A hardware-in-the-loop simulation platform for distributed UAV swarms

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Abstract. To improve the functional verification efficiency of intelligent UAV swarm systems, this paper proposes a distributed UAV swarm hardware-in-loop (HIL) simulation platform. The proposed platform uses fine-grained 3D scenes and real aircraft aerodynamic models as inputs to simulate the control and mission decision-making process of the UAV swarm by building a swarm data interaction network. The simulation platform is equipped with real on-board electrical equipments, which can fully verify the compatibility between software and hardware in the UAV swarm system and is able to shorten the research cycle effectively. The platform supports the addition and deletion of all-digital virtual simulation nodes and can be used for large-scale swarms. The tests on individual strap-down terminal guidance and multi-aircraft coordinated search show that the platform has good simulation results for features such as data interaction, autonomous decision-making, and control of UAV swarms.

1. Introduction

The development of swarm technology stems from the human imitation of the behaviour of swarms of organisms living in groups. Biological groups achieve complex group behaviour through collaboration and information exchange between simple individuals. Simple individuals can adapt to their environment, observe and learn from the behaviour of other individuals, and make autonomous decisions about subsequent actions. By studying biological groups, people have proposed an idea of using local control without relying on a centre from the perspective of system control, and have constructed swarm systems based on this [1]. Swarm systems are characterized by distributed control without central nodes and self-organizing behaviour [2].

In the course of research on swarm intelligence, various swarm projects have emerged, such as Gremlins, Low-Cost UAV Swarming Technology (LOCUST), and Perdix. Through the research of the above projects, a complete set of swarm theoretical systems and technical methods have been basically formed. The two core problems of such systems are swarm control and collaborative decision making. The Multi-Agent Particle Environments (MPE) [3] proposed by OpenAI is used to validate swarm decision-making and mission planning. Employing reinforcement learning, MPE takes the actions of the intelligent body and the state of the environment as the input of training and trains the intelligent body to find the optimal combination of strategies to complete the predetermined task on its own. MultiUAV [4] supported by Air Force Research Labs (AFRL) integrates the functions of UAV control simulation, kinematics simulation, and communication simulation. The simulation system can display targets and raw terrain in a 2D scene. SwarmFare [5] is focused on architecture and algorithms to create functioning autonomous UAVs. It’s a Self-Organization (SO) sandbox in which many varying scenarios and swarm behaviours can be tested.
The MPE simulation environment simplifies the controlled object's motion model. It replaces the controlled object with a particle, which cannot simulate the state changes of the controlled object in the real environment. MultiUAV has the limitation of simulation nodes, so it is not suitable for large-scale swarm simulation. SwarmFare cannot verify the control and task execution capabilities of the swarm in a 3-dimensional space. Therefore, for large-scale intelligent swarm simulation, we build a fine-grained semi-physical simulation platform for efficient verification of swarm control, collaborative decision-making, and collaborative perception methods to shorten the development cycle and cost of such swarm systems.

In this paper, we build a distributed UAV swarm simulation platform with the small fixed-wing UAV as the controlled object, the functional characteristics of the swarm simulation system as the starting point, and the swarm control capability and mission execution capability as the main verification objects. The main innovations in this paper include: (1) the fine-grained visualization of individual behavioural capabilities in the swarm; (2) the use of Fast Real Time Publish Subscribe (Fast-RTPS) domain control-based swarm information interaction to achieve efficient data transmission within the swarm.

2. Intelligent swarm simulation platform design

2.1. Functional analysis

Key technologies that need to be addressed in order to achieve full autonomous control of intelligent swarm systems include [6]:

(1) Environmental perception and attitude perception.
(2) Collaborative decision-making and task planning.
(3) Information exchange and swarm control.

