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Design of a High-Precision Positioning System for UAV Formation Based on RTK

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Abstract: For the high-precision positioning requirements of UAV formation cooperative operation, a distributed control system based on RTK technology is proposed in this paper. By using the U-blox F9P GNSS module to build an RTK base station/mobile terminal, combined with Pixhawk 6C flight control and MAVESP8266 communication module, centimeter-level (< 2 cm) positioning accuracy is achieved. The system adopts the "centralized planning distributed execution" architecture, transmits RTCM differential data and MAVLink messages through the UDP protocol, and integrates ROS to realize status information subscription. Experiments show that the system can effectively support large area surveying and mapping and other complex tasks, and significantly improve the autonomy and reliability of formation operations.

Keywords: UAV; RTK; Pixhawk 6C; MAVLink

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1. Introduction

Early UAV research focused on single-rotorcraft optimization (power, stability, navigation) [1]. Now, multi-agent cooperation dominates, with formation technology enabling precision agriculture (spraying, monitoring) [2], disaster response (fire/flood assessment), and logistics (medical delivery), leveraging spatial distribution advantages.

The development of UAV formation control technology can be divided into three key stages: in the 1950s, the US Air Force rq-2 "fire bee" target aircraft system first realized formation flight controlled by radio command, which laid a basic engineering paradigm [3]; in the 1980s, the multi-agent system (MAS) theoretical framework proposed by the Massachusetts Institute of technology provided a decentralized control scheme for UAV clusters through distributed decision-making, contract network protocol and fault-tolerant mechanism [4,5]; in the 1980s, the United States Air Force rq-2 "fire bee" target aircraft system provided a decentralized control scheme for UAV clusters; In the 1990s, roboflag project realized the transformation from theory to practice, developed the distributed slam framework and adaptive formation algorithm, improved the positioning accuracy to less than 0.3 meters, and finally completed the technological leap from centralized control to autonomous collaboration [6,7].

This evolution process reflects the deep integration of aviation engineering and distributed artificial intelligence [8].

The traditional UAV formation system mainly relies on global positioning system (GPS) for outdoor positioning [9], but this technology has significant limitations: the signal delay error caused by the change of ionospheric electron density can reach 5–8 meters; The number of visible satellites decreases sharply (usually less than 4) due to the urban canyon effect; The positioning error caused by multipath effect is even more than 10 meters. In order to solve these problems, this paper innovatively combines the RTK high-precision positioning and distributed consistency protocol [10], constructs a new UAV formation control system architecture, and realizes the centimeter-precision autonomous cooperative flight.

2. Design of UAV formation system

2.1. Overall system framework

The rotor UAV formation system uses Pixhawk 6C flight control (stm32h743 processor + triple redundant IMU) to run and optimize PX4 firmware. The positioning system integrates a U-blox F9P GNSS module (l1/l2 dual band) and a fixed RTK reference station (geodesic antenna) to achieve centimeter accuracy. The communication system adopts distributed networking, the ground station is equipped with a high-power AP, the UAV is equipped with a customized MAVESP8266 module (esp8266+MAVLink hardware acceleration), and the protocol stack is optimized to ensure multi-machine low-delay communication. The architecture realizes high-precision cooperative flight control through hardware integration and algorithm optimization (see **Figure 1** for system architecture).

