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360° Borescope with Adjustable LED Lighting: A Solution for Photogrammetry in Extremely Restricted Spaces

Luigi Barazzetti[1], Mattia Previtali[1], Fabio Roncoroni[2], Riccardo Valente[3]

[1] Dept. of Architecture, Built environment and Construction engineering (ABC)
Politecnico di Milano, Piazza Leonardo da Vinci 32, Milan, Italy
[2] Polo Territoriale di Lecco, via Previati 1/c, Lecco
(luigi.barazzetti, mattia.previtali, fabio.roncoroni)@polimi.it
[3] Institute of Heritage Science (ISPC), National Research Council of Italy (CNR)
Via Cozzi 53, Milan, 20125, Italy, riccardo.valente@cnr.it

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ABSTRACT:
The system described in the paper is a prototype of a novel 360° borescope for digital documentation in confined spaces. The method was designed for both 360° inspections and photogrammetric applications in very tight and narrow spaces (even less than 30-40 cm), in which traditional digital documentation is usually impossible. The prototype is based on a panoramic camera and an integrated lighting LED system to allow for efficient image acquisition in small chambers where other documentation methods (like laser scanning and traditional photogrammetry) are not feasible due to space restrictions. Laboratory tests have demonstrated the system's capability to achieve metric precision of approximately ±1-2 cm, making it a reliable tool for confined-space documentation. By offering high-resolution imaging and the ability to generate 3D models with minimal intervention, this system represents a significant step forward in the field of confined-space documentation, with applications ranging from industrial inspections to heritage preservation.

1. INTRODUCTION

Documenting narrow or confined spaces is a complex endeavor that presents numerous technical and logistical challenges. These challenges arise primarily from the physical constraints of such environments, which hinder accessibility, visibility, and mobility. Confined spaces, by their very nature, impose severe limitations on the positioning and movement of equipment, operators, and documentation tools. Examples of these environments include industrial pipelines, archaeological sites, burial chambers, and structural cavities, all of which vary in size, shape, and accessibility. The limitations in space make it difficult, and often impossible, to employ traditional methods like laser scanning or standard photogrammetry, which require sufficient room to maneuver and capture data effectively (Mandelli et al., 2017).

In many cases, confined spaces feature apertures narrower than 20 to 30 cm, limiting both the operator’s ability to access the area and the capacity to position necessary equipment. This physical restriction affects the documentation process in significant ways. First, it often rules out the use of large or standard-sized tools like terrestrial laser scanners, which are typically used for large-scale and open-area surveys. Second, confined spaces can impose restrictions on the operator's ability to achieve the correct angles or positions needed to capture complete and accurate data, leading to gaps or inaccuracies in the documentation. These issues are exacerbated in particularly tight environments, where the operator might only have minimal or no direct access to the area being documented.

The literature on confined space documentation highlights these accessibility issues across various fields. In industrial settings, for example, pipelines and enclosed reactors are typically characterized by narrow and long geometries that prevent the insertion of conventional scanning devices. Achieving accurate 3D documentation in such environments demands specialized techniques, often involving remote sensing or robot-assisted methods that can be inserted into the space with minimal human intervention. Similar challenges arise in archaeological contexts, where burial chambers or underground vaults are often protected by structural elements that make access difficult without damaging the site or partially excavating the archaeological context. Another critical factor in the documentation of confined spaces is the limited lighting conditions that are often present. Many confined environments, especially those in industrial and archaeological settings, are poorly lit or entirely devoid of natural light, making it difficult to capture high-quality images. Poor lighting can lead to overexposure, underexposure, or uneven illumination in captured images, which, in turn, can introduce errors into the 3D reconstruction process. For example, reflective surfaces may cause glare, while dark spaces can lead to insufficient data points being collected, reducing the accuracy of the resulting model.

Different papers in the scientific literature have discussed the documentation of narrow spaces. One of the techniques used is spherical photogrammetry. Several authors have explored the application of spherical photogrammetry for 3D modeling, emphasizing its effectiveness as a tool for documenting small and constrained environments. This technique has been utilized in a variety of projects, including Heritage preservation and the rapid mapping of buildings and monuments, among other applications (Barazzetti et al, 2010; Abate et al., 2017; Aghayaria et al., 2017; D’Annibale et al, 2009; Fangi, 2007, 2009, 2010, 2017; Matzen et al, 2017).

