Contents

Experimental Platform Configuration

1. Introduction to the core components of RflySim platform

The RflySim platform contains a number of software involved in the development process of unmanned system modeling, simulation, algorithm verification, etc. The core components include CopterSim, QGroundControl, RflySim3D/RflySimUE5, Python38Env, WinWSL subsystem, SITL /HITLRun one-click run script, MATLAB automatic code generation toolbox, Simulink cluster Co ntrol interface, PX4 Firmware source code, RflySim supporting information files and supporting h ardware systems. Through the study of these core components, users can quickly get started with t he development and testing of unmanned systems.

FIG. 1 The relationship between RflySim software and hardware components and the overall proces s1

1.1. CopterSim

CopterSim is one of the core software of RflySim platform, which is a hardware-in-the-loop s imulation software developed for Pixhawk/PX4 autopilot platform. The multi-rotor model can be c onfigured in the software, and the hardware-in-the-loop simulation can be realized by connecting with the Pixhawk autopilot through the USB serial port. To achieve the effect of indoor simulation of outdoor flight test. It mainly consists of two parts: model and communication. Model means that simulation can be carried out directly after calculation according to the model parameters set. It supports running dynamic model (DLL) and forms software/hardware in the loop simulation together with other software. CopterSim is the center of all data communication; Flight controller and CopterSim were connected through serial port (hardware-in-loop HITL) or network TCP/UDP (software-in-loop SITL), and data transmission was carried out by MAVLink to realize control closed loop and simulate outdoor flight situation. CopterSim sent the aircraft pose and motor data to the 3D engine for visual display. The MAVLink messages were forwarded to the Python vision or QGC ground station to transmit the real-time status of the aircraft, and the top-level planning and control were realized. And so on. At the same time, CopterSim software compressed MAVLink data and sent it to the cluster control software in the form of UDP structure to achieve the purpose of communication simplification (large-scale cluster requirements).

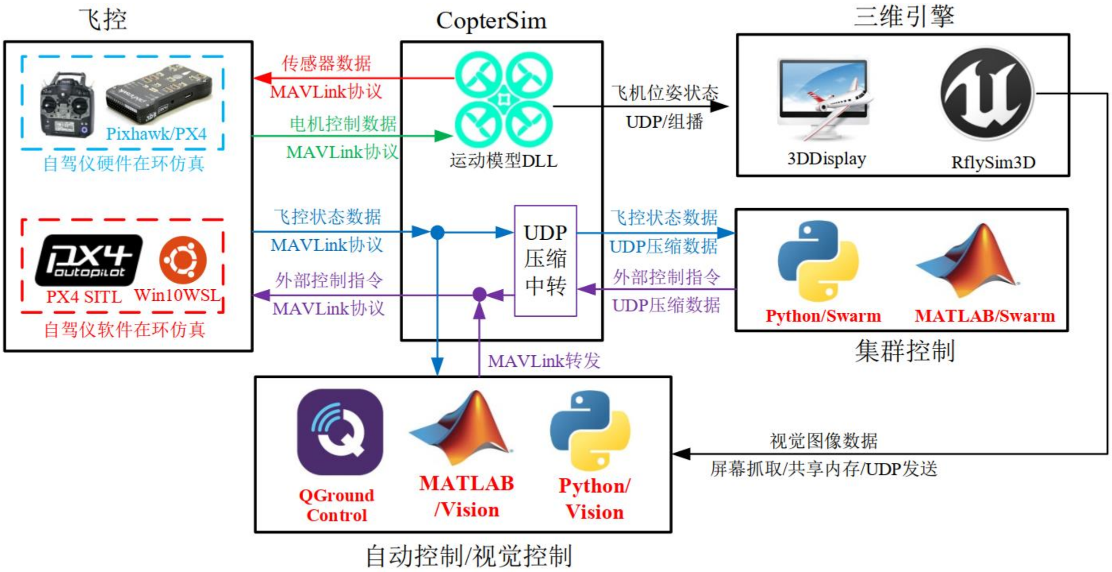


Figure 2 Data communication structure diagram of CopterSim software2

The main interface of CopterSim is mainly divided into three parts: model configuration area, simulation function area and status display area, as shown in the following figure.

1.1.1. Model configuration area

The configuration, size, weight and other data of the customized multi-rotor can be configured. CopterSim will calculate the parameters of the specified multi-rotor model to realize the simulation of different models.

1.1.2. Simulation Function Area

It supports the configuration of aircraft ID, communication interface, simulation mode, 3D scene, distributed online simulation, initial position of map, flight control COM serial port selection, communication mode and so on. At the same time, it can control the start, pause and restart of the simulation.

1.1.3. Status display area

The left side will show the model and Pixhawk return status, and the right side is the simulation data of the model. A representative small experiment is used to introduce the import function of DLL model.

