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RESEARCH ON THE DESIGN OF UNMANNED AERIAL VERICLE FOR MINE INSPECTION

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Abstract

The frequent occurrence of mine accidents not only brings huge property losses, but also seriously threatens the safety of workers. In order to ensure the safe production of the mine, it is necessary to inspect the mine in time, and obtain the mine environmental information and equipment operation status in time. But the mine environment is complex and full of dangers. The manual inspection method has low efficiency, high degree of danger, and is prone to safety accidents; the online monitoring method has small coverage, low inspection efficiency and high investment cost. Therefore, this paper intends to design a mine inspection drone. The drone has strong survivability, and has the functions of autonomous obstacle avoidance in complex mine roadways, mine environment reconnaissance, data processing and human-computer interaction. The inspection of hard-to-reach areas eliminates the need for manual inspection, thereby reducing the burden on workers to the greatest extent and reducing the occurrence of casualties.

Keywords: mine inspection drone, strong survivability, obstacle avoidance,hard-to-reach areas

1. General Introduction

The mine roadway is narrow, the space is limited, the environment is complex, and there are many dynamic obstacles such as underground personnel, vehicles and equipment. The situation of signal shielding and noise interference is more serious than that of the ground, and effective GPS positioning signals cannot be obtained. Therefore, GPS cannot be applied to the autonomous navigation of mine inspection robots.

The multi-rotor drone has the advantages of not being affected by the unevenness of the mine floor, accumulated water, gangue and leftover coal, low power, easy to operate, safe and explosion-proof, etc. It can be used for mine reconnaissance, search and rescue[1]. Mine drones carry CO, CH4 and other gas sensors, temperature and humidity sensors, cameras, reconnaissance and detection of the mine, and send the mine information back to the monitoring center in real time[2]. In the absence of GPS signal and complex electromagnetic environment, drones can realize autonomous obstacle avoidance, automatic inspection, and autonomous navigation by carrying modules such as ultrasonic wave, binocular vision, and lidar, which can effectively reduce the occurrence of underground accidents, and the operation is simple and economical. The energy consumption and safety factor are high, which is suitable for wide popularization and application, and is of great significance to the realization of automatic mining with few people and no one in the future.

At present, the anti-collision ability of drones on the market is weak. During the execution of the mission, it is very easy to collide with the outside world and cause damage to the airborne equipment, resulting in crashes, explosions and injuries. When drones conduct inspections in tunnels, mines, woods, factories, pipelines, and inside buildings, the environment they face is extremely complex and dangerous. It is difficult for drones to enter. Even if they barely enter, they are prone to collision and crash , and even lead to larger accidents. How to effectively improve the survival adaptability and operation ability of drones in harsh environments is an important issue for the more efficient and safe use of drones today.

2. Drone Structural Design and Analysis

2.1 Spherical protective frame design

The space in the mine is small and the equipment is complicated. The possibility of the mine inspection drone colliding with the mine wall and the equipment in the well is high. In order to avoid accidents as much as possible, the protection device of the drone is an integral package, even if no one is unmanned. If the drone collides and falls, it can also prevent the onboard equipment of the drone from colliding with the ground again.The spherical protective frame is shown in Figure 1.

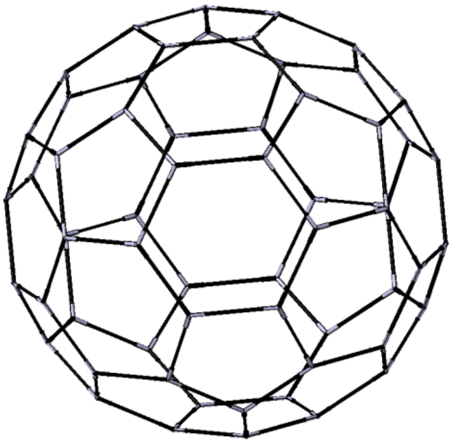


Figure 1 – Spherical protective frame.

Mine inspection drones use a full range of protective frames. Considering the requirements of mechanical strength and weight constraints, the spherical protective frame uses hollow carbon fiber tubes with high strength and low density as materials to increase its anti-collision ability during flight. At the same time, it can effectively improve its flight performance. The protection frame of the mine inspection drone is designed with reference to football, and adopts a spherical truss structure, and each carbon tube can be disassembled separately. The protective frame is surrounded by 90 carbon tubes to form 12 pentagons and 20 hexagons. The outer diameter of the carbon tubes is 3mm and the inner diameter is 1.5mm. According to the relationship between the radius of the frame and the length of the sides, the length of the carbon tubes can be obtained as 80mm. After the drone collides, it can quickly adjust its attitude to avoid crashing. The tee parts are made by 3D printing, and the material is PLA material. 60 tee parts and 90 hollow carbon tubes are splicedinto a spherical frame structure.

