Model of Collaborative UAV Swarm Towards Coordination and Control Mechanisms Study

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Introduction

UAV term

An unmanned aerial vehicle (UAV), known in the mainstream as a drone and also referred to as an unpiloted aerial vehicle and a remotely piloted aircraft (RPA) by the International Civil Aviation Organization (ICAO), is ***an aircraft without a human pilot aboard***.

Introduction

UAV applications

Modern Technology Make it:

1. Cheaper;
2. Easier & Faster to Deploy;
3. smaller and flexible.

Disaster

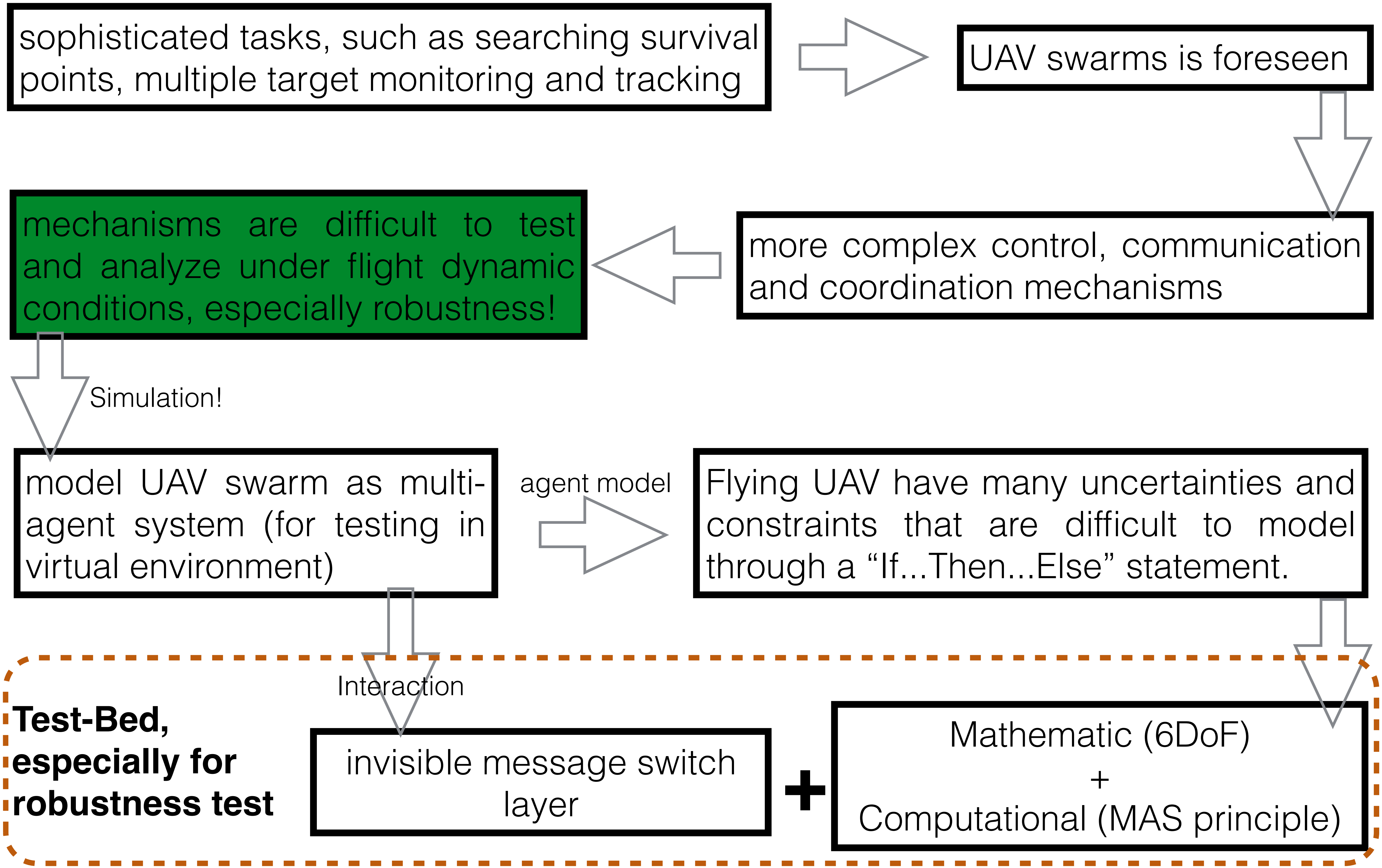
Delivery

UAV Civilian Applications:

1. Disaster management;
2. Remote area surveillance; and hazardous environment monitoring;
3. Fast package delivery;
4. Aerial photo & video.

