Construction, Modeling and Automatic Control of a UAV Helicopter

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Outline of This Presentation

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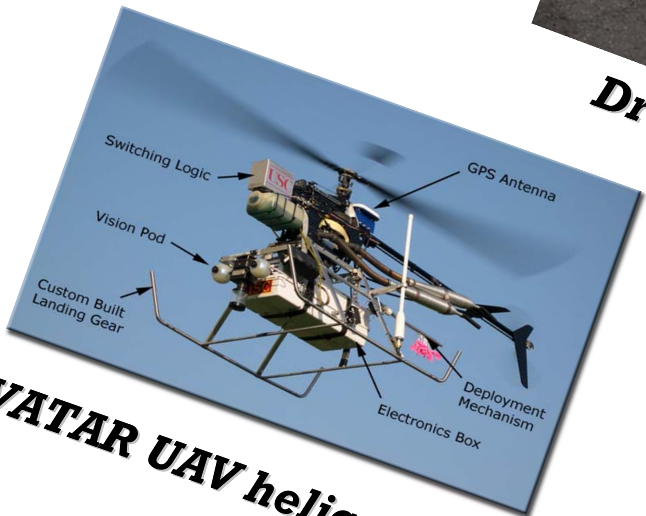
1. Brief introduction to unmanned aerial vehicle (UAV)
2. Hardware construction
3. Ground station software platform
4. Modeling the dynamics of the UAV helicopter
5. Automatic controller design
6. Demonstration of actual test flights
7. Continuing work

Introduction to UAV

- Arouse great interest in both military and civil applications.

Predator

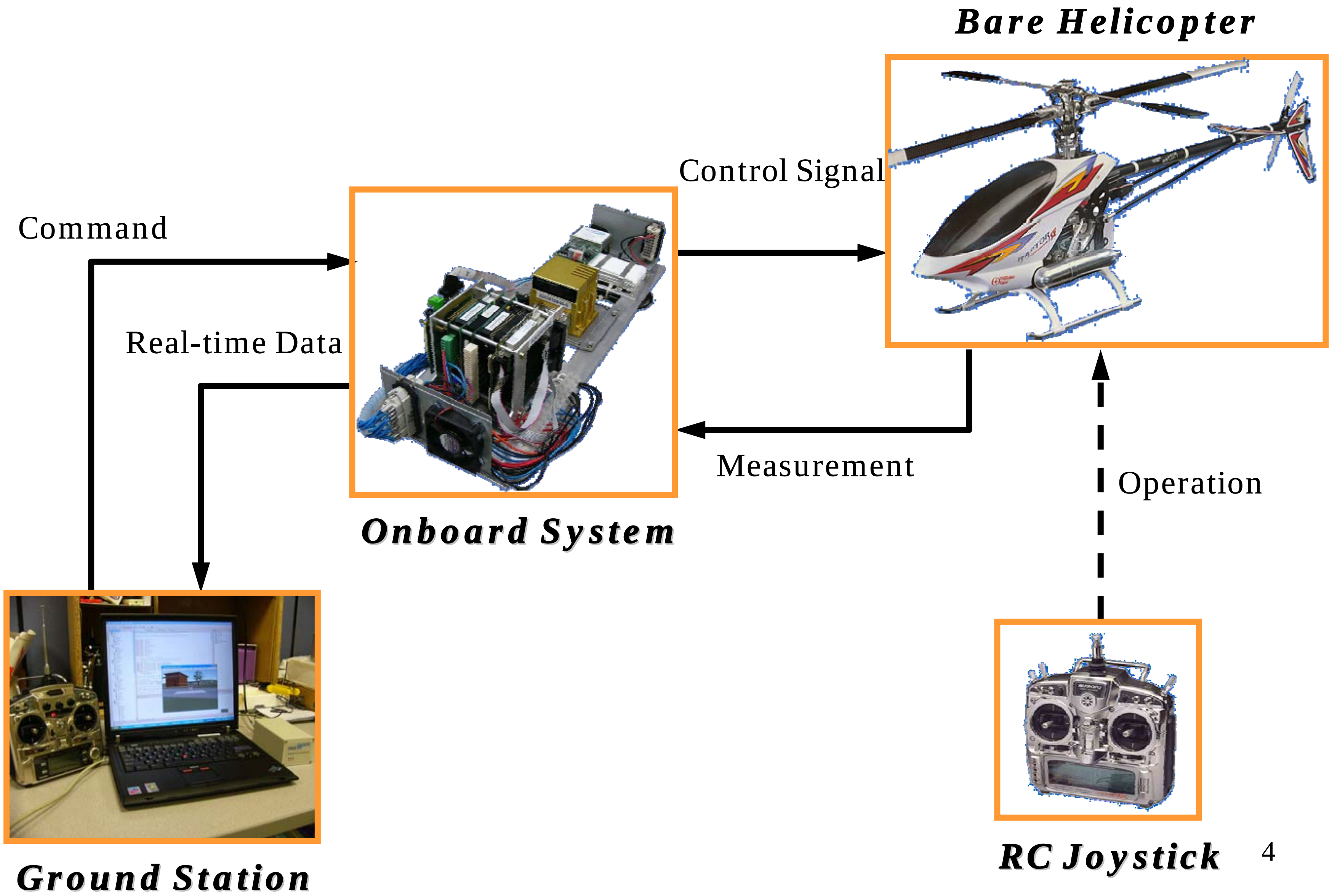
Dragonfly UAV



AVATAR UAV helicopter

- A hot topic in academic community. Many universities have developed their own UAV test beds.