In heritage documentation, spherical imagery has been widely adopted, with Barazzetti et al. (2017) showcasing its use in capturing monuments, particularly in cases where quick data collection is necessary for sites with access limitations. Applications also extend into virtual reality, where spherical images serve as foundational elements. Kwiatek et al. (2014, 2015) have discussed their use as immersive tools in 3D modeling, while Pérez Ramos and, Robleda Prieto (2015) discussed the integration of spherical and frame cameras. Other papers (e.g., Strecha et al., 2015) discussed the metric accuracy achievable with spherical cameras.

The objective of this paper is to introduce a photogrammetric solution using spherical images for documenting extremely confined spaces which are otherwise inaccessible with conventional documentation methods. The proposed approach utilizes a 360° camera equipped with an integrated lighting system, allowing for manual insertion into the restricted area. The overall processing workflow closely resembles that of a standard project based on spherical images. This paper primarily focuses on the importance of adequate lighting conditions and provides a detailed description of the prototype, which serves both as an inspection tool (capturing images and videos) and as a metric tool. The paper also presents experiments and tests that demonstrate the achievable metric accuracy of the solution.

2. DESCRIPTION OF THE 3D BOROSCOPE

The core component of the system is an Insta360 ONE R camera, which can record 5K resolution video footage. This commercial camera, mounted on a telescopic pole, is inserted into small apertures to capture 360-degree videos of the interior spaces. This video data is later processed into individual frames that are used for photogrammetric modeling. The 360° borescope prototype described here uses a flexible LED lighting system, which can be adjusted depending on the specific characteristics of the space being documented. The lighting system consists of multiple LED strips placed around the camera in a ring configuration, with additional front- and rear-facing lights. The user can selectively turn on or off specific LED strips based on the lighting needs of the environment (Figure 1).

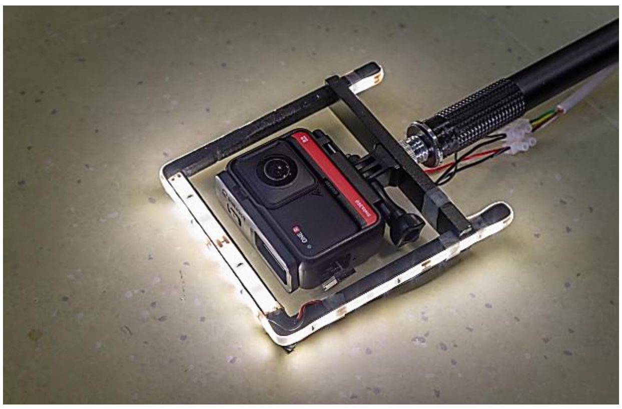

Figure 1. The prototype of the 360° borescope with the adjustable LED lighting system.

The LED lighting system, powered by an external battery, provides the necessary illumination to capture high-quality images in dark environments, as most narrow spaces lack adequate lighting. In the context of using the 360° borescope prototype for inspection and digital documentation, adjusting the LED lighting system is critical to ensuring high-quality image capture, especially in dark spaces. Achieving the correct lighting conditions is necessary to minimize multiple effects such as overexposed areas, flares, reflections, and shadows, which could interfere with the photogrammetric process and reduce the accuracy of the final 3D models.

Key elements of the LED system configuration include:

1) *Adjustable Brightness*: The power and intensity of the LEDs can be adjusted. In narrow or highly reflective environments, the user may reduce the brightness to avoid creating flares or overexposed images. Conversely, in larger, darker spaces, higher brightness settings may be necessary to ensure the entire area is adequately lit;

2) *Directional Control*: The system allows the user to turn off specific strips oriented towards different directions. For instance, if there are areas that don't need direct illumination or reflections are caused by lights facing a particular direction, the user can selectively deactivate those lights. This directional control ensures that only the necessary areas are illuminated, helping to minimize shadows and flares;

3) *Use of Diffusers or Filters*: In cases where the LED lights cause strong reflections or create harsh lighting conditions, semi-transparent films or diffusers can be applied to the LEDs to soften the light. This reduces the flare effects and ensures a more even light distribution across the surfaces, making it easier to capture images.