Outline

UAV challenges and proposed solution



Study Object

Fixed VS. Rotary

<table>
<tr><th>Fixed-wing</th><th>Rotary-wing</th></tr>
<tr><td>Hand/catapult launched
Long flight endurance, can cover a lot of area
Difficult to fly if not fully automated
Requires fully automated flight features for full usability
Minimal maintenance, modest expenses</td><td>Automated launch
Limited flight endurance
Hover capability -> Precise 3D inspection of stationary objects/ delivery of chemicals
Difficult to fly if not fully automated
Requires fully automated flight features for full usability
Minimal maintenance, modest expenses</td></tr>
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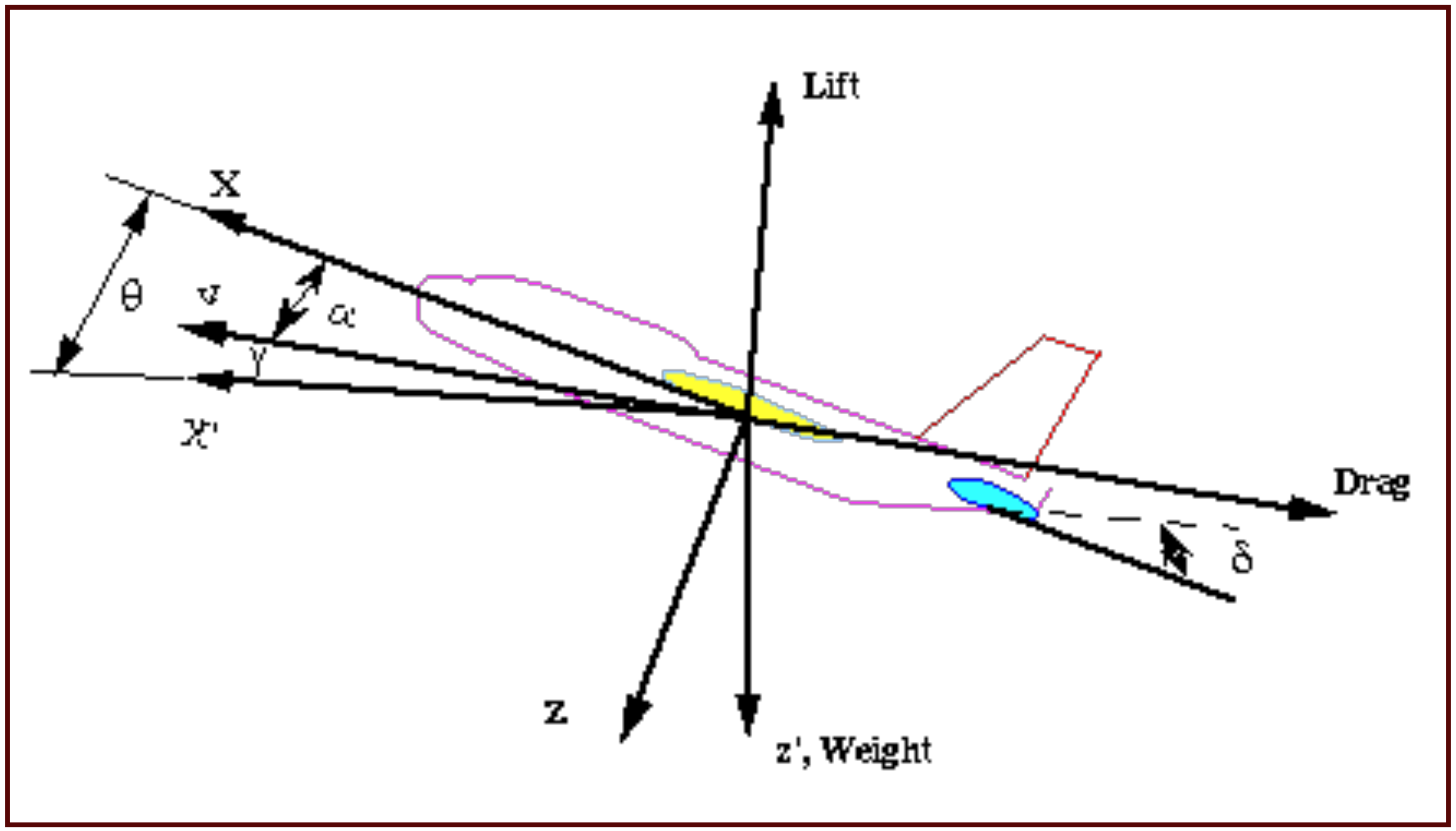
Fixed-wing as an example