1.2. RflySim3D/RflySimUE5

Unreal Engine has a powerful graphics engine that supports high quality 3D graphics and visual effects; The built-in blueprint visual scripting system enables developers to use a graphical way to create complex logic and interactive behaviors without writing code; Has a large community support and resource library, including models, textures, sound effects, plugins, and more, which can help developers speed up the development process and improve the quality of the model; Supports multiple platforms, including PC, console, mobile, VR, and more; Developers can customize and extend the functions and tools of the Engine according to their own needs, making Unreal Engine suitable for various types of game and application development.

RflySim3D/RflySimUE5 is a high fidelity unmanned system simulation software developed b ased on Unreal Engine Engine. It inherits various advantages of Unreal Engine Engine and commu nicates with other software on the platform through UDP to achieve high fidelity unmanned system simulation. At the same time, the visual image data can be transmitted to QGroundControl, MATL AB, Python and other software by means of screen capture and shared memory to realize the verifi cation and simulation of the visual algorithm of the unmanned system, as shown in Figure 3.FIG. 3 RflySim3D/RflySimUE5 displays the main interface3

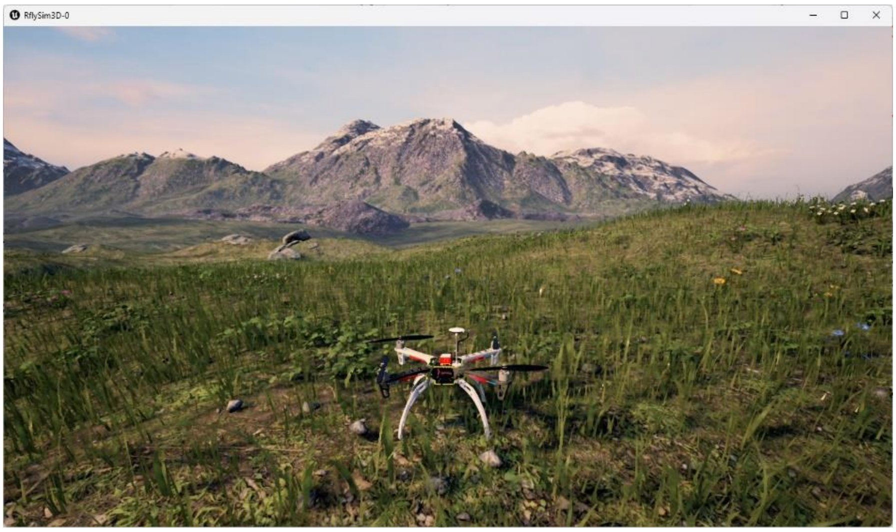


FIG. 3 RflySim3D/RflySimUE5 displays the main interface3

At the same time, for users with lower computer configuration, the RflySim platform provide s two other 3D simulation software, namely: FlightGear and 3DDisplay. The development team of FlightGear comes from all over the world, including programmers, pilots, physicists and experts in the field of aircraft manufacturers, providing a variety of different types of aircraft models and sce narios, including various civil and military aircraft models, as well as a variety of different scenari os and environment simulations. It is a very popular open source flight simulator software, which c an receive the flight status sent by Simulink through UDP, and conveniently observe the flight stat us of the aircraft during Simulink simulation. 3DDisplay is a virtual flight simulator software deve loped by the Reliable Flight Control research group of BeiAI.It provides a 3D model and virtual en vironment, and supports a variety of aircraft models and scenarios. Users can freely switch RflySi m3D/RflySimUE5, FlightGear and 3DDisplay according to the configuration of personal compute r.

1.3. QGroundControl ground station

The UAV ground station is a key component of the UAV application control system. The operator can operate the ground station through the mouse, touch screen and remote control handle to achieve the purpose of controlling the UAV. And by setting the waypoint information and planning the route on the ground station, the UAV can fly in accordance with the preset path and complete the waypoint tasks during the flight, including taking photos, aircraft action, and flight control. Video and so on. At present, the mainstream open source ground stations are QGroundControl and MissionPlanner, and QGroundControl is an open source ground station designed for the latest architecture of PX 4 software. It uses QT editor C++ language to write its core code, which supports source code modification and function secondary development. It is suitable for UAV ground station research experiments and also suitable for customization and modification of UAV ground station functions. Compared with QGroundControl, the advantages of QGroundControl are as follows: 1) Open source: QGroundControl is a completely open source software, which means that users can freely modify and customize it according to their needs. 2) Ease of use: The user interface is very clear, modern and easy to use, enabling users to quickly perform mission planning and flight planning. 3) Multi-platform support: QGroundControl can run on a variety of operating systems, such as Windows, Linux, MacOS, etc. 4) Modular architecture: The modular architecture of QGroundControl makes it easy for developers to add and extend new functions without affecting existing functions and performance. Overall, QGroundControl is a modern, easy to use, open source and highly customizable ground station software, which has obvious advantages in multi-platform support, multi-la nguage support, modular architecture and so on.

1.4. Python38Env

Python is a high-level, object-oriented, interpreted programming language. Originally created by Guido van Rossum in 1989, it has become a popular programming language used to develop Web applications, data analysis, artificial intelligence, scientific computing, network programming, and more. Python is a simple and easy language to learn, read, and write, so it is also widely used for teaching and introductory level programming.

