A Fuzzy Comprehensive Evaluation Approach for the 3D Modeling Accuracy of UAV Oblique Photogrammetry

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Abstract. 3D modeling is the important foundation of virtual reality and scene simulation. The technology of UAV oblique photogrammetry provides a new way for 3D modeling, and the accuracy becomes the key of its application. Since there are a lot of uncertainties in 3D modeling of UAV oblique photogrammetry, this paper proposed a fuzzy comprehensive evaluation approach to deal with this uncertain problem. Firstly, according to the composition of 3D modeling system based on UAV oblique photogrammetry, the main impact factors of 3D modeling accuracy are determined, and the indicator system of accuracy evaluation is therefore constructed. Secondly, by using the method of analytic hierarchy process, the weights and membership degrees of each indicator are calculated. Finally, the proposed approach is applied and validated in the case study. After the fuzzy mapping by the dot multiplication performance between the indicator weights and membership degrees, the comprehensive evaluation sets of different cases are obtained, and their corresponding 3D modeling accuracies can be determined based on the maximum membership degree principle. It is concluded that the fuzzy comprehensive evaluation approach proposed in this paper can quickly and correctly assess the 3D modeling accuracy of UAV oblique photogrammetry.

1. Introduction
In the information era, the demands for digital earth, visual simulation and virtual reality are getting stronger and stronger. Since Three Dimensional (3D) modeling plays foundational and key roles in these technologies, it has become an important research topic in the relevant fields. So far, there have been a lot of methods used to build 3D models, such as laser scanning, close range, aerial and satellite photogrammetry, and so on. Among these methods, the different platform-based photogrammetry is most widely used because of its fast, economical and macroscopic advantages in 3D modeling. Especially, compared with the traditional photogrammetry, the oblique photogrammetry could capture the texture information of models from all sides, which is very useful to enhance the intuition of 3D modeling results [1-2].

In recent years, with the rapid developments and extensive applications of the Unmanned Aerial Vehicle (UAV) technology, the UAV-based oblique photogrammetry has become a new effective way of 3D modeling [3-6]. The accuracy of 3D modeling based on different methods is decisive for their applications [7]. In order to use the 3D modeling achievements of UAV-based oblique photogrammetry, it is the first step for us to know the 3D modeling accuracy. Because the 3D modeling of UAV-based oblique photogrammetry is very complex and therefore affected by many different sources of factors, there is remarkable fuzziness in the 3D modeling accuracy analysis. In order to solve these problems,
in this paper, we try to propose a multi-level Fuzzy Comprehensive Evaluation (FCE) approach for the 3D modeling accuracy of UAV-based oblique photogrammetry.

2. Methodology

2.1. Principles of the 3D Modeling Based on UAV Oblique Photogrammetry

2.1.1. Composition of the 3D modeling system based on UAV oblique photogrammetry. The 3D modeling system of UAV oblique photogrammetry integrates the sensors of oblique photogrammetry onto the UAV platform, in which one orthographical and four oblique cameras are used to capture the image information of ground objects from different views, and therefore not only their top but also their side textures could be obtained (Figure 1). So the 3D models constructed using this technology are almost identical with the real world. This 3D modeling system is composed of two subsystems such as data acquisition subsystem and data process subsystem. The data acquisition subsystem is used to design the flight lines, capture the images and measure the ground control points, and the data process subsystem is used to build 3D models according to the photogrammetry theory [3-4].

![Figure 1. The sketch map of UAV-based oblique photogrammetry.](image)

2.1.2. Impact factors of the 3D modeling accuracy based on UAV oblique photogrammetry. The accuracy of 3D modeling refers to a lot of aspects, but the location accuracy and texture accuracy are the two most important ones. Since the 3D modeling system of UAV oblique photogrammetry consists of many components and each of them might bring about errors into the 3D models, the 3D modeling accuracy is impacted by many different factors. According to the system composition and operation flow, it has been revealed that the height of UAV, overlay ratio of flight lines, oblique angle of images and ground control points have the most important influences on the 3D modeling accuracy [3-7].

2.2. Principles of the Fuzzy Comprehensive Evaluation Method

The fuzzy comprehensive evaluation method, first proposed by American automatic control expert L.A. Zadeh in the mid-1960s, is an effective way to deal with fuzzy issues by converting qualitative evaluation to quantitative evaluation based on the concept of membership in fuzzy mathematics. The principles and processes are summarized as follows [8].

