High-Precision Monitoring during the Installation of Large Steel Structures by UAV Nap-of-the-Object Photogrammetry

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Abstract

This paper proposes and validates a method based on UAV nap-of-the-object photogrammetry for refined 3D digital modeling to achieve high-precision monitoring during the installation of large steel structures, offering a comparative analysis with traditional oblique photogrammetry methods. Through field tests and data processing on the steel structure of a sports stadium in Zhejiang Province, the results demonstrate that nap-of-the-object photogrammetry can capture high-resolution images, offering significant advantages in detail representation and modeling of complex structures. Experimental data reveal that the model's root mean square error (RMSE) generated by nap-of-the-object photogrammetry is 14.56mm, markedly lower than the 51.99mm achieved by traditional methods, meeting the Level II accuracy standard specified in the "Technical Specifications for Nap-of-the-Object Photogrammetry." The study further shows that, when combined with optimized flight path planning, nap-of-the-object photogrammetry enhances both the efficiency and accuracy of data collection while improving operational safety. This technique is highly applicable and flexible, making it suitable for data acquisition of complex structures and high-rise buildings. In summary, the proposed method exhibits significant advantages in terms of accuracy, efficiency, safety, and applicability, providing a practical solution for high-precision, comprehensive digital modeling of large steel structures.

1. Introduction

With the continuous advancement of modern construction technology, the application of steel structures in architectural engineering is becoming increasingly widespread. Steel structures, known for their high strength, lightweight nature, and ease of construction, are extensively used in large venues, bridges, industrial plants, and other fields. To ensure the construction quality and safety of steel structures, the application of digital technology is particularly crucial. The digitization of steel structures not only enhances construction precision and efficiency but also provides essential data support for subsequent maintenance and management (Sun et al., 2023).

Precise monitoring and data collection are of paramount importance during the construction of steel structures. Currently, the application of 3D digital technology in the construction of steel structures remains in its nascent stage. Traditional methods of pre-assembling steel components typically involve on-site assembly, which not only demands stringent on-site conditions but also consumes substantial manpower and resources (Liu et al., 2018). With the widespread adoption of 3D laser scanning technology, steel structure processing units have begun utilizing handheld 3D laser scanners for component modeling and digital pre-assembly (Cheng et al., 2023). Although this method is more efficient in terms of space utilization, manpower, and resources, the process of using handheld 3D laser scanners is complex and time-consuming. During operation, reflective markers and coded targets must be affixed to the nodes, coordinates must be obtained through photogrammetry, and finally, scanning is performed to acquire cross-sectional information. This results in intricate and inefficient field operations.

For overall structural scanning, the commonly used equipment is the tripod-mounted 3D laser scanner (Jia et al., 2021). Although the tripod-mounted 3D laser scanner boasts high efficiency and ease of operation, it performs poorly in terms of operational adaptability. When scanning multi-layer or high-rise steel structures, it requires the setup of stations between floors, thereby increasing fieldwork and potential safety hazards. The repeated relocation of stations also accumulates errors, leading to inaccurate scanning results. Moreover, for large-scale spatial steel structures, the tripod-mounted 3D laser scanner typically can only perform bottom-up scanning, failing to capture the more valuable data of the upper surface of the structure (Zhang et al., 2024).

In contrast, the emerging drone-based oblique photogrammetry technology offers significant advantages in terms of mobility, operational flexibility, ease of use, and applicability (Burdziakowski et al., 2021). This technique employs drones equipped with self-positioning systems and multi-lens high-resolution oblique cameras to capture side and frontal images of the scanned objects for 3D modeling. Thanks to the high mobility of drones, oblique photogrammetry significantly enhances the efficiency of modeling multi-layered and complex spatial projects, enabling top-down structural scanning to capture more valuable upper surface data, thereby compensating for the shortcomings of handheld and tripod-mounted 3D laser scanners.