Python38Env is a virtual environment for the Python 3.8 programming language, containing numpy, pymavlink, OpenCV, pyulog and other libraries, which can quickly carry out the related algorithm development of unmanned systems without requiring users to deploy python running environment and various functional libraries.

1.5. MATLAB automatic code generation toolbox

MATLAB Automatic Code Generation toolbox is a MATLAB extension toolkit for generating various forms of executable files such as C code, executables, static libraries and dynamic libraries from Simulink models. These executables can be run directly on the embedded platform without manual programming and debugging. A variety of embedded platforms are supported, including ARM Cortex-M and A-series processors, NXP MPC55xx and MPC56xx series, Pixhawk series, and more.

The module library includes GPS data module, battery data module, uORB module and many other modules. Based on the RflySim and Pixhawk Support Package platform, users can: ① design and simulate the control algorithm in Simulink; (2) automatically generate C code and PX4 firmware from Simulink model and burn them directly on Pixhawk board; ③ Configure and calibrate the Pixhawk board and its peripherals using MATLAB scripts and functions; ④ real-time reading and writing data with Pixhawk board and so on.

1.6. SITL/HITL batch scripts

Batch processing technology means that a computer can process a number of collected tasks in groups, and the whole process is completely automated without human intervention. This can also be called Workload automation (WLA) and job scheduling. It has the advantages of speed and cost savings, accuracy, and ease of operation.

RflySim has developed a number of batch processing scripts based on batch processing technology, allowing users to quickly start and deploy multiple, multiple, and multiple unmanned systems combined simulation with one click. It improves the speed of unmanned system development and simulation. The more commonly used batch scripts of the platform are: ① SITLRun.bat: it is a batch file that starts the simulation of multi-computer software in the ring, which is essentially a sc ript to start and configure some software and options of the RflySim platform; ② HITLRun.bat: It is a batch file for opening multi-computer hardware-in-the-loop simulation. After inserting multipl e flight controllers, double-click the batch file and input the Pixhawk serial port number that you w ant to participate in the simulation according to the prompts to open the hardware-in-the-loop simu lation of multi-computer (the aircraft ID is sorted by the input serial port order). In addition, the Rf lySim platform also provides many batch processing script files, such as: SITLRunPos.bat, SITLR unLowGPU.bat, SITLRunMAVLink.bat, HITLRunPos.bat, HITLPosSysID.bat, HITLPosStr.bat, a nd so on. Users can open these files through the editor. Modify the parameters according to person al needs, realize custom development, and quickly start the simulation or algorithm verification.

1.7. PX4 Firmware source code

PX4 is evolved from PIXHAWK, a software and hardware project of the Computer Vision an d Geometry Laboratory of the Swiss Federal Institute of Technology Zurich (ETH). The flight cont rol system is completely open source and provides a low-cost and high-performance high-end auto pilot for flight control enthusiasts and research teams around the world. After years of developmen t and improvement by world-class developers from industry and academia, the current PX4 flight c ontrol system has formed a perfect and reasonable software architecture. With the Pixhawk series a utopilot hardware platform, the Pixhawk PX4 autopilot software and hardware platform is formed, which can control multiple rotors, fixed wings, airships and other vehicles. It is an open source U AV autopilot software and hardware platform widely used in the world.

RflySim platform supports one-click deployment of PX4 compilation environment, you can c ustomize to choose different PX4 Firmware compilation commands and firmware versions, the pla tform will deploy the selected PX4 firmware source code on the set installation path, if the firmwa re exists, the old firmware folder will be deleted, and a new deployment will be performed. The eff iciency of PX4 environment deployment is greatly improved.

1.8. WinWSL subsystem

The WinWSL subsystem is a subsystem on the Windows operating system that allows users t o run Linux applications, use the Linux command line interface (CLI) and install Linux distributio ns on the Windows system. RflySim platform one-click installation of Linux system for Ubuntu18. 04.5, mainly used for PX4 source code compilation,

Msys2Toolchain compilation environment based on Msys2 and CygwinToolchain compiler b ased on Cygwin are also provided to simulate Linux compilation environment on Windows platfor m. Users can choose different compilation environments according to their own version of PX4, an d switch between different compilation environments can be completed by different choices in the one-click deployment and installation interface.

1.9. Simulink cluster control interface

RflySim platform has developed a cluster control interface based on Simulink S function, as s hown in Figure 4. The interface is realized by Simulink S function through C++ mixed programmi ng, with the advantages of Simulink UDP module, which has the advantages of high efficiency, sm all operation, low delay, more reliable and strong expansibility. FIG. 4 Cluster control interface4Us ers can load the module into their own control system by copying and pasting, which helps users to quickly realize the development of unmanned system cluster control.