1. Determine the comment set $U=\{u_1, u_2, \ldots, u_n\}$.
2. Determine the evaluation set $V=\{v_1, v_2, \ldots, v_n\}$.
3. Determine the weights set $W=\{w_1, w_2, \ldots, w_n\}$, where $\{w_1 + w_2 + \ldots + w_n = 1\}$.
4. Determine the fuzzy relation matrix $R$: For the comment set $u_i \in U$ ($i=1, 2, \ldots, n$), the fuzzy set on the evaluation set is $(r_{i1}, r_{i2}, \ldots, r_{im})$, using the fuzzy mapping $f: U \rightarrow F(V)$, the fuzzy relation matrix $R$ can be obtained as Formula (1),
Calculate the comprehensive evaluation set $B$: After the dot multiplication operation between the weight set $W$ and fuzzy relation matrix $R$, the comprehensive evaluation set $B$ can be obtained as Formula (2).

$$B = W \cdot R$$ (2)

Determine the comprehensive evaluation result: According to the principle of maximum membership degree, the comprehensive evaluation result is finally determined.

### 2.3. FCE of the 3D Modeling Accuracy Based on UAV Oblique Photogrammetry

The processes and impact factors of 3D modeling based on UAV oblique photogrammetry are very complex, which lead to obvious fuzziness in the accuracy analysis. In order to solve the fuzzy problem, we use FCE method to assess the 3D modeling accuracy of UAV oblique photogrammetry.

#### 2.3.1. Determination of the comment set and evaluation set

According to the impact factors of 3D modeling accuracy based on oblique photogrammetry, the comment set is divided into two levels. The first level is $U\{\text{data acquisition}(U_1), \text{data process}(U_2)\}$, and the second level includes $U_1\{\text{overlay ratio of flight lines}(U_{11}), \text{height of UAV}(U_{12}), \text{oblique angle of images}(U_{13})\}$ and $U_2\{\text{ground control points}(U_{21})\}$. The evaluation set $V = (V_1, V_2, V_3, V_4, V_5)$ is divided into five grades such as worse ($V_1$), bad ($V_2$), average ($V_3$), good ($V_4$) and excellent ($V_5$).

#### 2.3.2. Calculation of the indicator weights

The weights of indicators in the comment set are calculated using the methods of Analytic Hierarchy Process (AHP) and triangular fuzzy numbers [9-10]. Firstly, three experts give their pairwise comparison matrixes of the indicators, and these matrixes are processed with triangular fuzzy numbers. Secondly, the initial weights of the indicators are calculated after defuzzification of the comprehensive fuzzy values. Finally, the weights of the indicators can be obtained after standardization as shown in Table 1.

**Table 1.** The indicator weights of 3D modeling accuracy evaluation based on UAV oblique photogrammetry.

| The first level of indicator | Weight | The second level of indicator | Weight |
|-----------------------------|--------|-------------------------------|--------|
| Data acquisition($U_1$)    | 0.6129 | Overlay ratio of flight lines ($U_{11}$) | 0.1847 |
| Data process($U_2$)        | 0.3871 | Height of UAV ($U_{12}$)       | 0.5388 |
|                            |        | Oblique angle of images ($U_{13}$) | 0.2765 |
|                            |        | Ground control points ($U_{21}$) | 1.0000 |

#### 2.3.3. Calculation of the indicator membership degrees

Firstly, 10 experts are invited to vote for the possibilities of different indicator values to different 3D modeling accuracies ($V_1, V_2, V_3, V_4, V_5$). According to these vote results, for the continuous indicators such as overlay ratio of flight lines ($U_{11}$) and height of UAV ($U_{12}$), the rectangle and half rectangle $F$ distribution functions are used to determine their membership degree functions (Figure 2), and for the discrete indicators such as oblique angle of images ($U_{13}$) and ground control points ($U_{21}$), the membership degree of $m^{th}$ values in indicator $U_y$ to 3D modeling accuracy $V_n$ is obtained by calculating its experts percentage to the total 10 experts (Table 2).
Figure 2. The membership degree function of UAV height (a) and overlay ratio of flight lines (b).

Table 2. The membership degrees of image’s oblique angle and ground control points.

| Indicator                                | Type                                      | Membership degree |
|------------------------------------------|-------------------------------------------|-------------------|
| Oblique angle of image                   | Orthophoto                                | (0, 0, 0.1, 0.2, 0.7) |
|                                          | Orthophoto + right image                  | (0, 0, 0.1, 0.3, 0.6) |
|                                          | Orthophoto + left image                   | (0, 0, 0.3, 0.3, 0.4) |
| Distribution of the ground control points| Uniform points along the boundary +       | (0, 0, 0.3, 0.3, 0.4) |
|                                          | moderate points along the flight line      |                   |
|                                          | Uniform points along the boundary +       | (0, 0, 0.1, 0.4, 0.5) |
|                                          | a few points along the flight line         |                   |
|                                          | Uniform points along the boundary          | (0, 0, 0.1, 0.7, 0.2) |
|                                          | Grouped points at four corners             | (0.3, 0.7, 0, 0, 0) |
|                                          | Four points at four corners                | (0.7, 0.3, 0, 0, 0) |
|                                          | Nonuniform points                         | (0.9, 0.1, 0, 0, 0) |

3. Case Study
In order to validate the proposed approach, we designed 6 different cases of 3D modeling based on UAV oblique photogrammetry in a university campus, and their combined parameters are shown in Table 3. Each of them was carried out and the corresponding 3D models were obtained. In addition, the horizontal and vertical average errors, middle errors, maximum errors and minimum errors of these 3D models were also actually investigated and measured. That is to say, both the impact factors and 3D modeling accuracies of UAV oblique photogrammetry in these 6 cases are known.