Hardware Construction – HeLion, Home Made UAV Helicopter



Hardware – Bare Helicopter

Raptor 90 SE

Product of Thunder Tiger

Length - 1.41m (55.50")

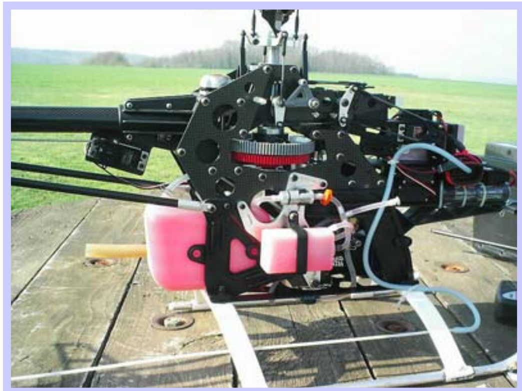
Width - 0.19m (7.50")

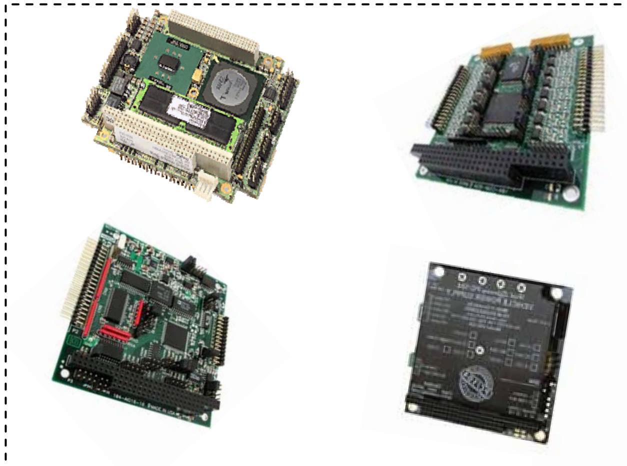
Height - 0.465m (18.25")

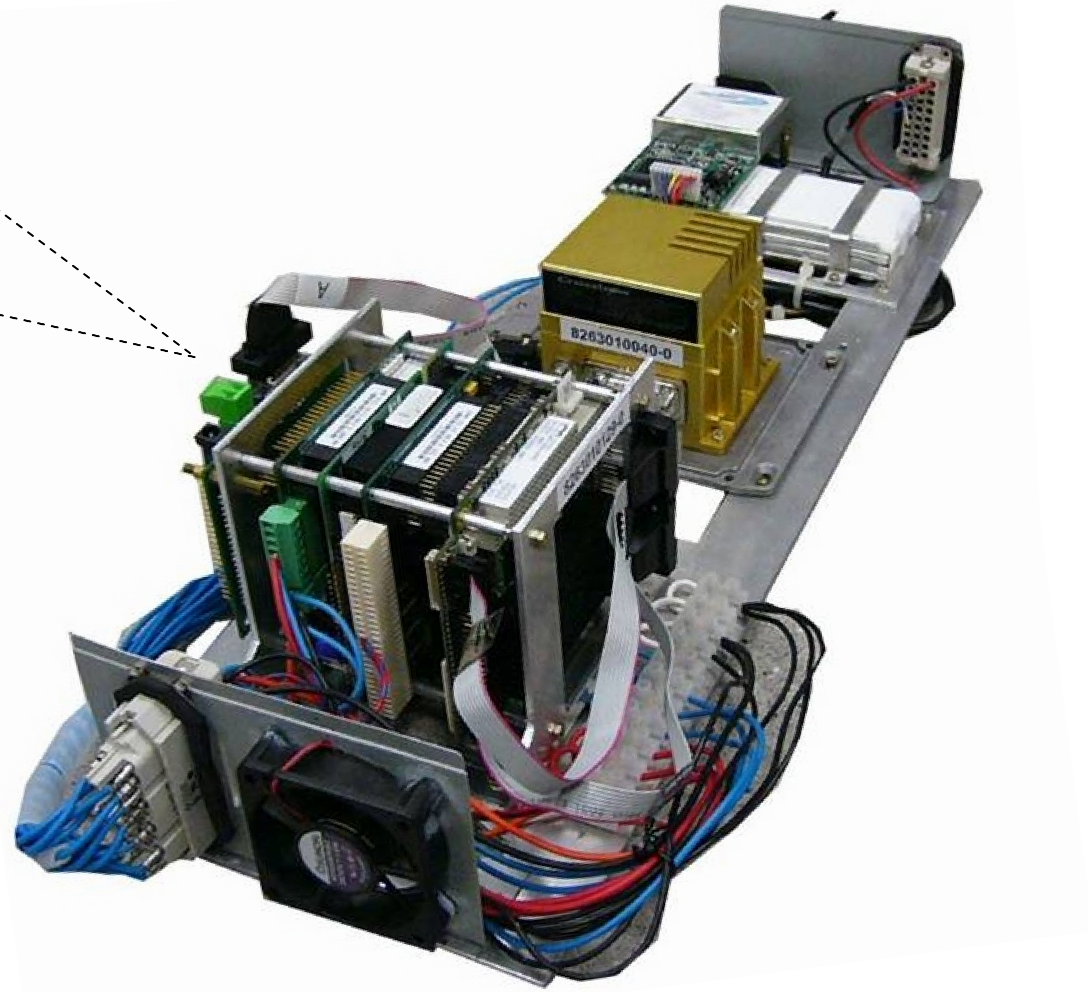
Weight - 4.8kg (10.5 lbs)