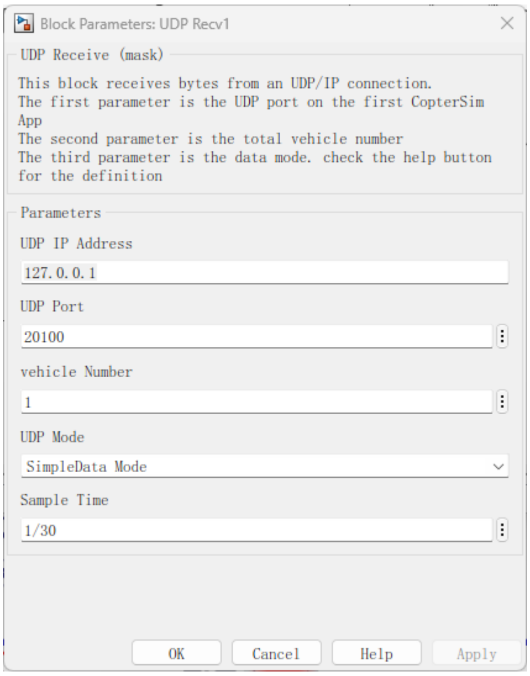


FIG. 4 Cluster control interface4

1. 10. RflySim supporting data files

The RflySim platform provides very complete learning materials and routine files. Through P PT courseware materials and RFlysim apis routine files, users can learn step by step and step by st ep, from the development and verification of unmanned system bottom control algorithm → middl e level decision algorithm → top level learning algorithm. One-stop construction and development of their own required unmanned systems.

2. RflySim platform supporting hardware system

RflySim platform provides a complete set of supporting hardware system, including quadroto r UAV, flight control, remote control and other components. These components are perfectly comp atible with the platform, and the software and hardware in the loop simulation experiment can be r ealized in the RflySim platform, and the flight of the UAV in the real environment can be realized based on the generated firmware.

2.1. Flysim series aircraft

At present, the supported aircraft include FSI X150, FSI X200, FSI X450 and other four-rotor Uavs, among which FSI X150 is a newly designed miniature four-rotor UAV for indoor cluster co ntrol research.

2.1.1. And Fresi X150 quadrotor UAV

The newly designed miniature quadrotor UAV for indoor cluster control and research, the sym metrical motor wheelbase is 140mm, and the innovative full protection structure design is designe d. It discuses the redundant cabling of carbon plate in the past, and the high-strength and light-wei ght body of carbon 3D printing is printed. The laser height and optical flow fixed point are adopte d, and the whole machine integration scheme is used to comprehensively improve the efficiency of indoor cluster research.

Research direction: optical positioning system navigation and positioning development; Centralize d/distributed cluster formation algorithm development vehicle and space-ground integrated cooper ative formation control development; ROS secondary development; matlab secondary developmen t;

Version and performance

Product Configuration	Standard Edition	Ultimate edition
Base Configuration	Optical flow fixed point, laser fixed height, external magnetic compass	
Airborne board card	ZYpi-3566	
Board performance	CPU: RK3566 Memory: 4GB, DDR4 Storage: 32GB WIFI: wifi6 integrated	
Vision sensor	There is no	Monocular sensor *2, 2 megapixels
Positioning sys	Indoor optical positioning	Indoor optical positioning sy

tem	system	stem /GPS
Means of communication	WIFI	
Basic software environment	Individual sensor drivers	
Functional Features	Focus on implementing centralized and distributed cluster formation functions	On the basis of realizing the centralized and distributed cluster formation function, the general vision function can be developed and applied. It can fly based on GPS positioning

Aircraft specifications

Fesi X150 smart drone	
Dimensions (with paddle)	200*200*85mm
Symmetrical motor wheel base	140mm
Aircraft weight	205g
battery	3s, 1300mAh 105g
Whole unit weight (including battery)	310g
Maximum rate of rise	2m/s
Maximum descent speed	2m/s
Maximum horizontal flight speed	5m/s
Maximum take-off altitude	3500m
Endurance (no load)	8 minutes
Working environment temperature	-20°C to 50°C

Application scenario: Perfect indoor micro UAV swarm cooperative formation scientific research solution, suitable for teaching and research in colleges and universities, as well as military research units, mainly used in the field of indoor UAV swarm control and distributed clustering algorithm verification.

2.1.2. Fesi X200 quadrotor UAV

Indoor small intelligent UAV, symmetrical motor wheelbase 200mm, full carbon fiber protective body design, propeller sinking installation mode, internal laser fixed height and optical flow fixed point, suitable for indoor UAV swarm cooperative formation application, with distributed cluste r UAV cooperative control ability. It can be equipped with a visible light camera and an airborne vision processing board, which has the ability to perform visual navigation, target recognition and target following.

Research Direction

Model-based design and development;

ROS control development;

matlab control development;

Centralized/distributed cluster control algorithm development;

Visual navigation, target recognition and target following algorithms were verified.

