Multicopter Design and Control Practice ——A Series Experiments Based on MATLAB and Pixhawk

Lesson 01 Introduction

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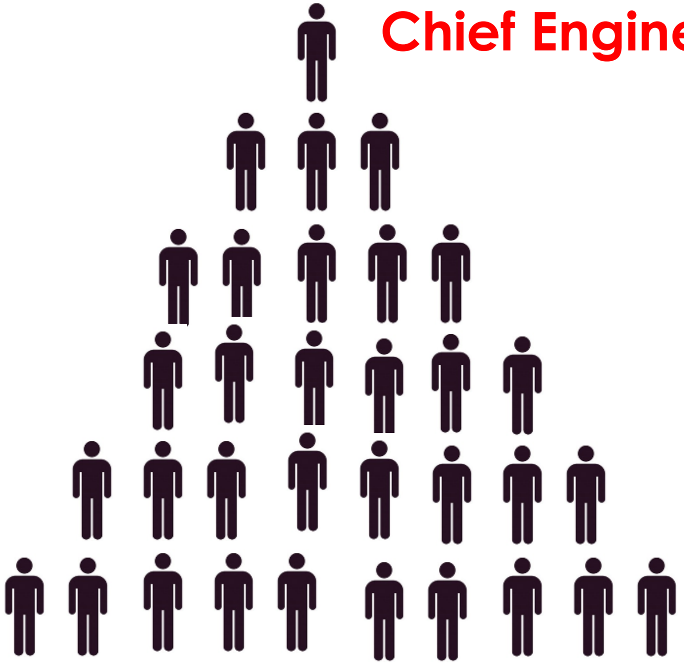
北航可靠飞行控制研究组
BUAA Reliable Flight Control Group

New Requirement



Chief Engineer

No lack of Engineers, Financial support, Experience, Resources

Traditional

- Fewer engineers
- Less experience
- Fewer resources

New

- A full-stack multicopter engineer has a functional knowledge of all techniques, languages and systems engineering concepts required in multicopter development.
- The term "full stack" refers to the technologies and skills needed to complete a project, with each individual component being a stack.

New Requirement

□ Theory

- Airframe Configuration
- Propulsion System
- Modeling
- Calibration and State Estimate
- Controller Design
- Planning Design
- Failsafe Design
- ……

New Requirement

◻ Theory

- Airframe Configuration
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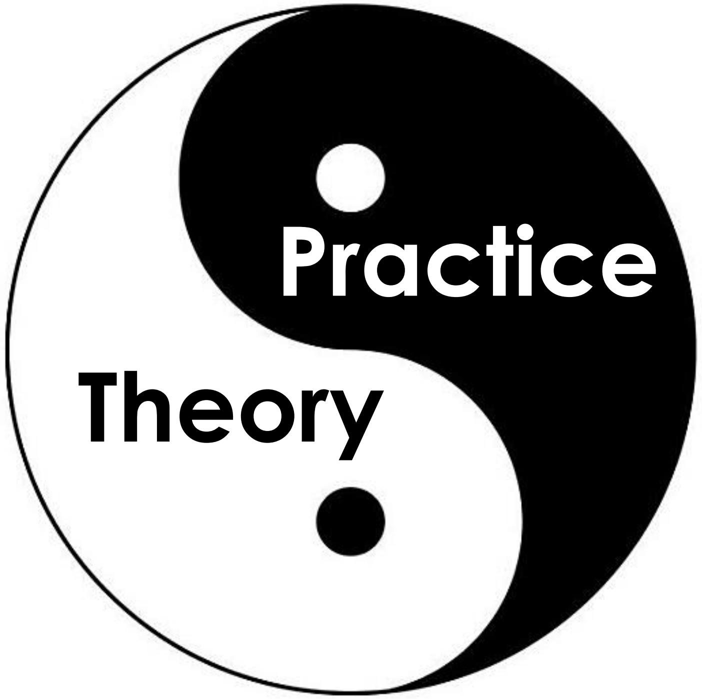
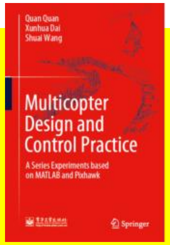
- Calibration and State Estimate
- Controller Design
- Planning Design
- Failsafe Design



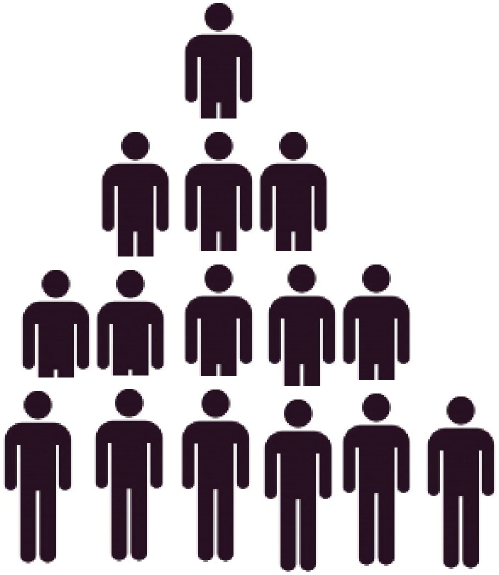
◻ Practice

- Develop Tool
- Operating System
- Coding
- Software Testing
- Flight Testing
- ……