We applied the FCE approach proposed above to assess the 3D modeling accuracies of these different cases. Firstly, according to the values of the parameters in different cases, the weights and membership degrees of all indicators were determined. Then, after the dot multiplication operation between the weights and membership degrees, the comprehensive evaluation sets were calculated, and from the principle of the maximum membership degree, the 3D modeling accuracy of each case was finally obtained (Table 4). From the comparisons between the evaluated accuracies and the actual errors in Table 4, it can be found that the evaluated accuracy of each case is very consistent with the actual error, and in addition, the 3D modeling accuracies of these 6 cases evaluated using the FCE approach proposed in this paper are sorted as 6<5<1<4<3<2, which is completely identical with their sorts of actual errors.
Table 3. Parameters of 3D modeling cases based on UAV oblique photogrammetry.

| Case | Overlay ratio of flight lines ($U_{11}$) | Height of UAV ($U_{12}$) | Oblique angle of images ($U_{13}$) | Ground control points ($U_{21}$)                  |
|------|----------------------------------------|--------------------------|----------------------------------|------------------------------------------------|
| 1    | 66%                                    | 250m                     | Orthophoto                       | Uniform points along the boundary + 17 points along the flight line |
| 2    | 78%                                    | 250m                     | Orthophoto                       | 6 nonuniform points                                      |
| 3    | 78%                                    | 250m                     | Orthophoto                       | 4 points at four corners                                  |
| 4    | 78%                                    | 250m                     | Orthophoto                       | 8 grouped points at four corners                         |
| 5    | 78%                                    | 250m                     | Orthophoto                       | 17 uniform grouped points at four corners                 |
| 6    | 78%                                    | 250m                     | Orthophoto                       | Uniform points along the boundary + 19 points along the flight line |

Table 4. Comparisons of the evaluated accuracy and actual error of 3D models.

| Case | Evaluation set ($V_1, V_2, V_3, V_4, V_5$) | Evaluated accuracy | Actual error (m) |
|------|---------------------------------------------|--------------------|-----------------|
| 1    | (0.0000, 0.0113, 0.3916, 0.2293, 0.3509)    | $V_5$ (average)    | 0.4215          |
| 2    | (0.3625, 0.0387, 0.2678, 0.1131, 0.2177)    | $V_1$ (worse)      | 3.1057          |
| 3    | (0.2851, 0.1161, 0.2679, 0.1131, 0.2176)    | $V_1$ (worse)      | 2.1064          |
| 4    | (0.1303, 0.2710, 0.2679, 0.1131, 0.2177)    | $V_2$ (bad)        | 0.6623          |
| 5    | (0.0142, 0.0000, 0.3066, 0.3814, 0.2951)    | $V_3$ (good)       | 0.3103          |
| 6    | (0.0142, 0.0000, 0.3066, 0.2680, 0.4113)    | $V_5$ (excellent)  | 0.2540          |

4. Conclusion
The technology of UAV oblique photogrammetry provides a new method for 3D modeling. However, the 3D modeling accuracy plays the key role in its application. It is very significant to quickly and correctly determine the 3D modeling accuracy of UAV oblique photogrammetry. In this paper, on the one hand, the 3D modeling system of UAV oblique photogrammetry is divided into data acquisition subsystem and data process subsystem, and each of them consists of some factors which have different impacts on the 3D modeling accuracy, and an indicator system with two levels is therefore constructed. On the other hand, the 3D modeling accuracy is divided into 5 grades, and by using the AHP method, the weights and membership degrees of every indicator to every grade of 3D modeling accuracy are calculated. Finally, after the dot multiplication operation between the weights and membership degrees, the fuzzy mapping is performed and the comprehensive evaluation set of 3D modeling accuracy is obtained. The applications in the case study show that the results of 3D modeling accuracy evaluated with the FCE approach of this paper are very consistent with the actual states. It’s concluded that since the FCE method considers the fuzziness in 3D modeling of UAV oblique photogrammetry, the evaluated results of 3D modeling accuracy are certain and stable, and the proposed FCE approach provides an effective and robust way to assess the 3D modeling accuracy of UAV oblique photogrammetry.

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