Product version

Product configuration	Standard Edition	Monocular version	Model design plate
Base configuration	Optical flow fixed point, laser fixed height, external magnetic compass		
Flight control	Racer Flight Control		
Onboard board card	NX Xavier		NX Xavier/ZYpi3566
Vision sensor	T265	Monocular camera	There is no
Means of communication	WIFI		
Basic software environment	Individual sensor drivers		
Functional Features	T265 was used for positioning, and high-precision indoor centralized/distributed cluster control algorithm was developed	Centralized/distributed cluster control algorithm development; Target identification and target following algorithm verification	Model-based design and development; ROS control development;

Aircraft metrics

Fesi X200 smart drone	
Dimensions (including OARS)	300*300*160mm
Symmetrical motor wheel base	200mm

Aircraft weight	580g
Battery	4s, 5300mAh, 469g
Unit weight (including battery)	1049g
Extra maximum load	200g
Maximum rate of rise	2m/s
Maximum descent speed	2m/s
Maximum horizontal flight speed	10m/s
Maximum take-off altitude	4000m
Endurance (no load)	20 minutes
Working environment temperature	-20°C to 50°C

Application Scenarios

As a professional intelligent aircraft product for universities and research institutes, the scientific research solution for collaborative formation of indoor small UAV swarm is mainly applied in the following research fields: model-based design and development; Indoor centralized/distributed swarm algorithm development; Visual navigation; Target following; Target recognition.

2.1.3. Fesi X450 quadrotor UAV

Professional outdoor small intelligent quadrotor UAV, symmetrical motor wheelbase 450mm, modular design of the whole machine, equipped with onboard computer at the same time, equipped with depth camera and laser radar and other functional modules, forming a perfect outdoor intelligent aircraft, excellent product performance can deal with complex outdoor flight environment, It is an intelligent aircraft research platform for outdoor cluster formation algorithm development, slam navigation and other research fields.

Research Direction

Model-based design and development;

ROS secondary development;

matlab secondary development;

Uav centralized/distributed swarm control;

Visual slam navigation, laser slam navigation development;

Product version

Product configuration	Pilot Edition	Ultimate Edition	Advanced Edition
Basic Configuration	Optical flow fixed point, laser fixed height, external magnetic compass		
Flight control	Racer Flight Control		
Onboard board card	NX Xavier		
Visual odometry	T265 camera		
Space detection	D435i depth camera	Silan S1 lidar	D435i depth camera Silan S1 lidar
Positioning system	GPS/RTK		
Communication links	Within 200m - onboard WiFi; 3km-ZY-H3; 10km—ZY-H12		
Basic Software environment	Individual sensor drivers Uav offboard control example program		
Functional Features	It can carry out outdoor cluster formation flight control for more than 20 minutes. The verification and development of visual slam navigation algorithm is realized on a single machine	Outdoor swarm formation flight control; The laser slam navigation algorithm was verified and developed on a single machine	On the basis of the functions of the cluster, the verification and development functions of visual slam navigation and laser slam navigation algorithm are realized on a single machine

Aircraft metrics

Fesi X450 smart drone	
Dimensions (without paddle)	420*420*240mm
Symmetrical motor wheel base	450mm
Aircraft weight	1200g
Battery	6s, 6000mAh, 862g
Weight of the whole unit (including battery)	2062g
Extra maximum load	1000g
Positioning accuracy	GPS: vertical: ±0.5m; Horizontal: ±2m
	RTK: Vertical: ±3cm; Horizontal: ±5cm
Maximum rate of rise	2m/s
Maximum descent speed	2m/s
Maximum horizontal flight speed	8m/s
Maximum take-off altitude	4000m
Endurance (no load)	30min
Working environment temperature	-20°C to 50°C

Application Scenarios

The perfect outdoor small UAV swarm cooperative formation research solution is suitable for teaching and research in colleges and universities, as well as military research units, and applied to Slam algorithm development/verification. Path planning/obstacle avoidance algorithm development; AI algorithm development/verification and other fields.

2.1.4. Fesi X680 quadrotor UAV

The symmetrical motor wheelbase of the medium-sized intelligent quadrotor UAV is 680mm. The whole aircraft adopts industrial design, and the high-strength fuselage can be used as a multi-task load flight platform. The laser high-point optical flow is used, and the depth camera and laser radar are equipped with functional modules. It is a multi-functional intelligent UAV that takes into account load, long endurance and scientific research and development.


Research direction:

Model-based design and development;

Uav centralized/distributed swarm control;

Outdoor airborne swarm control algorithm development;

ROS control development, supporting matlab control development;

Combined with unmanned vehicles for space-ground integration cooperative formation control;

The visual navigation, target recognition and target following algorithms were verified.

Product version:

Product Configuration	Standard Edition	Custom edition
Base configuration	Optical flow fixed point, laser fixed height, external magnetic compass	
Flight control	H7 Flight Control	
Onboard board card	NX Xavier	
Space Probe	D435i	LIDAR
Pods	There is no	G1 Pan-tilt pod

Other functional modules	There is no	Custom piggyback
Positioning system	GPS/RTK	
Communication links	3Km-ZY-H3; 10km—ZY-H12	
Basic Software environment	Individual sensor drivers	
Functional Features	Large load, long endurance; Outdoor multi-task load group formation flight can be carried out. The NX board is equipped to verify a variety of complex algorithms at the same time, and the single machine realizes the development of artificial intelligence applications such as target recognition and visual navigation.	It can be customized to carry sensors or functional modules according to specific application requirements to meet the functional requirements of image recognition, target following and so on. It is recommended to carry G1 pan-tilt-head pod, lidar, RTK high-precision positioning module, and customized pan-tilt-head pod.