2.2 Drone body structure design

The body structure of the drone is mainly composed of four outer frames, an upper center plate, a lower center plate, a top plate, four arms, a motor seat and an outer frame connector.The upper center plate is shown in the figure 2,The lower center plate is shown in the figure 3 below.

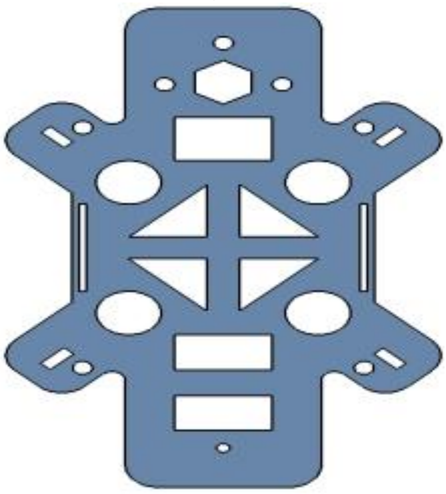


Figure 2 – Upper center plate.

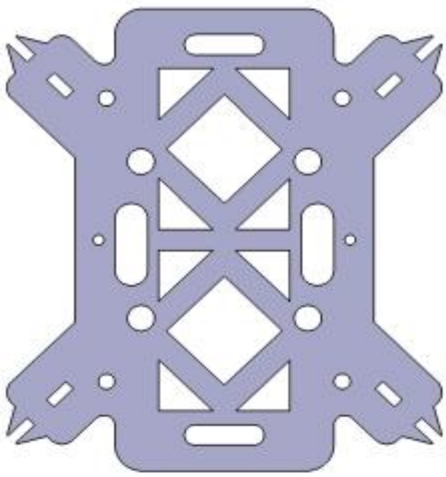


Figure 3 – Lower center plate.

The upper center plate and the lower center plate are roughly rectangular in structure, and the four corners extend outward. There are card slots designed here, and the four arms are fixed by the tenon-and-mortise structure[3]. In addition, four aluminum columns are designed between the upper and lower center plates to enhance the connection strength between the upper and lower center plates, and some equipment is placed between the upper and lower center plates. Under the condition of ensuring the strength and rigidity of the center body, the upper and lower center plates are perforated and hollowed out according to the force of the body and the circuit wiring, which reduces the weight of the overall structure and enables the drone to have a better flight effect.

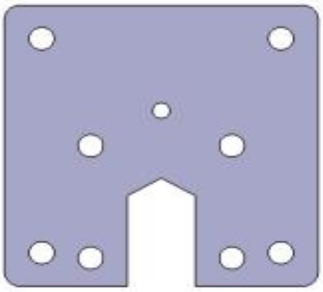


Figure 4 – Top plate.

The installation of the equipment adopts a layered structure. A top plate is installed above the upper center plate through nylon studs, and the airborne components can be installed between the two. This design structure is simple and the layout of the airborne equipment is neat and clear.The apical plate is shown in the figure 4.

Figure 5 – Outer frame.

Figure 6 – Round frame.

One end of the outer frame is provided with a protrusion, and one end is provided with a notch, and the four outer frames are connected end to end to form a round frame, and the firmness is enhanced by the tenon-and-mortise structure. The outer frame is shown in the figure 5,The round frame is shown in the figure 6.

Figure 7 – Outer frame connector.

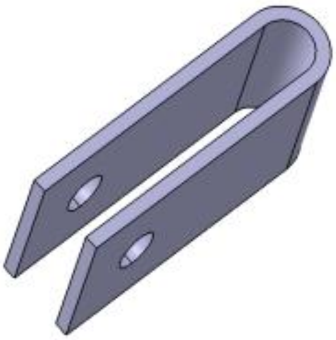


Figure 8 – Pipe clamp.

Each two outer frames are fixed by a pair of outer frame connectors. The round frame is mainly used to connect the drone and the spherical protective frame. There are mounting holes on the round frame, and the round frame and the protective frame are fixed by pipe clamps. The spherical protective frame and the round frame are connected with a pipe clamp, and they are movable connections. When the drone collides, the protective frame and the round frame can move in a small range.The outer frame connector is shown in the figure 7,The pipe clamp is shown in the figure 8.

For the traditional miniature multi-rotor, the arm generally adopts a horizontal structure, which has strict requirements on materials and complex structure. The horizontal structure of the arm is optimized to a vertical structure, which is more concise in overall layout and more reasonable in bearing capacity. The gap at one end of the drone arm is embedded in the round frame, and the other end is fixed by the tenon-and-mortise structure and the upper and lower center plates. There are motor mounting holes reserved on the machine arm. Insert the machine arm into the groove of the motor base and fix it with screws.The multi-rotor arm is shown in the figure 9.