- How we do it? New Tool + New Course



New Requirement

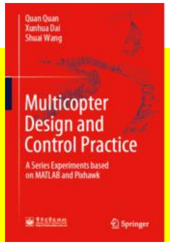


Education

People with Background of Electronic Engineering

Chief Engineers

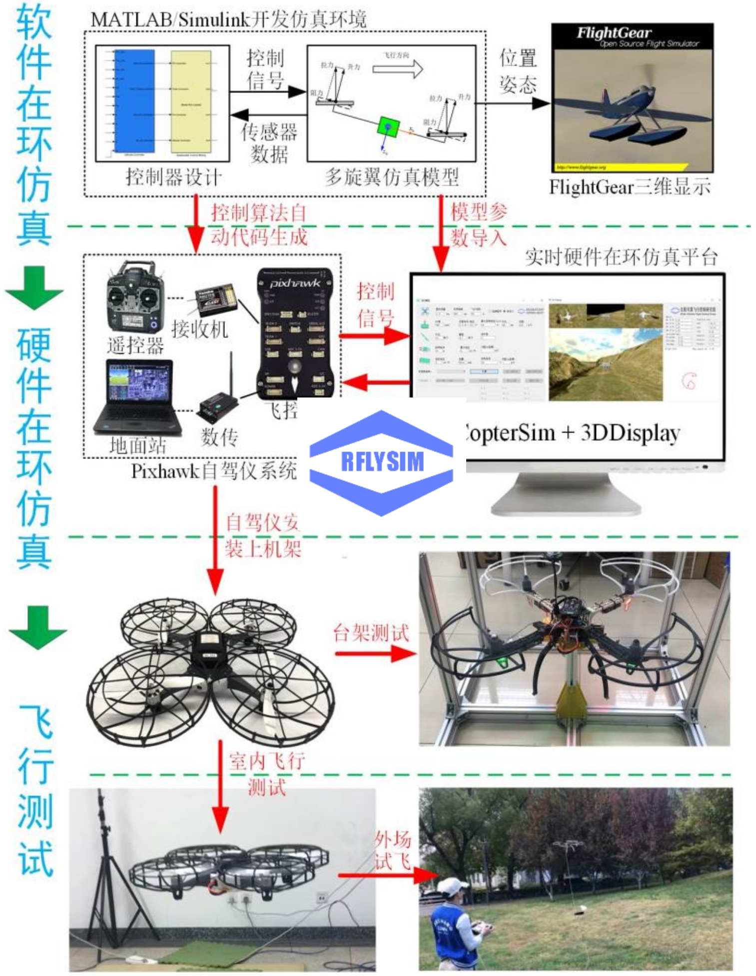
- How we do it?   New Tool + New Course



RflySim

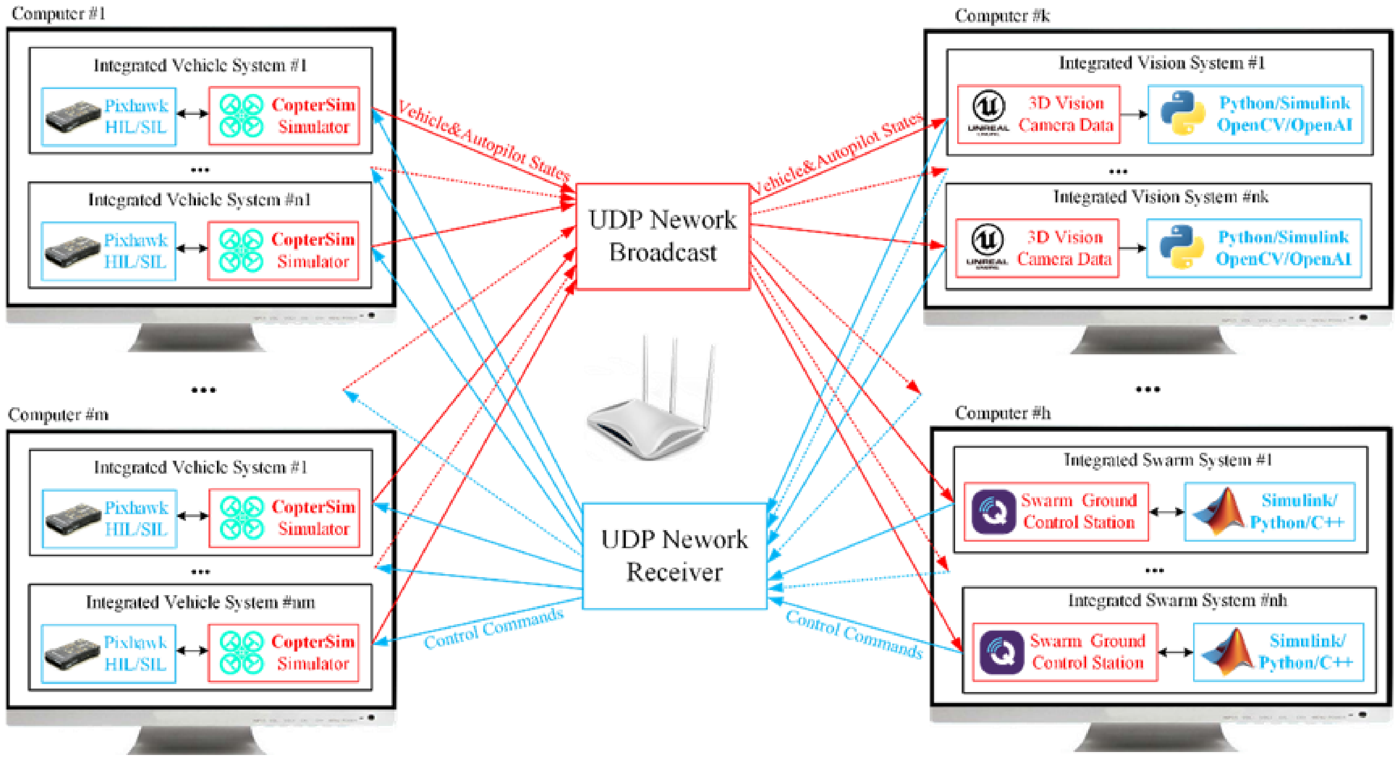
- RflySim, launched by BUAA Reliable Flight Control Group (rfly.buaa.edu.cn), is an ecosystem or a toolchain
- MATLAB/Simulink, supporting the full design phase of Model-Based Design, is chosen for control/vision/swarm algorithms.
- Python is supported by RflySim platform for top-level vision/swarm
- RflySim ecosystem has many open-source software, and some tools we design especially.

RflySim



- The core values of RflySim lie on Hardware-In-the-Loop Simulation, including CopterSim we design, Unreal plug-in, Model, and Hardware-In-the-Loop Architecture Design
- The education-level RflySim focuses on the ease-to-access, using personal computers to run the model and the serial port for communication with the control board.
- The commercial-level RflySim focuses on reliable performance, using real-time simulator with FPGA to run the models, sensors chips, and high-speed communication interfaces with the control board.

RflySim



- The education-level RflySim including CopterSim we design, Unreal plug-in

① Ease of Use

② Distributed Structure

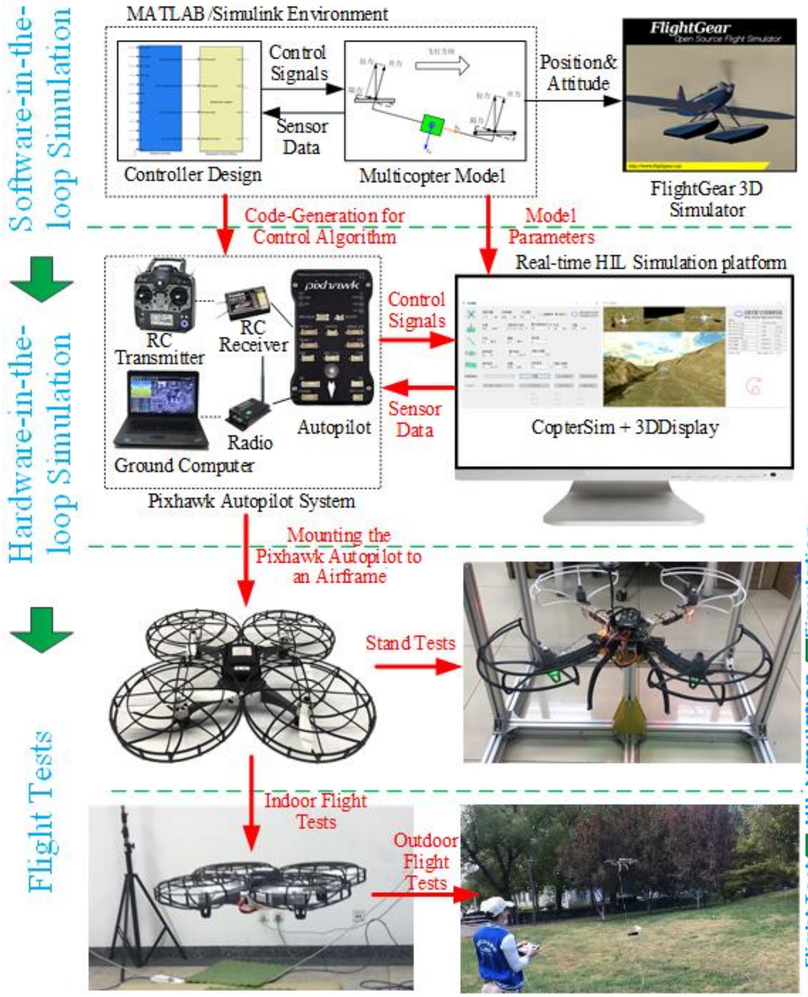
③ UAV Swarm Simulation

④ Multiple Vehicle Types

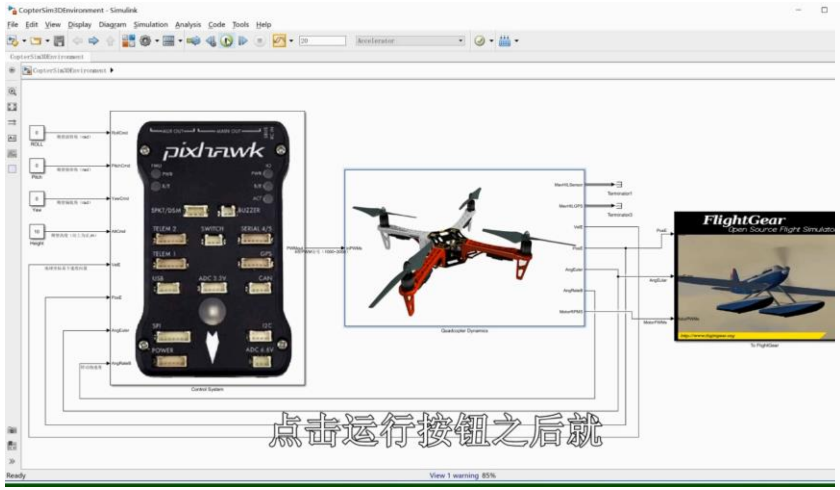
⑤ High-fidelity 3D Environment

⑥ Vision-based control

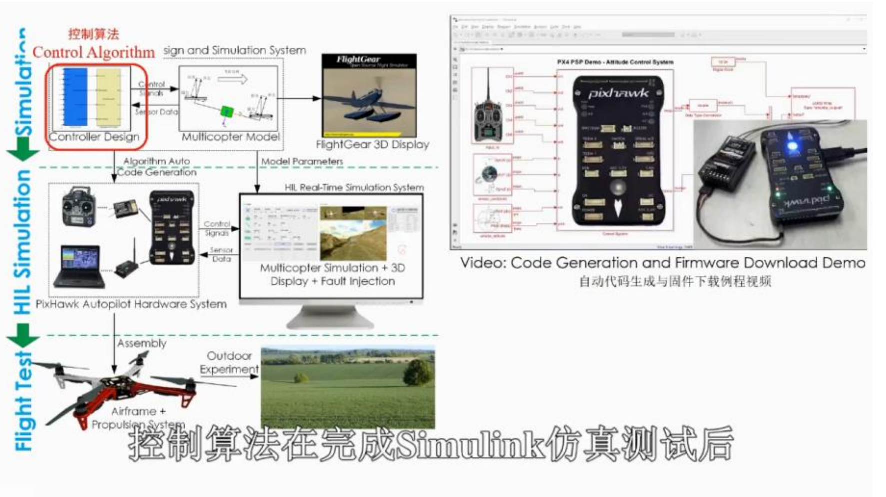
RflySim



Software-in-the-loop Simulation
MATLAB/Simulink Environment
Control Signals
Sensor Data
Position& Attitude
Controller Design
Multicopter Model
FlightGear 3D Simulator
Code-Generation for Control Algorithm
Model Parameters
Real-time HIL Simulation platform
Hardware-in-the-loop Simulation
RC Transmitter
RC Receiver
Control Signals
Sensor Data
Radio
Autopilot
Ground Computer
CopterSim + 3DDisplay
Pixhawk Autopilot System
Mounting the Pixhawk Autopilot to an Airframe
Stand Tests
Flight Tests
Indoor Flight Tests
Outdoor Flight Tests