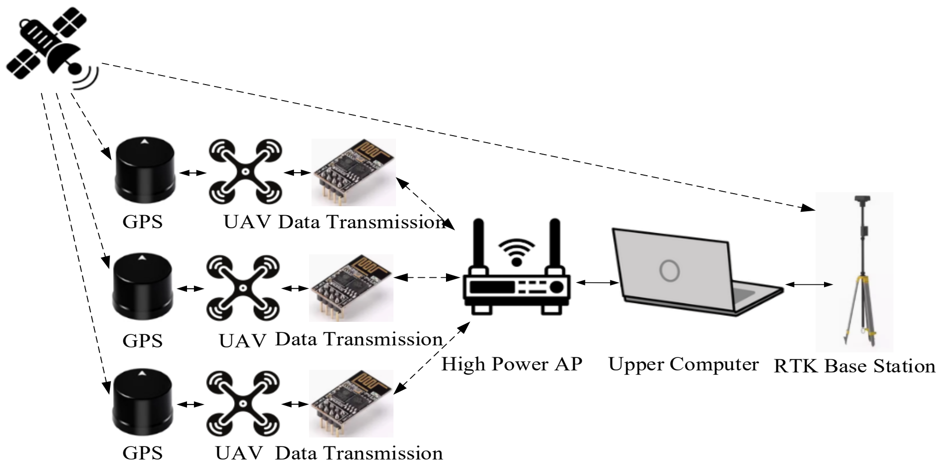

Figure 1. Overall hardware design block diagram

2.2. UAV formation system design

The UAV formation control system takes high-precision positioning as the core technology and adopts a hierarchical architecture design. When the system starts, it automatically detects the status of key sensors such as magnetometers, accelerometers, gyroscopes, and barometers. The UAV that passes the self-check establishes a connection with the ground station through MAVESP8266 module (IEEE 802.11n protocol) to receive path planning data. The master-slave control mode is adopted, and the ground station broadcast command triggers the formation task. The security mechanism ensures that the UAV that fails the self-check automatically enters the security mode and exits the formation. See **Figure 2** procedure flow chart for the detailed process.

U-blox F9P dual frequency RTK Positioning system adopts an advanced differential positioning technology architecture. The reference station needs to be deployed at a fixed point with known coordinates to receive the L1/L2 dual frequency signals of GPS/bds/glonass and other multiple systems in real time, accurately calculate the ionospheric delay, tropospheric refraction, and ephemeris error through Kalman filtering algorithm, generate the differential correction data in rtcm3.3 format and broadcast through the wireless data transmission module. The test results show that L2 band observation can significantly improve the positioning accuracy of ionospheric disturbance by more than 40%.

The mobile station uses PPP-RTK hybrid positioning technology to achieve rapid convergence through the dynamic solution of carrier phase ambiguity. Under the condition of SNR (Signal-to-Noise Ratio)>35db, the fixed solution can be obtained in 8 seconds, reaching the positioning accuracy of 1cm+1PPM at the level and 2cm+1PPM at the elevation. The system innovatively integrates IMU tight combination algorithm, which can still maintain centimeter-level positioning stability in the case of short-time interruption of satellite signal (< 5 s), and greatly improves the system's reliability. **Figure 3** is the flow chart of the RTK Positioning program.