Diameter of Main Rotor - 1.64m (64.75")

Diameter of Tail Rotor - 0.26m (10.25")







- **PC-104 computer stack:**

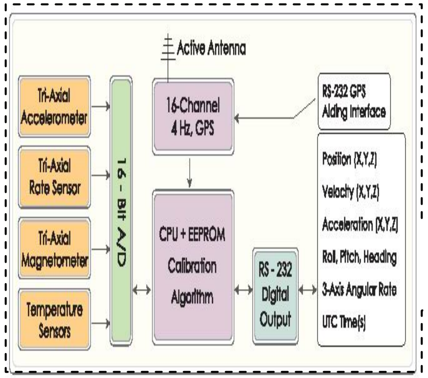
  1). Main processing board

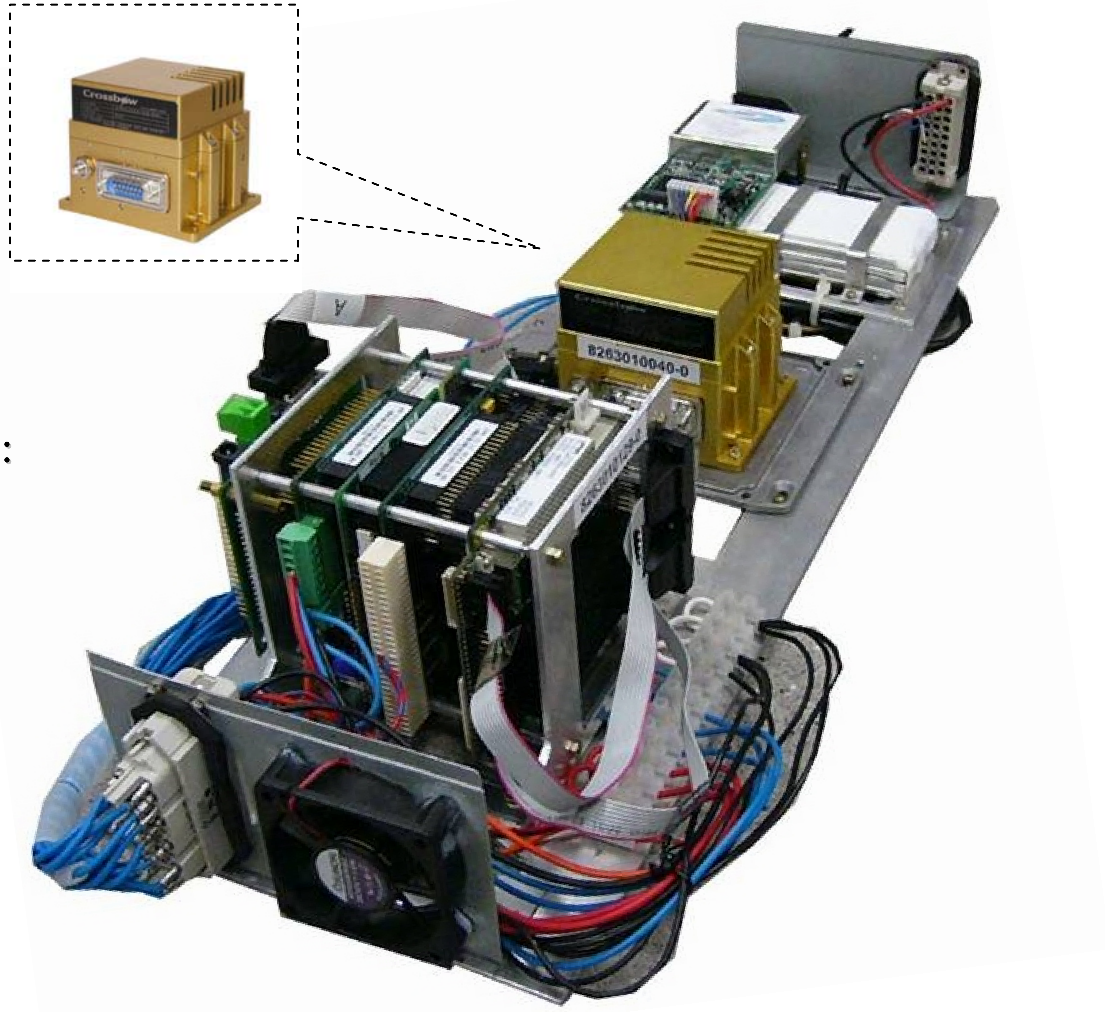
  2). Serial communication board

  3). Data acquisition board

  4). DC-to-DC converter board

Hardware – Inertial Measurement Unit (IMU)





