Study on 3D printing based on UAV oblique photogrammetry

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Abstract. UAV oblique photogrammetry can quickly reconstruct a three-dimensional real-scene model of an object, and the 3D printing technology based on the principle of additive manufacturing can print a digital three-dimensional model into a 3D object. These two high-technologies realize the mutual conversion between virtual (digital) and reality, and have good potential application value. This study takes the Zhuhai Sports Center Natatorium as an example to study oblique photography and 3D printing technology. We reconstructed the high-precision 3D real-scene model of the natatorium, and printed a 3D solid model of the natatorium with high reduction and rich details. Finally, we explored the establishment of oblique photography and 3D printing workflow.

1. Introduction
Unmanned aerial vehicle (UAV) oblique photography is a new measurement technology developed in recent years and has been widely used in many fields\cite{1, 2}. Due to the continuous improvement of the performance of digital cameras and computers, the development of UAV oblique photography has been explosive in recent years. Oblique photography uses a digital camera to take photos, then calculates and reconstructs a three-dimensional model of the target object, which has real-scene texture characteristics. Oblique photography turns two-dimensional photos into three-dimensional photos with spatial geographic information\cite{3, 4}.

Benefits from the popularity of consumer drones, the cost of taking photos from UAVs equipped with high resolution digital cameras has dropped significantly. The photos that used to be obtained by manned aircraft or helicopters can now be achieved with a lightweight UAV, which is a leap forward. In addition, the UAV can be equipped with high-precision Global Navigation Satellite System (GNSS) chips and inertial measurement unit (IMU) sensors, so that the collected digital photos have high-precision spatial geographic coordinates and position and orientation system (POS) data, which facilitates the realization of oblique photography modeling without image control points. High-precision oblique photography has brought a revolutionary impact to the field of surveying and mapping. In addition to reconstructing 3D real-scene models, it can also generate digital elevation models (DEM), digital surface models (DSM), and digital orthophoto map (DOM) and other result data, and extract topographic contour lines to draw refined topographic maps. Through the comparison of DEM data in different periods, the deformation of the target area can be analyzed, such as landslide deformation, land subsidence, etc\cite{5}.

Currently, the most widely used areas of UAV oblique photography are surveying and mapping, geology, and civil engineering\cite{6, 7}. The research and applications of the combination of UAV oblique
photography and 3D printing are very rare. He Yuanrong of Xiamen University of Technology conducted oblique photography and 3D laser scanning data collection on the Li’s family temple in Jianshan Village, a traditional Chinese village in 2019, and then merged the two kinds of point cloud data to reconstruct the 3D model of the Li’s family temple containing internal and external information, and finally the 3D solid model is printed using advanced 3D printing technology[8].

3D printing is widely used in the fields of machinery, industrial design, aviation, biomedicine and other fields[9-13], while oblique photography belongs to the field of surveying and mapping. Therefore, the application of combining the two is relatively rare and belongs to the category of interdisciplinary. But we think this is a very promising development direction. 3D printing is a technology that turns virtual into reality. Oblique photography is a technology that virtualizes and reality. Therefore, the combination of the two forms a bridge connecting virtual and reality. Based on these two technologies, scientists can clone an ancient bridge, a historical building, and a temple. In the field of planetary exploration in the future, humans will land on the moon and Mars, establish bases, and conduct habitability experiments.

In summary, the combination of UAV oblique photography and 3D printing is very promising and valuable. In addition to the potential application scenarios mentioned above, there are more application scenarios worth exploring in the future. This study introduces the two advanced technologies of UAV oblique photography and 3D printing in detail, and then applies these two technologies to the Zhuhai Sports Center Natatorium as the research object to provide a realistic and feasible case for more in-depth research in the future.

