according to a geometric framework. To establish a comprehensive framework where each piece of evidence corresponds to a specific location within the circus, we utilized the commercial GIS platform ArcMAP by ESRI. The initial step involved georeferencing the current city map provided by the municipality of Milan, along with significant historical surveys conducted in the late 1930s [De Capitani d'Arzago 1939] and in the 1980s [Mirabella Roberti 1984], and finally, with our updated 3D digitization of the underground remains.

Georeferencing was achieved by aligning the existing maps with the cadastral map provided by the municipality of Milan, using recognizable modern buildings depicted on the historical maps as reference points. The circus remains delineated on the map were then converted from raster to vector drawings using AutoCAD, facilitating their incorporation into the 3D reconstruction of the circus. Subsequently, this georeferenced map was linked to a geodatabase containing all archival data, with table fields aligned with existing metadata associated with archival documents. Each identified wall segment was linked to pertinent information regarding excavations, documentation, constraint decrees, and images [Guidi et al. 2017].

5. DIGITAL RECONSTRUCTION OF THE CIRCUS

This section presents the accurate reconstruction of the circus, achieved through a synthesis of on-site inspections, georeferenced 3D survey data of extant remains, and examination of historical sources including maps, drawings, archaeological reports, and archived photographs. While the georeferenced 3D survey clarified previously uncertain aspects of the monument, historical and archaeological data were instrumental in speculating about lost details. Particularly significant insights were drawn from comparable late Roman circuses, such as Nicomedia, Maxentius, Trier, Sirmium, and Constantinople, with a focus on the extensively excavated Maxentius circus in Rome, attributed to Emperor Maxentius, son of Emperor Maximian, who likely built the circus in Milan [Barnes 2013]. In the absence of physical evidence from the Milan circus, reconstruction efforts heavily leaned on the excavated features of Maxentius's circus. Additionally, earlier circuses like those in Lepcis Magna and Circus Maximus in Rome provided supplementary inspiration for reconstructing certain architectural elements. This iterative process of reconstruction was characterized by a robust interdisciplinary collaboration, wherein the supervising archaeologist at the Milan Superintendency continuously revisited and refined our reconstruction hypotheses based on a diverse array of datasets, ultimately aiming to arrive at the most precise and well-grounded assumptions.

5.1 Orientation of Arena and Walls

The style of construction of Roman circuses can be associated to the objective of Romans to make chariot racing as fair as possible for all the competitors. The most important feature that became important in the design of Roman circuses was the distance between the starting gates and the nearest turning post. In different eras, Roman architects proposed several designs to allow all competitors to follow an equal path before starting the race and avoid accidents at the race start. In the late Roman circuses, a solution which was adapted included the starting gates laid across a curve, inclined turning posts (and the barrier joining them) and changes in orientation in the walls of circus on both sides [Humphrey 1986].

A noteworthy finding from this analysis concerns the implication in our reconstruction regarding the tower's position with respect to the circus walls. Initially, the reconstruction proposed in De Capitani d'Arzago [1939] and shown in Fig. 1 assumed the external circus walls were parallel from the curve to the starting area. This implied the walls, where the tower stands, were tangent to it, placing the tower outside the circus perimeter. However, the accurate survey of underground remains reveals an actual change in orientation of the outer circus wall on both sides of the structure.

On the side with the standing tower, the survey indicated non-parallel directions, intersecting at a 3° angle as depicted in Fig. 11. This revised understanding aligns the outer circus wall with the tower facing the curve, as expected from similar circuses of the same era. Moreover, this change in orientation, as noted by Humphreys, accurately pinpoints the likely position of the race's starting line. Similarly, on the opposite side of the circus, the alignment of remains near the curve and the starting zone shows another angle change, approximately 1°, providing additional insight into the race's finish line location. This detail is crucial, as Humphrey suggests the Imperial box was constructed in correspondence of the finish line.