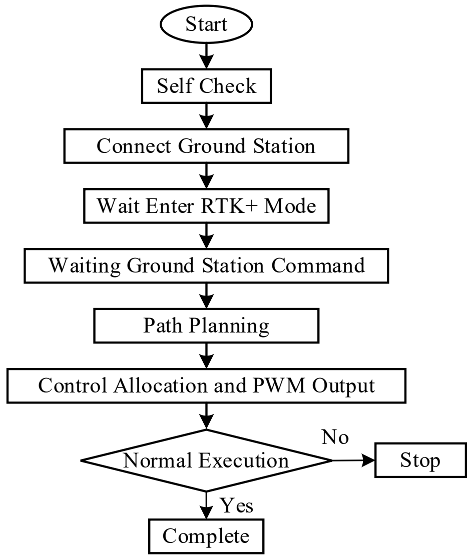

Figure 2. UAV group program flow chart

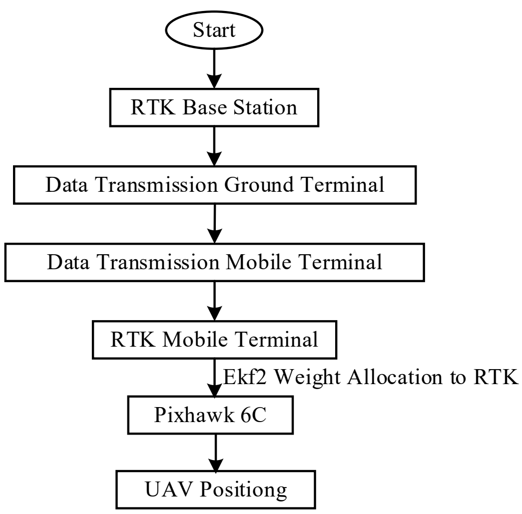

Figure 3. Flow chart of RTK high-precision positioning program

This system uses MAVESP8266 communication module based on Wi-Fi technology to build a UAV formation communication network (as shown in **Figure 4**). This scheme uses the mature IEEE 802.11 protocol standard to realize the seamless conversion from the flight control serial port to Wi-Fi through MAVLink protocol bridging technology. The module configuration includes IP address setting, AP access authentication, and port number definition, supports two-way data interaction between UAV and ground station (QGC), and can receive RTCM differential data sent by RTK base station. The module has the characteristics of low power consumption (working current<200ma) and lightweight firmware design (resource consumption<512kb). During deployment, it is necessary to ensure that all nodes are in the same LAN to ensure the communication quality, and the measured delay is controlled within 50ms to meet the real-time requirements of formation flight.

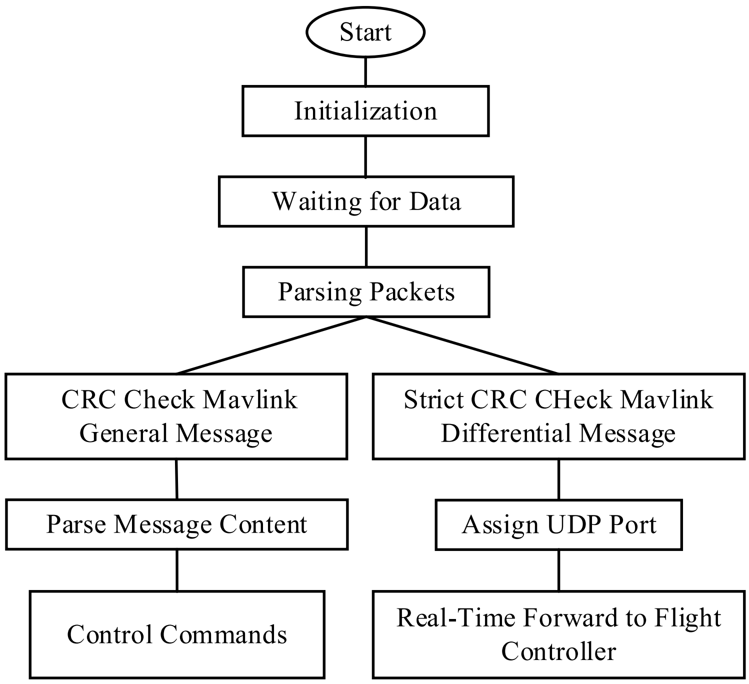

Figure 4. MAVESP8266 program flow chart

3. Simulation and experimental results

3.1. Simulation results

In the static positioning accuracy comparison test of U-blox F9P and m8n GNSS modules, the control variable method is used to ensure the experimental precision: the two modules are configured with the same working parameters (including 115200bps baud rate and 1Hz update rate), and the U-CENTER software is used for real-time data monitoring. The test results show that F9P module is significantly better than the m8n module (CEP [Circular Error Probable] ≥2.5m) in positioning accuracy (CEP≤10cm) and static dotting stability (point dispersion reduced by 62%) [11]. By synchronously receiving GPS/Galileo/Beidou multi-system satellite signals, F9P module shows better signal processing ability (the number of satellite locks increased by 40%) [12]. See the positioning error distribution statistics in **Figure 5** and the static dot test diagram in **Figure 6** for a specific performance comparison.

