Multi-Sensor Documentation of a Demolished Spaceflight Engineering Heritage Site

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Commission II

Keywords: Terrestrial Laser Scanning (TLS), Photogrammetry, Space Heritage, Industrial Heritage, Digital Documentation, Multi-sensor Documentation.

Abstract

Large-scale industrial and engineering heritage sites are increasingly threatened by obsolescence, restricted access, and demolition, making timely digital documentation essential for preserving their spatial and technical knowledge. This paper presents a multi-sensor documentation campaign conducted at a late twentieth-century space engineering training facility shortly before its demolition. The site's scale, curved geometry, dense infrastructure, confined spaces, and variable environmental conditions posed significant challenges for data acquisition and processing. A hybrid workflow was developed integrating terrestrial laser scanning (TLS), immersive 360-degree capture, and targeted indoor drone-based image acquisition. TLS formed the metric backbone of the documentation, while immersive capture supported spatial navigation and contextual understanding. Drone imagery was selectively used to enhance visualization of inaccessible interior areas rather than for full photogrammetric reconstruction, due to site-specific limitations. Results demonstrate that no single technology was sufficient to address the combined geometric and operational constraints of the site. Instead, a coordinated multi-sensor approach enabled the creation of a comprehensive digital record that balances accuracy, completeness, and interpretability. The study highlights both methodological limitations and practical solutions relevant to documenting complex space heritage under time-sensitive and constrained conditions. The workflow presented is transferable to other large-scale engineering heritage sites facing similar risks and challenges.

1. Introduction

Large-scale industrial and engineering heritage sites are increasingly threatened by functional obsolescence, redevelopment pressures, and the high costs associated with long-term maintenance. Many of these environments were designed for highly specialized purposes and cannot be easily adapted for reuse once their original functions have ceased (Xiong et al., 2023). When physical conservation is no longer viable, digital documentation becomes a critical strategy for preserving spatial, technical, and cultural knowledge embedded within such complex built environments (Letellier and Eppich, 2015; Moore, 2001).

Within the broader field of industrial heritage, infrastructure associated with spaceflight training and testing presents a distinct set of challenges. These facilities were often constructed at monumental scales and incorporate irregular geometries, dense mechanical systems, and highly controlled interior conditions. Unlike more frequently studied heritage typologies, such as historic architecture or manufacturing facilities, training environments for human spaceflight have received comparatively limited attention in digital heritage research (Miller, 2016; Westwood et al., 2016). Yet these sites played a central role in enabling mission operations and reflect important technological and organizational practices of the late twentieth century (Launius, 2009).

Documenting such structures requires more than the application of a single sensing technology. Complex surfaces, repetitive structural elements, crowded areas, limited access, and confined spaces frequently restrict line-of-sight and complicate data acquisition and registration using conventional digital technologies and methods. According to Stylianidis (2025) and Hess et al., (2015), hybrid documentation strategies that integrate multiple sensing modalities are increasingly necessary to achieve comprehensive and reliable records. Recent advances in laser scanning, close-range photogrammetry, drone-based aerial photography, and panoramic imaging have expanded the range of structures that can be documented (Liu et al., 2022), but their combined application in large-scale, confined spaceflight heritage contexts remains underexplored.

This paper presents a methods-oriented study of a hybrid digital documentation campaign carried out at a late twentieth-century spaceflight training facility. Rather than focusing on a finalized reconstruction or interpretive outcome, the paper emphasizes the planning, data acquisition, preliminary processing, and integration strategies employed to document a technically complex site under significant physical and operational constraints. The study examines how multiple sensing technologies can be coordinated to overcome the challenges posed by scale, geometry, accessibility, and environmental factors.

The contribution of this work lies in its examination of documentation workflows applicable to industrial and engineering heritage sites that are at risk, inaccessible to the public, or no longer extant. By analyzing methodological decisions and early results, the paper offers practical insights for researchers and practitioners engaged in the 3D reconstruction and visualization of complex architectures. The workflow discussed here is intended to be transferable, supporting future documentation efforts where rapid capture and multi-sensor integration are essential for preserving endangered built heritage.