点击运行按钮之后就

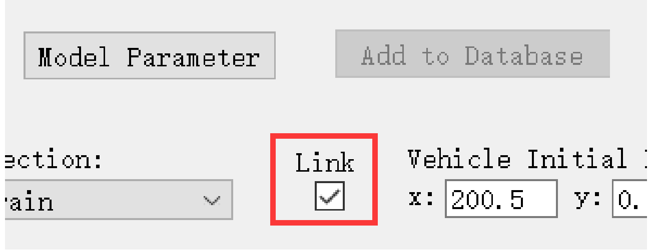


控制算法
Control Algorithm
Controller Design
Multicopter Model
FlightGear 3D Display
Simulation
HIL Simulation
Flight Test
Model Parameters
PixHawk Autopilot Hardware System
Multicopter Simulation + 3D Display + Fault Injection
Assembly
Outdoor Experiment
Airframe + Propulsion System
Video: Code Generation and Firmware Download Demo
自动代码生成与固件下载例程视频
控制算法在完成Simulink仿真测试后

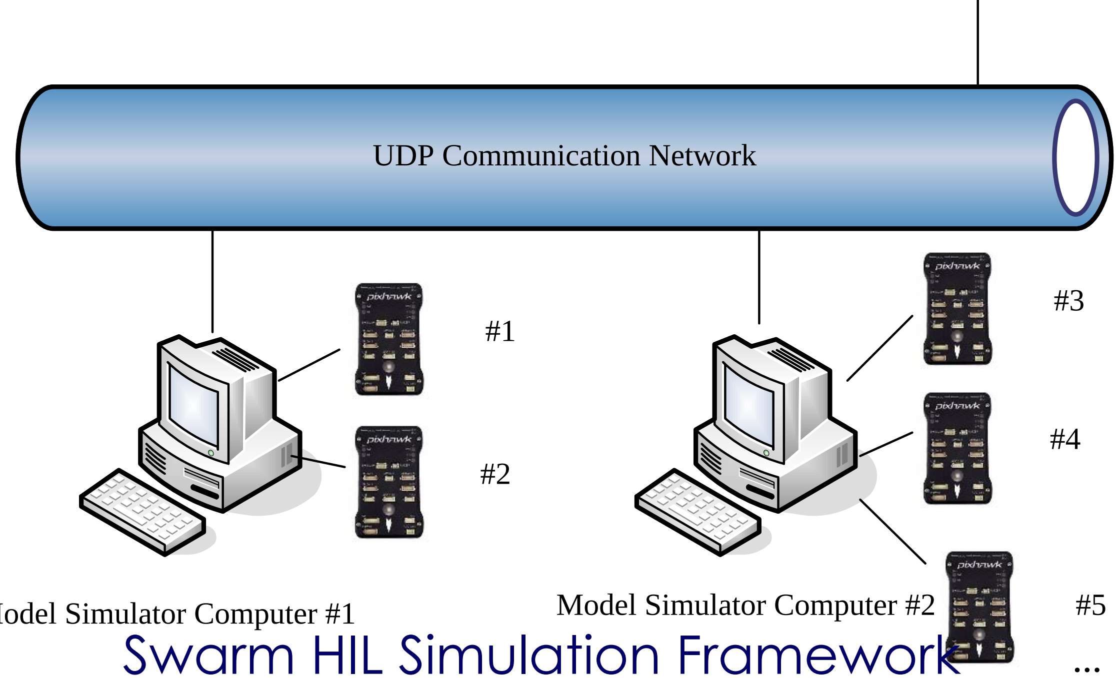
Futaba
T14SG

我们可以进一步地在室内

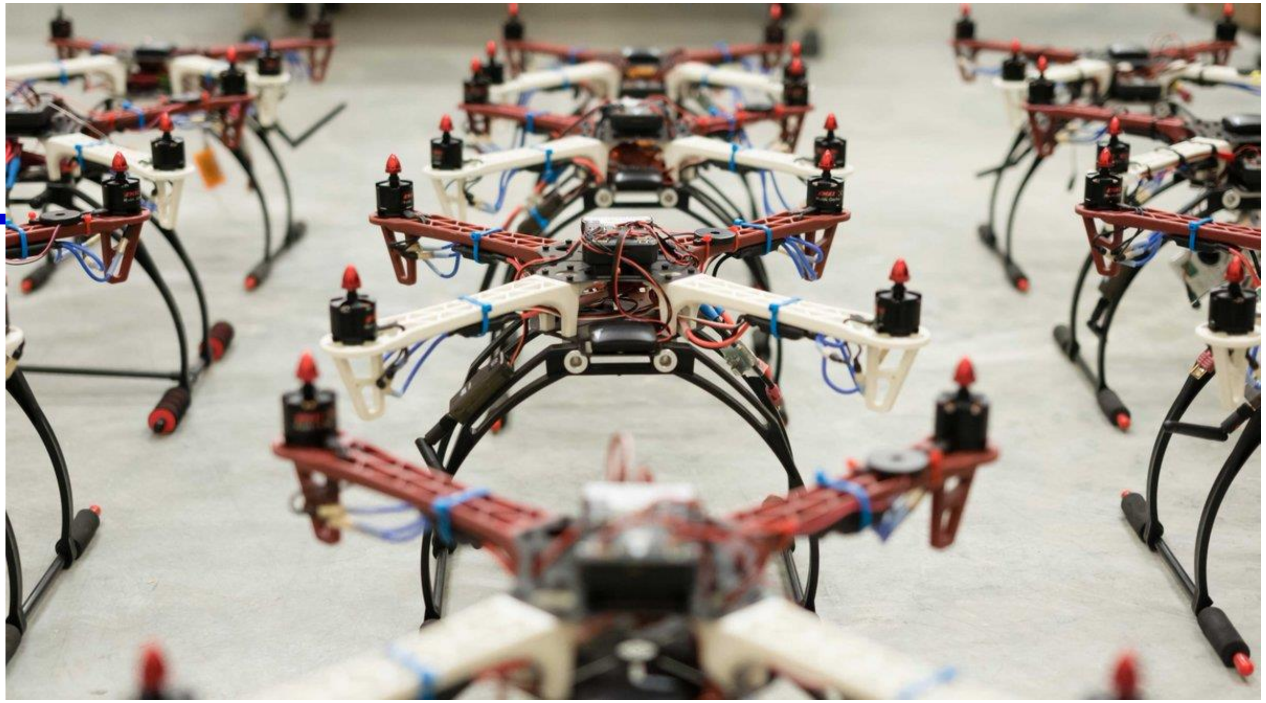
RflySim

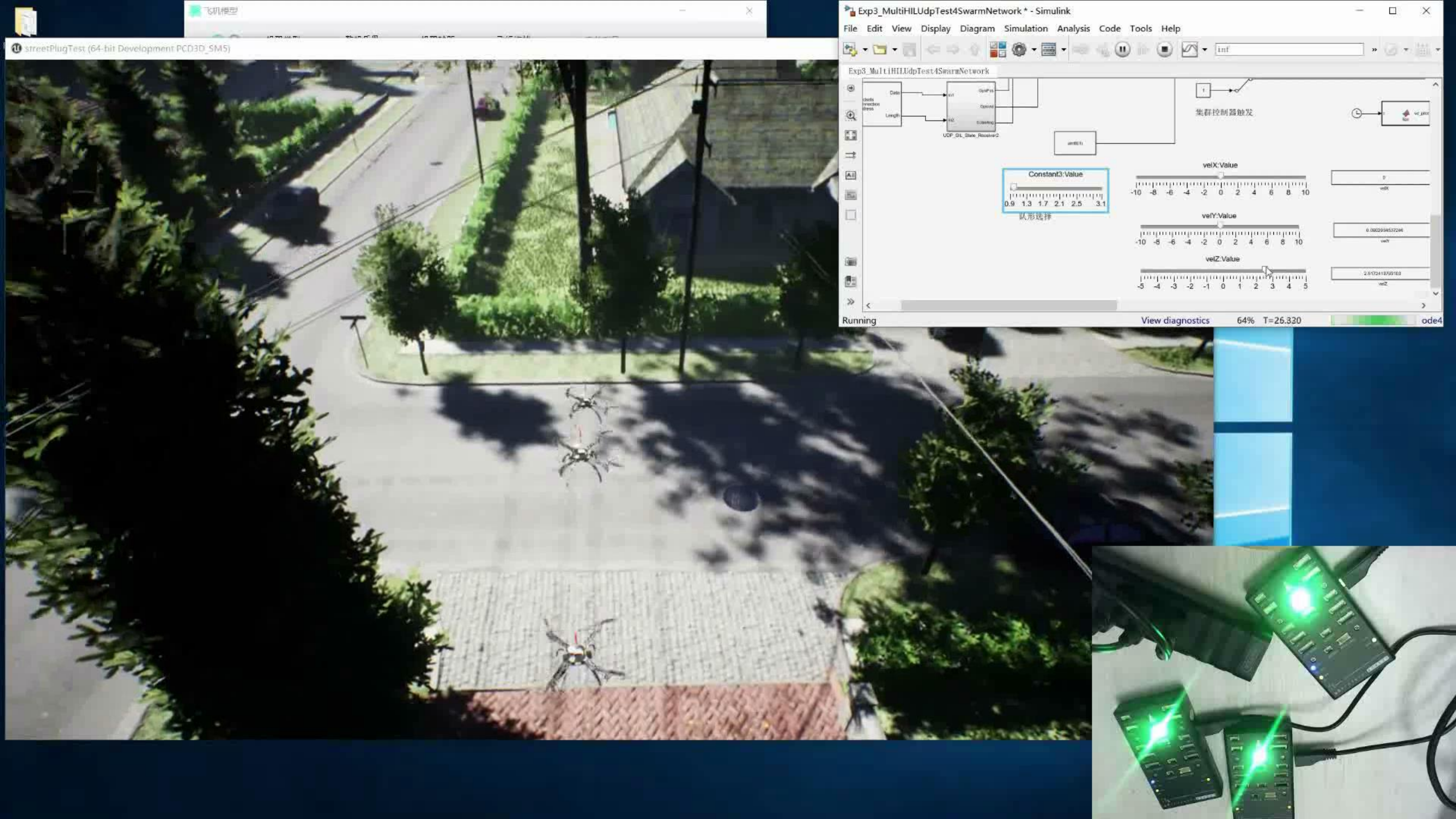


CopterSim “Link” button for broadcast

