An Improved Hybrid Index Structure for Per-Calculated Downwash Flow Field Visualization

Ming Ni\textsuperscript{a}, Hongjie Wang\textsuperscript{b}, Xingcheng Li\textsuperscript{c}, Yilin Liao\textsuperscript{d}, and Lin Fu*\textsuperscript{e}

College of Information Engineering, Sichuan Agricultural University, Ya'an, China

\textsuperscript{e}Corresponding author e-mail: F32056128@163.com, \textsuperscript{a}nm@sicau.edu.cn, \textsuperscript{b}kobosp@163.com, \textsuperscript{c}lxcyou111@163.com, \textsuperscript{d}liaoyilin2000@163.com

Abstract. With the application of aerial plant protection technology in field spraying, how to intuitively and quickly obtain the impact of propeller downwash flow field on droplet deposition has become an important aspect of field management. The unstructured grid is used for the propeller rotation area, the structured grid is used for the surrounding fluid domain; After the mesh generation, use Fluent software to iteratively calculate the propeller-fluid domain mesh model until the calculated residual values converge, In this way, the aerodynamic parameters of the propeller and the discrete grid value distribution of the surrounding fluid domain are obtained ; In the OpenGL environment, use SPH method to establish the physical attribute particle model of the droplet, Create a mixed space domain of octree and KD tree at the same time, import pre-calculated grid numerical distribution data, and initialize the octree and KD tree in the fluid domain; Finally, the hybrid structure index algorithm is used to obtain the changes of the flow field around the particles, and the motion is solved based on Newton's law to obtain the multi-particle flow field motion trajectory with high frame rate.

1. Introduction

Nowadays, many scholars have studied the deposition and drift characteristics of water droplet particles in the washing flow field under the drone.

Wang Changling [1] He Xiongkui et al. [2] studied the downwind airflow wind speed and the space deposition rate and distribution uniformity of the droplets under different flight modes (forward, reverse, side fly), flight altitude and side wind speed influences.

AJ Hewitt et al. [3] and the Spray Drift Task Force (SDTF) [4] developed a large general-purpose database to estimate air droplet movement after application. Yang Zhilun et al. [5] based on the xv-2 plant protection drone and used Solidworks to simulate the rotor wind field. The velocity distribution characteristics of the downwash airflow of the rotor of this type of drone were explored.

In terms of rotor airflow simulation, Xue Xinyu [6] and others used the CFD method to simulate the drift of pesticide fog droplets during spraying operations of the N-3 single-rotor drone, and compared them with the actual measured droplet drifts on the ground. The results show that the CFD method can qualitatively simulate the droplet drift.

At present, the spatial indexing method can be divided into three types: regular segmentation method, object segmentation method, and combined indexing technology [7].
In this paper, after obtaining more accurate and comprehensive data, import the established octree and KD tree mixed index model. Utilizing the spatial structure characteristics of the octree and the search characteristics of the KD tree. Finally, with the help of Newton's laws of mechanics, the animation of particles in the wind field is rendered.

2. Model Establishment
In the meshing software ICEM, a dynamic domain mesh and a static domain mesh are created, merged and exported in a top-down manner.

In addition, a multiple reference frame model (MRF) was set in the flow field motion. When using the MRF model for calculations, the entire calculation domain is divided into multiple small subdomains. Each subdomain can have its own motion, either stationary, or rotated, or translated. On the interface of the subdomain, the flow field information is exchanged by converting the speed to the absolute speed.

3. Simulation Result Analysis
Figure 1 shows the motion of multiple particles in the downwash flow field. The same color represents the same particle. It can be clearly seen in the figure that the particles gradually approach the blade through the area above the propeller, producing a ground effect and spreading to the surroundings.

![Figure 1. the motion of multiple particles in the downwash flow field.](image)

Under the above-mentioned model, the force and moment of the propeller in the simulation calculation were tested and compared with the published data. It can be concluded that the wind field structure of this calculation method is roughly consistent with the actual situation.

| Rotating speed (RPM) | Calculation result: lift(N) | Experimental measurement: lift(N) | error |
|----------------------|-----------------------------|----------------------------------|-------|
| 3000                 | 19.00                       | 19.83                            | +4.18%|
| 4000                 | 41.28                       | 42.68                            | +3.28%|
| 5000                 | 62.75                       | 65.49                            | +4.18%|

4. Index Structure Design
The octree structure is a regular data structure. The tree structure is used to recurse the model. According to X, Y, Z three different directions, the three-dimensional space entity to be represented is divided into eight equal-sized sub-cubes.