The camera can be maneuvered to explore hard-to-reach areas while capturing images from all directions thanks to its 360° field of view. Before starting the actual data acquisition, the operator performs trial runs to determine the optimal lighting setup. The operator can preview the camera feed in real-time on a connected device (like a tablet or mobile phone), allowing them to adjust the LED configuration and find the best light balance for the specific space (Figure 2).

Figure 2. The remote connection allows 360° inspection and data acquisition with real-time visualization.

A significant aspect of this system is its ability to document very narrow spaces with minimal intervention on the object. This is crucial in specific contexts, such as archaeological or forensic contexts, where preserving the scene's integrity is fundamental. The only alteration of the scene is the insertion of photogrammetric scale bars to ensure accurate scaling. These scale bars serve as reference points for processing the images and determining the actual dimensions of the documented objects and space. If introducing scale bars is not possible, the photogrammetric model may suffer from scale ambiguities, but the overall data capture will still be useful except for the scale factor.

Despite some challanges in lighting and camera movement in very tight spaces, the system was shown to provide reliable and useful data, which can later be processed into 3D models of the space. Regarding the workflow, video footage is captured and then processed using the camera's proprietary software to extract frames. These frames are further processed using photogrammetry software to create 3D models.

3. A REAL CASE STUDY

The proposed case study is the documentation of some inaccessible spaces within a church located in the municipality of Chiesa in Valmalenco. Two burial vaults near the church's facade and perimeter walls were selected as case studies for this research. Both vaults still had their stone slabs intact. The first vault likely had a rectangular shape with two breaches: one at the end, measuring about 1 m x 0.15 m, and another on the side, approximately 0.3 m x 0.20 m.

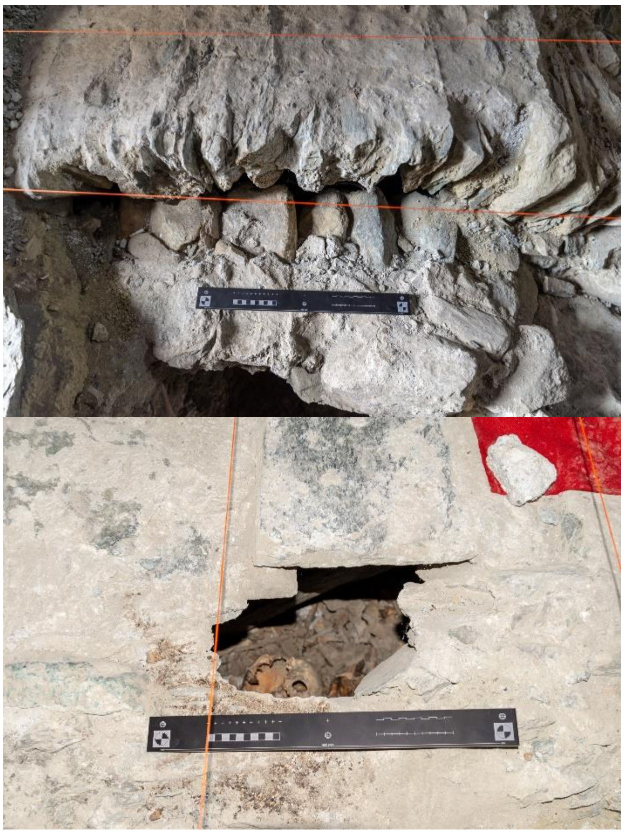

Figure 3. The small apertures used to operate the cameras in the two data acquisitions.

The borescope prototype was manually inserted into the vault through the breaches (Figure 4). The first acquisition, conducted from one breach using a telescopic pole, was able to cover most of the vault's interior. A second acquisition from the side breach helped gather additional data from the central area of the vault. The videos were captured at a resolution of 5760 × 2880 pixels, 30 fps, ISO 500, and a 1/100-second exposure time. Adjustments were made to reduce vibrations during filming due to the limited size of the breach. LED lights were diffused using semi-transparent film to prevent flare, an issue identified during lab tests. A textured mesh of the burial vault (1.8 million faces) was created, showing the camera locations. The vault covered an area of approximately 4.3 m x 1.9 m, with sections revealing an average wall thickness of about 0.45 m, though this value was not uniform.

Figure 4. Insertion of the 360° boroscope in the two breaches.