Aircraft specifications

Fesi X680 smart drone	
Dimensions (without paddle)	567*567*400mm
Symmetrical motor wheel base	680mm
Aircraft weight	2550g
Battery	6s, 16000mAh, 1475g
Machine weight (including battery)	4025g
Extra maximum load	2000g
Positioning accuracy	GPS: vertical: ±0.5m; Horizontal: ±2m
	RTK: Vertical: ±3cm; Horizontal: ±5cm
Maximum rate of rise	2m/s
Maximum descent speed	2m/s
Maximum horizontal flight speed	12m/s
Maximum take-off altitude	5000m
Endurance (no load)	40 minutes
Working environment temperature	-20°C to 50°C

Application Scenarios

The perfect outdoor medium-sized intelligent UAV solution is suitable for teaching and research in colleges and universities, as well as military scientific research. It is mainly used in the field of indoor UAV swarm control and distributed swarm algorithm verification.

2.2. PX4 series flight control

As the RflySim platform is developed based on the PX4 software system, any flight controlle r that supports the PX4 software system can be used on the RflySim platform under normal circum stances. The current long-term supported flight controllers are Pixhawk 2.4.8(also known as Pixha wk 1), Pixhawk 6C, and Pixhawk 6X.

2.3. Common remote control configurations

The remote control used by this platform is recommended to use the "American hand" operati on mode, that is, the throttle and yaw control amount corresponding to the left rocker, and the roll and pitch corresponding to the right rocker. In the remote control, the roll, pitch, throttle and yaw c orrespond to the CH1~CH4 channels of the receiver respectively, and the left and right upper side dial lever corresponds to the CH5/CH6 channel, which is used to trigger the flight mode switch.

The throttle lever (CH3 channel) from the bottom and top respectively corresponds to the PW M signal fluctuations from 1100 to 1900 (different channels or different remote controls will be dif ferent, so calibration is required); The roll (CH1 channel) and yaw (CH4 channel) rocker from the left end to the right end corresponds to the PWM signal from 1100 to 1900; Pitch (CH2 channel) r ocker from the bottom end to the top end corresponds to PWM signal from 1900 to 1100; CH5/6 is a three-section switch, from the top (the gear closest to the user) to the bottom (the gear closest to the user) gear corresponding to PWM signals of 1100, 1500 and 1900.

油门：控制上下运动，对应固定翼油门杆
偏航：控制机头转向，对应固定翼方向舵
俯仰：控制前后运动，对应固定翼升降舵
滚转：控制左右运动，对应固定翼副翼

3. Introduction to RflySim platform experimental process

3.1. Experimental process of underlying control system development

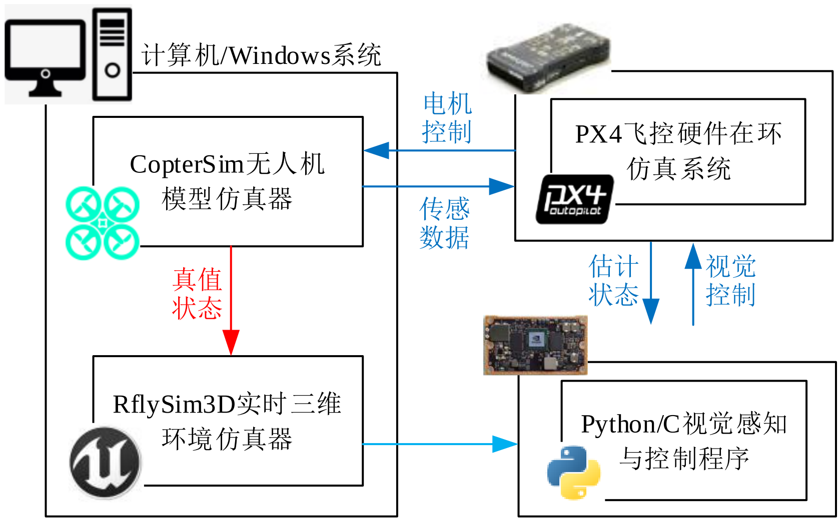
The development of the underlying control system is divided into four stages from easy to dif ficult: algorithm development and digital simulation verification stage, simplified model joint adju stment stage, software in the loop simulation stage, hardware in the loop simulation stage, indoor a nd outdoor flight experiment. The main task of the algorithm development and digital simulation v erification stage is to develop and verify the underlying control algorithm based on the simplified u nmanned system model, so that the developed algorithm meets the initial requirements. Based on t he development of the previous stage, the main task of the simplified model joint tuning stage is to realize the top control of the unmanned system by means of external control, so that the simulatio n of the unmanned system forms a closed loop, and the purpose of joint tuning of the unmanned sy stem is achieved. Software-in-loop Simulation (SIL) refers to compiling the generated source code on the host computer and executing it as a separate process. By comparing the results of normal m ode simulation and SIL simulation, the numerical equivalence between the model and the generate d code is tested. The whole SIL simulation stage of RflySim platform can be carried out in MATL