However, at present, drone-based oblique photogrammetry technology is primarily utilized in fields such as historical building modeling, geological surveying, and urban planning, with relatively little research focused on its application in steel structure construction (Martinez-Carricondo et al., 2020; Li, 2022; Wu et al., 2018). Moreover, the traditional drone photogrammetry methods exhibit lower accuracy, failing to

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meet the precision standards required for steel structure construction (Tian et al., 2021). This directly impedes the adoption of drone-based oblique photogrammetry technology in the steel construction sector.

In 2019, Academician Zuxun Zhang introduced the concept of nap-of-the-object photogrammetry, a third photogrammetric method distinct from traditional vertical and oblique photogrammetry (Si, 2019). As an emerging surveying technology, nap-of-the-object photogrammetry, when combined with drone technology, can comprehensively cover building structures and achieve centimeter- or even millimeter-level data collection. This effectively addresses the limitations of current drone modeling methods, making it particularly suitable for standalone buildings with intricate façade details. Building on nap-of-the-object photogrammetry, Qingquan Li proposed the optimized views photogrammetry (Li et al., 2023). By analyzing scene viewpoints and calculating optimized drone data collection routes, this method significantly improves façade model outcomes and further enhances the accuracy and efficiency of large-scale 3D reconstruction.

Although nap-of-the-object photogrammetry technology has achieved significant success in the application to small standalone buildings, it still faces numerous challenges in the modeling of large steel structures. This paper proposes a refined flight path planning method for nap-of-the-object photogrammetry using drone-based oblique photogrammetry technology, achieving visual validation of flight path safety and automated data collection execution. This approach offers the advantages of high efficiency and low cost, liberating fieldwork and meeting the high-precision, comprehensive digital data collection requirements of large steel structures. Consequently, it facilitates the full-scale 3D digital modeling of large steel structures to ensure high-precision monitoring during the installation process. Additionally, by avoiding tower cranes and other mechanical equipment at the construction site during the flight, this method provides a practical solution for high-precision monitoring in the installation of large steel structures.

2. Methodology

2.1 Principles of Nap-of-the-Object Photogrammetry

Nap-of-the-object photogrammetry, introduced by Academician Zuxun Zhang, is an innovative photogrammetric technique designed to meet the demands of precision measurement. Unlike traditional vertical and oblique photogrammetry, this method focuses on capturing the "surface" of objects by taking close-up photographs to obtain ultra-high-resolution images, enabling detailed extraction of geographic information. This technology is particularly well-suited for structures with complex details, such as steel buildings.

Nap-of-the-object photogrammetry is a process that evolves from nothingness to existence, from rough to refined, as depicted in Figure 1. In the initial stage, conventional drone flights are employed to capture low-resolution images of the survey area. These preliminary images are processed to generate a rudimentary model of the survey zone. The primary objective of this stage is to establish a foundational model framework that serves as a reference for subsequent detailed measurements. Subsequently, based on the rough model, precise flight routes oriented towards the target object are planned and designed. During this process, an optimized route planning algorithm analyzes the scene viewpoints and calculates the optimal flight path to ensure comprehensive and seamless image coverage. Ultimately, through intelligent close-range flights along these refined routes, high-resolution images and high-precision models are obtained.

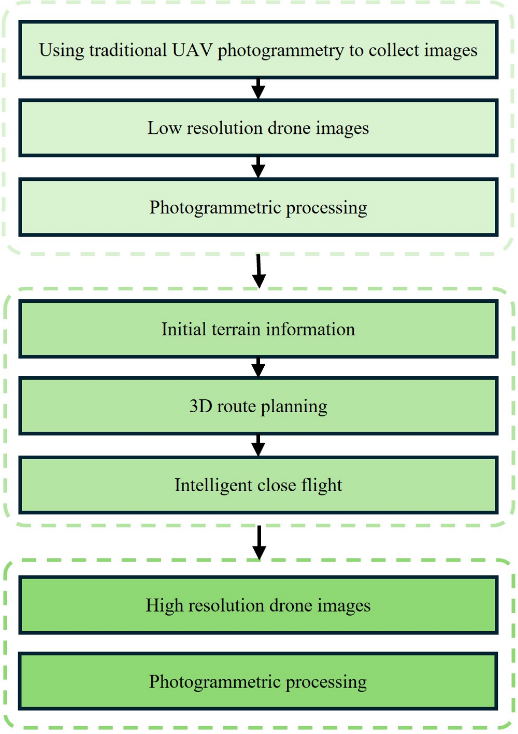

Figure 1. Flowchart of nap-of-the-object photogrammetry.