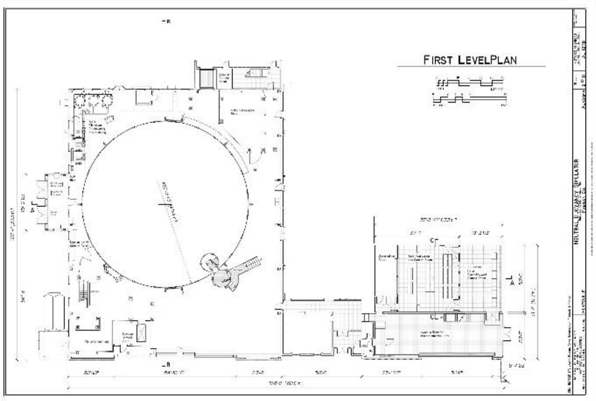
2. Background and Significance of the Heritage Site

The site documented in this study was a neutral buoyancy simulator (NBS), as shown in Figure 1, constructed in the late 1960s to support human spaceflight operations. The facility was centered on a large cylindrical water tank, approximately 23 meters in diameter and 12 meters in depth, designed to simulate reduced-gravity conditions through controlled buoyancy

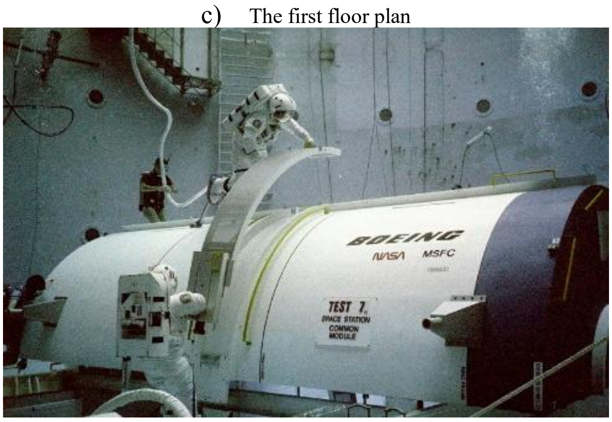
(Historic American Engineering Record, 1968). Within this environment, astronauts rehearsed extravehicular activities, assembly procedures, and maintenance tasks for crewed missions in Earth orbit under conditions approximating microgravity. Over several decades, the NBS supported training for multiple generations of spaceflight programs, including early lunar missions, orbital laboratories, and later long-duration orbital assembly operations (Bilstein, 1999; Gawdiak and Fedor, 1994). In recognition of its importance, the NBS was designated a National Historic Landmark in 1985 ("List of NHLs by State - National Historic Landmarks, U.S. National Park Service," 2008).


a) The NBS tank


b) Apollo-era spacesuit testing



c) The first floor plan



d) Astronauts practice assembly of the International Space Station assisted by divers in the NBS, photographed in 1985.

Figure 1. NBS in the record. (Historic American Engineering Record, 1968).

Beyond its functional role, the NBS represents a distinctive category of space-related industrial heritage. Unlike launch infrastructure or spacecraft hardware, training facilities were purpose-built environments that combined civil engineering, mechanical systems, and operational choreography. The tank interior featured complex curved surfaces, access platforms, lift systems, lighting rigs, and dense networks of pipes and cables, all of which were required to support life-support simulation, diver operations, and safety systems. These characteristics produced a spatial environment that was both technically sophisticated and difficult to document using conventional architectural survey methods. The heritage value of the NBS lies in both its association with major spaceflight milestones and its unique approach to astronaut training, which relied on physical simulation rather than digital or computational models. As such, the facility reflects a broader technological culture of the late twentieth century, in which large-scale mechanical systems were used to approximate extraterrestrial conditions. This makes the site particularly significant for understanding the material and spatial practices that underpinned human spaceflight during this period.

Despite its recognized historical importance, the facility was decommissioned in the late 1990s as training methods evolved and operational priorities shifted. Maintaining the structure posed increasing technical and financial challenges, particularly given its size, specialized systems, and limited adaptability for alternative uses. Ultimately, the facility was demolished, reflecting a broader pattern affecting large-scale industrial and engineering heritage sites whose original functions have become obsolete. Figure 2 illustrates the conditions of the NBS before its demolition in late 2025.