(Long flight endurance, can cover a lot of area)



heterogeneous (fixed and rotary) in the future.

the agent model

6DoF - agent model

Flight Dynamic

$$\boxed{F^b_{aero}} = \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} qS, \quad \boxed{M^b_{aero}} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} qSL, \quad q = \frac{1}{2}\rho V^2 \tag{1}$$

$$\begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix} = \boxed{mg_0} \begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \boxed{\begin{bmatrix} P \\ 0 \\ 0 \end{bmatrix}} \tag{2}$$

$$\text{e.g.,} \quad C_z = f\left(V, \alpha, \delta_y\right) = C_{z_0} + C_z^{\alpha} \cdot \alpha + C_z^{\delta_y} \cdot \delta_y \tag{3}$$

Where:

C_{z0} is the lift coefficient when both α and δ_z are equal to zero (the zero lift coefficient).

C_z^{α} and $C_z^{\delta_y}$ are related with velocity, write as: $C_z^{\alpha} = f\left(V\right)$, $C_z^{\alpha} = f^{'}\left(V\right)$.

6DoF - agent model

Parameters for Flight Dynamic Model

Table 1: List of aerodynamic data needed to model an UAV

Notation	Definition
m, I	The mass and moment of inertia of the rigid body.
S	Sum of wing area.
L	The chord length.
$\boldsymbol{C}^{\delta_z}_{x,y,z}$-$V$	The drag/side/lift force coefficient derivative due to corresponding horizontal tailplane to velocity.
$\boldsymbol{C}^{\alpha}_{x,y,z}$-$V$	The drag/side/lift force coefficient derivative due to angle of attack to velocity.
$\boldsymbol{C}_{(x,y,z)_0}$	The zero drag/side/lift force coefficient.
$\boldsymbol{m}^{\delta_z}_{x,y,z}$-$V$	The roll/pitch/yaw moment coefficient derivative due to corresponding horizontal tailplane to velocity.
$\boldsymbol{m}^{\alpha}_{x,y,z}$-$V$	The roll/pitch/yaw coefficient derivative due to angle of attack to velocity.
$\boldsymbol{m}_{(x,y,z)_0}$	The zero roll/pitch/yaw moment coefficient.

Physical Parameters

Aerodynamic Force Coefficient

Moment Coefficient

6DoF - agent model

Kinematic - Agent State Transition

$$\overset{O}{\boxed{\dot{V}_b}} = \frac{1}{m}\overset{I}{\boxed{\begin{bmatrix} F_{xb} \\ F_{yb} \\ F_{zb} \end{bmatrix}}} + V_b \times \omega, \quad \omega = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{1}$$