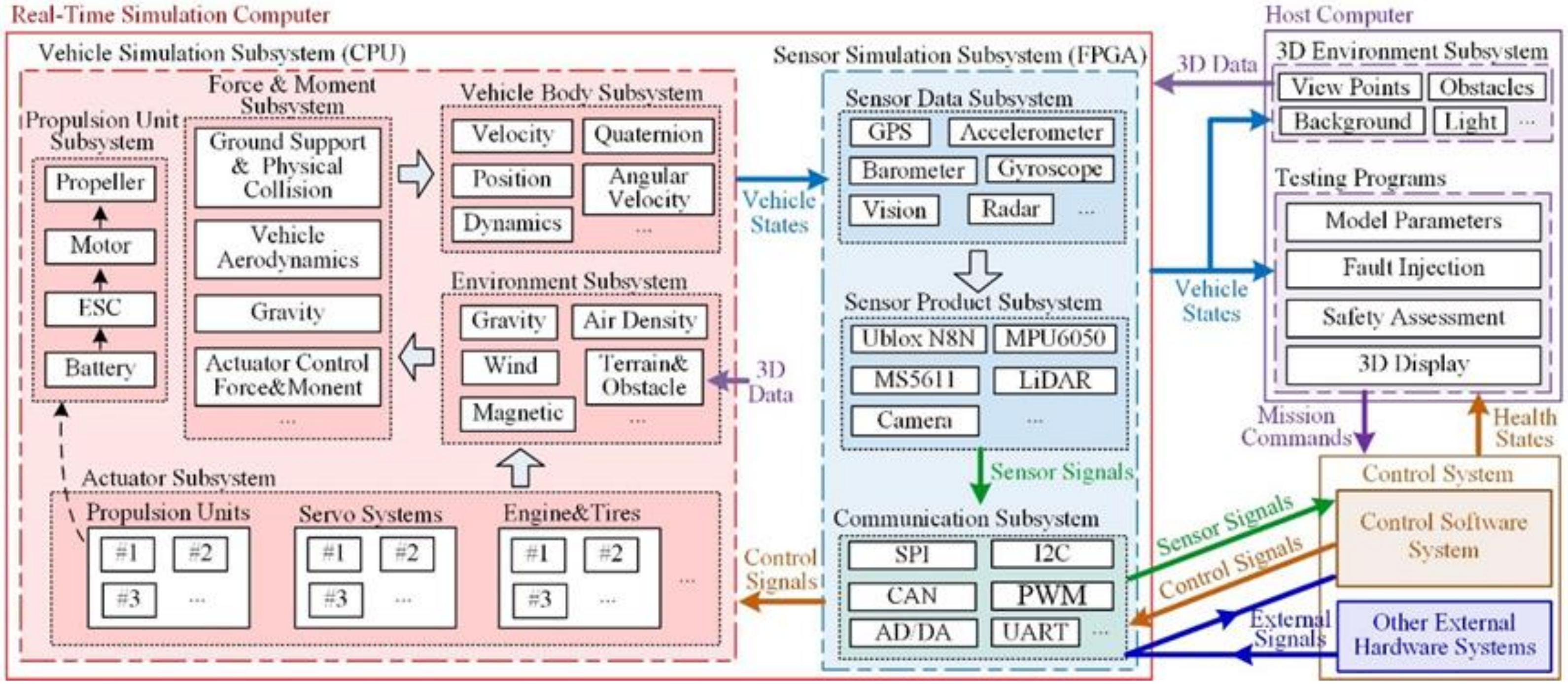


Swarm HIL Simulation Framework




飞机模型
streetPlugTest (64-bit Development PCD3D_SM5)
Exp3_MultiHILUdpTest4SwarmNetwork * - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
inf
Exp3_MultiHILUdpTest4SwarmNetwork
集群控制器触发
Constant3:Value
0.9 1.3 1.7 2.1 2.5 3.1
队形选择
velX:Value
-10 -8 -6 -4 -2 0 2 4 6 8 10
velY:Value
-10 -8 -6 -4 -2 0 2 4 6 8 10
velZ:Value
-5 -4 -3 -2 -1 0 1 2 3 4 5
Running
View diagnostics
64%
T=26.320
ode4

RflySim



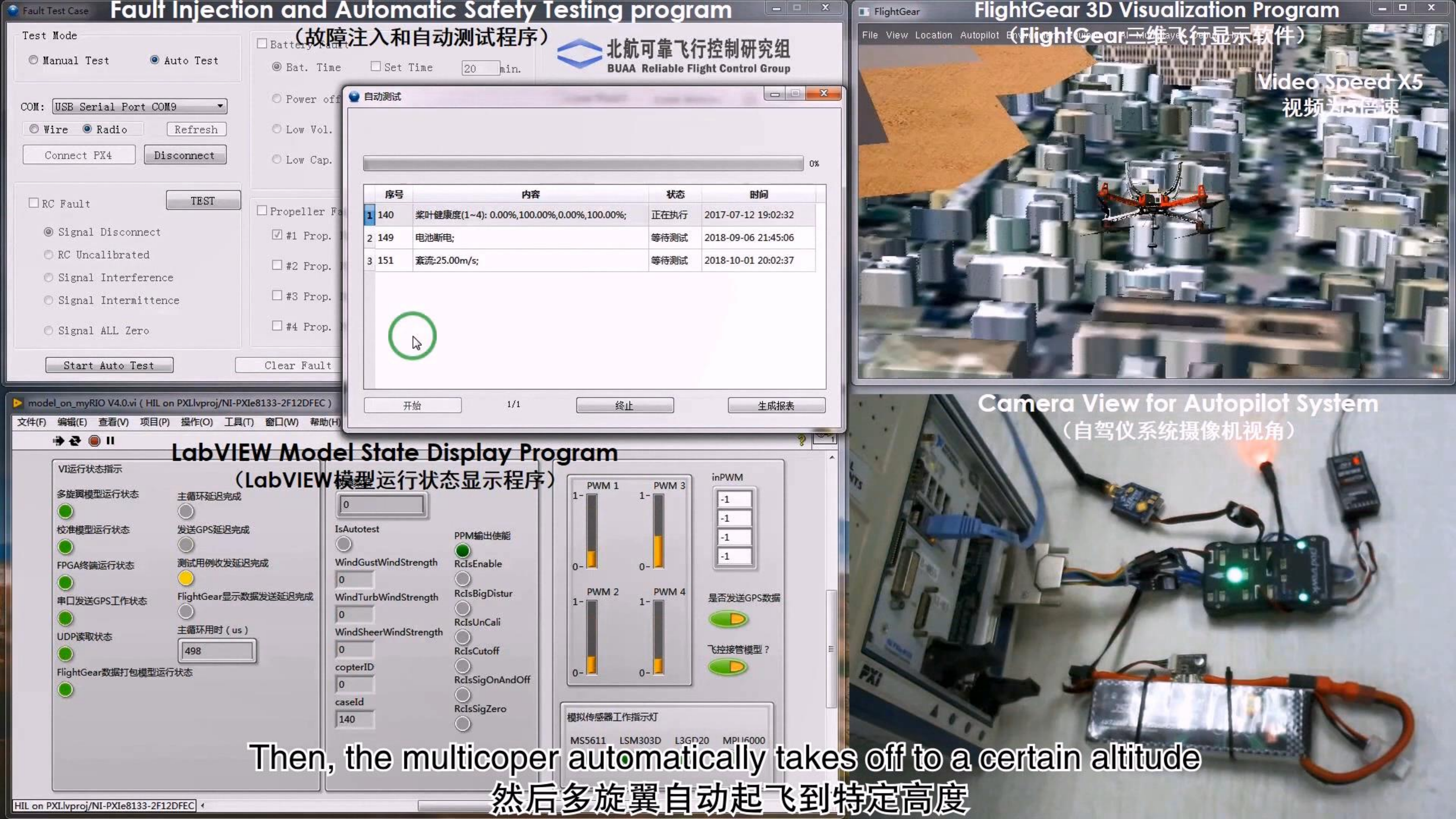
- The Commercial-level RflySim including Model and Hardware-In-the-Loop Architecture Design