2. UAV oblique photogrammetry

2.1. Introduction to oblique photogrammetry
Oblique photography is an advanced technology developed in the field of surveying and mapping in recent years. By mounting an adjustable tilt camera or multi-lens cameras on a drone or other flying carrier, images can be collected from five different angles, including vertical and four tilt angles[14-17]. When the drone takes photos, it can simultaneously record the altitude, speed, heading and side overlap rate, coordinates and other parameters, and then analyze the tilted image. Based on the principle of structure form motion (SfM) or simultaneous localization and mapping (SLAM), the three-dimensional geometric structure information of the environment and the spatial pose of the camera are restored through two-dimensional image to reconstruct the 3D real-scene model of the target.

2.2. Key techniques of oblique photogrammetry

2.2.1. Multi-view image joint adjustment. Multi-view images include not only vertical image data, but also oblique image data. Traditional aerial triangulation methods cannot process oblique photographic data well. Therefore, the joint adjustment of multi-view images needs to fully consider the geometric deformation and occlusion relationship between the images. This method combines the external orientation elements of the multi-view image provided by the POS system and adopts a pyramid matching strategy from coarse to fine. Automatic matching of points with the same name and free-net beam adjustment are performed on each level of image, and a better point matching result with the same name can be obtained. Establish the error equation of the multi-view image self-checking regional network adjustment between connection points and connection lines, control point coordinates, and GNSS/IMU auxiliary data, and ensure the accuracy of the adjustment results through joint solutions.

2.2.2. Multi-view image dense matching. Image matching is one of the basic problems of photogrammetry. Multi-view images have the characteristics of large coverage and high resolution. Therefore, how to fully consider the redundant information in the matching process, quickly and
accurately obtain the coordinates of the point with the same name on the multi-view images, and then obtain the three-dimensional information of the ground object is the key point of the multi-view image matching. Because it is difficult to obtain the points of the same name required for modeling by using a matching primitive or a matching strategy alone, the multi-primitive and multi-view image matching developed with computer vision in recent years has gradually become the focus of research. At present, research in this field has made great progress, such as automatic recognition and extraction of the side of buildings. By searching for features on the multi-view images, such as building edges, wall edges and textures, to determine the two-dimensional vector data set of the building, the two-dimensional features of different perspectives on the image can be converted into three-dimensional features. When determining the wall surface, you can set a number of influencing factors and give a certain weight, divide the wall into different categories, scan and segment each wall of the building, obtain the side structure of the building, and then reconstruct the side of the building to extract the height and contour of the roof of the building.

2.2.3. DSM generation and true DOM correction. Dense matching of multi-view images can obtain high-precision and high-resolution DSMs, which can fully express the undulating characteristics of the terrain and become an important content of the new generation of spatial data infrastructure. Due to the large scale difference between multi-angle oblique images, and serious problems such as occlusion and shadows, there are new difficulties in automatically acquiring DSM based on oblique images. In order to solve these problems, we can first analyze and select the appropriate image matching unit to perform feature matching and pixel-by-pixel dense matching according to the external orientation elements of each image calculated by the automatic aerial three solution, and introduce parallel algorithms to improve computing efficiency. After obtaining high-density DSM data, filter processing is performed to fuse different matching units to form a unified DSM.

The true DOM correction of multi-view images involves the continuous DEM of the object, a large number of discrete objects with very different granularity, and a large number of image-side multi-angle images, which are typically data-intensive and computationally intensive. On the basis of DSM, according to the geometric characteristics of the continuous terrain and discrete objects, the semantic information of the object is extracted through methods such as contour extraction, patch fitting, and roof reconstruction. At the same time, on multi-view images, image-side semantic information is obtained through image segmentation, edge extraction, and texture clustering. According to the results of joint adjustment and dense matching, the corresponding relationship between the object side and the image side with the same name is established. Then a global optimization sampling strategy and joint correction taking into account the geometric radiation characteristics are established. The data processing flow of oblique photogrammetry is shown in Figure 1.