The orthophoto generated from the vault had a ground sampling distance (GSD) of 0.6 mm, which allowed for detailed differentiation of bones. The photogrammetric project was scaled by inserting a small scale bar. The orthophoto was arranged in the format of a ceiling plan, providing a bottom-up view that enables the creation of a photorealistic and metrically accurate image, accurately representing the layout and dimensions of the vault structures.. This process eliminated the need for manual editing of the textured model and allowed for orthophoto generation of vaulted surfaces from within.

The second vault, with an uncertain shape, had only one breach measuring about 0.1 m x 0.12 m. Two video acquisitions were performed: the first to document the inner structure and human remains (Figure 5), and the second to connect the interior of the chamber with the top exterior visible in the nave of the church. A third video was recorded inside the nave to complete the survey. Similar to the first vault, LED lighting was used for the initial videos, while the third was shot without lighting. Due to the small breach and presence of human remains, camera movement was restricted to a specific descending and ascending path.

Figure 5. Example of 360°images of for the second vault.

A total of 663 images were processed, and six control points were set outside the burial vault for reference. A scale bar was placed inside the vault to verify the reconstruction's accuracy, and a bundle adjustment yielded residuals of approximately 0.015 m on the ground control points (GCPs) and 0.023 m on the reference scale bar.

The final 3D model revealed a square burial chamber (approximately 2.5 m per side) with a barrel-vaulted stone ceiling. In the center of the chamber was a pile of human bones, aligned with a stone slab visible from the church floor. However, some reconstruction gaps were noted due to lighting challenges and the shape of the breach (Figure 6).

In the second vault, the breach size limited survey coverage, resulting in incomplete reconstruction in certain areas. The large empty space also contributed to poor lighting, particularly in the corners, affecting image quality. The study highlights the importance of adequate lighting during image acquisition. Excessive light can cause flares, while insufficient light can result in dark frames, compromising the quality of photogrammetric reconstructions. Despite these challenges, the documented orthophotos provide valuable insights into burial contexts, revealing details such as debris and displaced vault elements. These findings can help estimate the extent of human remains and provide clues regarding taphonomic processes.

While the results varied due to factors like breach size, chamber dimensions, and lighting conditions, the method proved successful even in difficult situations. Frame extraction from video footage, though typically reliable, can pose challenges when significant changes in ground sampling distance occur between frames. A sampling rate of 1 Hz was found to be optimal for this study, striking a balance between data quantity and accuracy.

Figure 6. Point cloud (top) and mesh model (bottom) of the second vault: highlighted in blue the camera poses.

4. ACCURACY EVALUATION

4.1 Overview of the experiments

Two laboratory experiments were conducted to test and compare the accuracy of photogrammetric and laser scanning techniques in confined spaces: one simulating a burial chamber using a wooden box, and another in an existing narrow underground tunnel. Both experiments aimed to address the challenges posed by narrow geometries, limited visibility, and irregular surfaces, evaluating the accuracy of photogrammetric models derived from 360° camera footage. The results were compared with measures obtained from total station and laser scanner.

The first experiment involved a regular wooden box with internal targets measured using a Leica TS30 total station. The 360° camera was used to capture a video inside the box, and frames were extracted for photogrammetric processing. A comparison between the reference coordinates obtained from the total station and the photogrammetric results highlighted the impact of control point distribution on registration accuracy. The second experiment used a modern underground concrete tunnel as test environment. A 360° camera was deployed inside the tunnel, and the data obtained were compared to a reference point cloud generated by a Faro Focus S70 laser scanner.

4.2 Comparison with ground control points

The first laboratory experiment involved constructing a regular wooden box measuring 2 m × 0.5 m × 0.5 m to simulate an underground grave (Figure 7). Targets were affixed to three of the internal surfaces before sealing the box, and their precise coordinates were measured using a Leica TS30 total station, achieving an accuracy better than ±0.002 m.

Figure 7. The wooden box used for the experiments (top) and the inserition of the boroscope (bottom).

The 3D boroscope was placed inside the box, capturing a 58-second video by using the same parametres adopted in the Chiesa di Valmalenco case study. Frames were extracted at a rate of 2 frames per second, resulting in 116 frames that were processed using Metashape software with a spherical camera model. The camera was inserted through a 0.1 m × 0.1 m opening, simulating the conditions of a small aperture during real inspections. The interior of the box was completely dark, except for minimal external light from the aperture, and the only light source was the LED system on the camera. Data processing followed Metashape's standard workflow, including the manual addition of ground control points to the images and the import of the corresponding 3D coordinates from the total station measurements.