The nap-of-the-object photogrammetry technique emphasizes data refinement and accuracy during processing to ensure the final model's high quality and practicality. Its application in the digitization of steel structures offers significant advantages. Firstly, high-resolution imagery captures the intricate details of steel structures, making it ideal for the meticulous modeling of complex frameworks. Additionally, drones can flexibly adjust flight paths and shooting angles to adapt to various challenging environments, especially excelling in multi-story and high-rise buildings. Optimized route planning and automated data acquisition processes greatly enhance data collection efficiency, reducing the complexity and time cost of field operations. Through multi-angle, multi-directional image capture and meticulous data processing, comprehensive and highly precise three-dimensional modeling of buildings can be achieved.

Moreover, nap-of-the-object photogrammetry possesses the advantage of flight path safety visualization, ensuring the secure operation of drones. On steel construction sites, there are often tall obstacles such as tower cranes that pose potential threats to drone flight safety. Through flight path safety visualization, these obstacles can be identified and avoided in advance. This not only reduces the incidence of drone accidents but also enhances their adaptability in complex construction environments, enabling them to complete data collection tasks more safely and efficiently.

2.2 Flight Path Planning

Flight path planning plays a crucial role in nap-of-the-object photogrammetry. Unlike model-free methods that focus on real-time adaptability and exploration in unknown environments, model-based flight path planning relies on an initial rough model of the target scene. Through subsequent analysis and planning, it achieves a globally optimal flight path that meets the target requirements. This path is then used to execute the flight mission for precise 3D reconstruction. Initially, the survey area is analyzed using the initial model to establish viewpoint selection and optimization methods, as well as the path connections between viewpoints. Ultimately, the generated flight path is transmitted to the drone to perform the flight and photography tasks. This globally optimized flight path planning method provides a more complete and smoother flight path compared to model-free methods, improving the success rate of flight and photography tasks while enhancing the coverage and accuracy of the reconstruction results.

As illustrated in Figure 2, depending on the spatial dimensions of the flight path, the UAV's flight modes can be categorized into 2D, 2.5D, and 3D modes. Conventional photogrammetry typically employs a 2D flight mode, where the UAV flies at a fixed altitude, capturing images with a downward or fixed-angled tilt. This method is suitable for relatively flat areas; however, when the terrain has significant elevation differences, the images may exhibit geometric distortion, resulting in resolution discrepancies and varying degrees of image overlap, which can affect reconstruction accuracy or even cause data loss. The 2.5D flight mode, an enhancement of the 2D mode, adjusts the fixed altitude based on the terrain elevation of the target area, using a digital elevation model (DEM) or digital surface model (DSM) as the initial model. This approach, also known as terrain-following flight, maintains a consistent photographic distance, partially resolving the issue of inconsistent image resolution. However, since the camera orientation remains fixed, image distortion persists. In contrast to the first two modes, the 3D flight mode requires the flight path planning to determine variable waypoint positions (x_i, y_i, z_i) and dynamically adjust the camera's pitch and yaw angles ($pitch_i$, yaw_i) to ensure it faces the target for imaging.

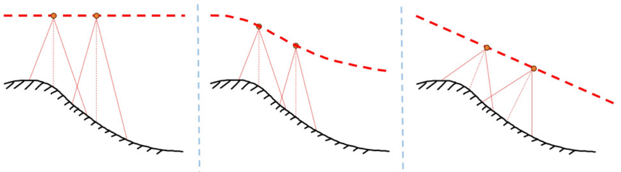
(a) 2D flight mode
(b) 2.5D flight mode
(c) 3D flight mode

Figure 2. Different flight modes.