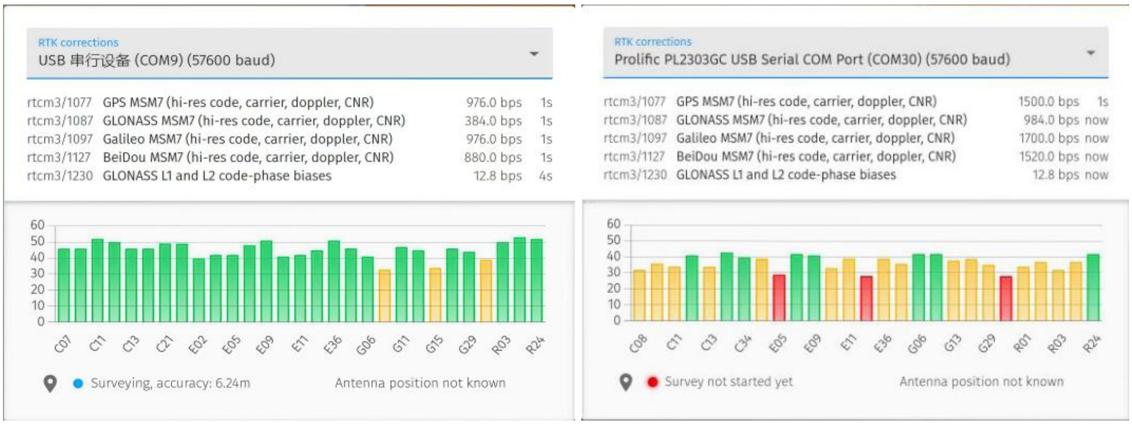

Figure 5. Fuzzy PID anti-interference simulation design diagram

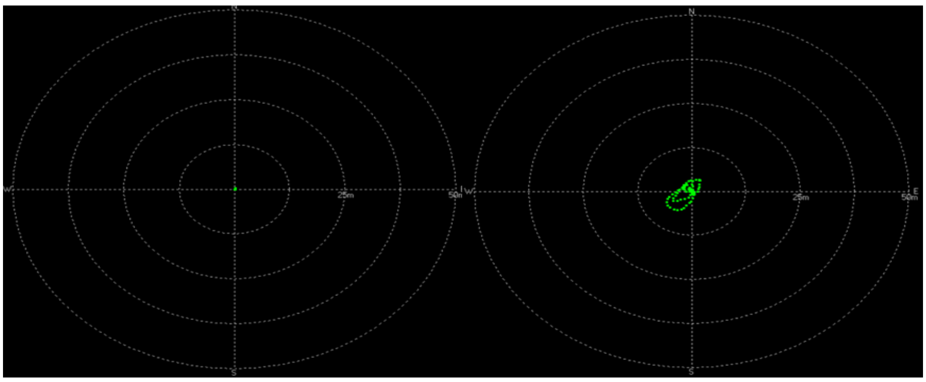

Figure 6. Static dotting test of U-bloxF9P (left) and m8n (right) GNSS modules

In blender 3.6 environment, through the integration of a self-developed formation control plug-in (v2.1), the three-dimensional trajectory planning of eight UAVs is carried out. The key frame animation technology (with an interval of 0.5 seconds) is used to realize the smooth transition from diamond to V-shaped formation, and generate spatio-temporal trajectory data. As shown in **Figure 7**, the simulation results verify the feasibility and synchronization of the formation path.