a) Exterior of the tank

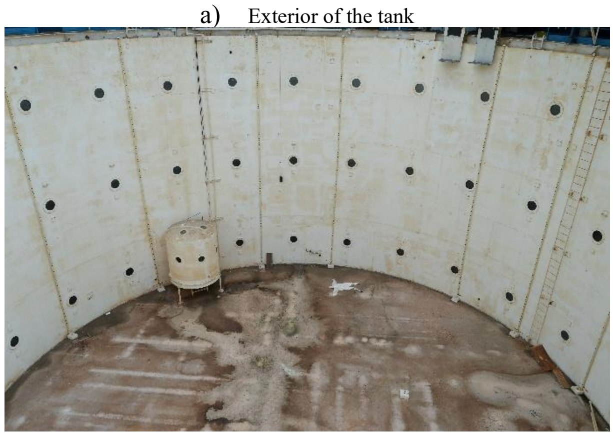

b) Interior of the tank

Figure 2. Condition of the NBS before its demolition in late 2025. (Authors' photos)

The demolition of the site highlights the urgency of documenting heritage environments that are both technically complex and physically vulnerable. Once dismantled, the spatial relationships, construction details, and experiential qualities of such facilities cannot be recovered through archival drawings or photographs alone. In this case, the imminent loss of the structure provided a narrow window in which comprehensive digital documentation could be undertaken.

From a methodological perspective, the site offers an important test case for developing and evaluating digital documentation workflows under constrained conditions. Its scale, complex geometry, dense infrastructure, and restricted access posed challenges that are representative of many industrial heritage contexts. At the same time, its cultural significance and eventual loss amplify the value of creating a detailed digital record that can support future research, visualization, and interpretation.

In this respect, the documentation of the NBS extends beyond the preservation of a single site. It contributes to a growing body of work concerned with how endangered industrial and engineering heritage can be captured, analyzed, and made accessible when physical conservation is no longer possible. The site thus serves as a historically significant artifact and a methodological proving ground for multi-sensor documentation of complex structures.

3. Documentation Strategy and Planning

The documentation strategy for the NBS facility was shaped by a combination of technical complexity, restricted accessibility, and time sensitivity. As a large-scale industrial environment designed for highly specialized operations, the facility presented challenges that could not be addressed through a single documentation method (Willkens et al., 2024). Planning therefore focused on selecting and integrating complementary technologies capable of capturing geometric accuracy, visual detail, and spatial context under such constrained conditions.

3.1 Site-Specific Challenges

Several characteristics of the structure influenced the documentation strategy. The central water tank was defined by a large cylindrical geometry with continuously curved interior surfaces, which limited the availability of planar reference features typically used for scan registration and photogrammetric alignment. The interior and surrounding service areas contained dense networks of pipes, cables, wires, platforms, lighting rigs, and structural supports, creating frequent occlusions and restricting clear lines of sight for terrestrial instruments (Figure 3). Also, repetitive structural patterns, both inside and outside the tank, increased the risk of misregistration and false correspondences during data processing.

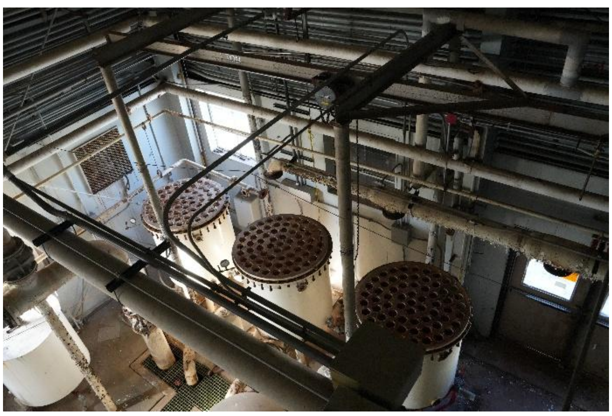


Figure 3. Dense networks of occlusions and restricted lines of sight. (Authors' photo)

Figure 4. Access opening to the air-lock tank, illustrating a confined-space condition. (Authors' photo)

Environmental conditions further complicated the documentation process. The tank and its associated structures were predominantly constructed of metal, making them highly responsive to changes in ambient temperature. Documentation fieldwork was conducted during summer months in the southeastern United States, when daytime temperatures were high. The facility was not air-conditioned, and its roof structure was thin and partially translucent (Figure 5), allowing solar radiation to penetrate the interior spaces. As a result, thermal expansion of metal surfaces occurred throughout the day, introducing subtle but measurable variations in surface conditions that affected data stability and registration. During field operations, researchers could audibly perceive the expansion of metal components as temperatures increased.