In the realm of photogrammetric design, to collect image data that meets the demands of precise 3D reconstruction, the flight path planning for nap-of-the-object photogrammetry must comprehensively consider various geometric reconstruction constraints, such as sensor parameters, image resolution, intersection angles, and overlap rates. Furthermore, in terms of path planning, it is essential to perform spatial analysis of the target scene information, taking into account spatial occlusions, physical obstacles, and no-fly zones. During close-proximity flights near structures, there are inherent safety risks. Visual observation alone is often insufficient to prevent collisions with obstacles in time. Therefore, it is crucial to conduct reliable pre-flight safety validations. By superimposing the planned flight path and the preliminary model within a unified coordinate system, one can visualize and analyze the regions through which the flight path passes. This provides a clear depiction of the positional relationship between the flight path and obstacles, offering a quantitative assessment of the safety for subsequent close-proximity operations. This approach allows for the early identification and avoidance of obstacles, optimizing the flight path, ensuring the UAV remains clear of hazardous areas, reducing the incidence of UAV accidents, and enhancing its adaptability in complex construction environments, thereby enabling it to complete data collection tasks more safely and efficiently.

3. Experiments and Results

3.1 Experimental Design

This study selects the steel structure of a sports stadium in Zhejiang Province as the research area. First, using the DJI Phantom 4 RTK drone (Table 1), a comprehensive scan of the stadium's steel structure and its surrounding terrain and obstacles was conducted, generating an initial 3D model containing detailed terrain and obstacle information. Based on the generated 3D model, we then planned uniform nap-of-the-object photogrammetry flight paths. To ensure the accuracy and comprehensiveness of data collection, appropriate photographic parameters were set, such as camera focal length, shooting angle, flight altitude, and image overlap. Throughout this process, special emphasis was placed on the visualization and safety verification of the flight paths. The planned paths were superimposed on the preliminary model for visual analysis to identify and avoid potential obstacles such as cranes and other tall structures. This process optimized the flight paths to ensure they fully covered the steel structure's facades and roof while guaranteeing flight safety. Finally, the meticulously verified flight paths were input into the UAV flight control system, enabling the DJI Phantom 4 RTK drone to perform fully automated nap-of-the-object photogrammetry missions. The drone followed the predetermined paths, continuously adjusting its position and shooting angle in real time to capture high-resolution images. This process not only enhanced the efficiency and accuracy of data collection but also ensured operational safety, providing high-quality image data for subsequent 3D reconstruction and analysis.

Hardware	Specification	Parameter
Aircraft	Takeoff Weight	1391 g
	Max Flight Time	Approx. 30 minutes
GNSS	Positioning Accuracy	Vertical 1.5 cm + 1 ppm (RMS) Horizontal 1 cm + 1 ppm (RMS)
Gimbal	Stabilization	3-axis (tilt, roll, yaw)
	Pitch	-90° to +30°
	Max Controllable Angular Speed	90°/s
Camera	Sensor	1" CMOS; Effective pixels: 20 M
	Lens	8.8 mm / 24 mm(35 mm format equivalent:24 mm)
	Max Image Size	4864×3648（4:3）； 5472×3648（3:2）

Table 1. Main parameters of DJI Phantom 4 RTK.

3.1.1 Initial Model Construction

First, the DJI Phantom 4 RTK drone was employed to conduct oblique photogrammetry of the study area, following a "#" shaped flight path with a longitudinal overlap rate of 70% and a lateral overlap rate of 60%. During this flight, a total of 176 photographs were taken. The DJI Phantom 4 RTK, equipped with centimeter-level Real-Time Kinematic (RTK) technology, significantly enhances the precision of digital results, achieving a 1:500 standard without control points.

The flight data were imported into ContextCapture software for oblique 3D modeling, generating a 3D oblique photogrammetry model of the study area, which was then output to the CGCS2000 coordinate system. Figure 3 illustrates the generated oblique photogrammetry model, encompassing the terrain conditions and obstacle information within the study area. The large steel structure depicted in the figure is the primary building for this nap-of-the-object photogrammetry study. This model provides foundational data support for subsequent detailed flight path planning and safety validation.