![Figure 1. Data processing of oblique photogrammetry](image)

3. Introduction to 3D printing

3.1. Principle of 3D printing

3D printing, also known as additive manufacturing, is a type of rapid prototyping manufacturing technology, which originated from the technology of using layered manufacturing principles to make topographic maps and photographic sculptures in the United States in the late 19th century. 3D printing can manufacture various forms of objects, which are widely used in education, industry,
commerce and other fields[18-21]. The principle of 3D printing technology is: first create a 3D digital model on the computer, then load the printing materials such as powder or colloid into the printer, connect the printer to the computer, read the 3D digital model data in the computer, and control the movement of the print head and output of the material, overlaying the printing materials layer by layer, and finally turn the blueprint on the computer into a real object.

At present, the principles of 3D printing can be divided into many types, such as Stereo Lithography Apparatus (SLA), Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), three-dimensional printing (3DP), Digital Light Processing (DLP), etc. Among them, SLA, LOM, SLS and FDM are currently the mainstream of the 3D printing.

3.2. 3D printing workflow

3.2.1. 3D model creation. The 3D model can be reconstructed by computer-aided design software (CAD, computer-aided design) or other 3D modeling software. The model can be designed independently or obtained by scanning real objects. For example, for small-scale rock samples, high-precision micro-nano-level CT scans are used to obtain images of the internal structure of natural rocks, and then a three-dimensional reconstruction method is used to establish a digital three-dimensional structure network model.

3.2.2. Selection of printing materials. After the creation of the 3D model is completed, the appropriate printing should be selected according to the physical and mechanical properties of the printed object. There are many materials available for 3D printing. For example, the material used in SLA is liquid photosensitive resin, LOM uses paper, metal film, plastic film, and SLS can use thermoplastic, metal powder, and ceramic powder. For the 3DP printing of large buildings, the materials used are mainly building waste materials, and resin mortar, clay, and concrete materials can also be used.

3.2.3. Selection of the printing instrument. After the printing materials are determined, a suitable 3D printer must be selected. Currently, 3D printers are divided into two categories: industrial grade and desktop (consumer grade). Well-known companies that can produce 3D printers include 3D Systems, Stratasys, Formlabs, Hewlett-Packard, EOS, Objet, etc. Since 3D printers have strict requirements for printing materials, researchers should choose suitable printers and printing materials according to the research purpose, requirements and budget.

3.2.4. Printing and post-processing of the 3D model. After the three-dimensional model is reconstructed, the model is divided into slices in the computer. Then set the printing path and parameters, transmit the signal to the 3D printer, and print the 3D digital model into a physical object. After the printing, the physical object will be post processed according to the instructions of the printer to obtain the final 3D printing entity.

4. Study on oblique photogrammetry and 3D printing of Zhuhai Sports Center

This study takes the Zhuhai Sports Center Natatorium as the research object to establish the application process of UAV oblique photography and 3D printing.

4.1. Project overview

Zhuhai Sports Center is located in Xiangzhou District, Zhuhai City, Guangdong Province. It consists of four venues: stadium, natatorium, gymnasium and badminton hall (Figure 2), with a total area of 700,000 m². The object of this study is the natatorium, which consists of two semi-circular reticulated shells of different sizes, called diving area and swimming area. The diving area has a span of 38.7 m, the swimming area has a span of 53.7 m, and the building height is 23.15 m (not counting the
suspended cable part). The top of the semi-circular mesh shell is a corrugated roof, which looks like a shell.

![Distribution map of the Zhuhai Sports Center](image)

**Figure 2. Distribution map of the Zhuhai Sports Center**

### 4.2. Reconstruction and repair of 3D model of oblique photography

This oblique photography uses the DJI Phantom 4 RTK drone, the flight mode is five-direction flying, the flying height (relative to the ground) is 55 m, and the oblique shooting angle is 60°. In addition, in order to better obtain the facade image of the natatorium, two additional circular flying routes were added. The shooting angle was horizontal and the flying height (relative to the ground) was 23 m and 33 m respectively (Figure 3). A total of 1099 photos were collected for this mission.