① Extensibility

② Practicability

③ Standardization

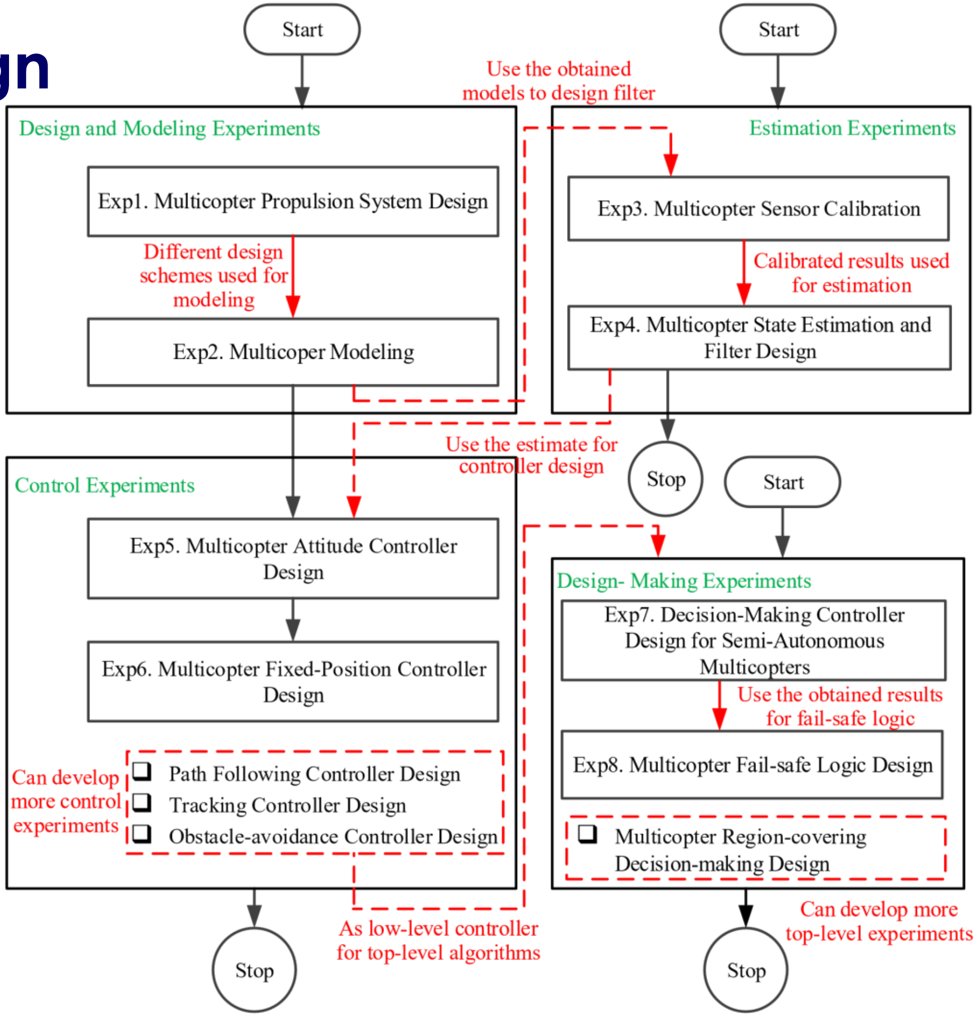
④ Automation


Fault Test Case
Fault Injection and Automatic Safety Testing program
（故障注入和自动测试程序）
北航可靠飞行控制研究组
BUAA Reliable Flight Control Group
Test Mode
Manual Test
Auto Test
COM: USB Serial Port COM9
Wire
Radio
Refresh
Connect PX4
Disconnect
RC Fault
TEST
Signal Disconnect
RC Uncalibrated
Signal Interference
Signal Intermittence
Signal ALL Zero
Start Auto Test
Clear Fault
Battery Fault
Bat. Time
Set Time
20 min.
Power off
Low Vol.
Low Cap.
Propeller Fault
#1 Prop.
#2 Prop.
#3 Prop.
#4 Prop.
自动测试
0%
序号 | 内容 | 状态 | 时间
1 140 桨叶健康度(1~4): 0.00%,100.00%,0.00%,100.00%; 正在执行 2017-07-12 19:02:32
2 149 电池断电; 等待测试 2018-09-06 21:45:06
3 151 紊流:25.00m/s; 等待测试 2018-10-01 20:02:37
开始
1/1
终止
生成报表
FlightGear
FlightGear 3D Visualization Program
（FlightGear三维飞行显示软件）
File View Location Autopilot
Video Speed X5
视频为5倍速
model_on_myRIO V4.0.vi (HIL on PXI.lvproj/NI-PXIe8133-2F12DFEC)
文件(F) 编辑(E) 查看(V) 项目(P) 操作(O) 工具(T) 窗口(W) 帮助(H)
LabVIEW Model State Display Program
（LabVIEW模型运行状态显示程序）
VI运行状态指示
多旋翼模型运行状态
校准模型运行状态
FPGA终端运行状态
串口发送GPS工作状态
UDP读取状态
FlightGear数据打包模型运行状态
主循环延迟完成
发送GPS延迟完成
测试用例收发延迟完成
FlightGear显示数据发送延迟完成
主循环用时（us）
498
IsAutotest
WindGustWindStrength
WindTurbWindStrength
WindSheerWindStrength
copterID
caseId
140
PPM输出使能
RcIsEnable
RcIsBigDistur
RcIsUnCali
RcIsCutoff
RcIsSigOnAndOff
RcIsSigZero
PWM 1
PWM 3
PWM 2
PWM 4
inPWM
-1
-1
-1
-1
是否发送GPS数据
飞控接管模型？
模拟传感器工作指示灯
MS5611 LSM303D L3GD20 MPU6000
HIL on PXI.lvproj/NI-PXIe8133-2F12DFEC
Camera View for Autopilot System
（自驾仪系统摄像机视角）
Then, the multicoper automatically takes off to a certain altitude
然后多旋翼自动起飞到特定高度

Course Design

■ Experiment Content and Framework Design

- Propulsion system design
- Dynamical modeling
- Sensor calibration
- State estimation and filter design
- Attitude controller design
- Fixed-position controller design
- Semi-autonomous control design
- Failsafe logic design