- **IMU** (Inertial Measurement Unit):
  Most important sensor in HeLion, collecting in-flight data including:

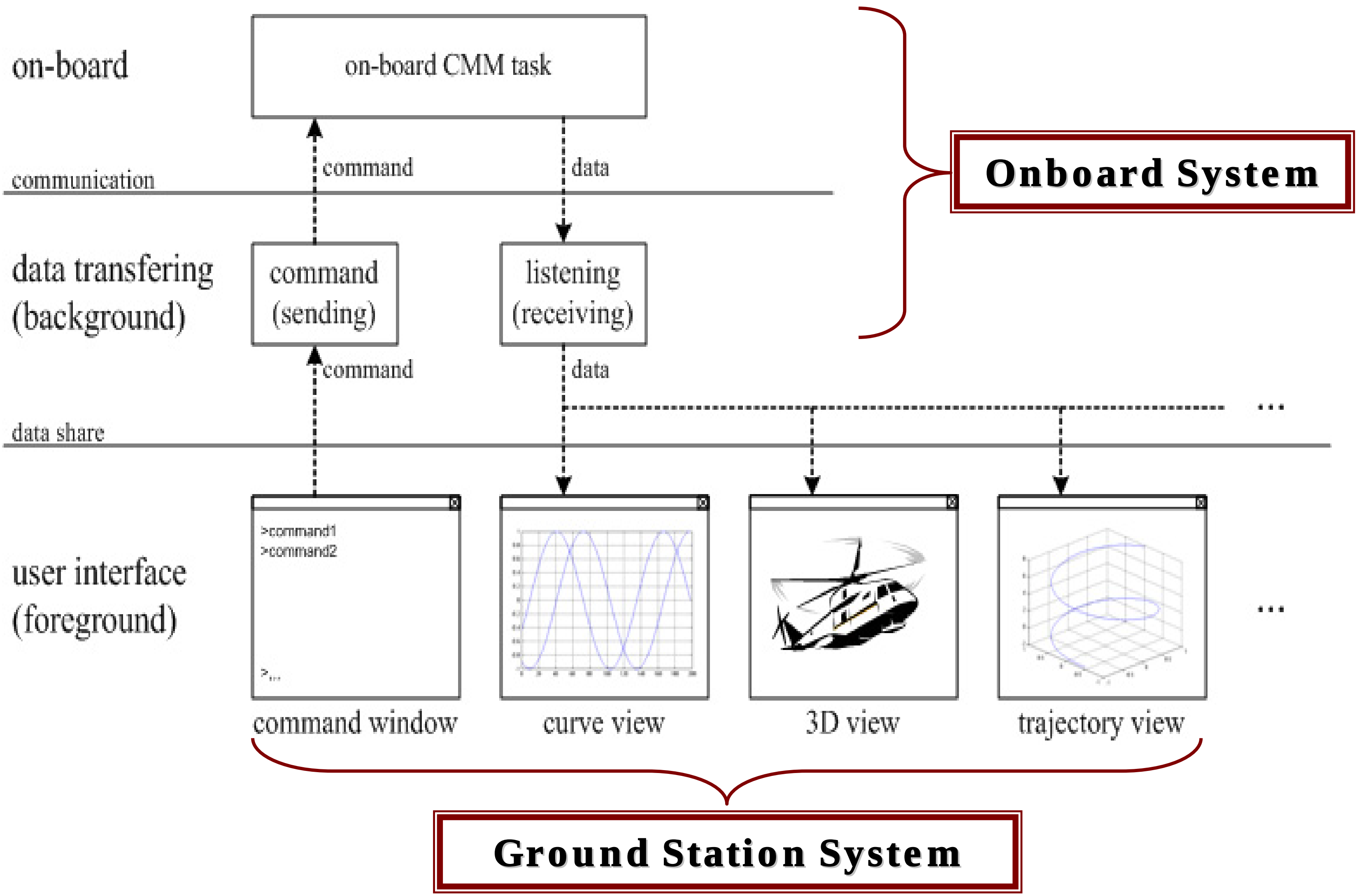
  1). Accelerations & velocities