Figure 3. Oblique photogrammetry model of the study area.

3.1.2 Flight Path Planning

The advantage of nap-of-the-object photogrammetry lies in its capacity to closely approach the surveyed object and capture detailed images oriented directly at it. Based on the preliminary model of the large steel structure, we planned the flight paths for nap-of-the-object photogrammetry of the building's main structure. The ground resolution for the meticulously designed flight paths was set at 0.005 meters, with equidistant shots taken at an altitude of 18 meters from the building's surface. Detailed parameter settings are shown in Table 2.

Parameter	value
Ground resolution/m	0.005
Flight speed/(m/s)	2
Close vertical spacing/m	18
Fore-and-aft overlap/(%)	80
Side overlap/(%)	70

Table 2. Design parameters for detailed flight paths in nap-of-the-object photogrammetry.

Through meticulous flight path design, employing an upward autonomous flight pattern, a total of 55 detailed flight paths for close-range photogrammetry were completed. This flight path design ensures comprehensive data coverage and significantly enhances image resolution and reconstruction accuracy. The results of the flight path planning for nap-of-the-object photogrammetry are illustrated in Figure 4, showing the distribution and coverage of the detailed flight paths over the steel structure.

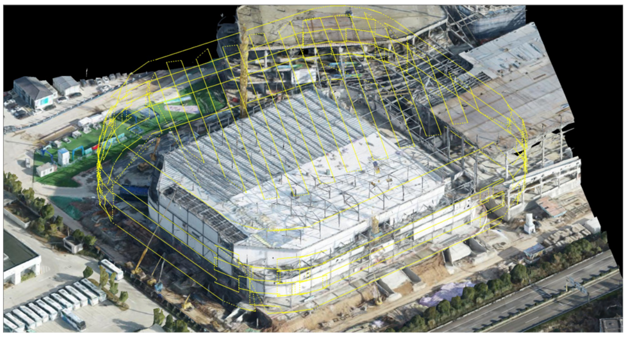

Figure 4. Flight path planning for nap-of-the-object photogrammetry.

3.1.3 Safety Verification

In this study, there are inherent safety risks during close-proximity flights around large steel structures. Relying solely on visual observation to detect impending collisions between the UAV and obstacles is often insufficient for timely response, necessitating reliable pre-flight safety verification. First, the planned flight paths and the preliminary model were integrated based on a unified coordinate system. Then, through visual analysis of the superimposed flight paths and the preliminary model, the regions traversed by the flight paths were clearly depicted to provide a quantitative assessment of the safety for subsequent close-proximity operations.

As shown in Figure 4, the study scene contains numerous mechanical equipment such as tower cranes, which are spaced closely together, preventing nap-of-the-object photogrammetry with the principal optical axis perpendicular to the target surface. To ensure flight safety, flight paths and photography directions were adjusted to avoid obstacles. Figure 5 illustrates the adjusted flight paths and photography directions, ensuring that all flight paths maintain a sufficient safety margin from obstacles, thereby mitigating collision risks. This safety verification method not only enhances the safety of the flight mission but also ensures the effectiveness and continuity of data collection.

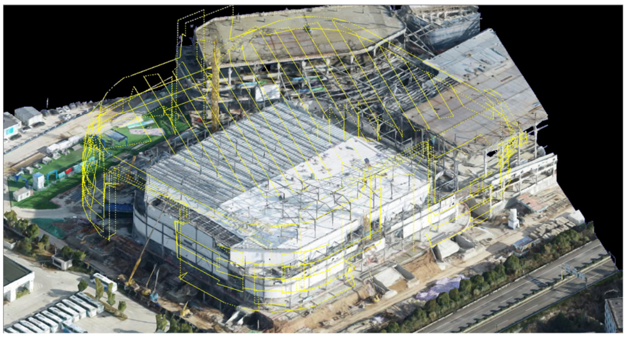

Figure 5. Adjusted flight paths for nap-of-the-object photogrammetry.