Figure 11. Positioning of the reconstructive hypothesis of the Roman Circus, overlapped with the modern city map of Milan.

While previous hypotheses vaguely suggested these orientation changes, the precise identification of intersection points between parallel lines near the curve and oblique lines near the finish area was lacking. In both instances, this new information derived from meticulous underground surveys not only aids in three-dimensional reconstruction of the building, but also represents an archaeological discovery that could lead to the identification of new excavation sites by the superintendency archaeologists.

All the mentioned elements can be found in the new plan of the monument, visible in Fig. 11, elaborated based on the position of the existing detected and georeferenced remains (in dark red) and taking into consideration all the bibliographic information collected during the project.

5.2 Length of Arena and Circus Planimetry

The previously proposed arena length, lacking precise 3D data and geo-referencing, was estimated at 485 meters [De Capitani d'Arzago 1939:56]. This conjecture, originating from the early 20th century, assumed the Milan circus's arena length matched that of the excavated circus of Maxentius [De Capitani d'Arzago 1939]. However, within the scope of this research, the analysis of elevation remains and the available foundation segments in the southern area enabled the accurate identification of the curve's position, resulting in a revised arena length estimation of 460 meters, evaluated internally, as shown in Fig. 11.

In addition to the arena length, this investigation, leveraging contemporary survey and geographical positioning technologies unavailable during previous studies, systematizes previously gathered information. Figure 12 illustrates a comparison between the newly proposed plan (in red) and the graphical depiction from the most recent reconstruction hypothesis [Caporusso et al. 2014] (in green), making visually evident the significant difference among the two.

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Figure 12. Comparison between the plan proposed in our reconstruction following the underground survey with state-of-the-art technologies (red), and the last most recent hypothesis published in 2014 (green).

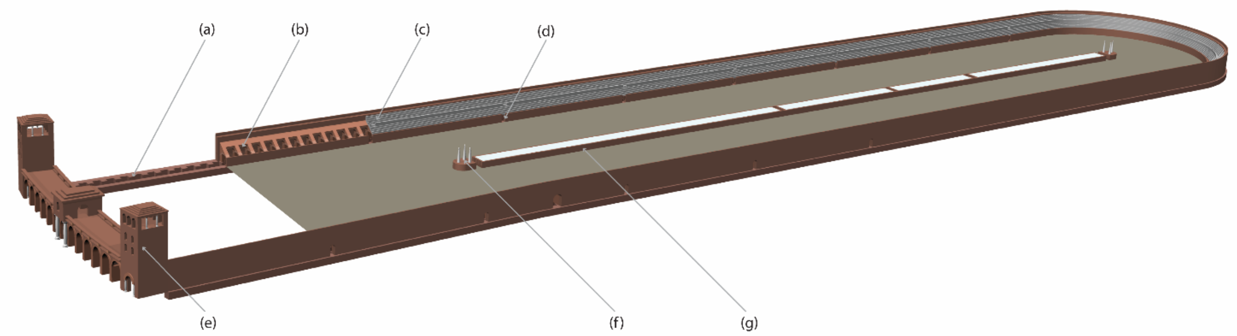


Figure 13. Three-dimensional model of the roman circus of Milan with some sections to demonstrate important details: (a) basement, (b) internal and external walls with the vaults system sustaining the podium and gallery, (c) seating tiers, (d) access to the tribune, (e) tower of carceres, (f) cone of the meta, (g) barrier.

Following the accurate planimetry defined according to the latest data, the three-dimensional model of the circus was developed (Fig. 13), incorporating all relevant data concerning raised portions, historical sources, and comparisons with contemporary constructions of the same period.

The distinctive features of the reconstruction, detailed in subsequent subsections, underwent evaluation by archaeologists from the Civic Archaeological Museum and the Archaeology Superintendence of Milan, contributing to the identification of the most reliable solutions.