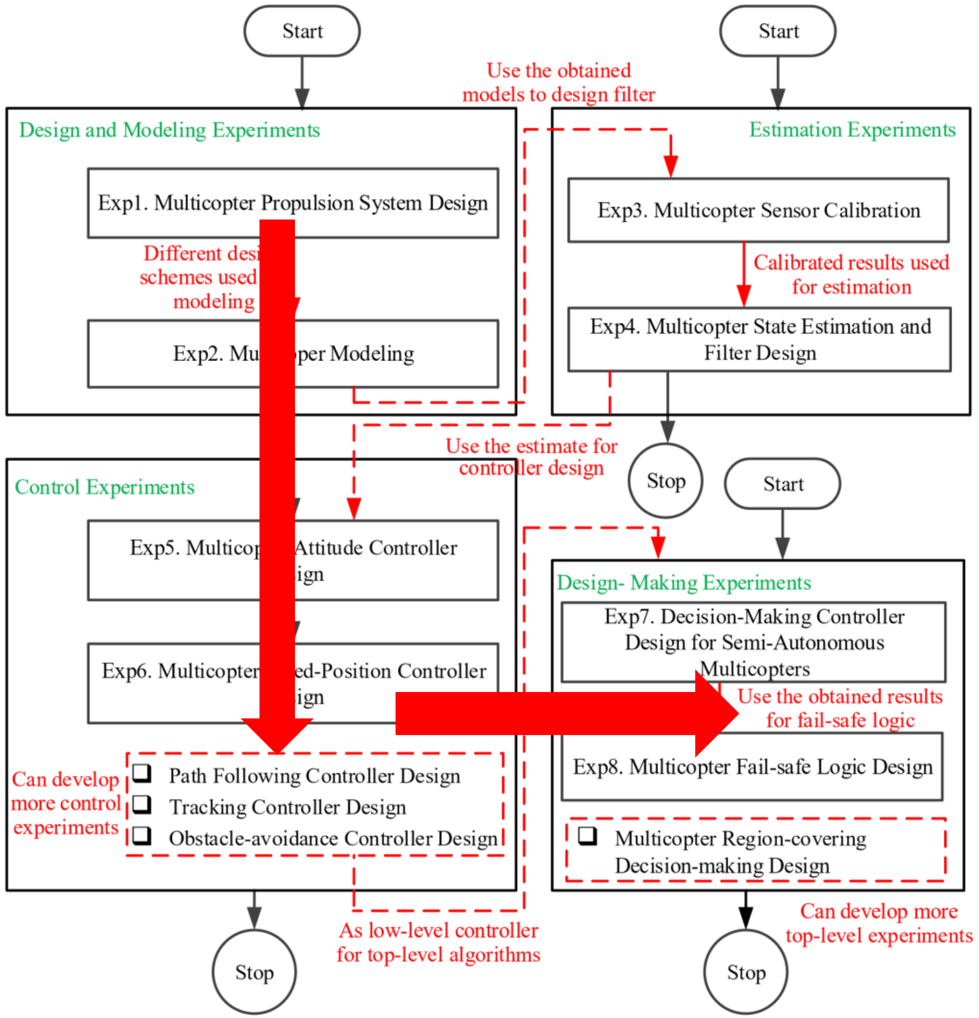
Course Design

The progressive studying routes are as follows:

(a) Design and modeling experiments → Control experiments

(b) Design and modeling experiments → Control experiments → Decision-making experiments

(c) Design and modeling experiments → Estimation experiments → Control experiments → Decision-making experiments



Course Design

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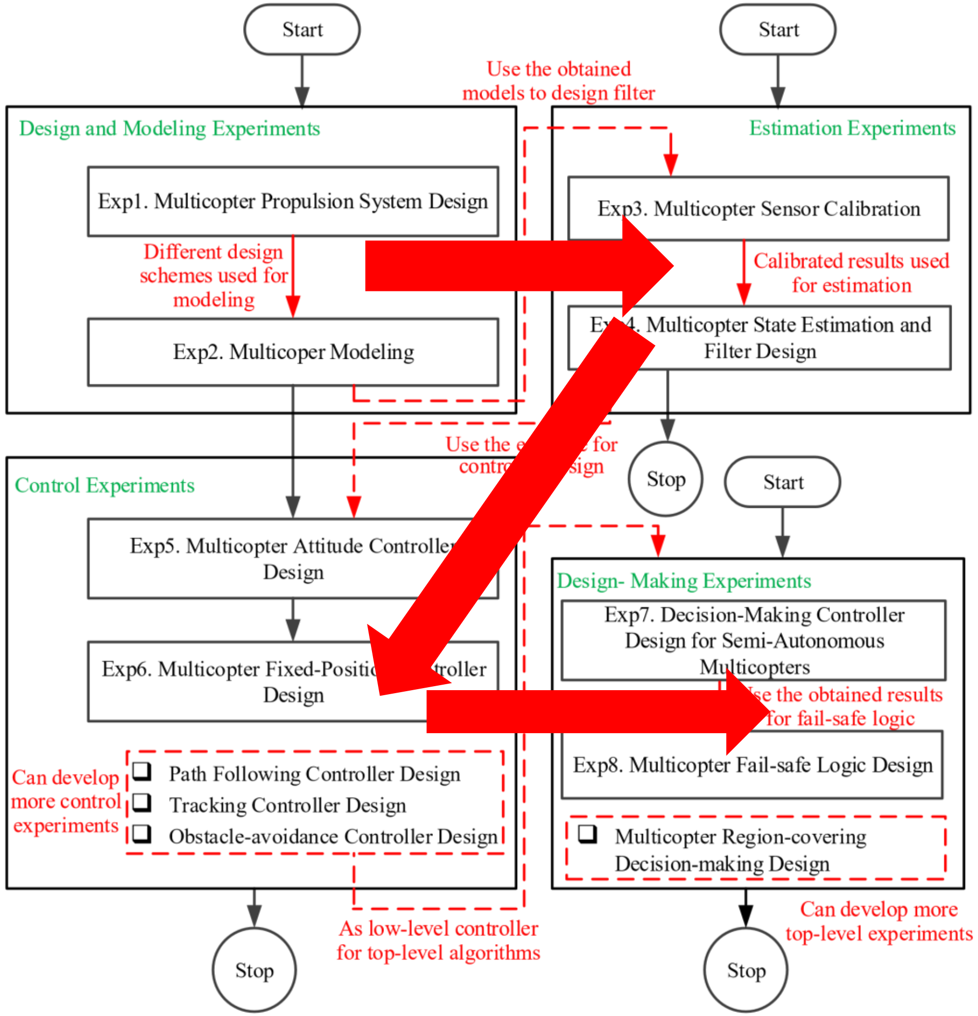
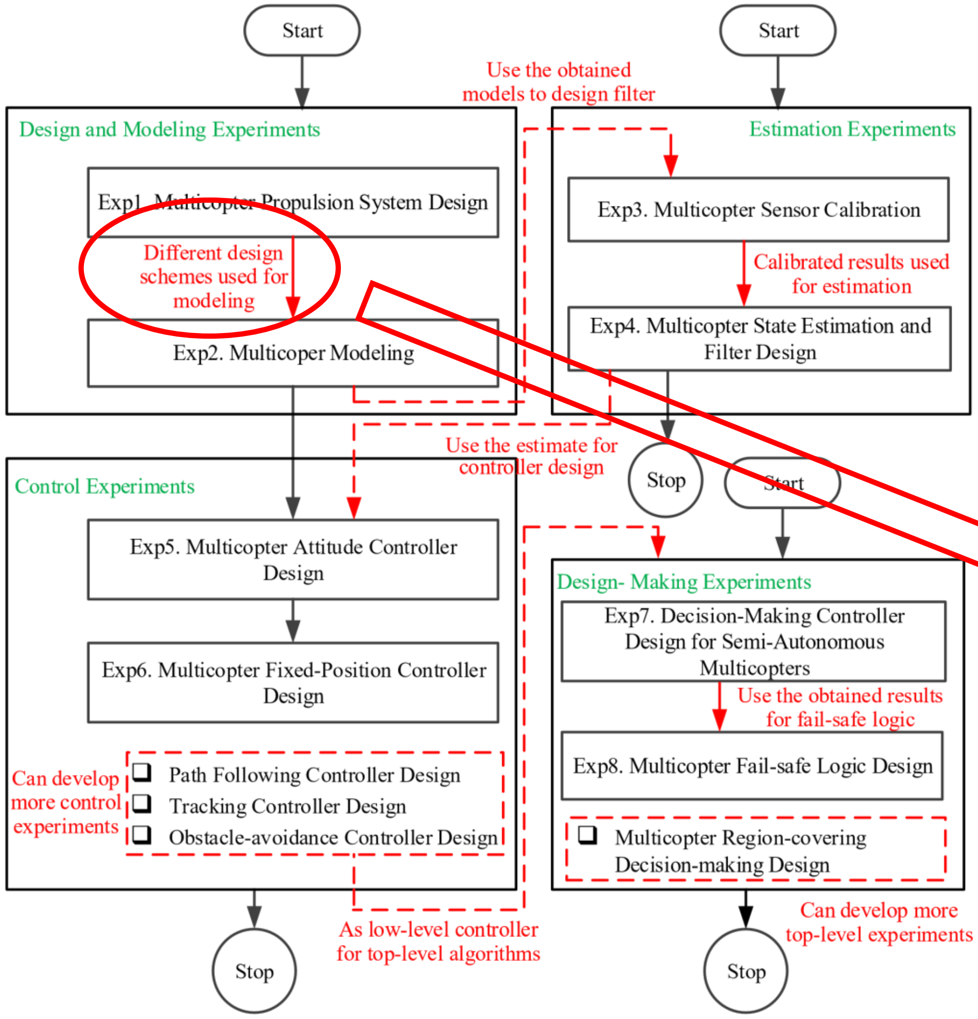
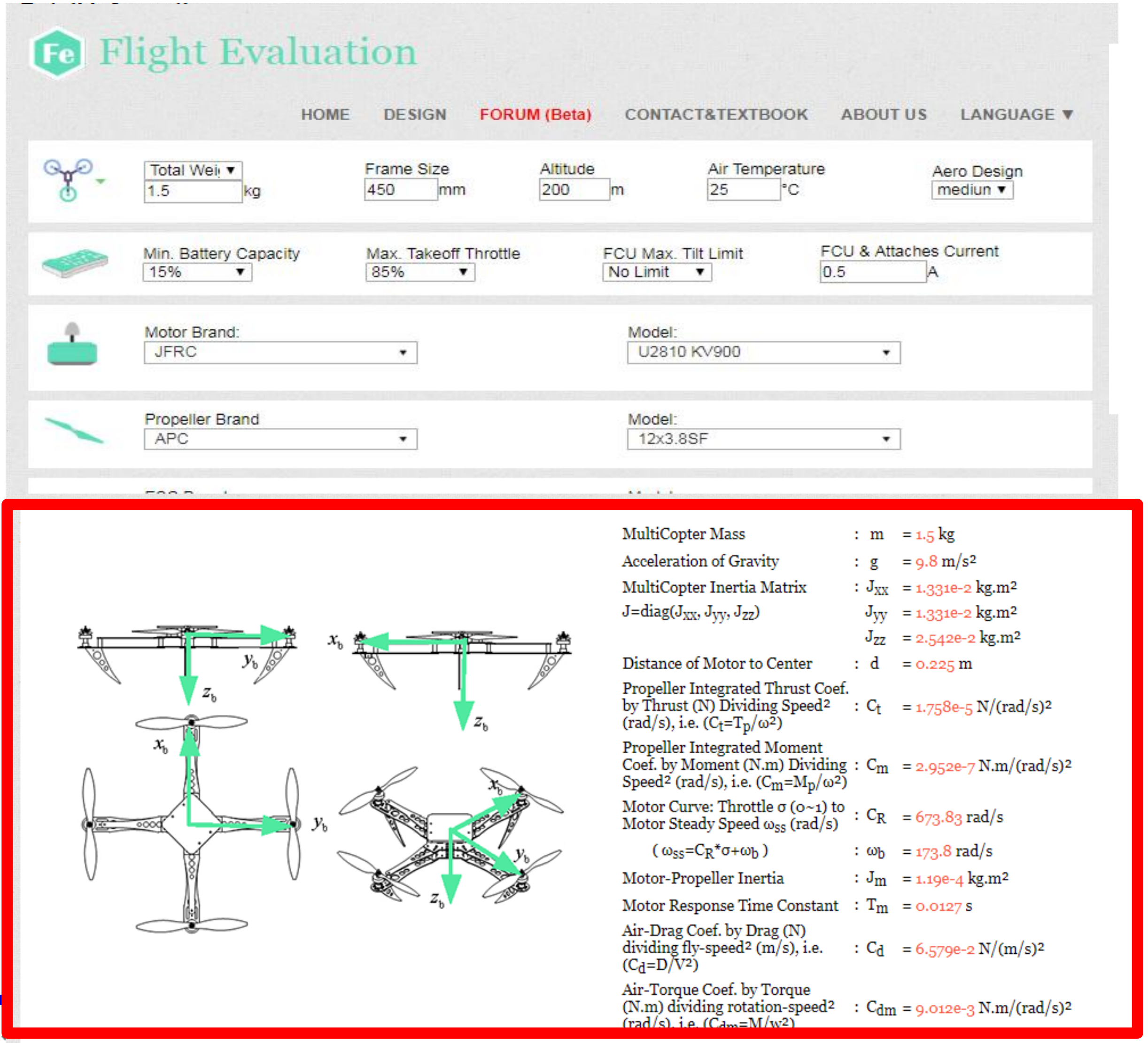