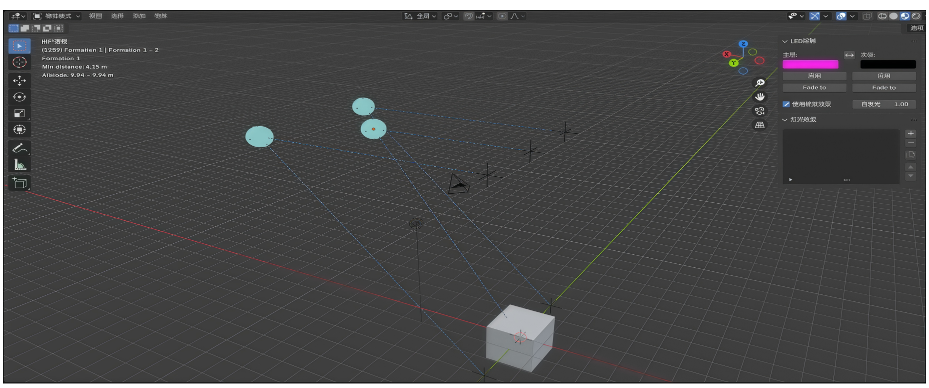

Figure 7. UAV formation path planning diagram

In the formation flight test phase, rtk_simulator node (v1.2) in ROS environment is used to simulate RTK Positioning Data output. The test process includes: (1) start the simulation of three iris UAVs through Px4 autopilot (command:/ Tools/simulation/gazebo-classic/sitl_multiple_run.sh -miris-n3); (2) Build the gazebo simulation environment; (3) Qgroundcontrol (v4.2), which supports formation control, is used to issue formation commands. As shown in **Figure 8**, the simulation results verify the feasibility of formation control.

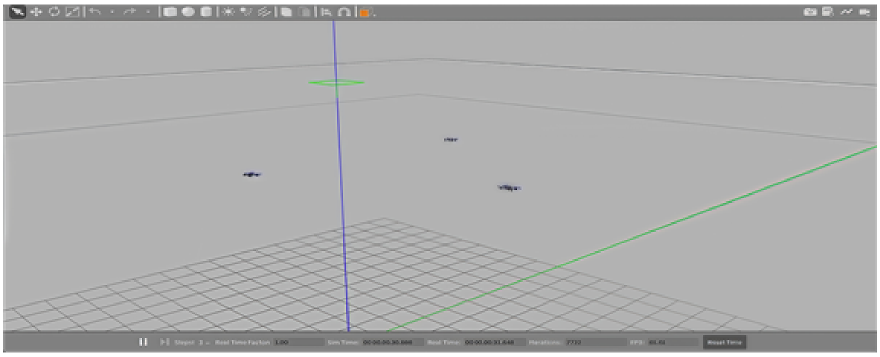

Figure 8. UAV formation path planning diagram

In the formation flight test, three UAVs successfully achieved triangle formation flight. The test data show that: (1) the position error in the takeoff and return stages is controlled at the centimeter level; (2) During formation flying, the positioning accuracy of UAV group RTK is 1.5cm, which fully meets the design requirements of high-precision formation system; (3) Through the real-time relative position keeping algorithm, the spacing error of each machine is less than 5cm, which effectively avoids the risk of collision. The simulation results show that the formation system has excellent positioning stability and flight safety, and can reliably perform high-precision formation tasks.

3.2. Experimental results

Before carrying out the UAV formation test, the following preparations need to be completed: first, select an open site to deploy the RTK base station, and verify its positioning accuracy; Secondly, ensure that the battery power of all UAVs is sufficient (it is recommended to be ≥ 95%), and comprehensively evaluate the test environment, including meteorological conditions, terrain characteristics and potential electromagnetic interference sources.

During the test, the three UAVs established a stable communication link with the Qgroundcontrol ground station (v4.2) through the LAN, and strictly followed the preset triangle formation trajectory. The system real-time monitoring shows that: 1) maintain centimeter-level positioning accuracy throughout the flight (RTK error ≤ 1.5cm); 2) During the landing phase, the dynamic obstacle avoidance algorithm is used to maintain a safe distance (≥0.5m) and return to the designated shutdown area in order. As shown in **Figure 9**, the measured data verify the reliability and cooperative control ability of the formation system in complex environments.

Figure 9. Outdoor flight test of UAV formation

After completing the UAV formation flight experiment, the flight data are analyzed in detail. Firstly, the flight log data of each UAV is exported, and the fixed-point position information is imported into Matlab R2024a software platform for three-dimensional trajectory analysis. The positioning performance of U-blox F9P GNSS module is verified by comparing the deviation between the actual flight path and the preset route in the X, Y, and Z axes.

The experimental data analysis shows that the UAV formation system equipped with U-blox F9P GNSS module shows excellent positioning accuracy. In the x-axis and Y-axis directions, the positioning error is controlled within 1.5 cm; In the z-axis direction, the error is not more than 2.0 cm. This result fully proves that the GNSS module can provide centimeter-level high-precision positioning service for UAV formation.