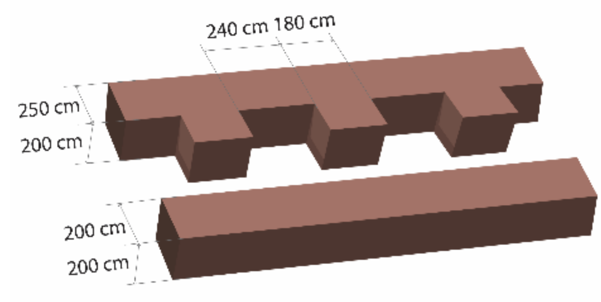
5.3 Foundations and Walls' Height

The foundation details are proposed based on a combination of actual measurements taken in the field at via Vigna 1, via Circo 10, and via Cappuccio 21, alongside a prior survey conducted at via S. Orsola n. 15 by Alberto de Capitani d'Arzago in the first half of the 1900s. The measurements obtained during previous comprehensive excavations of the foundations were deemed more reliable, given the limitations in fully surveying the height, width, and depth of the foundation remains in the current scenario. These foundations were characterized by an inner face attached to pilasters supporting arches of the vaults.

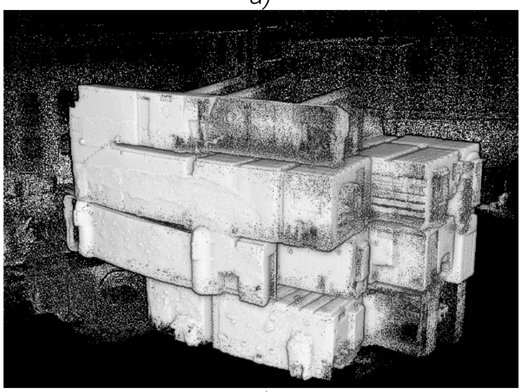
By scrutinizing areas where the transition from foundations to masonry is discernible, the potential height of the arena floor has been determined. This analysis reveals a greater elevation in the North and a lesser one in the South, consistent with insights derived from bibliographic sources.

Likewise, the height of the exterior wall was verified at locations where the entire height remains intact. Measurements taken at the remains of the outer wall of the circus in via Vigna 1 yielded a height of 7 meters, conflicting with various other sources. Consequently, additional measurements were taken at the curved end of the circus in via Circo 9, where the complete height of the exterior wall is preserved within a three-story building (see fig. 14c). Laser scan measurements at this juncture confirmed the total height of the circus to be 8.40 meters.

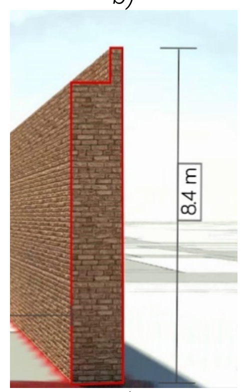
a)



b)



c)



d)

Figure 14. 3D data obtained from the remains of the circus and the reconstructed foundation and height of wall: a) 3D data of the foundation remains in via Cappuccio 21 with circus foundations highlighted in green; b) reconstruction of the basement on the basis of 3D survey and previous excavations in via S. Orsola n. 15; c) 3D data of the curved part of the circus wall still preserved in via Circo 9 which was used as a reference to verify the height of external wall of the circus; d) reconstruction of the exterior wall.

5.4 Interior/Exterior Wall Distance and Vault Details

Verification of the distance between external and internal walls was conducted at various sites, including via Vigna 1 on the eastern side and via Cappuccio 21 on the western side. Particularly at via Vigna 1, where remains of external walls in the courtyard and foundations of interior walls in the basement (Fig. 15a) remain visible, the laser scanning survey facilitated precise measurement of the distance between exterior remains and those in the basement. These measurements indicated a width of 4.75 meters for the *cavea* (Fig. 15b).

The configuration of vaults connecting the outer wall with the inner wall was hypothesized by integrating 3D data from photogrammetry and studying analogous structures used for performances in the Roman Empire. Apart from providing support to the podium, these vaults also functioned as galleries for public access to seating tier exits from the circus.