  2). Rotating angles

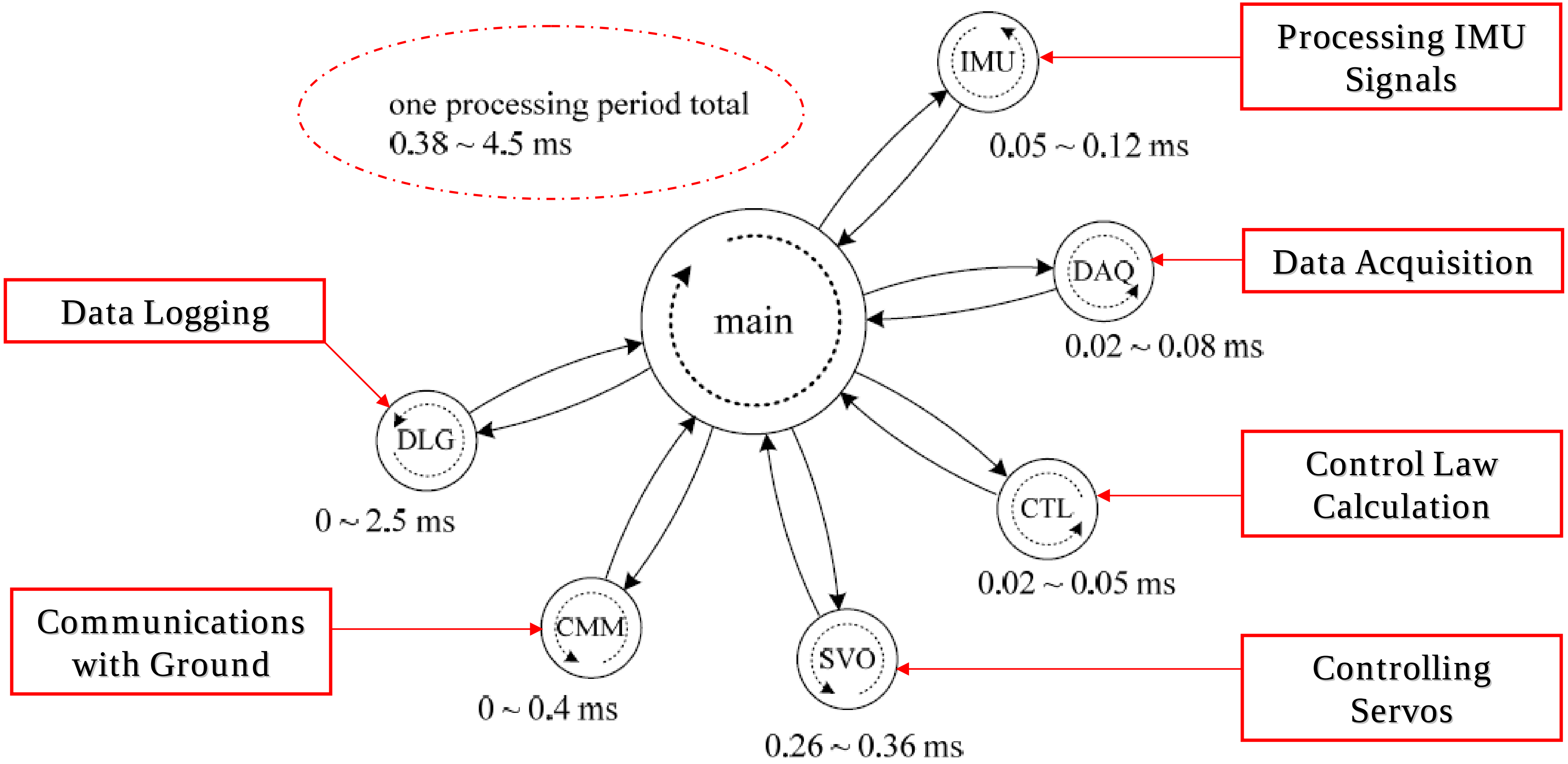
  3). Heading angles

  4). 3D-GPS signals

Software System Structure



An Onboard System Execution Cycle:



Ground Station Software Interface

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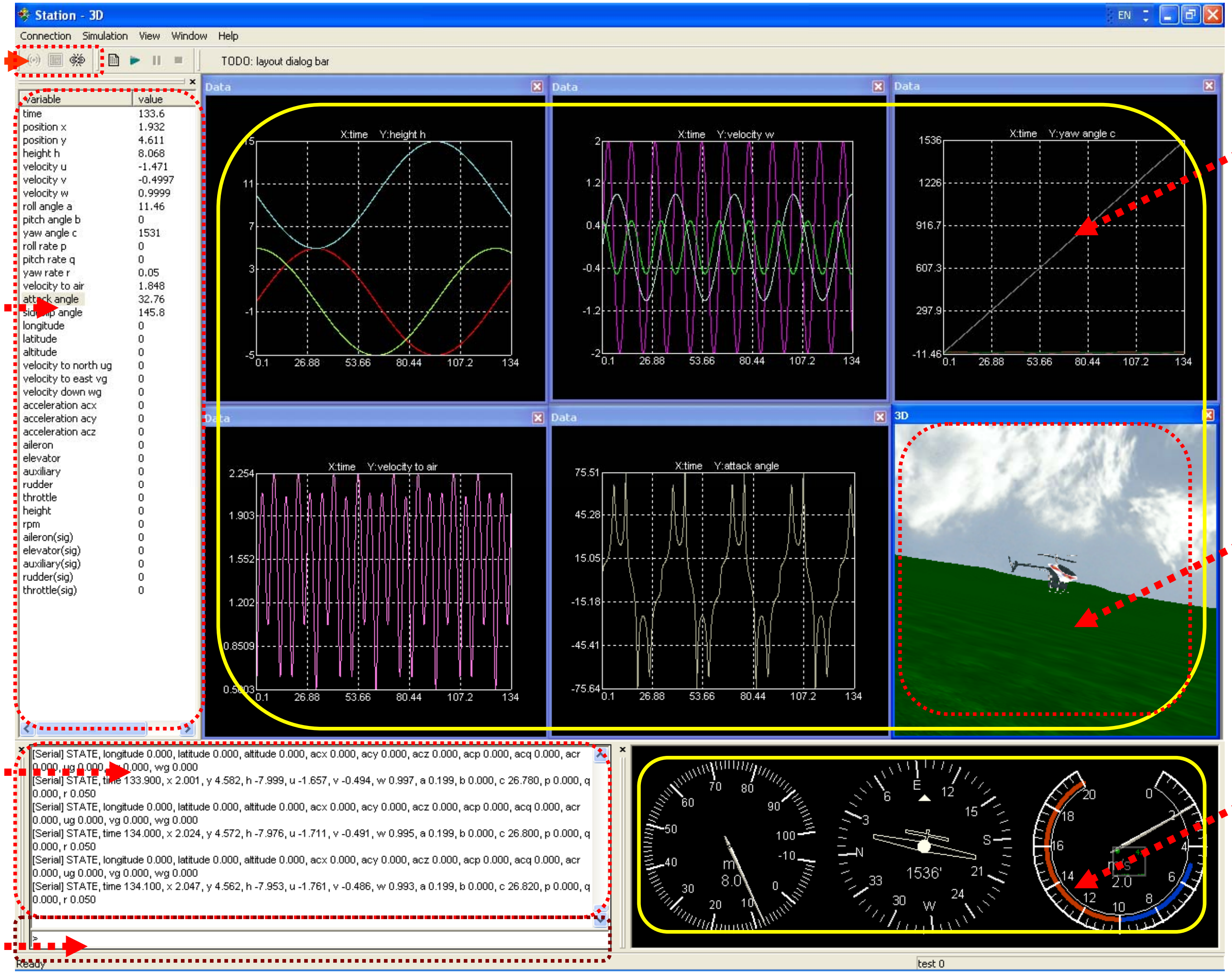
Connection Button

Optional Data Display

Online Data Display

Command Window



Graphical Display

3D View

Gauge View

Ground Station Software – 3D View

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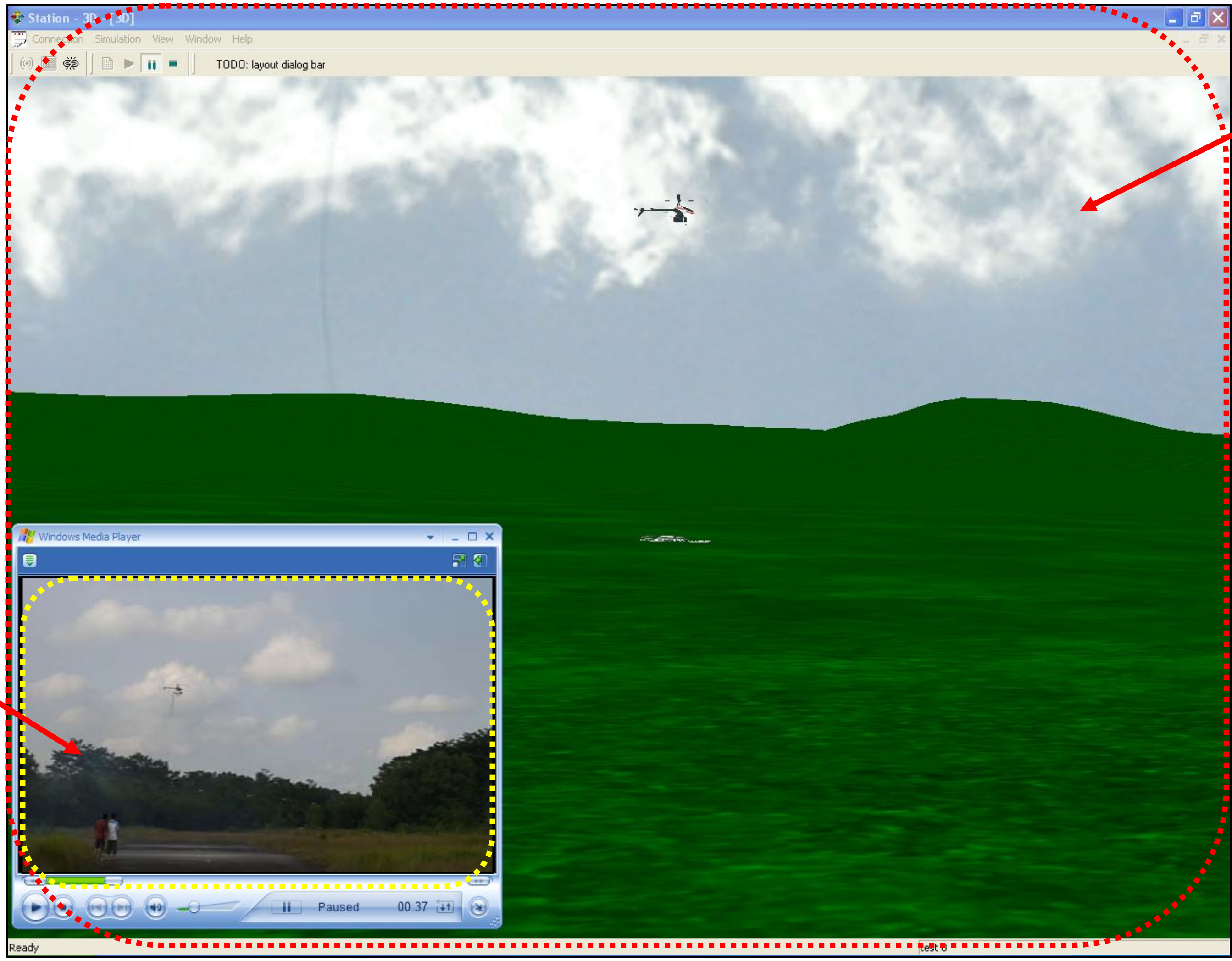
3D View