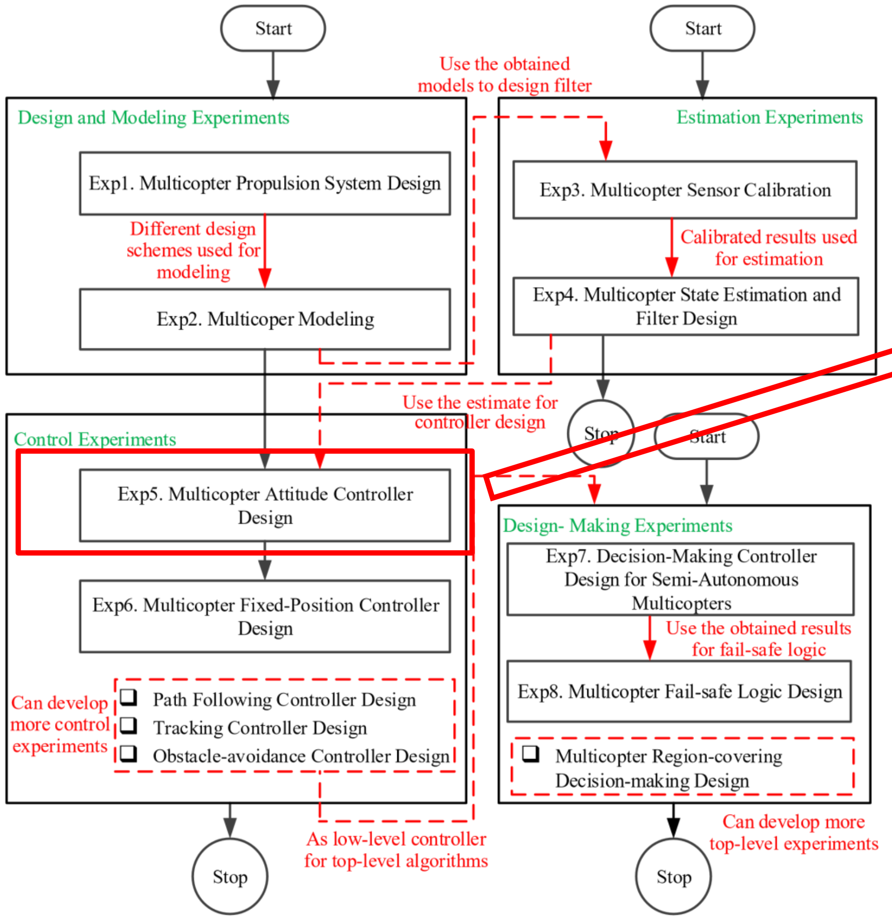
Start
Start
Use the obtained models to design filter
Design and Modeling Experiments
Estimation Experiments
Exp1. Multicopter Propulsion System Design
Exp3. Multicopter Sensor Calibration
Different design schemes used for modeling
Calibrated results used for estimation
Exp2. Multicoper Modeling
Exp4. Multicopter State Estimation and Filter Design
Use the estimate for controller design
Stop
Start
Control Experiments
Exp5. Multicopter Attitude Controller Design
Design- Making Experiments
Exp7. Decision-Making Controller Design for Semi-Autonomous Multicopters
Exp6. Multicopter Fixed-Position Controller Design
Use the obtained results for fail-safe logic
Exp8. Multicopter Fail-safe Logic Design
Can develop more control experiments
Path Following Controller Design
Tracking Controller Design
Obstacle-avoidance Controller Design
Multicopter Region-covering Decision-making Design
As low-level controller for top-level algorithms
Can develop more top-level experiments
Stop
Stop