Figure 15. Data integration from various sources for reconstruction of vaults: a) Laser scanning in the basement of via Vigna 1; b) point cloud generated from laser scanning to calculate the distance between the exterior and interior wall of the circus; c) reconstruction of exterior and interior wall; d) details of vaults in the remains of Maxentius's circus in Rome; e) details of vaults in circus of Maximus in Rome; f) detail of our 3D reconstruction.

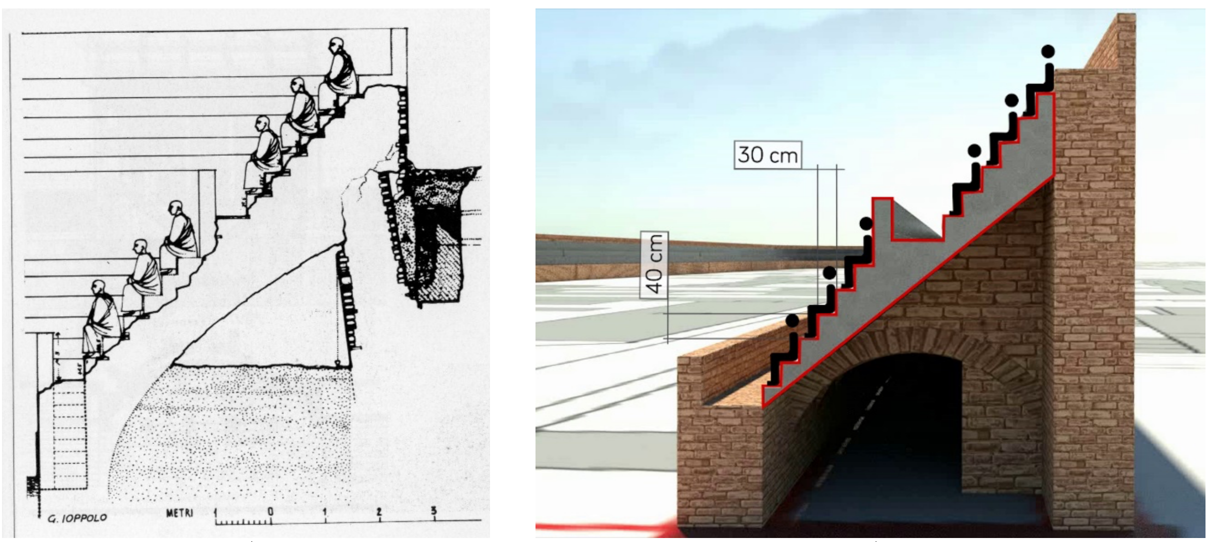
The analysis of the photogrammetric survey showing 3D arches and pillars at via Vigna 1 (Fig. 7b) suggested that the outer wall of the circus was linked to segmental arches measuring 3 meters in width and 4.45 meters in height from the foundations (Fig. 15b). While limited ground clues exist regarding vault structure reconstruction, the hypothesis presented in Figure 15f combines studies of construction techniques from the Roman period with comparisons to physical evidence from the Milan circus's remains. The most plausible structure entails vaults forming the corridor ceiling intersected by architraves supporting the podium. This hypothesis combines 3D measurements of the Milan circus remains with vault designs from the circus of Maxentius in Rome (Fig. 15d) and the fully visible vault structures in the Circus Maximus in Rome (Fig. 15e). Despite the Circus Maximus chronologically preceding the Milan Circus, it serves as the best-preserved example for analyzing and understanding Roman construction techniques in performance buildings.

Due to the insufficient height of the interior wall remains, detailed measurements of podium support pillars were unattainable. Consequently, the inclination of the podium support was hypothesized by comparing it with other Roman-era structures. A comprehensive report on vault reconstruction has been previously published [Guidi et al. 2017].