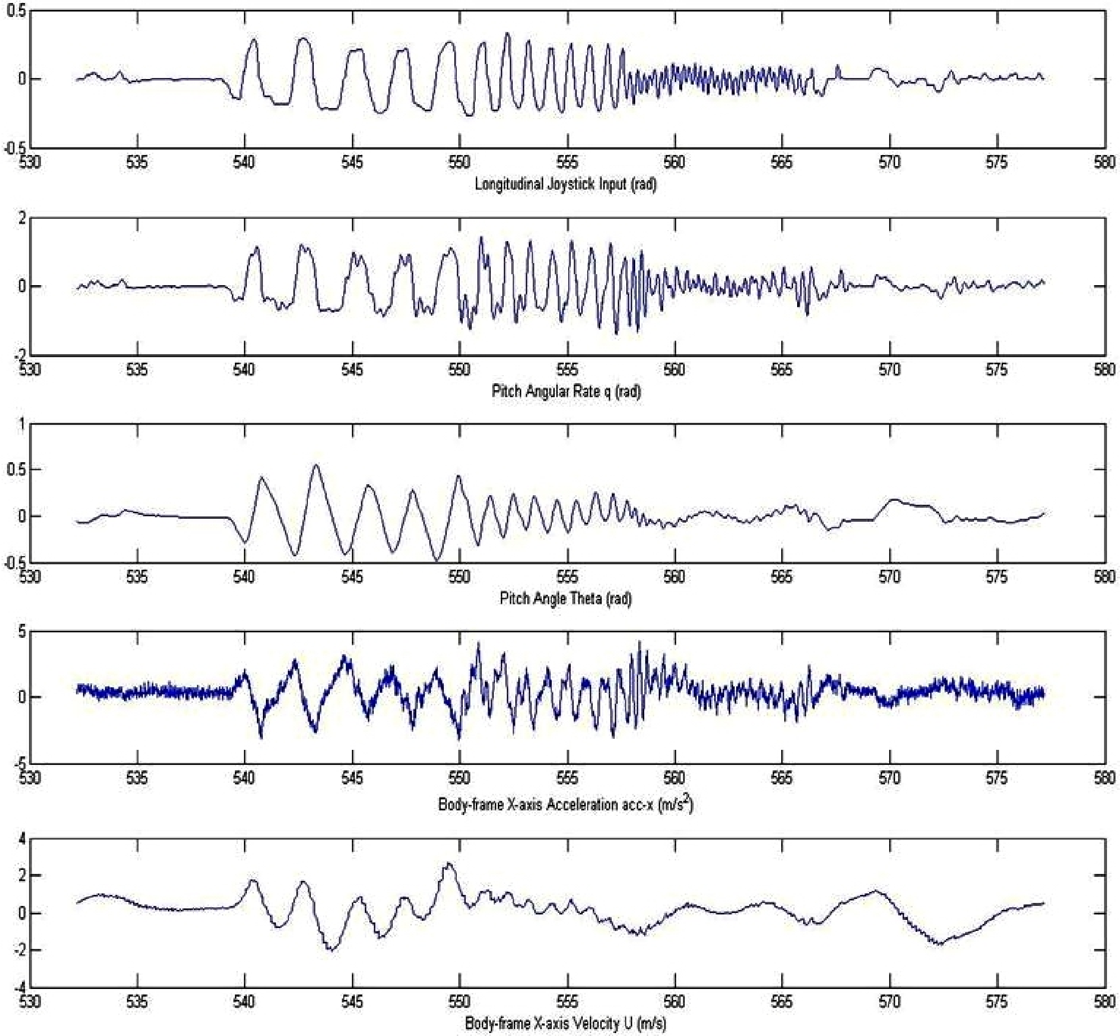
Real Fly

Data Collection Procedure

1). Chirp-like signal issued in single channel;

2). Chirp-like signal issued in multi-channels;

3). Step-like and random signals issued for validation.