Thus, the simulation system should have the following features:

(1) Simulation of the aerodynamic characteristics of aircraft
(2) Simulation of individual and swarm flight control functions
(3) Simulating the environment perception function of individual
(4) Simulation of the data interaction function of the swarm
(5) Simulation data storage and analysis function

The proposed simulation platform takes the fixed-wing aircraft as the control object of the nodes in the swarm and uses the aircraft internal and external loop control algorithm to control the individual and the swarm. The simulation platform simulates the generation of images captured by the strap-down light camera. This image is used as a data source for the environmental perception module. This platform simulates the swarm's data interaction function by adding a mathematical model of the swarm data communication.

2.2. Mathematical Model

In order to ensure the fine-grained simulation of the platform, the control system, the controlled object, and the communication system in the platform are mathematically modelled. The control system model is shown in equation (1).

\[ C = f_c(A, P, V) \]  

Where \( A \) is the attitude of the aircraft, \( P \) is the position of the aircraft, \( V \) is the speed of the aircraft, and \( C \) is the control amount of the aircraft's throttle and rudder angle. The control system takes the attitude, position, and speed vector of the aircraft as input and outputs the aircraft's rudder angle and throttle control quantity. The controlled object model is as in equation (2).

\[ S = f_s(T, R) \]  

Where \( T \) is the amount of throttle of the aircraft, \( R \) is the rudder angle of the aircraft, and \( S \) is the state of the aircraft, including attitude, position, speed, and other data. The controlled object takes the control amount of throttle and rudder angle as input and outputs the aircraft's system state, including attitude, position, speed, and other data in real-time. The communication system model is as in equation (3).

\[ Q = f_q(P_{node}, B_{node}, N, E) \]
Where $P_{node}$ is the location information of each node in the swarm, $B_{node}$ is the transmission bandwidth of each node in the swarm, $N$ is the network structure of the swarm, $E$ is the environmental information, and $Q$ is the quality of communication, including packet loss rate and communication delay. The communication system uses node location information, node transmission bandwidth, swarm network structure, and environmental information as inputs to settle the quality of communication between nodes, including packet loss rate, communication delay, etc.

2.3. System components

The structural composition of the swarm hardware in the loop simulation system proposed in this paper is shown in Figure 1. The flight control module, the swarm control module, and the environment perception module are the core of the simulation system, and their hardware components are shown in Figure 2(a).

The 3D flight simulation module's function is to build a 3D flight simulation environment and simulate the generation of various sensor data of the aircraft. The above functions are mainly realized by X-Plane10, which supports adding custom aircraft models and landform models. X-Plane10 can simulate and generate aircraft status information and provide feedback to the flight control module based on the aerodynamic model of the aircraft [7]. X-Plane10 can simulate the aircraft's optical acquisition equipment, generate the first view of the aircraft, and adjust the image resolution, field of view angle, camera mounting angle and other parameters.

The flight control module uses Pixhawk2.1 as the hardware platform. PX4 open source software adds swarm information interaction and terminal guidance function to realize individual and swarm control of the aircraft. According to the simulation module's status data output, this module outputs control instructions to the simulation model and issues its status data to other modules.

The swarm control module and environment perception module are based on Jetson TX2 as the hardware platform. The environment perception module's role is to collect the airborne first-view image generated by the simulation module and identify and track the suspicious target in the image. The role of the swarm control module has three points:

1. Receive the environment perception results and obtain information about the suspicious target;
2. Receive control instructions from the simulation monitoring module and return the swarm simulation state in real-time;
3. Merge the information from other modules and other individuals to make autonomous decisions, and at the same time to publish its information to the outside.

The simulation monitoring module's role is to control the simulation start and stop and monitor the swarm simulation state. This module mainly consists of ground station and self-developed image decoding software. The ground station is to monitor the status of each aircraft. The image decoding software receives the airborne images back from the simulation system and can also upload instructions for guidance status switching.
The function of the simulation display module is to visualize the simulation process so that the operator can intuitively monitor each UAV's simulation status. The visualization effect of the simulation display module is shown in Figure 2(b), which can display the different perspectives of different UAVs simultaneously.