Figure 9 – Multi-rotor arm.

In order to realize the ultrasonic obstacle avoidance of the drone, according to the characteristics of the three-dimensional movement of the multi-rotor drone in space, a total of 6 ultrasonic modules are arranged: front, rear, left, right, up and down. The ultrasonic module has a certain beam angle when transmitting ultrasonic waves. In order to prevent the spherical protective frame from affecting the obstacle avoidance function, the front, rear, left and right modules are installed on the round frame through the mounting seat 2, and the upper and lower modules are installed on the round frame through the mounting seat 1. All-round obstacle avoidance of the drone can be realized through 6 ultrasonic obstacle avoidance modules.The mounting seat 1 is shown in the figure 10,The mounting seat 2 is shown in the figure 11.

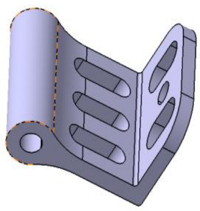


Figure 10 – Mounting seat 1.

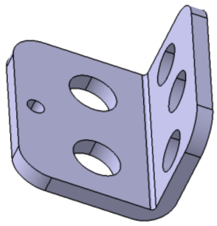


Figure 11 – Mounting seat 2.

The three-dimensional electronic prototype of the mine inspection drone is shown in the figure 12, and the prototype of the test principle produced is shown in the figure 13 below.

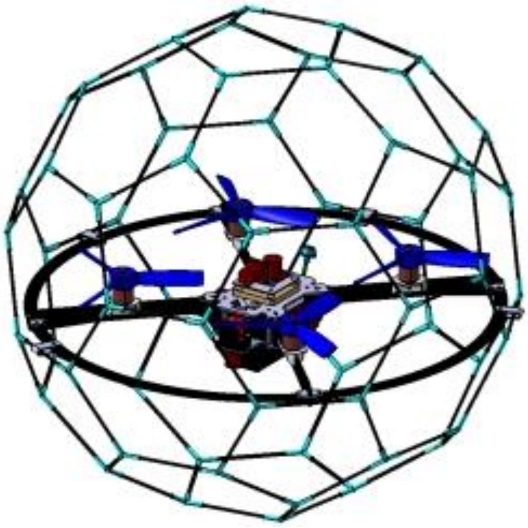


Figure 12 – Electronic prototype.

Figure 13 – Test prototype principle.

2.3 structure Analysis

Use RBE2 units for multi-point constraints at the connection of each component of the drone frame, as shown in Figure 14 for all RBE2 units of the whole aircraft.

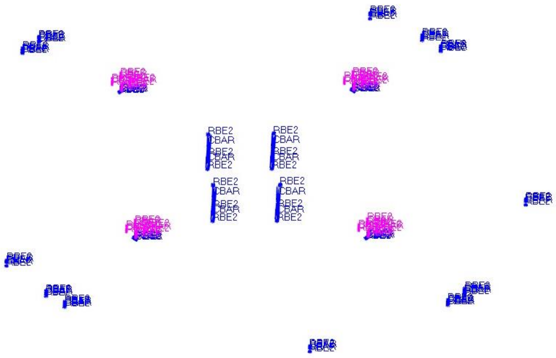


Figure 14 – All RBE2 connection units for drones.

According to the structural design results in the previous section, this section will use the finite element analysis software HyperWorks to analyze the strength and stiffness of the structure.The following will analyze the force state of the drone during take-off and hovering, as well as the force deformation of the spherical protective frame[4].

Condition 1:the 0.825kg pulling force generated by the motor is evenly applied to the motor base in the form of a distributed load, and the take-off weight of 1kg is applied to the lower center plate in the form of a concentrated load.The load is applied as shown in Figure 15.

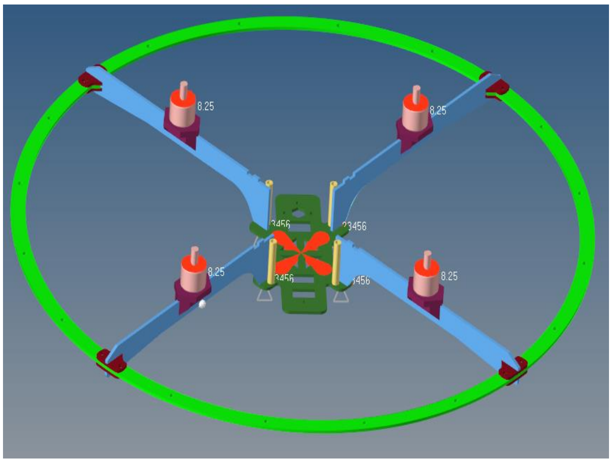
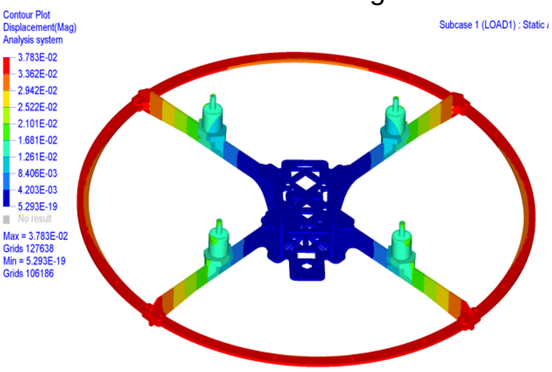