![Flying route planning for the natatorium of Zhuhai Sports Center](image)

**Figure 3. Flying route planning for the natatorium of Zhuhai Sports Center**

Bentley Context Capture software was used to reconstruct the 3D model of oblique photography, and the aerial triangulation (AT) was performed on the five-direction and circular flying photos. The accuracy of the AT results is shown in Table 1. The average ground resolution of five-direction and circular flying are 13.2 mm/pixel and 10.6 mm/pixel, respectively, and the reprojection error is 0.67 and 0.53 pixels, respectively. Then the two AT results are merged (Figure 4), and the 3D model is reconstructed. After a certain period of modeling and calculation, a high-precision 3D real-scene model of the natatorium is reconstructed (Figure 5). However, we found that the model has some problems, such as floating objects in the air, and the facade of the natatorium is hollow and blurred due to the glass material. Therefore, it is necessary to repair the model before 3D printing.
Figure 4. Oblique photography AT results of the natatorium

Figure 5. The 3D real-scene model of the natatorium

Table 1. Accuracy of AT results for the natatorium.

| Flying mode       | Date       | Number of Photos | Average Ground Resolution | Reprojection Error (RMS) |
|-------------------|------------|------------------|---------------------------|--------------------------|
| Five-direction flying | 19-10-2020 | 786              | 13.2 mm/pixel             | 0.67 pixels              |
| Circular flying   | 19-10-2020 | 313              | 10.6 mm/pixel             | 0.53 pixels              |

Geomagic Wrap software is suitable for model repair, and can export STL format files that can be used for 3D printing. Therefore, this study uses the software to repair the reconstructed 3D model. The repair of the natatorium model took two days in total. We mainly carried out the operations of removing floating objects, repairing holes, and wiping convex and concave surfaces. Finally, the restored natatorium model was obtained, and a 3D printing file in STL format was generated (Figure 6).

Figure 6. The 3D model of the natatorium after repair
4.3. 3D printing model
This study uses the third-generation desktop 3D printer Form3 launched by American 3D printer manufacturer Formlabs in 2019. This printer uses an exclusive molding technology - Low Force Stereolithography (LFS), which belongs to the SLA principle: a custom-designed laser and mirror system and a flexible film tank are used to cure from liquid resin in a precise manner solid isotropic parts. The thickness of the printing layer of Form3 is 25~300 µm, the laser spot size is 85 µm, the maximum molding volume is 14.5×14.5×18.5 cm, and it supports up to 20 resin materials, covering the needs of models, dentistry, jewelry, functional parts, etc.

Load the restored 3D printing file of the natatorium to the computer, connect to the printer, and print the solid model. After the printing is completed, the printed solid model is processed according to the printer's instructions, and finally a 3D printing solid model of the natatorium is obtained (Figure 7). From the details of the model, we can find that the details of the 3D printing model are very rich, and the texture of the stairs and the surface of the metal roof are very clear.

Figure 7. The 3D printing solid model of the natatorium

4.4. Oblique photography and 3D printing workflow
Based on this exploratory research, the workflow of UAV oblique photography and 3D printing is proposed (Figure 8). The workflow mainly consists of three steps: 3D model reconstruction of UAV oblique photography, model repair, and 3D printing. In the future, with the deeper research, the process can also be optimized.

Figure 8. Oblique photography and 3D printing workflow
5. Conclusion
UAV oblique photography and 3D printing are two emerging high-technologies. Marked by the popularity of consumer drones and desktop 3D printers in 2012, both technologies have entered a stage of rapid development. Because oblique photography belongs to the field of surveying and mapping, and 3D printing belongs to the field of mechanical design and additive manufacturing, there is not much overlap between the two. However, this study believes that these two technologies have potential joint application value. Especially in the production of large-scale 3D models, such as the protection of historical cultural relics. Therefore, this article first briefly introduces the principles of the two technologies, and then uses the UAV oblique photography and 3D printing technology to print the solid 3D model of the natatorium, and establishes the oblique photography and 3D printing workflow. The results show that the UAV oblique photography can quickly build a high-precision 3D model of the target object at low cost, and the printed 3D model has high degree of reduction and rich details.

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