KD tree is a structure that generalizes binary search tree to multidimensional data, and realizes the organization and storage of multidimensional spatial data.

After using the octree split data model to generate leaf nodes, a pointer value is set at the non-empty leaf node of the octree to point to the associated KD tree. The KD tree divides the point cloud data in the leaf nodes of the octree into two subspaces. Then, each subspace is further recursively divided, and finally a complete KD tree is obtained. That is, all leaf nodes containing point cloud data are associated with KD trees. The specific creation method of the hybrid index structure is shown in the Figure 2 and Figure 3.
Figure 2. the process of the hybrid index structure
Select a bounding box cube according to the size of the data model, and use this cube as the root node of the octree.

If the number of data points contained in the current node is greater than the specified number, use a depth-first strategy to perform recursive octree decomposition on the node to decompose the cube into 8 subcubes.

If the current node contains less than or equal to the specified number of points, stop decomposition. Set the node as a leaf node of the octree, generate a node data field, and set the KD attribute value of the node.

Create a KD tree for the local data contained in the leaf nodes of the octree. According to the sampling results of the 3 axes, the divided coordinate axes are selected to divide the local data of the octree leaf nodes into two planes;

Each plane is further recursively divided until each node of the KD tree is generated. After the KD tree is generated, an index of the octree leaf node and the KD tree is established.

Point the current pointer to the next node of the octree and repeat step 2) until all octree nodes are processed.

**Figure 3.** The process of the improvement of the KD tree
Studies have shown that [8], for point cloud data after initial registration, Euclidean distance threshold method is used to remove point noise between data. On the other hand, if a small number of erroneous search results are allowed, the search efficiency of the KD tree will be greatly improved [9]. The specific calculation process of this method is as follows.

Establish multi-level index structure of octree and KD tree for data model.

Iterative initialization: Select the target point set \( P_k \) of the requested data, set the allowable distance threshold \( V_t \) and the default flow field value \( V_c \).

According to the coordinates \((x, y, z)\) of each point \( P \) in the target point \( P_k \) set, the spatial position and size \((x, y, z, l)\) of the octree bounding box, find the leaf node where the nearest point \( P_l(x, y, z) \) is located in the octree.

The KD tree containing the local point cloud is found through the leaf nodes of the octree, and the nearest two points from each point in the data point set \( P_k \) are searched based on the KD tree.

Use the Euclidean distance between two points to compare with the allowable distance threshold \( V_t \) to determine whether the point is available. If both points are available, skip to step 7)

The unavailable point returns the default flow field value \( V_c \).

The available point returns the value of the flow field at that point.

Use the weighted average of the Euclidean distance and the attribute value of the point as the final result of this method, and perform the next dynamic calculation.

Let the number of particles be \( N \) and the number of pre-calculated node data derived by Fluent be \( M \), the ratio of the number of data \( M \) to the data points contained in a leaf node of the octree is \( K \) (segmentation parameter), and the depth of the octree is \( h \). It can be obtained that the average number of points contained in each leaf node of the octree is \( M/K \), and the number of leaf nodes is \( K \). Simplifying the octree into the ideal full octree processing, we can calculate the octree depth as

\[
h \geq \lfloor \log_2 K \rfloor + 1
\]  

For \( N \) particles to be queried, the corresponding octree search time complexity is \( O(N \log_2 K) \); At a local space node, the leaf nodes of the octree are searched for two nearest neighbors through the KD tree, and the time complexity is \( O(N \log_2 (M/K)) \). Therefore, the search time complexity using this hybrid index structure is

\[
O(N \log_2 K) + O \left( N \log_2 \left( \frac{M}{K} \right) \right)
\]

Studies have shown that [1], in the case of random distribution of examples, the time of depth first search for the nearest neighbor of KD tree is \( O(N \log_2 (M)) \). In the worst case of backtracking, the time is \( O \left( 3MN^2 \right) \)

\[
O(N \log_2 K) + O \left( N \log_2 \left( \frac{M}{K} \right) \right) < O(MN)
\]

After obtaining this point data, the position of the particle can be solved according to the following Newton's law. Through cyclic calculation, the effect of each particle in the flow field by the air current can be presented.