Figure 5. The thin and partially translucent roofing structure contributed to environmental challenges due to solar heat gain and temperature fluctuations. (Authors' photo)

3.2 Selection of Documentation Technologies

To address these challenges, three complementary technologies were employed (Figure 6): terrestrial laser scanning (TLS), indoor drone-based photogrammetry, and immersive 360-degree capture using Matterport. Together, these methods support both technical documentation and visual interpretation of a complex industrial heritage environment (Alathamneh et al., 2024; Liu et al., 2025; Willkens et al., 2024).

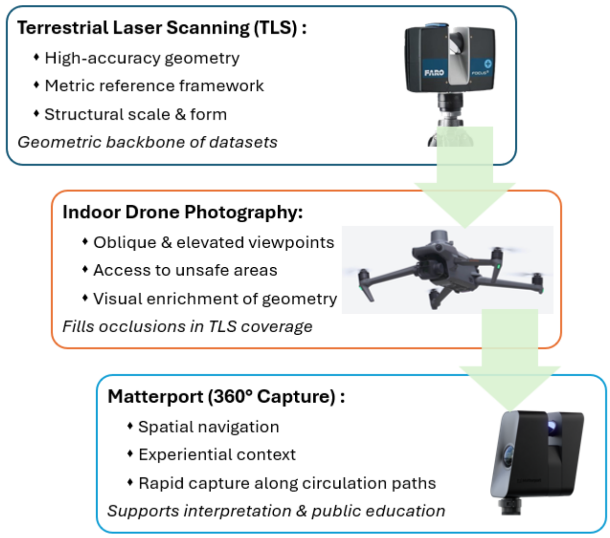


Figure 6. Complementary documentation technologies are used to capture the complex structure of the NBS

TLS was selected as the primary method for capturing the overall geometry of the facility. Its ability to rapidly acquire dense, high-accuracy point clouds made it well-suited for documenting the scale and form of the tank and surrounding structures. TLS provided a metric backbone for the dataset, supporting measurements, spatial analysis, and subsequent integration with other data sources. However, the effectiveness of TLS was limited in areas with severe occlusion, complex overhead structures, or restricted access.

A compact indoor drone was used to capture photographic imagery and intended to perform a photogrammetric reconstruction of the interior of the tank. The drone was used exclusively inside the tank, due to regulatory restrictions, to obtain oblique and elevated viewpoints that were inaccessible or unsafe for terrestrial technologies. However, the complex geometry, repetitive surface features, and limited availability of reliable reference points within the tank made robust photogrammetric processing challenging. Therefore, drone imagery was primarily used for visualization, documentation of structural details, supplementing TLS datasets, and support for interpretive representations.

Matterport technology was incorporated to capture immersive 360-degree imagery and support spatial navigation. Although not intended as a primary source of metric data, the Matterport platform provided rapid acquisition of contextual information and facilitated the creation of an immersive virtual environment. This capability was especially useful for conveying spatial relationships and experiential qualities that are difficult to communicate through static plans or point cloud visualizations alone. The Matterport dataset also supported cross-referencing between detailed geometric data and broader spatial context during analysis and interpretation.

Table 1 summarizes these three reality capture (RC) devices used in the study, along with their key technical specifications and intended roles within the documentation workflow.

Device	Capture Technology	Max Resolution / Accuracy	Field of View (FOV)	Data Output Format	Range / Effective Distance	Weight	Cost (Approx.)
TLS Scanner: FARO Focus Premium	Terrestrial LiDAR (Phase-based)	Point Cloud: ±1 mm accuracy @ 10 m	360° horizontal / 300° vertical	E57, LAS, XYZ, FLS	Up to 350 m	~4.2 kg (9.3 lbs)	USD 60,000–75,000
Drone: DJI Mini 4 Pro	12-bit Dual-Native ISO CMOS sensor with autofocus	Photo: 48 MP (8000×6000) stills	~82.1° (wide)	JPEG, DNG (RAW), MP4/MOV	N/A	249g (0.5 lb)	USD 1,000
3D Camera: Matterport PRO3	LiDAR + Photogrammetry	Point Cloud: ±20 mm @ 20 m; Photo: 134 MP	360° horizontal / ~70° vertical	OBJ, E57, XYZ, MatterPak	Up to 20 m	~2.3 kg (5 lbs)	USD 8,000

Table 1. Three reality capture devices used in the study and their key specifications.