Figure 15 – Drone take-off state.



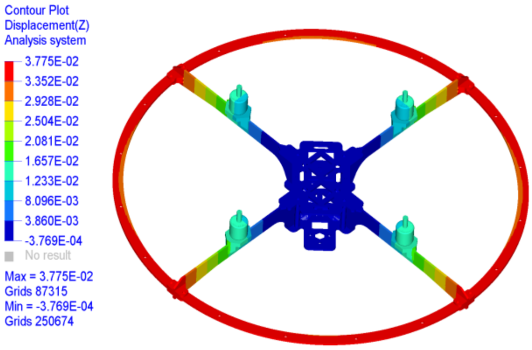


Figure 16 – Structural Strain Diagram. Figure 17 – Z-direction structural strain diagram.

It can be seen from Figure 16 that the maximum deformation of the drone structure is 0.038mm, and the deformation at the round frame is the largest, but the direction is unknown. The deformation of the whole machine structure is analyzed from the Z-direction deformation diagram of Figure 17, and it can be seen that the maximum deformation along the positive direction of the Z-axis is 0.0377mm, and the maximum deformation is still at the round frame. Due to the imposition of fixed constraints at the center plate, the deformation at the center plate is small and can be ignored.

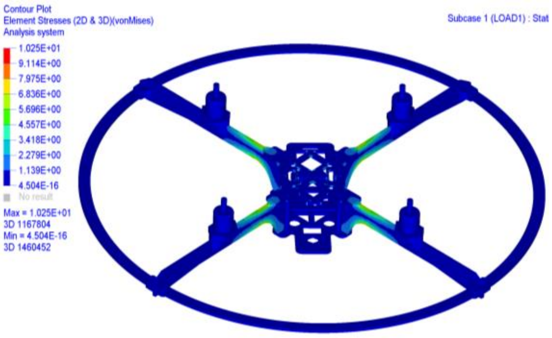


Figure 18 – Structure stress diagram.

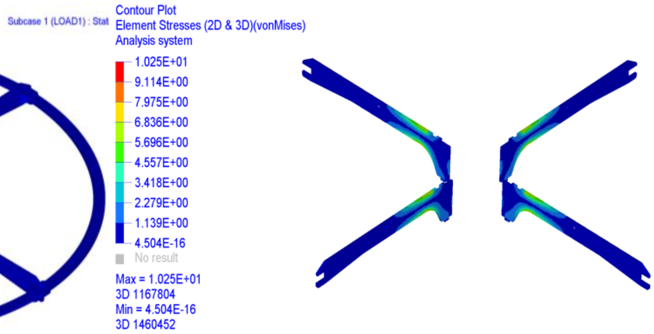


Figure 19 – Arm structure stress diagram.

As can be seen from Figure 18 and Figure 19, the maximum stress of the whole machine is concentrated on the inside of the motor base, near the center plate, and on the upper and lower sides of the machine arm, the maximum stress is 10.25MPa; the minimum stress is very small, concentrated in At the center plate where the fixed constraint is applied.

Condition 2:a fixed load is applied to the four motors, and a vertical downward pulling force of 10N is applied to the lower center plate to simulate the state of the drone when it is hovering.The load is applied as shown in Figure 20.

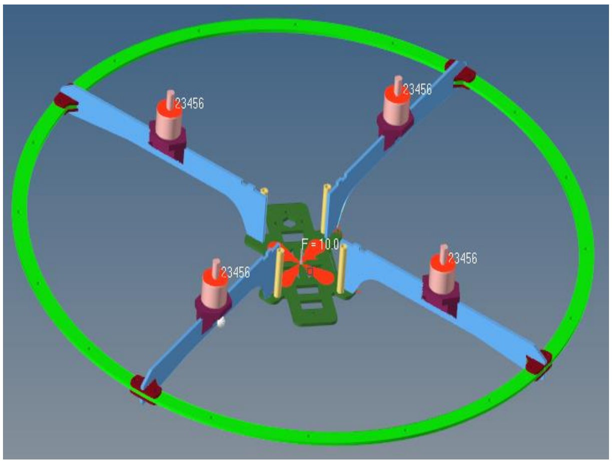


Figure 20 – Drone hovering state.