5.5 Seating Design

The first step of reconstructing the seating design involved combining the precise measurement between the exterior and interior walls of the circus (i.e., 4.75 meters), with a seating tier inclination of 45 degrees as per bibliographic sources from other circuses of the same period [Humphrey 1986]. Another aspect considered in reconstructing the seating arrangement was the subdivision of seating tiers into two different parts based on social classes, as suggested in the literature [Mirabella Roberti 1984]. Additionally, insights from Giovanni Ioppolo's proposed reconstruction of seating tiers in the circus of Maxentius, depicted in figure 13a [De Angelis Bertolotti et al. 1988], provided additional valuable clues.

These previous studies, coupled with measurements of the remains, guided the hypothesis of a probable seating tier design comprising two classes of three seats each, with seating width, footrest width, and step height set at 30 cm, 30 cm, and 40 cm, respectively, as illustrated in figure 16b. A detailed report on the logic process leading to the seating tier sizing and reconstruction has also been published previously [Guidi et al. 2017].



a) b)

Figure 16. Seating design in Roman circuses: a) reconstruction of seating tiers of the circus of Maxentius proposed by Giovanni Ioppolo; b) Our reconstruction hypothesis of seating tiers in the circus of Milan.

5.6 Towers of the *Carceres*

Nestled within the courtyard of Milan's Archaeological Museum stands the structure known as the "square tower," now serving as the bell tower for San Maurizio, one of the city's most celebrated churches, renowned for the abundance of frescoes adorning its interiors, and for this reason nicknamed the "Milan's Sistine Chapel."

The current state of this tower is the result of an elevation of the ancient tower of the carceres from the Roman Circus of Milan, commissioned by Emperor Maximian between 286 and 305 CE.

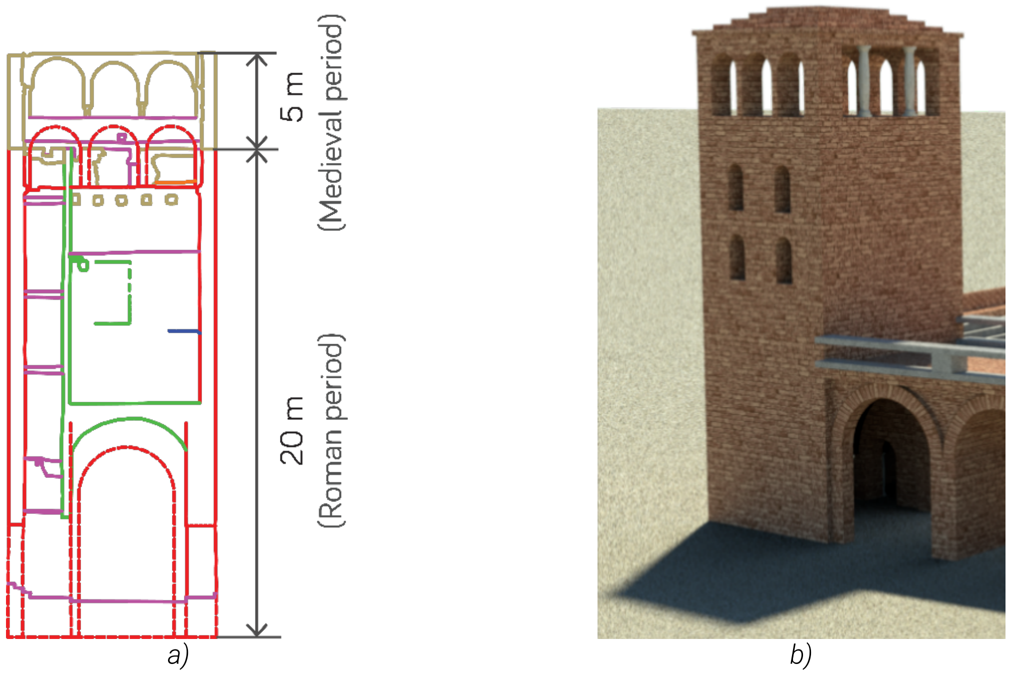


Figure 17. Digital reconstruction of the circus towers derived from the 3D model of San Maurizio's church bell tower: a) schematic representation showing the Roman portion of the tower; b) Virtual reconstruction derived by the reality-based 3D model.