4. Data Acquisition and Processing

Documentation fieldwork was conducted by a two-member team over a concentrated two-and-one-half-day campaign in July 2026. Prior to the full-scale onsite work, Reconnaissance visits and engineering drawings (Historic American Engineering Record, 1968) were used to determine scanner placements, scan routes, and equipment settings. Safety planning was particularly important because the tank and its surrounding structures were classified as confined spaces with limited entry and exit points.

4.1 Terrestrial Laser Scanning (TLS)

TLS, as the primary method for capturing the geometric structure, was carried out using a FARO Focus Premium Max scanner over a total duration of approximately 15 hours. A total of 176 scan stations were placed, including 13 around the exterior of the facility, and 163 distributed throughout the interior spaces, with denser coverage in areas characterized by complex geometry and dense infrastructure. Interior scanning was conducted at a resolution of 1/8 with a quality setting of 3×, while exterior scans were acquired at a resolution of 1/4 and a quality setting of 2×. Color capture was enabled for most interior and all exterior scans. Sphere targets were deployed inside and around the tank to support registration, with approximately three to four targets visible per setup.

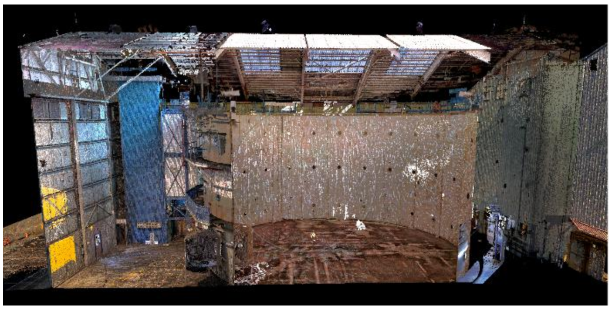
Challenging field conditions imposed several constraints on scanner placement. Interior access was limited by confined spaces, narrow entrances, and restricted circulation routes. Outside the tank, four levels of metal platforms surrounding its curved metal walls constrained scanner positioning and line of sight. Certain elements, including the whole circumference of dense piping networks and portions of the tank exterior at height, could not be fully captured using terrestrial scanning alone due to occlusion and access limitations.

https://doi.org/10.5194/isprs-archives-XLVIII-2-W12-2026-255-2026

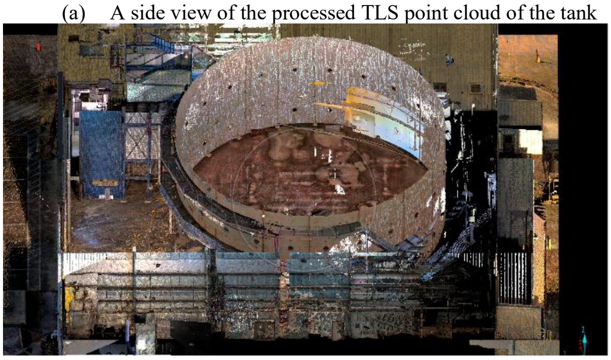
4.2 TLS Registration and Processing

TLS data processing followed a hybrid registration strategy in FARO SCENE software, combining target-based registration with cloud-to-cloud alignment (Figure 6). Target-based registration utilized sphere targets placed on site and provided initial control within and around the tank, while cloud-to-cloud methods were employed to refine alignment across scan stations and integrate exterior scan datasets.

Scan registration presented several challenges. The curved geometry of the tank walls and the dominance of repetitive structural elements increased the risk of false correspondences during alignment. In addition, environmental conditions affected scan stability. The predominantly metal construction of the tank and roof of the facility, combined with high summer temperatures, led to thermal expansion of the structural components throughout the day. These effects introduced variations in surface conditions that influenced registration accuracy.