3.1.4 Processing UAV Image Data

Upon completing the precise nap-of-the-object photogrammetry with the UAV, it is essential to preprocess the image data to ensure the successful creation of a 3D model. Images with poor lighting conditions and extensive shadow areas are discarded to maintain data quality. The preprocessed image data is then imported into ContextCapture software for 3D reconstruction.

This software automatically detects and matches homologous points, utilizing the principle of multi-image observation to select the optimal image pairs for modeling.

After generating the dense point cloud data, a Triangulated Irregular Network (TIN) is produced through data transformation, as shown in Figure 6(a). Subsequently, the TIN is further optimized to generate a 3D untextured model, as depicted in Figure 6(b). Finally, the software automatically extracts the corresponding texture information based on intrinsic geometric relationships and maps it onto the 3D untextured model, ultimately creating a detailed 3D model, as illustrated in Figure 6(c).


(a) Triangulated Irregular Network (b) 3D Untextured Model (c) 3D Model

Figure 6. 3D model of the steel structure.

3.2 Analysis of Results

To better compare the effects of traditional oblique photogrammetry and nap-of-the-object photogrammetry on 3D reconstruction, this paper conducts a comparative analysis focusing on model quality and accuracy.

3.2.1 Analysis of Model Quality

In terms of reconstruction quality, traditional oblique photogrammetry captures images from higher altitudes, generating models that, while capable of reflecting the overall outline of the steel structure, fall short in detailing and modeling complex areas. Particularly when dealing with the facades and intricate regions of steel structures, data gaps and resolution reduction are common issues. Additionally, models generated by oblique photogrammetry often exhibit texture distortion due to limitations in shooting angles and resolution, leading to surface texture distortions and blurred details.

In contrast, nap-of-the-object photogrammetry, which captures images in close proximity to the steel structure's surface, yields ultra-high-resolution images. This method results in models with more refined detail representation and superior reconstruction of complex structural areas. Models generated through nap-of-the-object photogrammetry not only accurately reflect the overall form of steel structures but also precisely capture fine features and intricate geometric shapes. Moreover, this approach effectively reduces errors caused by changes in image overlap, thereby enhancing the accuracy and completeness of the model.

Figure 7 showcases a comparative analysis of the models generated by both methods. It is evident from the figure that the model produced by nap-of-the-object photogrammetry displays more detailed facades, edges, and complex structural parts of the steel structure, providing a more accurate representation of the actual structure. On the other hand, the model generated by oblique photogrammetry exhibits texture distortion and resolution inconsistencies in these detailed areas. This outcome verifies the advantages of nap-of-the-object photogrammetry in high-precision 3D modeling, offering a reliable data foundation for subsequent detailed modeling and applications.


(a) Nap-of-the-object photogrammetry (b) Oblique photogrammetry

Figure 7. Comparison of the effect of the models generated by the two methods.

3.2.2 Analysis of Model Accuracy

To evaluate the model accuracy, we measured the corresponding dimensions of the steel structure in both the oblique photogrammetry model and the nap-of-the-object photogrammetry model, using the actual dimensions of the steel structure as a reference. The results are shown in Table 3. As depicted in Table 3, the root mean square error (RMSE) of the oblique photogrammetry model is 51.99mm, whereas the RMSE of the nap-of-the-object photogrammetry model is only 14.56mm. Evidently, the nap-of-the-object photogrammetry technique demonstrates a significant advantage in model accuracy.

No.	Actual value/mm	Oblique photogrammetry		Nap-of-the-object photogrammetry	
		Measured value/mm	Error value/mm	Measured value/mm	Error value/mm
(1)	9000	8943	-57	8984	-16
(2)	9000	8940	-60	9019	+19
(3)	9000	8938	-62	8990	-10
(4)	9000	8945	-55	9016	+16
(5)	11400	11337	-63	11417	+17
(6)	9000	8930	-70	8987	-13
(7)	9000	8930	-70	8983	-17
(8)	3700	3652	-48	3716	+16
(9)	3700	3698	-2	3690	-10
(10)	3700	3652	-48	3690	-10
(11)	3700	3672	-28	3683	-17
(12)	3700	3664	-36	3691	-9
(13)	3700	3682	-18	3714	+14
(14)	3700	3670	-30	3713	+13
(15)	3700	3687	-13	3715	+15
(16)	5450	5385	-65	5436	-14
(17)	5450	5396	-54	5433	-17
(18)	5450	5390	-60	5433	-17
(19)	5450	5390	-60	5437	-13
(20)	5450	5391	-59	5438	-12
(21)	5450	5392	-58	5437	-13
(22)	5450	5397	-53	5434	-16
(23)	5450	5399	-51	5435	-15