AB/Python environment. The control algorithm is designed in Simulink/Python using the given unmanned vehicle simulation model and routine, and the model and controller are correctly connected to ensure that the input and output signals are consistent with the actual unmanned system. Example: Multi-rotor UAV system: The multi-rotor model sends sensor data or state estimation information (e.g., attitude Angle, angular rate, position and speed, etc.) to the controller, and the controller sends the PWM control command of each motor back to the model, thus forming a SIL simulation closed-loop system. The user can observe the control performance and modify or design the controller by himself to achieve the desired performance requirements. Hardware-in-the-loop Simulation (HIL) stage is a development and testing technique for real-time embedded systems. HIL simulation provides a dynamic system model, which can simulate the real system environment, add the mathematical representation of the relevant dynamic system, and connect it with the simulation system platform through the input and output of the embedded system [3]. The RflySim platform can import the model parameters of Simulink unmanned vehicle into CopterSim, and download the Simulink controller algorithm generation code to Pixhawk autopilot, and then replace the virtual signal line in Simulink with a USB physical signal line. CopterSim sends sensor data (e.g., accelerometer, barometer, magnetometer, etc.) to the Pixhawk system via USB data cable; The PX4 autopilot software in the Pixhawk system will receive sensor data for filtering and state estimation, and send the estimated state information to the controller through the internal uORB message bus. The controller then sends the PWM control command of each motor back to CopterSim through the USB data line, thus forming a hardware-in-the-loop simulation closed loop.

3.2. The top-level control system development experiment process

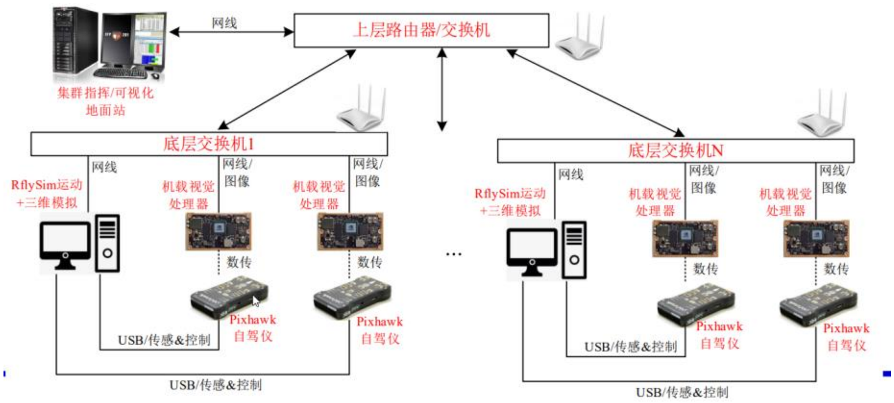
3.2.1. Airborne board hardware in the loop phase

Based on the HIL simulation stage, more hardware is added in this stage, such as: networking communication module, vision processing module, data acquisition module, etc. At this stage, we need to deploy the system to the actual hardware equipment, integrate and debug different hardware to ensure that they can cooperate with each other to realize the efficient operation of the whole system. This stage is an important part of the whole development process, and it is also a key stage to ensure that the system can finally run normally in the actual scene.



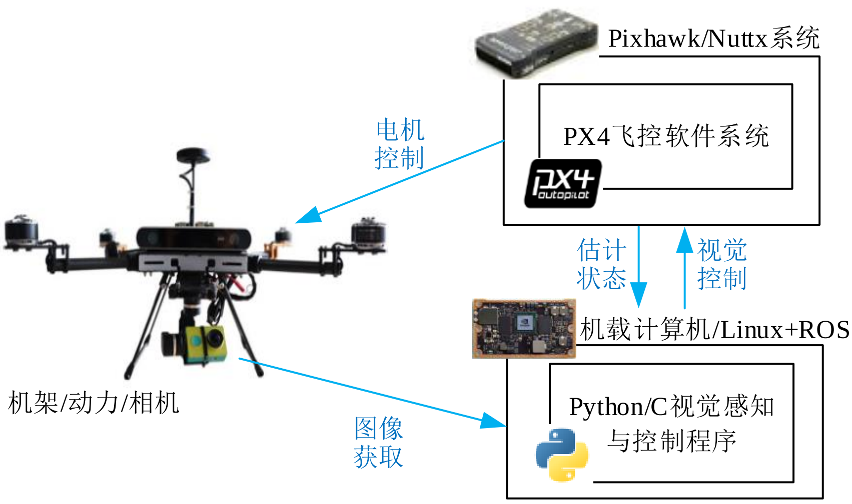
3.2.2. Multi-machine HIL simulation stage