(a) A side view of the processed TLS point cloud of the tank



(b) Processed TLS point cloud of the tank with surrounding structures

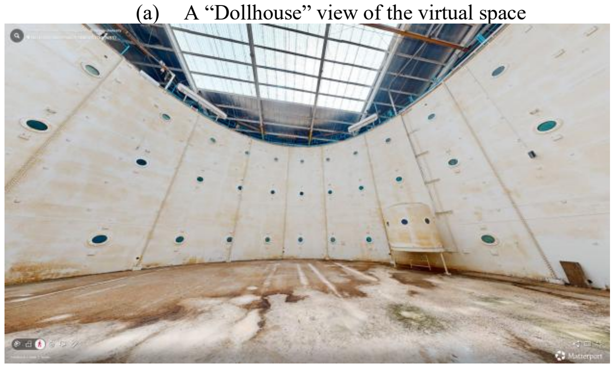
Figure 6. Screenshots of the processed TLS scans in FARO SCENE showing the tank and its surroundings. (Authors' photos)

4.3 Immersive 360-Degree Capture Using Matterport

Using a Matterport Pro3 camera paired with an Apple iPad mini, immersive spatial context and support for navigating the facility were captured. A total of 303 scans were completed over approximately 5 hours of fieldwork with the camera. Matterport scans were conducted along accessible circulation paths and service areas. Data acquisition was constrained by narrow pathways, confined spaces, and low lighting conditions. Certain areas, including elevated elements and the entire circumference of piping and structural components, could not be captured due to access limitations.

Despite these constraints, the Matterport system provided rapid capture and processing, and produced a user-friendly 3D walkthrough of the facility (Figure 7). In addition to the immersive environment, the platform generated a point cloud in E57 format, which was used primarily for reference and visualization rather than metric analysis. The ease of sharing and accessibility of the Matterport outputs made them valuable for communication with project stakeholders and for preliminary interpretation.

(a) A "Dollhouse" view of the virtual space



(b) A panoramic view of the tank's interior showing the navigation system

Figure 7. An immersive virtual walkthrough captured using Matterport technology. (Authors' photos)

4.4 Indoor Drone-Based Image Capture

An indoor drone (DJI Mini 4 Pro) was used to capture photographic imagery exclusively within the interior of the tank. A total of 203 images were collected and organized into nine panoramic image sets, each comprising between 21 and 35 images. Drone flights were conducted manually, as automated mapping was not feasible given the confined space, complex geometry, and lack of clear flight paths. Several factors complicated image capture, including highly repetitive structural elements, metal grating used for flooring and guardrails, and the inability to place targets at elevated locations within the tank. High temperatures and humidity further affected operational conditions.

Drone imagery was processed using Agisoft Metashape Professional (v2.1.0) software. Although the imagery was aligned successfully, the dataset was not sufficient to support a robust photogrammetric reconstruction due to the challenges noted above. Instead, the outputs, including a partial point cloud and surface texture model (Figure 8), were used only to enhance visualization, document structural details, and support qualitative interpretation of areas that were difficult to assess from terrestrial data alone.

(a) The interior texture model

(b) Highlights of flawed reconstruction artifacts, including missing surfaces on the air-lock tank and distorted vertical metal railings.

Figure 8. A photogrammetric texture model showing the tank interior. The model was created using photos taken by a drone. (Authors' photos)

5. Results and Discussion

5.1 Data Quality, Accuracy, and Limitations

The 176 TLS scans achieved consistent registration across interior and exterior scan clusters, with a final registration tolerance of 0.060 inch (~1.5 mm). This consolidated dataset captures the overall form of the tank, its internal configuration, its surrounding service areas, and the majority of the facility that hosts it, with sufficient fidelity to support spatial analysis, visualization, and future interpretive use. Given the scale and complexity of the structure, and the challenging environmental conditions during acquisition, this level of accuracy was considered appropriate for the intended documentation and visualization purposes.

Several factors influenced data quality. The continuously curved interior surfaces of the tank reduced the availability of planar reference features typically used to stabilize registration, while repetitive structural patterns increased the risk of false correspondences during cloud alignment. Dense piping, platforms, and structural supports further complicated acquisition by introducing frequent occlusions and limiting scanner placement options.

Environmental conditions also played a significant role. The facility's predominantly metal construction, combined with high summer temperatures, lack of air conditioning, and a thin, partially translucent roof, resulted in thermal expansion of structural components throughout the day. These conditions introduced noticeable geometric variability that required careful sequencing of scans and additional attention during post-processing. While such effects could not be entirely eliminated, their impact was mitigated through the hybrid registration strategy and conservative interpretation of accuracy metrics.