The photogrammetric model was then registered in the total station's reference system using a 7-parameter transformation (rotation, translation, and scale), with various configurations of control and check points. Table 1 shows the results of different point distributions. When all points were used as control points, the root mean square error (RMSE) was below 0.02 m, representing a relative error of about 1% compared to the overall dimensions of the box.

The experiment was repeated using fewer control points, placed at the beginning and end of the box. Despite the reduced number of control points, the error remained comparable to the previous case due to the homogeneous distribution covering the entire object. However, when the final experiment was conducted with only 4 control points and 14 check points, a significant error emerged along the box's longitudinal axis (Z). This was due to the unbalanced distribution of control points, which were concentrated near the entrance, resulting in poor registration accuracy.

GCP and Check	RMSE X (m)	RMSE Y (m)	RMSE Z (m)
18 control points	0.014	0.017	0.011
no check points	-	-	-
6 control points	0.007	0.0019	0.007
12 check points	0.017	0.018	0.015
4 control points	0.008	0.008	0.001
14 check points	0.028	0.018	0.074

Table 1. Experiments conducted in confined space with comparison of photogrammetric check points and known coordinates.

This experiment highlights a key challenge: narrow geometries, like those discussed in this study, often prevent the use of homogeneously distributed control points. Consequently, registering the photogrammetric data in an external reference system can be problematic, potentially leading to inaccurate metric results when measurements need to be compared with data acquired through other methods. For example, this could affect the accurate estimation of the thickness of vaulted tomb surfaces.

4.3 Comparison with laser scans

For the second test, a modern underground concrete tunnel was selected to simulate a narrow environment. The opening of the tunnel measured approximately 1.20 × 0.9 m, and a 4-meter section near the entrance was surveyed. The dark blue paint inside the tunnel added complexity to the photogrammetric process, making it harder to detect and distribute tie points in the images effectively.

The goal of this experiment was to compare the point cloud generated from 360° video footage with a point cloud captured using a Faro Focus S70 laser scanner, which served as the reference for comparison. The laser scanner, mounted on a small cart, captured four scans inside the tunnel. These scans were registered using the Iterative Closest Point (ICP) method, achieving a precision better than ±2 mm. Additionally, five checkerboard targets were placed on the entrance and lateral walls to provide control points for the photogrammetric processing.

Photogrammetric data was acquired using two different lighting configurations: (i) LEDs arranged in a ring around the 360° camera and (ii) the same configuration with additional front- and rear-facing lights. The first setup produced darker videos, particularly in areas parallel to the camera's optical axis. The second setup produced brighter footage but introduced flares caused by the front- and rear-facing LEDs. This flare effect remained consistent in most frames unless the camera-object distance changed significantly. Fortunately, the flares could be masked during photogrammetric processing since its location was predictable across frames.

Another key factor was the exposure time, which needed to be optimized to ensure sharp frames when manually inserting the camera into the narrow space. The final decision was to use an exposure time of 1/80 seconds, capturing the footage with slow, careful movements to avoid vibrations or sudden shifts.

The camera was inserted horizontally into the tunnel, with its lenses directed toward the floor and ceiling. This orientation was chosen because in a real-life scenario objects laid on horizontal surfaces would be better recorded, as one lens could capture the floor directly. A different camera orientation, pointing toward the lateral walls, was not tested in this experiment. Additionally, two different videos were recorded: one while inserting the camera into the tunnel and another while retrieving it. It was observed that smoother camera movement occurred during retrieval, leading to a more stable video. The length of the videos also varied, resulting in different frame counts despite using the same sampling rate used in the other tests presented in this paper.

Data processing was carried out using Metashape software, with frames extracted at a sampling rate of 1 Hz, yielding two photogrammetric projects with 74 and 116 frames. This frame count variation reflects the difference in camera movement during insertion and retrieval. Once the spherical camera model was applied, the images were oriented, and a dense point cloud was generated. The final stages included mesh extraction and orthophoto production for the tunnel's surfaces (Figure 8).