Figures 10, **11**, and **12**, respectively, show the flight trajectory data of the three UAVs in the X, Y, and Z axes during the flight mission. These visualization results intuitively show the consistency between the actual flight path and the planned route, and further verify the reliability and stability of the system. The experimental data show that the U-blox F9P GNSS module fully meets the strict requirements of UAV formation flight for positioning accuracy.

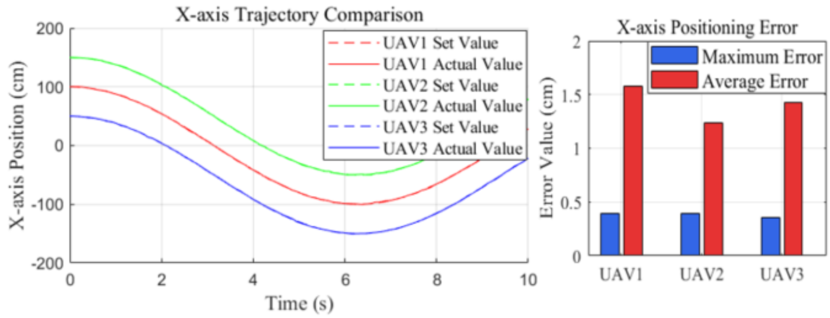

Figure 10. X-direction position offset error of UAV formation

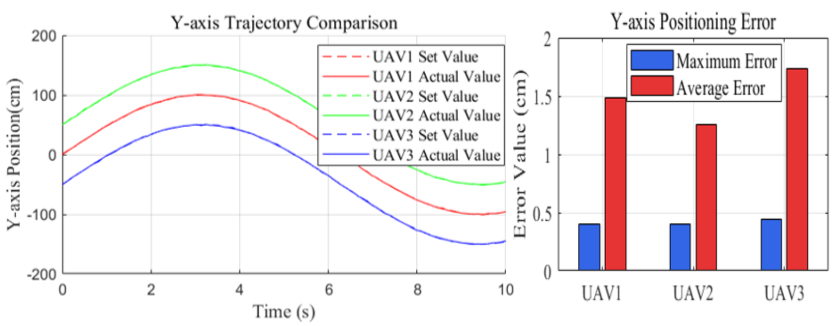

Figure 11. Y-direction position offset error of UAV formation

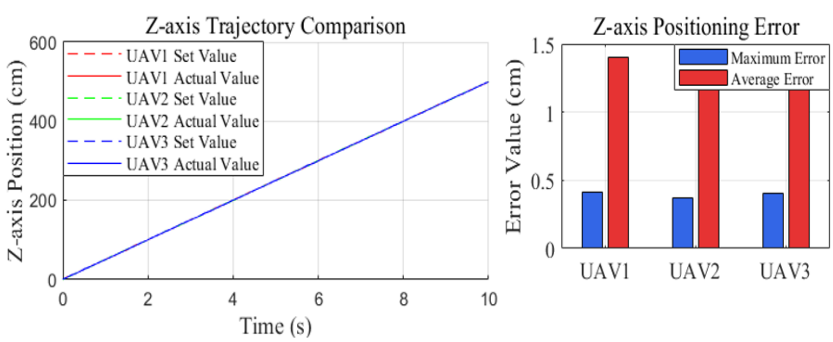

Figure 12. Z-direction position offset error of UAV formation

4. Retrospect and prospects

According to the technical requirements of UAV formation positioning system, this research innovatively proposes a high-precision positioning system design scheme based on real-time dynamic positioning (RTK) technology. The scheme adopts a hybrid architecture of “centralized planning + distributed execution,” realizes track planning and task allocation through the ground control station, and realizes autonomous and precise positioning based on the airborne RTK positioning module, which effectively improves the stability and controllability of the UAV cluster system.

Future research will focus on solving the following problems: (1) improving the anti-interference ability in a complex electromagnetic environment; (2) Communication delay optimization of a large-scale cluster; (3) Real-time path planning in a dynamic obstacle environment. These improvements will further enhance the reliability of the system in the actual combat environment.

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Disclosure statement

The authors declare no conflict of interest.

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