In the Roman Circus, the carceres were a pair of identical towers serving as the starting gates for chariot races, typically stout in stature and crowned with a series of columns at their summits to support a flat roof.

In our case, only one of these two towers survived, likely preserved due to its later use as a bell tower, thus escaping medieval destruction. This tower underwent significant modifications over time. Notably, in the late 4th century CE, the spaces between the original columns were filled, likely for structural reinforcement. However, the most significant alteration occurred in the 9th century CE when the tower became part of a vast monastery known as "Monastero Maggiore." Archbishop Ansperto from Biassono, the ruling authority at the time, ordered the tower's elevation from its original height of 20m, with the addition of a 5m tall loggia (Fig. 17a), where the space for the bell was accommodated, transforming its structure into the bell tower we see today [Blockley 2017].

The towers' three-dimensional modeling process comprised three key steps: First , the current bell tower underwent 3D scanning to create a detailed mesh model based on reality [Morandi 2017]. Next, medieval additions were digitally removed from the model, restoring it to its original Roman-era height (see Fig. 17b). Subsequently, this mesh model served as the foundational representation of the original tower, allowing for the creation of a hand-drawn CAD model. This CAD model was then duplicated and incorporated into the 3D model of the circus' carceres, the flat side opposite to the circus's curve.

5.7 Barrier or *Spina*

A characteristic feature of Roman circuses was the presence of a central dividing barrier known as a *spina*, which linked the turning posts at both ends. This structure, consisting of a series of interconnected pools of water, served to equalize the distance between competitors and eliminate the need for sharp turns, particularly for those on the outermost lanes. Additionally, the turning posts at either end of the barrier supported three large cones, a traditional architectural element. Typically, the barrier was the first component of the circus to be constructed.

While no remains of such a barrier have been discovered in the Milan circus, analysis of other Roman circuses indicates that barriers with water pools and turning posts were integral features of any circus in the Roman era. Therefore, it is highly probable that the Roman circus in Milan possessed similar features that have not yet been unearthed. The reconstruction of the barrier, turning posts, and cones depicted in Fig. 18a is based on a combination of designs observed in the circuses of Lepcis Magna and Circus Maxentius (Fig. 18b). The choice to draw inspiration from Lepcis Magna stems from its well-preserved barrier, providing valuable insight into the original appearance of such structures in Roman circuses. Furthermore, the design of the four water basins within the barrier was influenced by Circus Maxentius, where remains of the barrier's foundations are still visible.