Certain areas remained incompletely documented. Portions of the full circumference of piping systems and elevated exterior surfaces could not be fully captured using terrestrial scanning due to access and height limitations. Matterport and drone imagery partially mitigated these gaps by improving visual legibility and contextual understanding, though they did not replace the need for complete metric coverage. These limitations highlight the practical constraints inherent in documenting large-scale industrial heritage sites under time-sensitive and restricted conditions.

5.2 Role of Non-Metric Datasets in Supporting Interpretation

While TLS provided the metric benchmark of the documentation, the results demonstrate the value of integrating non-metric datasets in a carefully defined manner. The Matterport capture proved particularly effective for conveying spatial continuity, circulation patterns, and experiential qualities of the facility. Its rapid acquisition and processing enabled the creation of an accessible virtual environment that supports communication with diverse stakeholders and provides an intuitive entry point for non-specialist audiences.

Indoor drone imagery, although not suitable for full photogrammetric reconstruction in this context, contributed meaningfully to visualization and qualitative analysis. The oblique and elevated viewpoints obtained by the drone clarified spatial relationships and structural details that were difficult to interpret from point clouds alone, particularly within the interior of the tank. Rather than representing a shortcoming, this outcome highlights the importance of clearly defining the intended role of each technology within a hybrid workflow.

5.3 Implications for Documenting Complex Industrial Heritage

The results of this study reinforce the necessity of multi-technology documentation strategies for large-scale industrial and engineering heritage sites. No single method was sufficient to address the combined challenges of scale, geometry, access restrictions, and environmental variability encountered at the site. Instead, the coordinated use of TLS, immersive capture, and targeted drone imagery allowed the project team to balance geometric reliability, visual completeness, and practical feasibility.

Furthermore, the findings demonstrate that effective documentation does not require full metric integration of all datasets. Selective use of non-metric imagery can substantially enhance legibility and interpretability without compromising the integrity of the primary geometric record. This approach is particularly relevant for sites facing imminent loss, where rapid capture and pragmatic decision-making are essential. For such a large and complex heritage site as NBS, the small research team successfully completed the fieldwork using three technologies in just two and a half days.

More broadly, the digital record produced through this effort provides a foundation for future visualization, interpretation, and comparative research on space-related industrial heritage. Although the physical structure has been demolished, the integrated datasets preserve critical spatial and technical information that would otherwise be irretrievable.

6. Conclusions

This study presented a multi-sensor documentation approach applied to a large-scale space engineering heritage site shortly before its demolition. Faced with challenges related to scale, curved geometry, dense infrastructure, restricted access, and environmental variability, the documentation strategy combined TLS, immersive 360-degree capture, and indoor drone imagery. The resulting datasets preserve both the geometric structure and experiential qualities of a facility that is no longer physically accessible. TLS formed the cornerstone of the documentation, with 176 scan stations successfully registered to a tolerance of 1.5 mm. While this level of accuracy was influenced by curved surfaces, repetitive elements, and thermal expansion of metal components, it proved sufficient for spatial analysis and visualization at the scale of the site. Immersive capture using Matterport complemented the TLS dataset by providing continuous spatial context and intuitive navigation, supporting interpretation and communication without introducing additional metric uncertainty. Indoor drone imagery enhanced the visualization of complex interior areas that were difficult to document using terrestrial methods alone. Direct results of the documentation efforts, including TLS and photogrammetric point clouds, an immersive virtual walkthrough, and aerial photographs, are planned to be used for the development of a heritage building information model (HBIM) as a digital archive of this significant structure, and to support interpretation and public education related to the history of the NBS.

Several limitations of his research should be acknowledged as well. Time constraints associated with imminent demolition limited opportunities for repeated scanning under more ideal environmental conditions. Access restrictions and safety requirements prevented complete coverage of certain elevated or occluded elements, particularly dense piping networks and portions of the exterior structure. In addition, the absence of reliable reference geometry or installed targets constrained photogrammetric reconstruction and limited the potential for integrating drone imagery into the TLS dataset.

Future research can build on this work in several directions. Comparative studies examining alternative registration strategies or sensor combinations may further improve data stability in environments dominated by curved and repetitive geometry. Advances in automated feature extraction, semantic enrichment of point clouds, and AI-assisted scan registration may also enhance the documentation of complex industrial and space heritage sites, such as the NBS. Also, integrating the resulting datasets into interpretive and educational platforms offers opportunities to extend public access to heritage environments that are no longer physically present.

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