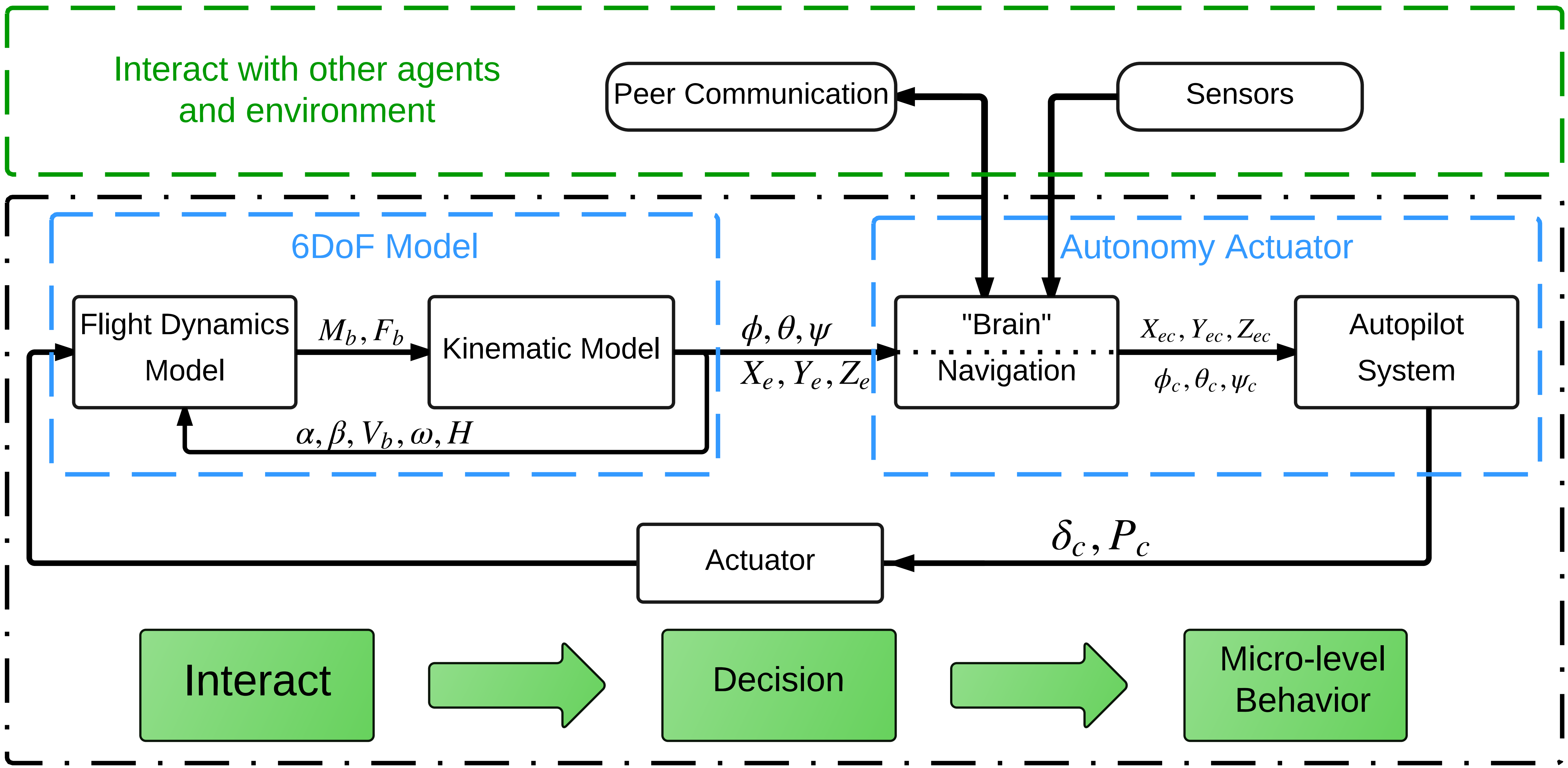
$$\dot{\omega} = I^{-1}\left(\overset{I}{\boxed{\begin{bmatrix} M_{xb} \\ M_{yb} \\ M_{zb} \end{bmatrix}}} + (I\omega) \times \omega\right), \quad I = \begin{pmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{pmatrix} \tag{2}$$

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \dot{\varphi} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} = J^{-1} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{3}$$

$$\overset{O}{\boxed{\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}}} = J \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & (\sin\varphi\tan\theta) & (\cos\varphi\tan\theta) \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & (\sin\varphi\sec\theta) & (\cos\varphi\sec\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{4}$$

$$\overset{O}{\boxed{\alpha}} = \arctan\frac{V_{zb}}{V_{xb}}, \quad \overset{O}{\boxed{\beta}} = \arcsin\frac{V_{by}}{\sqrt{{V_{xb}}^2 + {V_{yb}}^2 + {V_{zb}}^2}} \tag{5}$$

Model Concept of UAV as an Agent



Model an unmanned aerial vehicle as autonomous agent. The sensors and communication devices give it possible to **interact** with companions and environment. The 6 degree-of-freedom (6DoF) flight dynamic model reflects **constraints** and **uncertainties** as well as **state transition**.

Communication amongst UAVs

(base of interaction)

Communication amongst UAVs

(crucial for agents to coordinate properly)

Communication Mode / Media

Direct	In-direct
• WiFi, ZigBee, Bluetooth etc; • low power consumption, less latency, free of charge, etc; • without support base station; • distance restriction.	• GSM, Satellite etc; • high power consumption, long latency, pay by bytes; • with ground support base station; • almost no distance restriction.