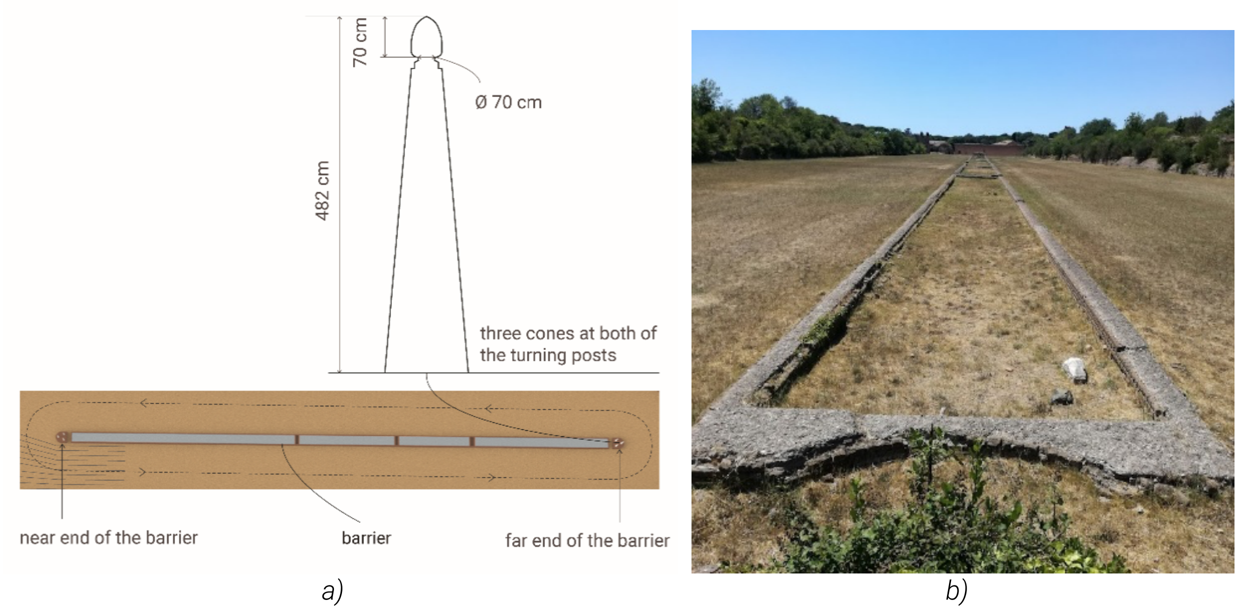


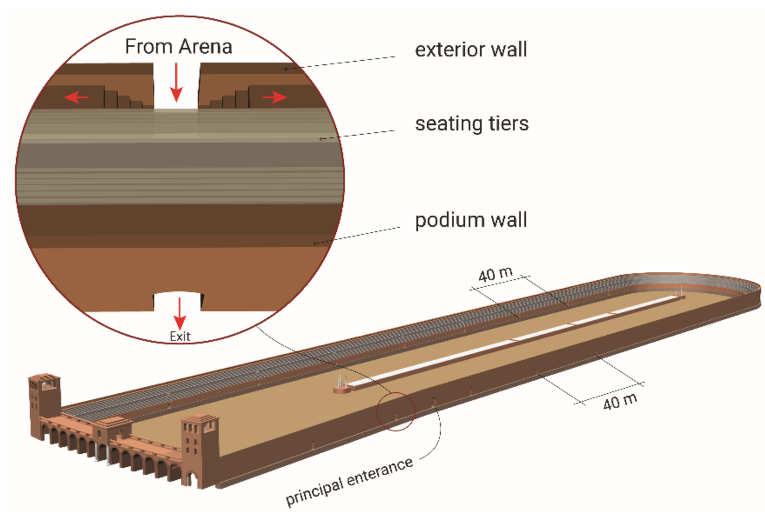
Figure 18. The reconstruction hypothesis of the barrier, turning posts and cones: a) probable orientation of barrier with respect to the arena and details of cones on the turning posts based on the remains of Lepcis Magna; b) remains of barrier in circus Maxentius.

5.8 Access to the Tribune and Stairway

In a typical Roman circus, there were numerous entrances and exits positioned at regular intervals for the convenience of spectators, a feature still discernible in the layouts of both the Lepcis Magna and Circus Maxentius (Fig. 19a). These entrances and exits provided access to the galleries beneath the seating areas, as depicted in Fig. 16b, granting passage to the arena doors and staircases leading to the seating tiers. Additionally, a primary entrance, typically located near the starting line, facilitated the passage of chariots at the conclusion of each race.

The reconstruction proposal for the access points to the seating tiers and staircases shown in Fig. 19b is informed by the surviving architectural features observed in the Circus Maxentius and the circus at Lepcis Magna. The placement of entrances at regular intervals of 40 meters, with a principal entry near the starting line, as posited in this reconstruction, is based on precise measurements taken from the remains of the Circus Maxentius in Rome.

a)



b)

Figure 19. Reconstruction hypothesis of the access to the tribune and stairway: a) circus Maxentius' remains; b) reconstruction hypothesis for the Milan's circus.