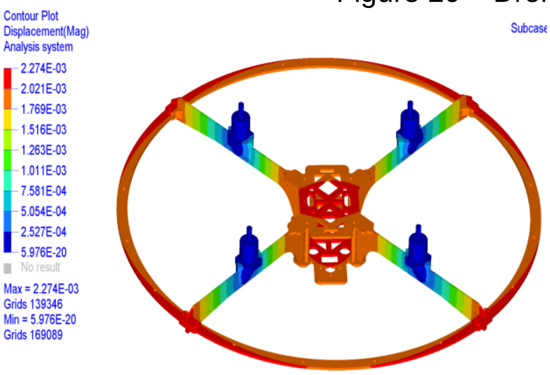


Figure 21 – Structural Strain Diagram.

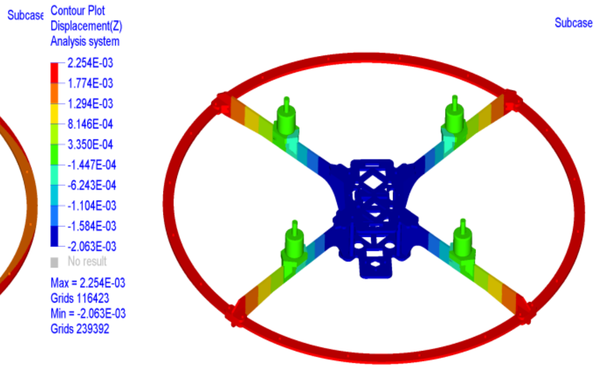
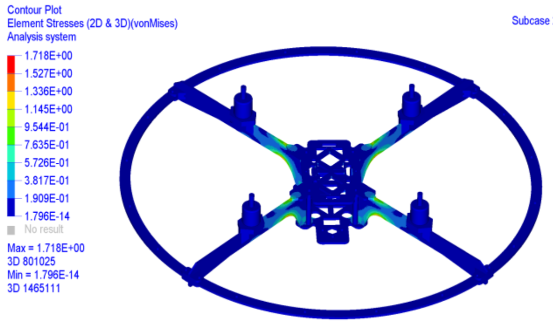


Figure 22 – Z-direction structural strain diagram.

As can be seen from Figure 21, there are two places with the largest deformation of the whole machine, one is the round frame, which is 0.0023mm, and the other is the center plate, which is 0.002mm. Due to the fixed constraints imposed at the motor mount, the amount of deformation here is very small, almost no. As can be seen from Figure 22, the deformation directions of the center plate and the circle frame in the Z direction are opposite. This is because the load is applied at the center plate and the restraint is applied at the motor base, causing the circle frame to be in the opposite direction.



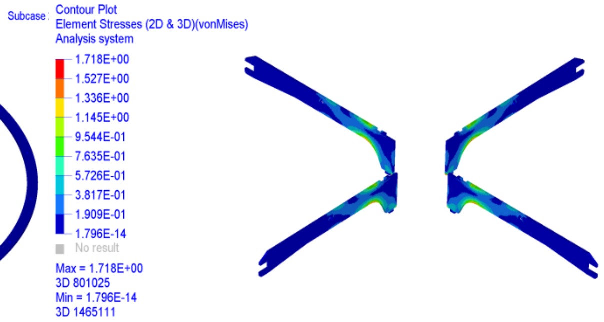


Figure 23 – Structure stress diagram. Figure 24 – Arm structure stress diagram.

As can be seen from Figure 23 and Figure 24, similar to working condition 1, the maximum stress of the whole machine is concentrated on the inner side of the motor base, near the center plate, and on the upper and lower sides of the machine arm, the maximum stress is 1.72MPa, Much smaller than the working condition. Since no load is applied near the circular frame, the stress is small.

The spherical protective frame has three carbon tubes at one node, which are respectively inserted into the tee connectors, and contact constraints are adopted between the components. Figure 25 shows all the contact constraints of the model, Figure 26 is a contact constraint at a node.

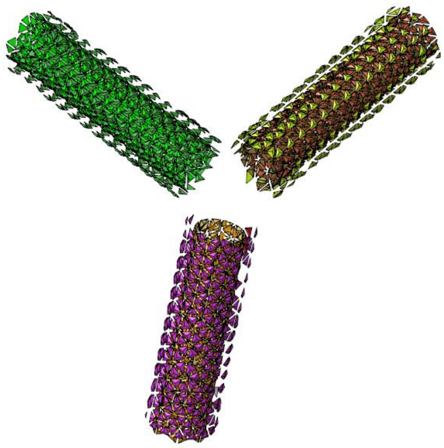


Figure 25 – All the contact constraints. Figure 26 – A contact constraint .