Proper combination could be better;
communication ways should be carefully considered;

Interaction message amongst UAVs

message types	description
broadcast	an agent share its current state to a set of agents **actively**;
query	an agent send a message to **a set of agents** to request their states;
sync	an agent (e.g. group leader) send a ***sync*** request message to **a group of agents**, then all the agents who receive the sync request will broadcast their current state to **all the** other group members.

As for implementation, we implemented a **message switch layer** (MSL) work in an **observer** role (not exist in real situation, only for implementation, all information about simulation world is accessible by observer), all the communication amongst UAVs will pass through this layer and MSL will record all these messages for post-simulation analysis. This provides a flexible way for control mechanism designer to optimize the communication policies in micro-level behavior.

A proof-of-concept Case Study

Demo. Application

Environment Model:

$$z(x,y) = \sum_{i=1}^{n} h_i * exp\left(-\left(\frac{x - c_{x_i}}{g_{x_i}}\right)^2 - \left(\frac{y - c_{y_i}}{g_{y_i}}\right)^2 \right)$$

z is the altitude of the given coordinate (x, y) in the simulated terrain.

n is the number of peaks (mountains).

Where:

h_i controls height of peak i;
c_{x_i} and c_{y_i} mark central position of peak i;
g_{x_i} and g_{y_i} control peak gradient in x and y orientation respectively.

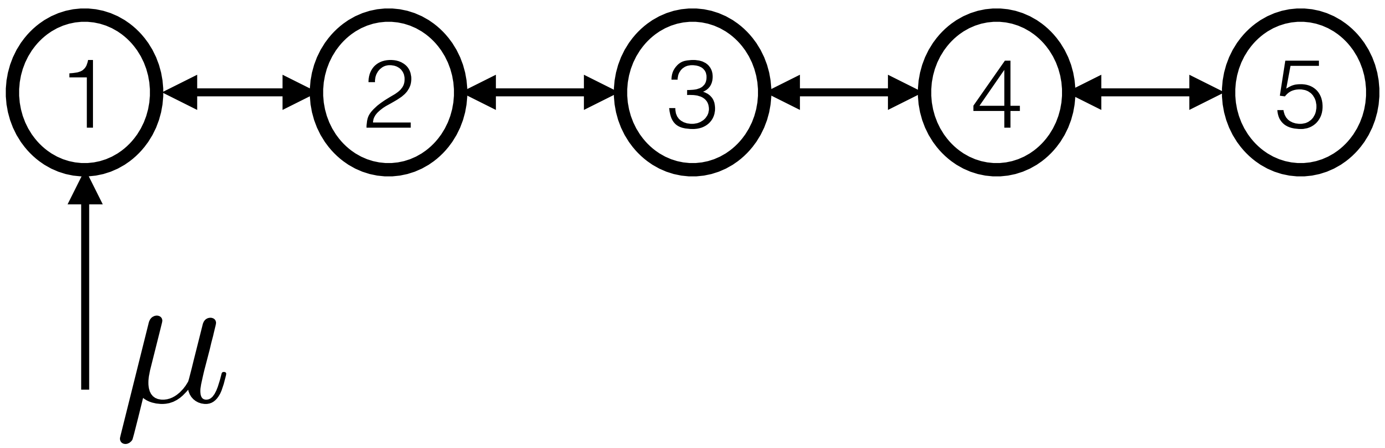
Demo. Application

Simulating Conditions

1. a mountain area of size $10 \times 20km^2$;
2. Five UAVs "**scan**" the area on preset height (100 meters over ground);
3. distance between two neighboring UAVs should be kept as **500 meters** (due to the restriction of sensor, e.g., camera)**;**
4. vehicles are set to fly with their curing **speed** (35 m/s) to save power consumption.