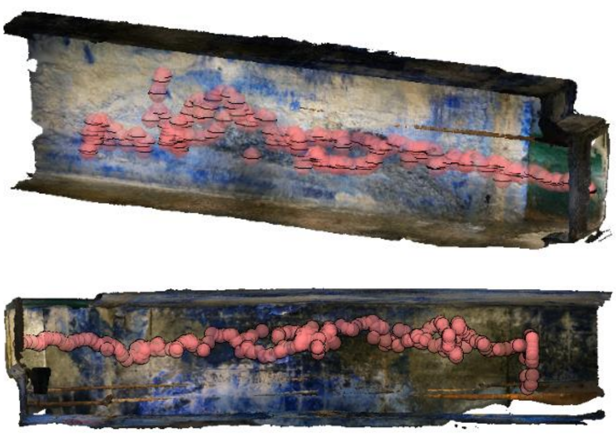

Figure 8. Reconstructed tunnel: sidewall of the tunnel (top) and floor of the tunnel (bottom). Highlighted in red are the 360° camera poses.

The five control points were imported into the photogrammetric projects, and their coordinates were manually measured in the images. The photogrammetric data was then registered in the laser scanning reference frame using a 7-parameter transformation (scale, rotation, and translation). This section of the tunnel was chosen to evaluate the metric accuracy of the resulting point cloud, with control points physically placed during the laser scanning process. Once two dense point clouds were created from the photogrammetric data, they were compared using CloudCompare software. The comparison, which covered all four tunnel walls, revealed very similar results between the two photogrammetric projects, with an overall discrepancy of 0.008 m ± 0.006 m.

Overall, the proposed method achieved a precision of about ±0.01 m. After generating the final orthomosaic, basic image enhancement techniques, such as histogram equalization, were applied to improve the image quality, which remained darker compared to more traditional photogrammetric applications. While it is possible to enhance individual frames before processing, doing so would lead to inconsistent parameters across frames. Therefore, the decision was made to work with the original frames and apply enhancements only to the final outputs.

5. CONCLUSIONS

The 360° borescope system offers a non-invasive solution for documenting narrow and confined spaces. High-resolution imaging, adjustable lighting, and advanced photogrammetric processing make it a valuable tool in different applications. The system's ability to provide detailed and accurate 3D models with minimal intervention is its most significant advantage, allowing for the preservation of the scene while still capturing the necessary data for further study. This capability has been demonstrated through laboratory experiments and real-world case studies, underscoring the system's flexibility and precision.

One of the strengths of the system is its innovative lighting configuration, which addresses the common challenges of uneven illumination and reflective surfaces in confined environments. By allowing users to adjust the LED by brightness and side, the system effectively minimizes overexposure and shadows, leading to clearer, more accurate image captures. This adjustable lighting, combined with the 360° camera, ensures that even the most restricted spaces can be documented comprehensively.

In terms of accuracy, the system has demonstrated the ability to achieve metric precision within a range of ±1-2 cm, making it suitable for various industrial and Heritage conservation applications. However, it should be noted that the distribution of control points plays a crucial role in maintaining this level of accuracy, as uneven point distribution can lead to errors, particularly along long axes in confined spaces. Nevertheless, the ability to use scale bars or ground control points mitigates this issue in most scenarios.

A full control on the acquisition of photogrammetric blocks undoubtedly helps to obtain better 3D reconstructions and to estimate in advance certain parameters such as the GSD and it should be preferred when possible. Nevertheless, environments such as those here presented as real and test case studies do not allow any planned photographic coverage, basically leaving no suitable solutions other than an uncontrolled acquisition of frames.

The system's application in documenting narrow spaces has proven its capability to provide valuable insights into otherwise inaccessible areas. The successful reconstruction of 3D models in these challenging conditions can be suitable for archaeological researches, forensic investigations, structural inspections, and industrial maintenance in confined environments. Furthermore, the system's minimal physical intervention is particularly beneficial in sensitive contexts, such as archaeological sites, where preservation of the context is paramount.

Future research could explore the integration of this system with other emerging technologies, such as automated robotic systems, to extend its applicability to even more challenging environments. Additionally, advancements in image processing software, particularly those leveraging machine learning, could further enhance the system's capacity to manage lighting anomalies and increase the precision of 3D reconstructions.

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