The finite element analysis of the spherical protective frame is carried out below. A fixed constraint is applied to a pentagon face of the spherical protective frame, and a force of 20N is applied to the opposite face of the pentagon to simulate the situation when the drone collides. The constraints and loads are applied as shown in Figure 27 shown.

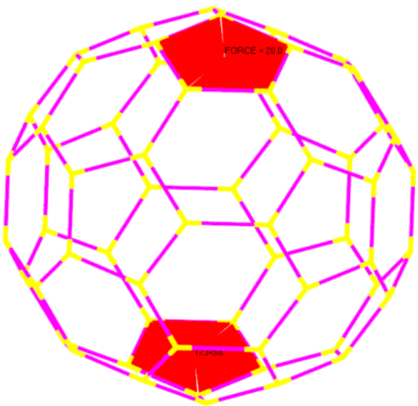
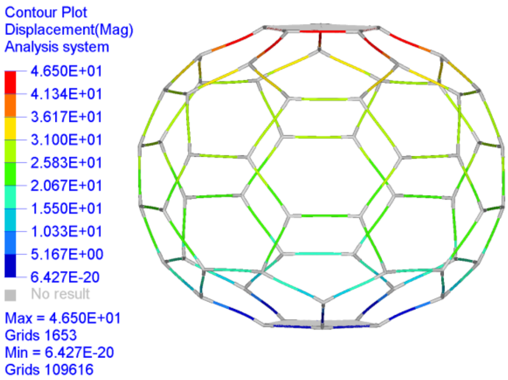


Figure 27 – The constraints and loads.



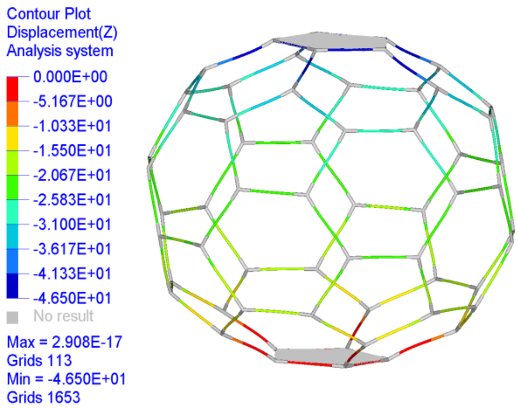
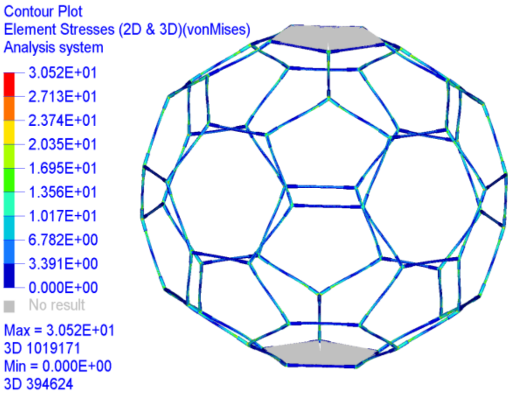


Figure 28 – Structural Strain Diagram. Figure 29 – Z-direction structural strain diagram.

It can be seen from Figure 28 that the deformation of the protective frame is the largest near the place where the load is applied, with a maximum of 46mm, while near the constraint, the deformation is very small, only 0.064mm. It can be seen from Figure 29 that the deformation amount gradually decreases from the load application point to the fixed constraint point, and the deformation amount of each layer of carbon tubes is the same from top to bottom. The spherical protective frame has a large amount of compression after the protective frame collides or falls.



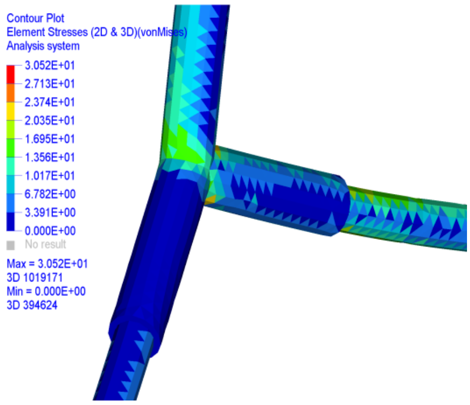


Figure 30 – Structure stress diagram. Figure 31 – Stress diagram of tee connectors.

It can be seen from Figure 30 and Figure 31 that the maximum stress of the spherical protective frame is 30.5MPa. On one branch of the tee connector, the stress is 0, while on the other two branches, the stress is large and can reach 23.7 MPa. The angle between the branch with zero stress and the other two branches is both 120°. Under the action of the load, the branch and the carbon tube inserted into it are not compressed in the radial direction, and the branch only serves to constrain the two ends of the carbon tube. The stress distribution of each carbon tube is similar except for the carbon tube with 0 stress.