5.9 Textured 3D Model of the Complete Building

Once the phase of definition of the planimetric, volumetric and structural aspects was completed, a texturing phase was carried out with the attribution of hypothetical materials to the various surfaces.

Unfortunately, neither the sources nor the realized acquisition allow us to describe the original materials with certainty, so the mappings are intended to create only a suggestion of the original appearance of the circus.

Figure 20. Digital reconstruction of the Roman circus of Milan, generated through the methodology here described.

6. CONCLUSIONS

The work outlined in this article underscores the critical importance of integrating a comprehensive understanding of the current state of the asset to be reconstructed with thorough documentary research on previous archaeological studies and available ancillary documents. This necessity becomes even more pronounced when dealing with limited and scattered artifacts, particularly when they pertain to a structure of significant dimensions like a circus. Ensuring that all available information is consolidated into a unified representation is paramount for providing a comprehensive understanding of the monument's current state.

In this specific case, apart from contending with the dispersion of artifacts in space, we faced the additional challenge of artifacts distributed across multiple levels. While the site's location in an uninhabited area facilitated access for archaeologists, the task was considerably more complex when dealing with artifacts located within a densely populated city. Accessing detailed surveys of these artifacts posed significant challenges, overcome only through legal mechanisms, such as decrees of constraint and Italian legislation on the protection of cultural heritage, allowing access to private property containing culturally significant elements under legal constraint.

The results presented demonstrate the remarkable precision achievable through modern technology in estimating building components and their spatial positioning. This level of precision stands in stark contrast to earlier surveys, as evidenced by a significant disparity between our findings and those of previous surveys conducted in the 1940s and 1980s. The latter, in particular, gave a size estimation of the entire building along the longitudinal axis that was about 10m larger than the value found with our improved approach.

Furthermore, our findings have provided new insights into the interpretation of the circus's layout. By identifying an inclination in the outer wall as it approached the starting gates, we were able to propose a plausible location for the finish line of chariot races, shedding light on the possible positioning of the imperial box. This interpretation not only addresses longstanding discrepancies in previous hypotheses but also presents avenues for further investigation and excavation in previously unidentified areas of structural significance.

All these elements, identified as archaeological discoveries facilitated by accurate survey technologies, have defined the layout and orientation of the building in relation to the modern city.

Once the plan was ready for extruding the main walls, additional survey outcomes allowed us to add details to the building reconstruction.

The 3D laser scanning of a small built remains where the inner and the outer walls of the circus are still visible, allowed us to estimate the width of the seating area. In addition, the integration of 3D scanning with photogrammetry provided a high-resolution textured model of some crucial remains where the traces of the arches supporting the seating structure are still visible. This completed the set of missing geometrical information and allowed us to hypothesize the repetition frequency of the arched structures supporting the seating.

The shape and size of the towers was determined by considering the horizontal section of the portion of the San Maurizio bell tower that has been shown, via wall stratigraphy, to belong to the ancient Roman tower. All the various pieces of geometrical information were incorporated in the 3D digital reconstruction of the building that the archaeologists involved in the project consider a very logical and credible reconstruction hypothesis.

A particularly noteworthy outcome of this endeavor is the newfound connection between the inhabitants of central Milan and their historical heritage. Many residents were previously unaware of the existence of a circus beneath their city, only recognizing its presence through the name of a street. Experiencing the original form of this monumental structure has fostered a sense of awareness and affection for the territory among the populace, emphasizing the cultural significance of the bond between a community and its history [Micoli et al. 2021].

In summary, the integration of advanced technology with meticulous research methodologies has not only yielded precise archaeological reconstructions but has also enriched the cultural fabric of the community, highlighting the intrinsic value of preserving and understanding our collective heritage.

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