In this stage, the whole simulation system can be regarded as composed of multiple HIL simulation subsystems, but it is not a simple superposition of subsystems. It is necessary to consider the system topology and configuration between different hardware, the model structure of network and communication, and the resource scheduling and management of the simulation host. In the simulation process, each hardware device needs to be properly configured and debugged to ensure that each hardware device can work normally. Whether from the perspective of multi-machine HIL simulation or from the perspective of real cluster control of unmanned systems, communication bandwidth and computing performance are always important bottlenecks restricting the increase of the number of clusters. Due to the performance bottleneck of the simulation computer, and a single computer can only connect a limited number of Pixhawk for HIL simulation. At the same time, with the increase of the number of Uavs, the amount of data communicated between aircraft increases rapidly until the communication bandwidth reaches saturation. Therefore, the RflySim platform realizes the arbitrary expansion of the number of Uavs through the networking of multiple computers, divides the UAV cluster as a whole into several subgroups, and uses the way of network stratification to realize larger scale cluster simulation, such as 错误!未找到引用源。As shown.



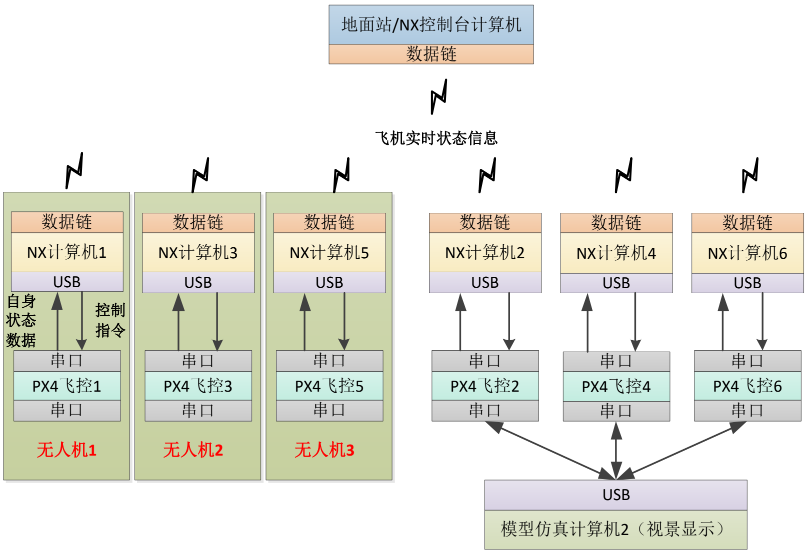
3.2.3. Stand-alone autonomous control phase

Stand-alone autonomous control is the ability of a single computer to plan and execute tasks independently without human intervention. For example, an autonomous UAV should have internal and external state perception systems, internal communication links between onboard systems, onboard fault management systems, and mission replanning systems 错误!未找到引用源。 Based on the RflySim platform, top-level control algorithms in the field of unmanned systems can be rapidly developed, such as SLMA algorithm, trajectory planning algorithm, obstacle avoidance algorithm, etc.



3.2.4. Hardware-in-the-loop cluster control stage

The semi-physical cluster control phase refers to the real-time simulation of part of the physical objects in the simulation loop of the simulation experiment system. It is a typical application in the development process of complex control system, which can be used to verify and optimize the cluster cooperative control decision algorithm. Subsection 10.3.5 of this book is a multi-aircraft hardware-in-the-loop simulation case. Based on the development and verification of UAV swarm ultra-low altitude collision avoidance algorithm, the "three real and three virtual" hardware-in-the-loop simulation experiment of fixed-wing UAV is used to complete the transplantation and verification of UAV swarm ultra-low altitude collision avoidance algorithm, the development of UAV digital twin model, and virtual-real collaboration.



3.2.5. The control phase of real UAV swarm

The real machine cluster control phase refers to the experiment or test of cluster control in the real environment, using real equipment, which can verify the performance and reliability of the sy stem. There are many practical factors, such as communication, interference, fault, security, etc., to be considered in the control phase of real computer cluster. For example, the optical motion captur e system is used to capture the position, attitude, speed and other motion information of the UAV. I t can be used to study and verify the motion control, navigation, formation, coordination and other functions of UAV. In general, it is necessary to use high-speed and high-resolution cameras, and to paste reflective markers on the UAV to achieve high-precision, high-real-time and high-stability m otion capture effects.

3.2.6. Multi-uav collaboration stage in a completely real environment

This stage refers to the stage in which multiple Uavs are used to cooperate to complete a com mon task through inter-aircraft communication and swarm intelligence in a real environment. It is t he highest level of UAV swarm collaboration technology, which is used to study and verify the pat h planning, situation awareness, task collaboration and other functions [错误!未找到引用源。] of UAV swarm. The stage of multi-UAV collaboration in the completely real environment of UAV requires the use of high performance, high reliability and high security UAV, communication and control systems to achieve high efficiency, high flexibility and high robustness. Such as 错误!未找到引用源。Shown is the virtual-real combined simulation architecture of UAV swarm.