3. Mine environment reconnaissance information collection system

The mine environmental reconnaissance information collection system is composed of the image transmission system and the lighting system.

3.1 Image transmission system

Continuous inspection of the dangerous and complex mine environment is an important condition to ensure the safety and health of personnel and safe production of mines. Operators can remotely access information about the environment in the mine for troubleshooting and better control of drones.The image transmission system consists of a 600MW adjustable image transmission and a 1200TVL camera, with a reference distance of 2000-3000m without occlusion in the air. The video transmission system is powered by 6-24V. Figure 32 shows the image transmission system.

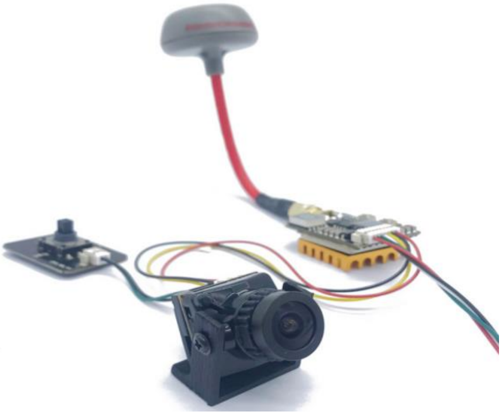


Figure 32 – Image transmission system.

3.2 Lighting system

The lighting system provides supplementary light for the flight of the drone in the dark or low-light space, ensuring that the environmental information in the mine can be obtained through the image transmission system, and it is also conducive to the operation of the operator. The lighting system adopts LED lamp bead spotlights.

The lighting system uses 12V LED lamp bead spotlights. The power of the lamp bead is 5W, and the light-emitting angle is 60° and 90°. The 60° lamp bead is more concentrated than the 90°, but the 90° illumination range is larger. Choose the appropriate lamp bead according to the light intensity of the environment.

Figure 33 – LED light.

The lighting system is connected to the flight controller and powered by the power distribution board, and the LED lights can be turned on and off through one channel of the remote control.

4. Drone obstacle avoidance system

This paper has designed an anti-collision structure for the UAV, and adding an obstacle avoidance module will keep the UAV away from obstacles and prolong its service life[5].

The height of mine roadway is usually less than 3m, and the space is small and the air pressure is uneven, the built-in barometer module in the flight controller has poor height measurement accuracy, and it is difficult to meet the requirements of mine roadway height setting, so an external height setting module is required. The ultrasonic sensor uses the principle of sound wave ranging to calculate the time between the sound wave is sent and received to measure the distance between the sensor and the obstacle.

The sound wave propagates in the air at a speed of 340m/s. The time for the ultrasonic sensor to return after encountering an obstacle is t, and the distance between the sensor and the obstacle is[6]:

$$L = 340 * t / 2 \qquad (1)$$

Ultrasonic waves are not easily affected by light and airflow, and the loss during propagation is small. Ultrasonic sensors are light in weight, low in power consumption, and simple and fast in data calculation.

SUI04, a comprehensive ultrasonic obstacle avoidance module, with high ranging accuracy, a very low delay time of only 30ms, and fast distance data update speed. The beam angle is 60°, real-time monitoring of environmental information and perception of obstacles, which can simultaneously achieve forward, backward, left, right, upward and downward obstacle avoidance, ensuring that the drone avoids obstacles in time during flight, to achieve precise obstacle avoidance. Figure 34 shows the dimensions of the ultrasonic obstacle avoidance module.

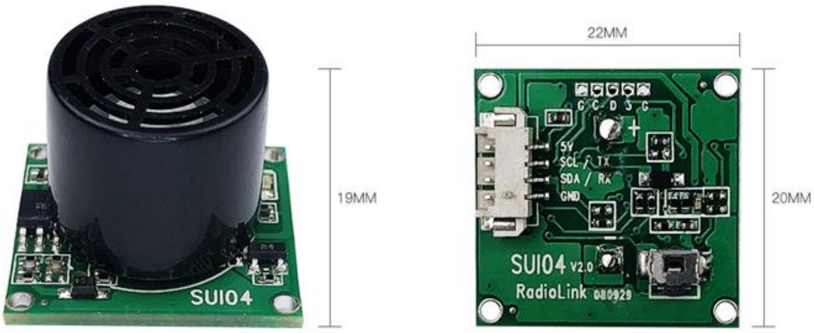


Figure 34 – Ultrasonic obstacle avoidance module and size.