Table 3. Comparison of the accuracy of models generated by the two methods.

Specifically, oblique photogrammetry, constrained by shooting angles and resolution, tends to produce larger errors in the details and edges of complex steel structures. These critical areas in the oblique photogrammetry model often fail to accurately reflect the actual dimensions, resulting in a decrease in overall model accuracy. In contrast, nap-of-the-object photogrammetry, through close-range high-resolution image acquisition, can more precisely capture the detailed features and geometric shapes of the steel structure, thereby significantly reducing model errors. Additionally, the accuracy of our nap-of-the-object photogrammetry model complies with the Level II accuracy standard stipulated in the "Technical Specifications for Nap-of-the-Object Photogrammetry" (T/CSGPC 021-2024), which requires the RMSE to be less than or equal to 20mm when the image resolution is 5mm. The accuracy standards for nap-of-the-object photogrammetry are shown in Table 4.

Level	Image resolution/mm	RMSE/mm
I	1	5
II	5	20
III	10	30

Table 4. Accuracy standards for nap-of-the-object photogrammetry.

4. Conclusions

This study delves into the application of UAV-based nap-of-the-object photogrammetry for refined 3D modeling to achieve high-precision monitoring during the installation of large steel structures, and provides a comparative analysis with traditional oblique photogrammetry methods. Field tests and data processing on the steel structure of a sports stadium in Zhejiang Province demonstrated that nap-of-the-object photogrammetry, which captures ultra-high-resolution images by photographing close to the steel structure's surface, has significant advantages in detailing and modeling complex parts. The experimental results show that models generated by nap-of-the-object photogrammetry exhibit more intricate detailing in facades, edges, and complex structural areas of the steel structure, accurately reflecting the actual condition of the building.

In terms of model accuracy, nap-of-the-object photogrammetry also shows clear superiority. Comparative analysis of actual measurement data indicates that the RMSE (Root Mean Square Error) of the models generated by nap-of-the-object photogrammetry is 14.56mm, significantly lower than the 51.99mm RMSE of traditional oblique photogrammetry, meeting the Level II accuracy standard stipulated in the "Technical Specifications for Nap-of-the-Object Photogrammetry" (T/CSGPC 021-2024), which requires an RMSE of less than or equal to 20mm for a 5mm image resolution. This demonstrates that nap-of-the-object photogrammetry can meet the high accuracy requirements of steel structure construction.

The integration of nap-of-the-object photogrammetry with optimized flight path planning greatly enhances the efficiency and accuracy of data collection. The UAV's fully automated flights along an upward arched flight path ensure comprehensive image data coverage while effectively avoiding obstacles at the construction site, thereby improving operational safety. The efficient data collection process not only saves time and human resources but also enhances the overall quality of the modeling.

Furthermore, nap-of-the-object photogrammetry offers high applicability and flexibility, particularly suited for complex structures and multi-story or high-rise buildings. Compared to handheld and tripod-mounted 3D laser scanners, nap-of-the-object photogrammetry can flexibly adjust flight paths and shooting angles to adapt to various complex environments, excelling in facade and roof data collection for steel structures. In summary, the method of detailed 3D digitization of steel structures using UAV-based nap-of-the-object photogrammetry has significant advantages in terms of accuracy, efficiency, safety, and applicability, providing a practical solution for high-precision, comprehensive digital data acquisition of large steel structures. As technology continues to advance and its applications become more widespread, nap-of-the-object photogrammetry is expected to play a greater role in the digital modeling of steel structures and other complex forms.

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