Demo. Application

Swarm Contro Model



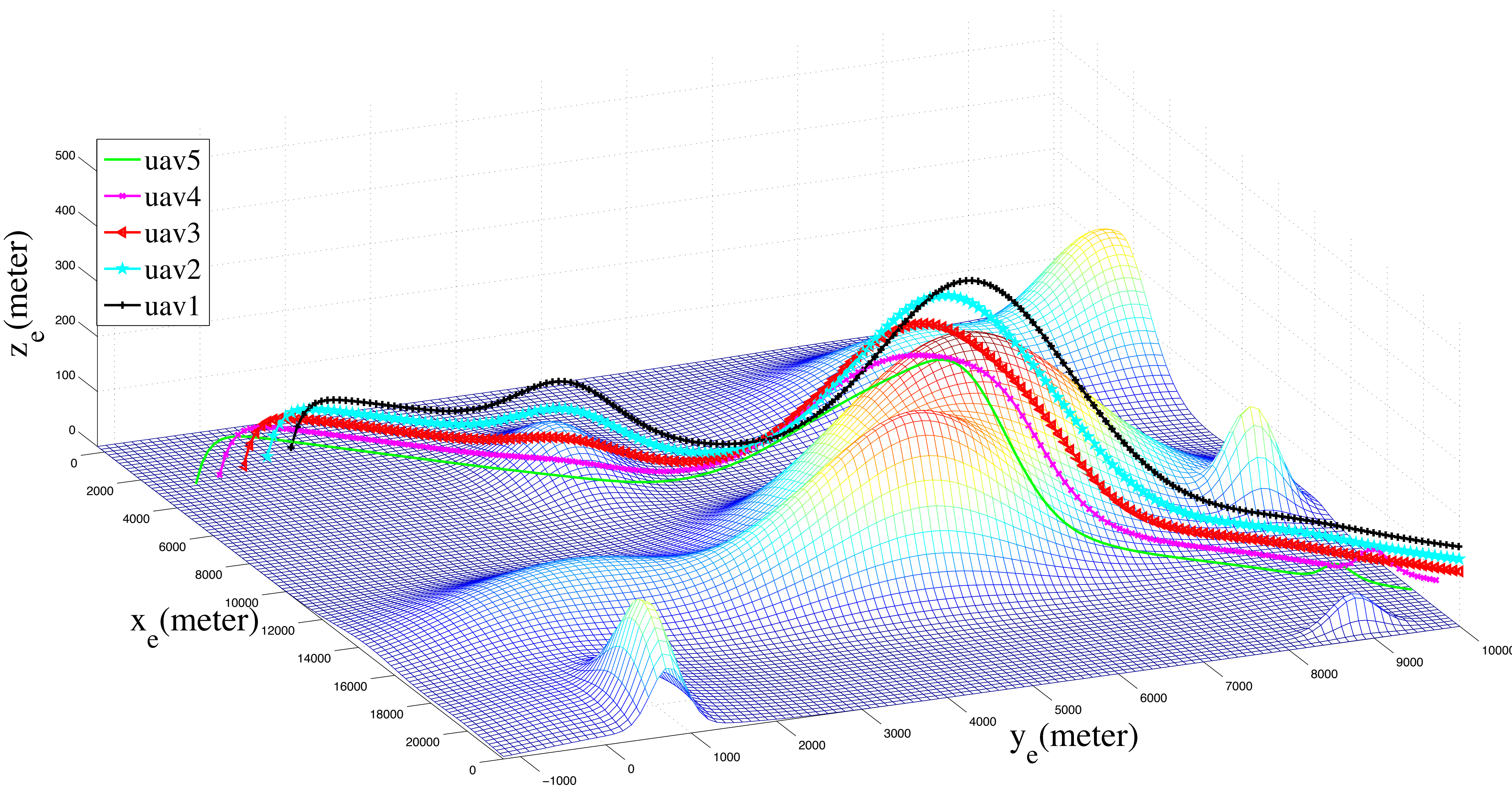
$$\ddot{x} = -L\dot{x} + b\mu$$

$$y = c^T\dot{x}$$

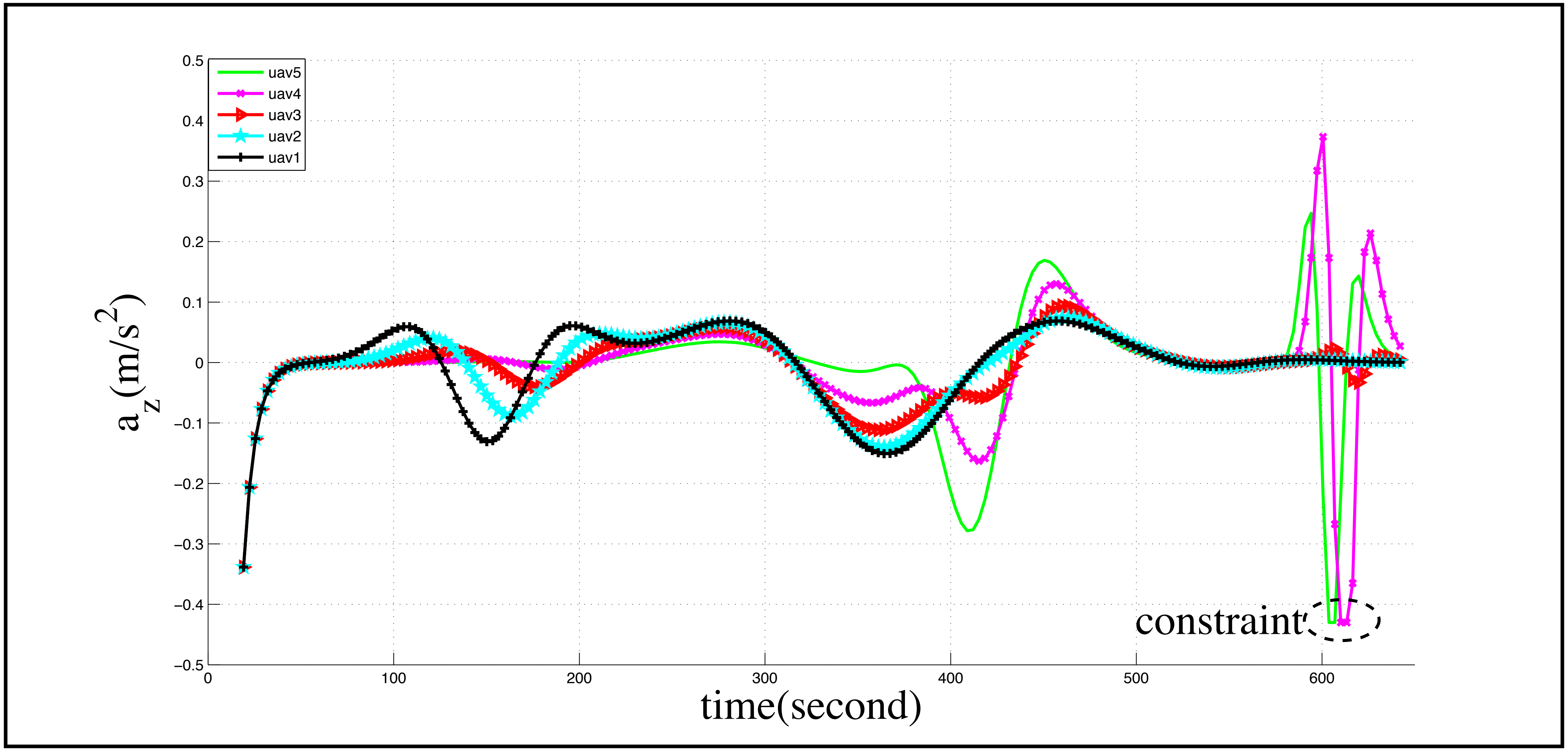
$$\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \\ \ddot{x}_4 \\ \ddot{x}_5 \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 \\ 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \mu$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix}$$