After the drone is switched to the obstacle avoidance mode, the SUI04 ultrasonic module continuously reads the distance between the drone and the obstacle. After judging the ultrasonic data, the flight control system outputs the corresponding PWM signal, thereby changing the speed of the motor and controlling the drone to avoid obstacles.

During the flight of the drone, the speed of the motor is changed according to the distance between the ultrasonic module and the obstacle, thereby changing the flight attitude. When the distance between the drone and the obstacle is less than the set threshold, continue to operate the drone, and the drone will not continue to move in this direction.The obstacle avoidance process is shown in the figure 35.

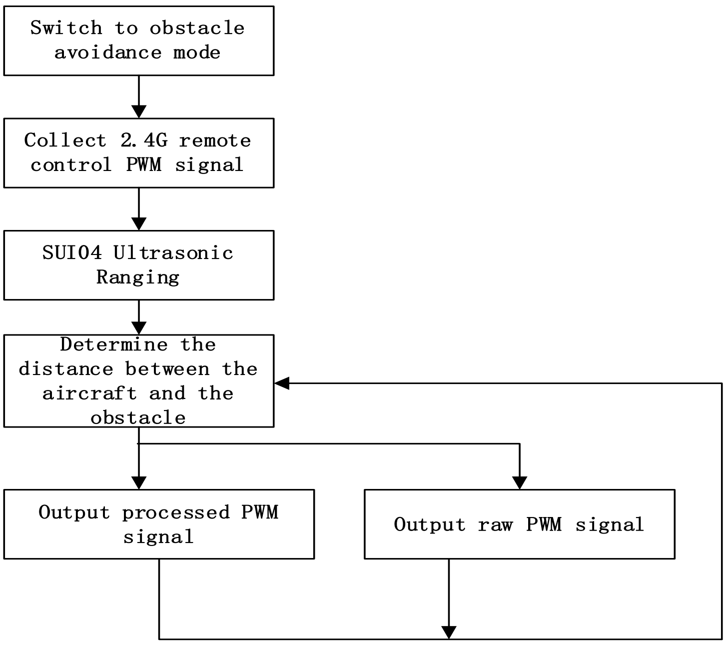


Figure 35 – Obstacle avoidance process.

5. Test flight

There is a certain gap between the theoretical situation of the drone and the real situation. The flight test can most truly and intuitively explain the advantages and disadvantages of the drone's performance and whether the drone meets the various design indicators. According to the design content of this paper, the prototype of the test principle of the mine inspection drone is completed, and the test flight verification is carried out.The flight process of the drone is shown in the figure 36.

Figure 36 – Test flight.

During the entire flight process, the drone always maintains a stable flight attitude, and the body will not shake; in the obstacle avoidance mode, the drone will not collide with the wall and the ground, and always maintain 1 meter with the walls and ground on both sides Left and right distance; when the space is relatively narrow, the drone can also fly close to the ground. The battery life of the drone is about 4 minutes and 45 seconds. The test flight shows that the drone lighting system can illuminate the place three meters away in front, and has strong environmental survivability. The images returned by the drone are clear and stable, and can complete the mine inspection task.

6. Conclusions

This paper introduces the overall scheme of mine inspection drone. The test flight of the prototype shows that the drone has a good flight effect and a good effect of autonomous obstacle avoidance; it can scout the surrounding environment and transmit images in real time, and can perform mine inspection tasks; it has strong collision ability and survives.The main performance of the drone is shown in the following table 1.

Table 1 – Actual performance of mine inspection drone.

project	data
The maximum diameter(mm)	400
Taking off weight(g)	869
Working time	4min45s
obstacle avoidance distance(m)	1
Lighting distance(m)	≥3.3
cruising speed(m/s)	2
Mission radius(m)	560
image transmission	clear and stable

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8. Copyright Statement

References

[1] Sun Jiping. The development trend of coal mine informatization and automation. Industrial and Mining Automation. Vol. 41, No. 4, pp 1-5,2015.

[2] Wu Xiao. Analysis and research based on mine wireless communication technology and UAV joint search and detection. Inner Mongolia Coal Economy. No.17, pp 85-87, 2018.

[3] Liu Bin, Liu Jianjun, Zuo Shaojie. Research on material and structure optimization of a model machine. Mechanical Engineering and Automation. No. 6, pp 56-58,2018.

[4] Yao Guangle, Wang Shoulei. Research on indoor flight technology of quadrotor UAV with Pixhawk flight control system. Electronic World. No. 7, pp 86-88,2021.

[5] Yan Shu. Design of ultrasonic rangefinder based on single chip microcomputer. Electronic Technology and Software Engineering. No. 15, pp 129,2014.

[6] Tian Weijun, Li Yu, He Koufang. Structural design and modal analysis of four-axis rotorcraft. Manufacturing Automation. No. 4, pp 37-39,2014.