\[
\dot{P}_{\text{total}} = P \times 2\pi R
\]

\[
\left( \frac{v_t + dt}{x_t + dt} \right) = \left( \frac{v_t + dt \times \dot{P}_{\text{total}}(t + dt) \times M^{-1}}{x_t + dt \times V_{t+dt}} \right)
\]

\[
\left( M - dt \times \frac{dF}{dv} - dt^2 \times \frac{dF}{dx} \right) \times dV = dt \times \left( F(t) + dt \times \frac{dF}{dx} V(t) \right)
\]
5. Particle Animation Implementation

The traditional traversal algorithm is selected as the comparison object, and the real-time update frame rate is used as the evaluation criterion of the experimental results. The following screenshots can be used to obtain more intuitive results.

Figure 4. The number of particles is 1200, and the speed is 3000rmp.

Table 2. The FPS of traditional way and mixed indexing in the downwashing wind field simulation experiments with various propeller speeds and different numbers of particles.

| Particles number | Traditional way | Mixed indexing |
|------------------|-----------------|----------------|
|                  | 3000rmp         | 5000rmp        | 3000rmp        | 5000rmp        |
| 400              | 235             | 210            | 2221           | 2122           |
| 800              | 149             | 145            | 1583           | 1544           |
| 1200             | 74              | 69             | 1067           | 823            |

It can be seen from the experimental data in the table above, compared with the traditional method, the hybrid index structure can effectively reduce the search time of the two nearest neighbors, greatly improve the real-time nature of simulation animation and save hardware resources.

6. Conclusions

After obtaining more accurate and comprehensive data, import the established octree and KD tree mixed index model. Utilizing the spatial structure characteristics of the octree and the search characteristics of the KD tree, the Euclidean distance threshold and weighted average algorithm are used to obtain specific point data. Finally, the particle position was solved by the help of Newton’s laws of mechanics.

Due to the pre-calculation characteristics, compared with the real-time flow field calculation method using the Navier–Stokes equation, it has the characteristics of less calculation and high frame rate. But there are also shortcomings in adaptability and flexibility.

References

[1] G Wang Changling, Song Jianli, He Xiongkui, etc. Effects of flight parameters of plant protection drones on the distribution characteristics of spray droplets during spraying [J]. Journal of Agricultural Engineering, 2017, 33 (23): 109-116.

[2] He Xiongkui. Change the status quo of China’s severely backward plant protection machinery and pesticide application technology [J]. Journal of Agricultural Engineering, 2004, 20 (1): 13-15.
[3] Hewitt A.J., Johnson D.R., Fish J.D., et al. Development of the spray drift task force database for aerial applications[J]. Environmental Toxicology & Chemistry, 2002, 21(3):648-658.

[4] Xue X.Y., Tu K., Kang Q.T., et al. Drift and deposition of ultra-low altitude and low volume application in paddy field[J]. International Journal of Agricultural and Biological Engineering, 2014, 7(4):23-28.

[5] Yang Zhilun, Ge Luzhen, Qi Lijun, et al. Study on the influence of the underwash airflow on the spray width of the plant protection UAV rotor [J]. Transactions of the Chinese Society of Agricultural Machinery, 2018,49 (01): 116-122.

[6] Xue Xinyu, Qin Wencai, Sun Zhu, et al. Effects of N-3 unmanned helicopter application on the control effects of rice plant hopper and rice leaf roller [J]. Chinese Journal of Plant Protection, 2013, 40 (3): 273-278.

[7] Liu Z X, An J, Jing Y. A simple and robust feature point matching algorithm based on restricted spatial order constraints for aerial image registration[J]. IEEE Transactions on Geoscience and Remote Sensing, 2012, 50(2):514-527.

[8] Zhong Ying, Zhang Meng. Automatic Point Cloud Registration Based on Improved ICP Algorithm[J]. Control Engineering, 2014, 21 (1): 37-40.

[9] Arya S, Mount D M, Netanyahu N S, et al. An optimal algorithm for approximate nearest neighbor searching fixed dimensions [J]. Journal of the ACM, 1998, 45 (6): 891-922.

[10] Zhu Ji hua, Yin Jun, Wu Wenzin, et al. Efficient registration for low-dimensional point sets Nearest neighbor search method [J]. Pattern Recognition and Artificial Intelligence, 2014, 27(12): 1071-1077.