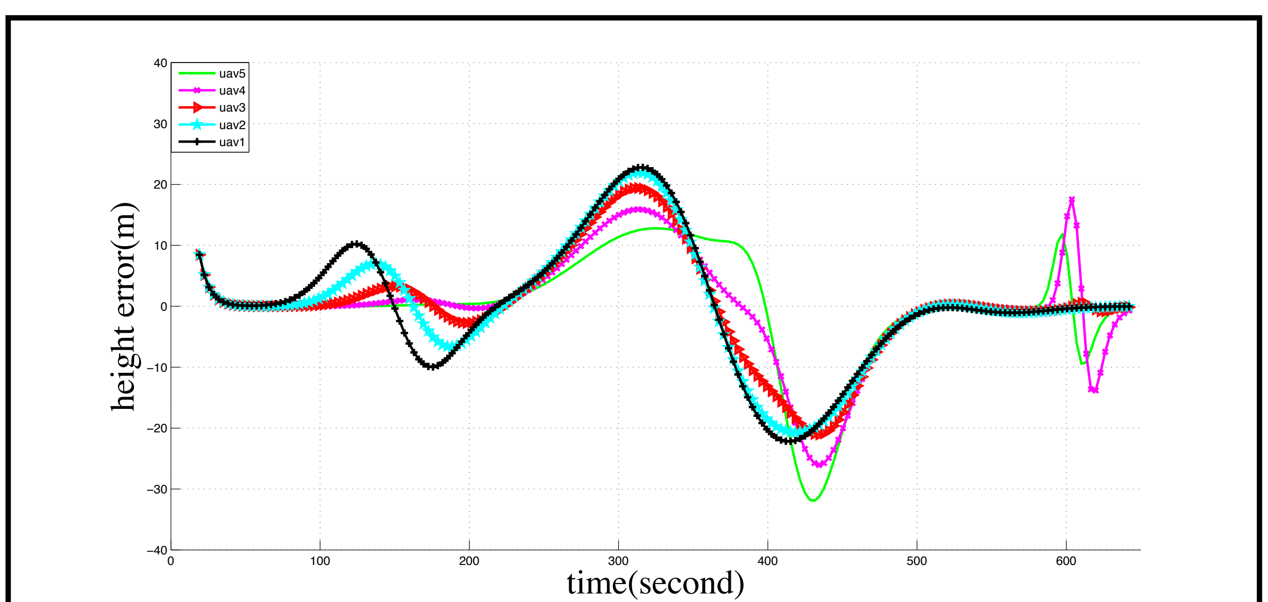
Demo. Application



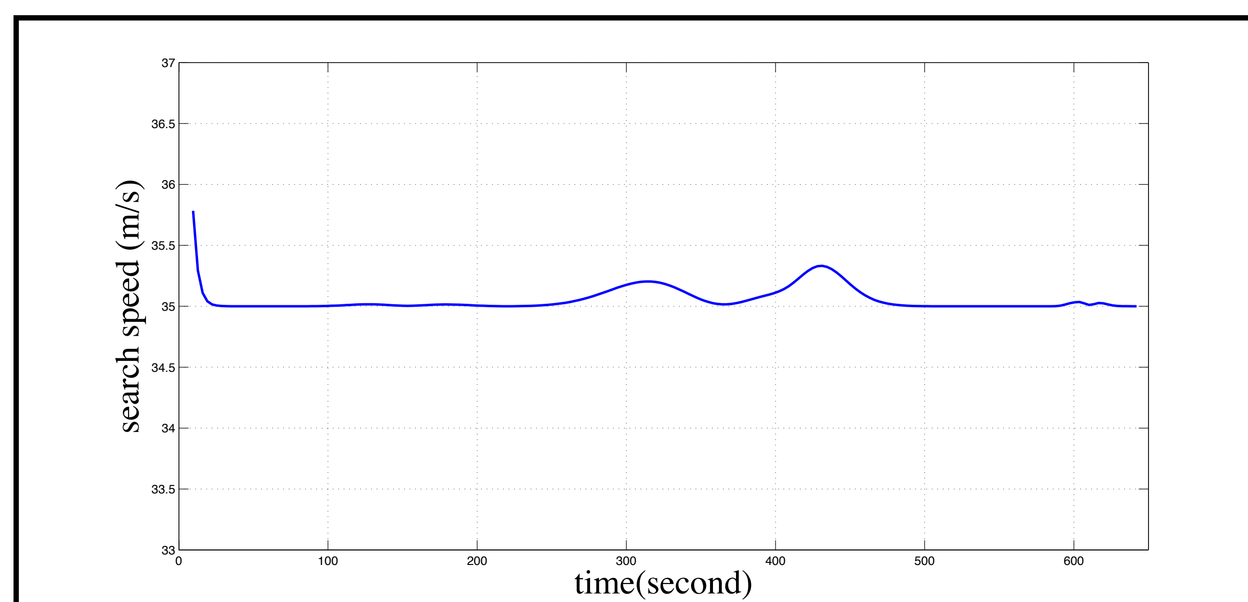
3D View of UAV swarm trajectory



uav5
uav4
uav3
uav2
uav1
$a_z(m/s^2)$
time(second)
constraint



uav5
uav4
uav3
uav2
uav1
height error(m)
time(second)



search speed (m/s)
time(second)

Conclusions and Future work

(Conclusions)

1. This work is a part of a longterm project about intelligent UAV swarm application.
2. Model of UAV swarm;
3. Implemented a prototype in NetLogo3D;
4. one proof-of-concept case study was presented to show its potential usage;

Conclusions and Future work

(future work)

1. in a Netlogo3D world the number of patches grows very quickly that slow the model down or even cause NetLogo to run out of memory. => implement by using Google's Go programming language without concept of patch.

2. **rotary-wing**, such as quadcopter is also widely used in some application. So, we will construct the model of quadcopter in order to provide the ability of building **heterogeneous** UAV swarm.

Thank You Very Much for Your Attention!

Q + A = Progress

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