![Figure 2. The physical hardware of the simulation system](image)

### 2.4. Software framework

The simulation platform's software framework is shown in Figure 3. The self-driving device in the node communicates with the TX2 using UART serial port, and the transmission protocol conforms to Fast RTPS. The self-driving device is equipped with Nuttx operating system and uses Micro Object Request Broker (uORB) to manage the message transfer between applications. In Figure 3, node 1 and node 2 use the User Datagram Protocol (UDP) for transmission, which follows the Fast RTPS protocol. TX2 controls the data transfer within nodes and between nodes. The message domain mechanism of Fast RTPS can control the flow of different data. The data transfer between all nodes within a swarm is the same between node 1 and node 2.

### 3. Simulation Platform Testing

#### 3.1. Individual strap-down terminal guidance test

The individual strap-down terminal guidance mainly tests the individual control function, the target tracking function, and the data interaction function within the simulation platform's node. The individual
simulations use Xplane10's aircraft GP_PT_60 as the controlled object. In the normal cruise state, the individual uses the original L1 [8] and Total Energy Control System (TECS) [9] control algorithms of PX4. When the aircraft is switched to the guidance state, the aircraft control quantity is solved according to the received guidance information to achieve the guidance function. Under the condition of using the same control algorithm and control parameters, comparing the trajectory of simulation and actual flight as shown in Figure 4, it can be concluded that the simulation platform has a good simulation effect on the single flight control.

Figure 4. Comparison flight tracks between the simulated individual aircraft serpentine search and the field test

The target tracking algorithm outputs the horizontal and vertical line-of-sight angles of the target relative to the aircraft in the terminal guidance state. These two line-of-sight angles are used in conjunction with guidance commands as inputs to the aircraft's guidance information. The tracking algorithm can track the selected target in real-time during the terminal guidance state in the simulation platform. The aircraft can fly to the target according to the guidance information outputted by the tracking algorithm, and the simulation results are shown in Figure 5. Therefore, the simulation platform has good simulation results for target tracking and terminal guidance.
Figure 5. Terminal Guidance Simulation Test: Figures (a) to (f) depict the process of selecting and attacking a target for the UAV terminal guidance. The blue boxes in the figure indicate the selected targets, and the blue circles indicate the attack targets.

3.2. Multi-aircraft coordinated search function test

The multi-aircraft collaborative search function test is mainly used to verify multi-aircraft communication, swarm control, and autonomous flight path planning functions in the simulation platform. In this test, multiple UAVs search the mission area in a serpentine formation. During the flight, the flight path of each UAV is generated in TX2 by the swarm control module in real-time based on the position of other UAVs, the desired formation, and other data.

At the beginning of the simulation, each UAV flew to the mission staging point using an automatic take-off. After arriving at the assembly point, each UAV searches the target area according to the formation. According to the simulation results, as shown in Figure 6(a), the testers adjust the UAVs' relevant safety parameters, such as flight altitude and turning radius. As shown in Figure 6(b), the actual flight results are basically consistent with the simulation results, and the UAV can fly according to the route of the simulation results. Thus, it shows that the simulation system proposed in this paper can reasonably simulate the actual flight process of the swarm.

Figure 6. Serpentine formation coordinated search: 8 UAVs coordinated search of 1 km² area.
4. Conclusion
The distributed UAV swarm simulation platform can be used as an effective means to verify several key
 technologies of the swarm system early, ensuring simulation accuracy and saving testing costs. The
 platform can customize the 3D scenario and import the target motion model and the aerodynamic model
 of the aircraft. The platform can effectively verify the swarm control capability and mission execution
 capability and has good simulation results for individual and swarm control, individual perception, and
 swarm data interaction. This platform is an open and standardized simulation platform with flexible
 expansion capabilities. Based on the existing foundation, expanding the number of hardware nodes or
 adding all-digital simulation nodes can realize the fine-grained, visualization simulation of large-scale
 intelligent swarms. In order to further increase the simulation credibility, we will consider adding sensor-
 level hardware-in-loop simulation later.

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