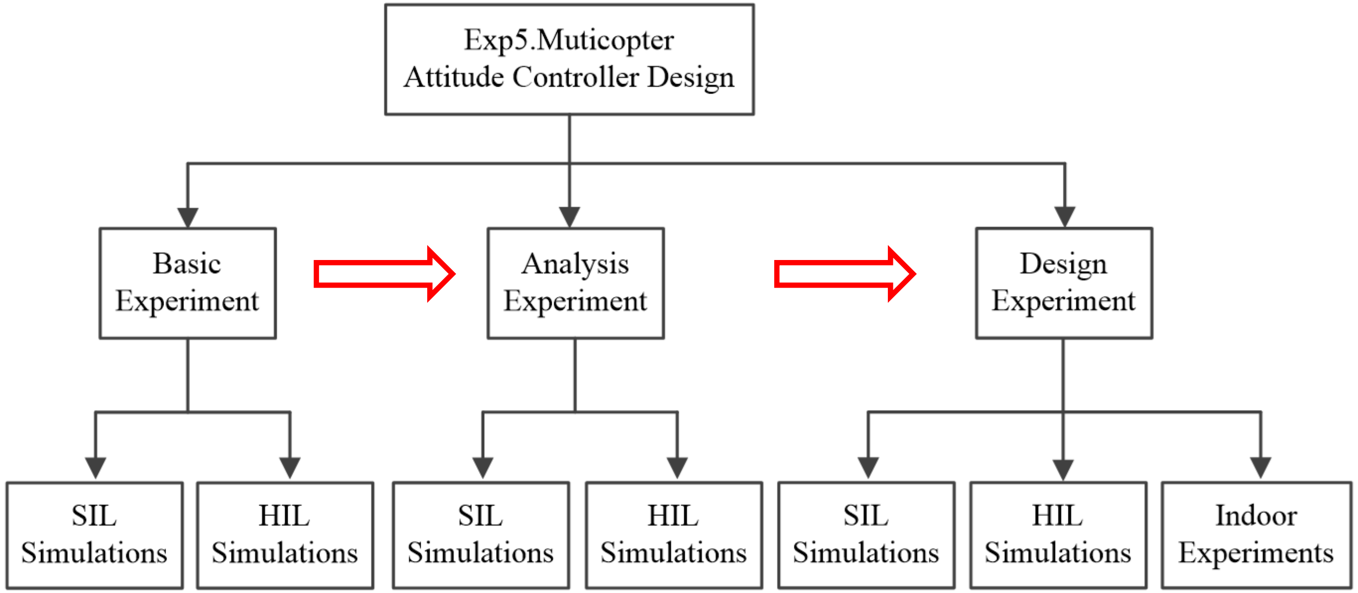


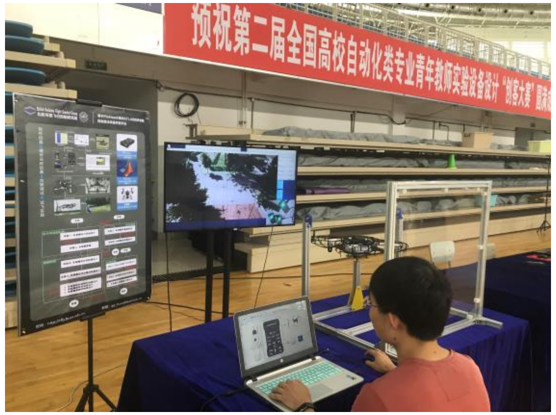
Flight Evaluation
HOME DESIGN FORUM (Beta) CONTACT&TEXTBOOK ABOUT US LANGUAGE
Total Wei 1.5 kg
Frame Size 450 mm
Altitude 200 m
Air Temperature 25 °C
Aero Design medium
Min. Battery Capacity 15%
Max. Takeoff Throttle 85%
FCU Max. Tilt Limit No Limit
FCU & Attaches Current 0.5 A
Motor Brand: JFRC
Model: U2810 KV900
Propeller Brand APC
Model: 12x3.8SF
MultiCopter Mass : m = 1.5 kg
Acceleration of Gravity : g = 9.8 m/s²
MultiCopter Inertia Matrix J=diag(Jxx, Jyy, Jzz) : Jxx = 1.331e-2 kg.m², Jyy = 1.331e-2 kg.m², Jzz = 2.542e-2 kg.m²
Distance of Motor to Center : d = 0.225 m
Propeller Integrated Thrust Coef. by Thrust (N) Dividing Speed² (rad/s), i.e. (Ct=Tp/ω²) : Ct = 1.758e-5 N/(rad/s)²
Propeller Integrated Moment Coef. by Moment (N.m) Dividing Speed² (rad/s), i.e. (Cm=Mp/ω²) : Cm = 2.952e-7 N.m/(rad/s)²
Motor Curve: Throttle σ (0~1) to Motor Steady Speed ωss (rad/s) : CR = 673.83 rad/s
(ωss=CR*σ+ωb) : ωb = 173.8 rad/s
Motor-Propeller Inertia : Jm = 1.19e-4 kg.m²
Motor Response Time Constant : Tm = 0.0127 s
Air-Drag Coef. by Drag (N) dividing fly-speed² (m/s), i.e. (Cd=D/V²) : Cd = 6.579e-2 N/(m/s)²
Air-Torque Coef. by Torque (N.m) dividing rotation-speed² (rad/s), i.e. (Cdm=M/w²) : Cdm = 9.012e-3 N.m/(rad/s)²

Course Design

- Experiment Step Design







Course Design

- Experiment Step Design

Basic Experiment

Open the given code example. Then, read and run its source code directly to observe and record the results.

Analysis Experiment

Modify the given code example. Then, run the modified example program to collect and analyze the data.

Design Experiment

Based on the above two experiments, complete the given design task independently.

Course Design

All codes are implemented in real flight tests

Manual Mode Switch

Failsafe

Course Design

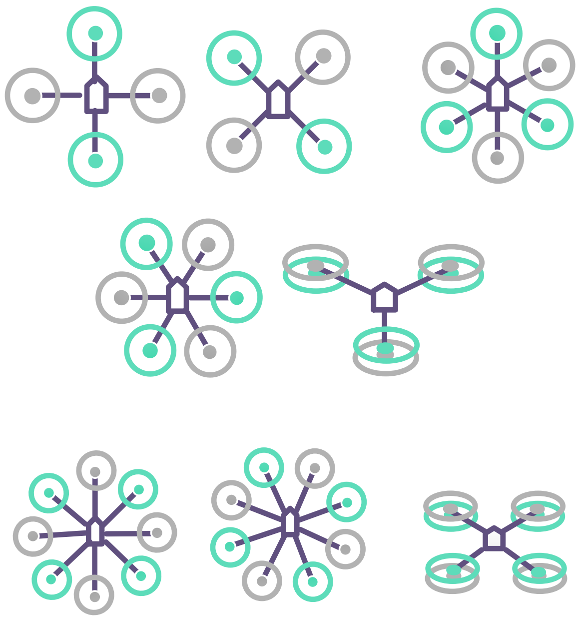
Table. Experimental types, projects and content

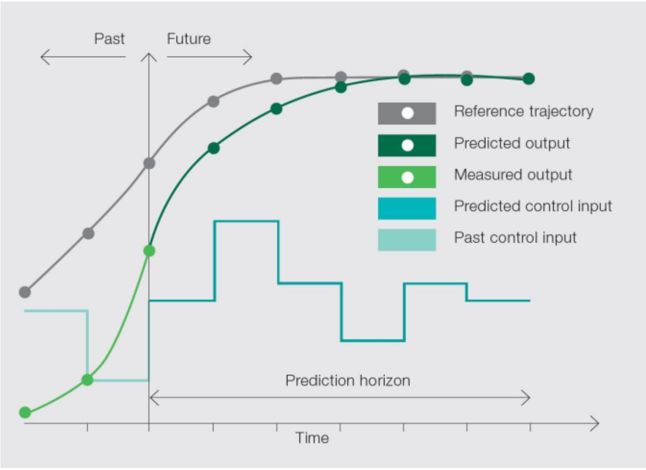
Project	Basic experiment	Analysis experiment	Design experiment
Development platform	✓	✓	✓
Analysis process	×	✓	✓
Design methods	×	×	✓
SIL simulation	✓	✓	✓
HIL simulation	✓	✓	✓
Flight tests	✓	✓	✓

Course Design

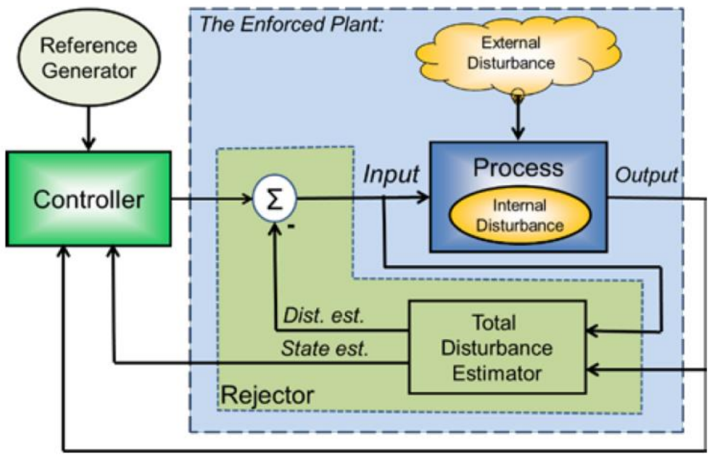
■ Teaching Design

- Modifying the goals in the propulsion system design and modeling experiments
- Different progressive studying routes and opening new experiments





Predictive control



Active disturbance rejection control

Conclusions

No.	Questions
Q1	Given a payload and flight endurance requirements, how design a multicopter prolusion system?
Q2	Given a Pixhawk autopilot, how calibrate its accelerometer and magnetometer and how design the filter to estimate the state?
Q3	Based on the designed multicopter prolusion system and airframe configuration, how establish a multicopter dynamical model?
Q4	Based on the dynamical model established, how design a motor controller, a control allocator and an attitude controller?
Q5	Based on the designed attitude controller, how design a set-position controller?
Q6	Based on the designed an attitude controller and set-position controller, how design a semi-autonomous controller?
Q7	Based on the semi-autonomous controller, how design a fail-safe logic for the designed multicopter?
Q8	Given a new algorithm, how to realize it by the model-based design?
Q9	How new functions are developed based on the platform, such as health evaluation or vision-based autonomous flight?
Q10	Given a group of engineers, how to organize them effectively?

Thank you!