Chirp-like signal and corresponding responses

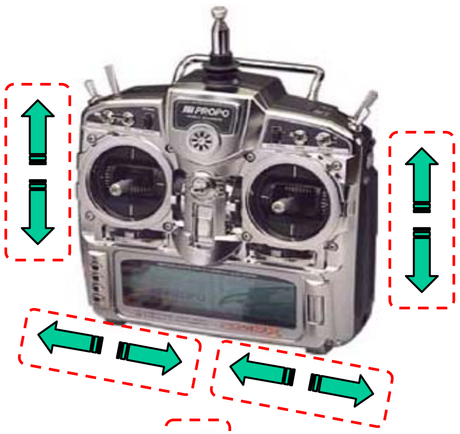
Modeling – Test Flights

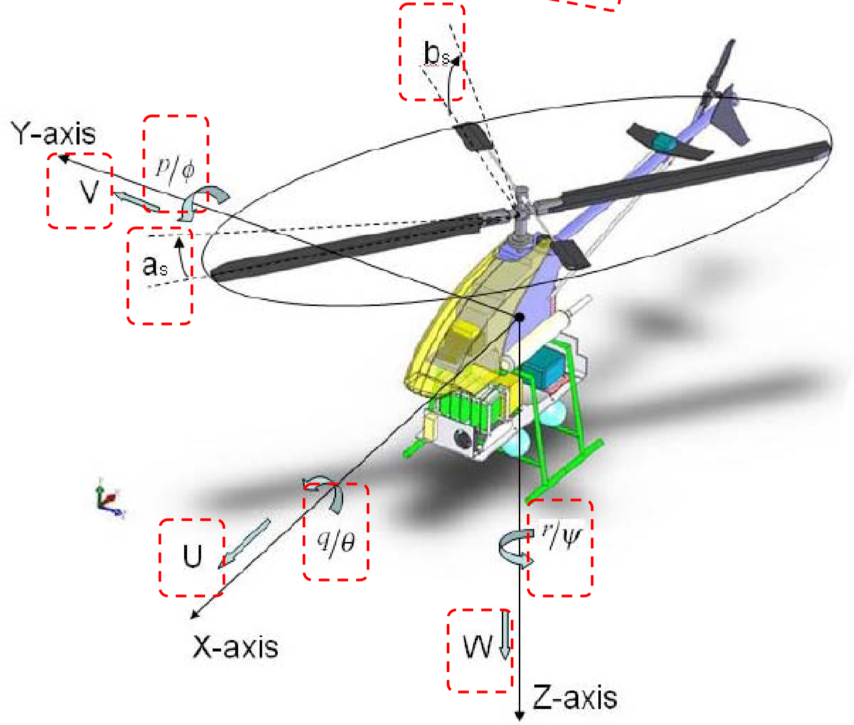
Flight testing for modeling purpose

Hover Model of HeLion

$$\dot{x} = Ax + Bu$$

$$
= \begin{bmatrix}
X_U & 0 & 0 & 0 & 0 & -g & X_{a_s} & 0 & 0 & 0 & 0 \\
0 & Y_V & 0 & 0 & g & 0 & 0 & Y_{b_s} & 0 & 0 & 0 \\
L_U & L_V & 0 & 0 & 0 & 0 & L_{a_s} & L_{b_s} & 0 & 0 & 0 \\
M_U & M_V & 0 & 0 & 0 & 0 & M_{a_s} & M_{b_s} & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & -1/\tau_f & A_{b_s} & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & B_{a_s} & -1/\tau_f & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & Z_{a_s} & Z_{b_s} & Z_w & Z_r & 0 \\
0 & 0 & N_p & 0 & 0 & 0 & 0 & 0 & N_w & N_r & -N_{ped} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_r & -K_{r_{fb}}
\end{bmatrix}
\begin{bmatrix} U \\ V \\ p \\ q \\ \phi \\ \theta \\ a_s \\ b_s \\ W \\ r \\ r_{fb} \end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
A_{lati} & A_{longi} & 0 & 0 \\
B_{lati} & B_{longi} & 0 & 0 \\
0 & 0 & Z_{col} & 0 \\
0 & 0 & N_{col} & N_{ped} \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \delta_{lati} \\ \delta_{longi} \\ \delta_{col} \\ \delta_{ped} \end{bmatrix}
$$





- **Parameter Identification:**

1). Angular rate dynamics; 2). Horizontal velocity dynamics;

3). Yaw dynamics; 4). Heave dynamics.

$$A=\begin{bmatrix} -0.489 & 0 & 0 & 0 & 0 & -9.78 & -9.78 & 0 & 0 & 0 & 0 \\ 0 & -0.524 & 0 & 0 & 9.78 & 0 & 0 & 9.78 & 0 & 0 & 0 \\ -1.491 & -0.427 & 0 & 0 & 0 & 0 & 51.08 & 360.24 & 0 & 0 & 0 \\ -0.096 & -0.543 & 0 & 0 & 0 & 0 & 172.45 & -58.87 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -7.31 & 4.902 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0.891 & -7.31 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.052 & 9.779 & -0.541 & -0.131 & 0 \\ 0 & 0 & -0.283 & 0 & 0 & 0 & 0 & 0 & -0.144 & -5.556 & -36.674 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.749 & -11.112 \end{bmatrix}$$

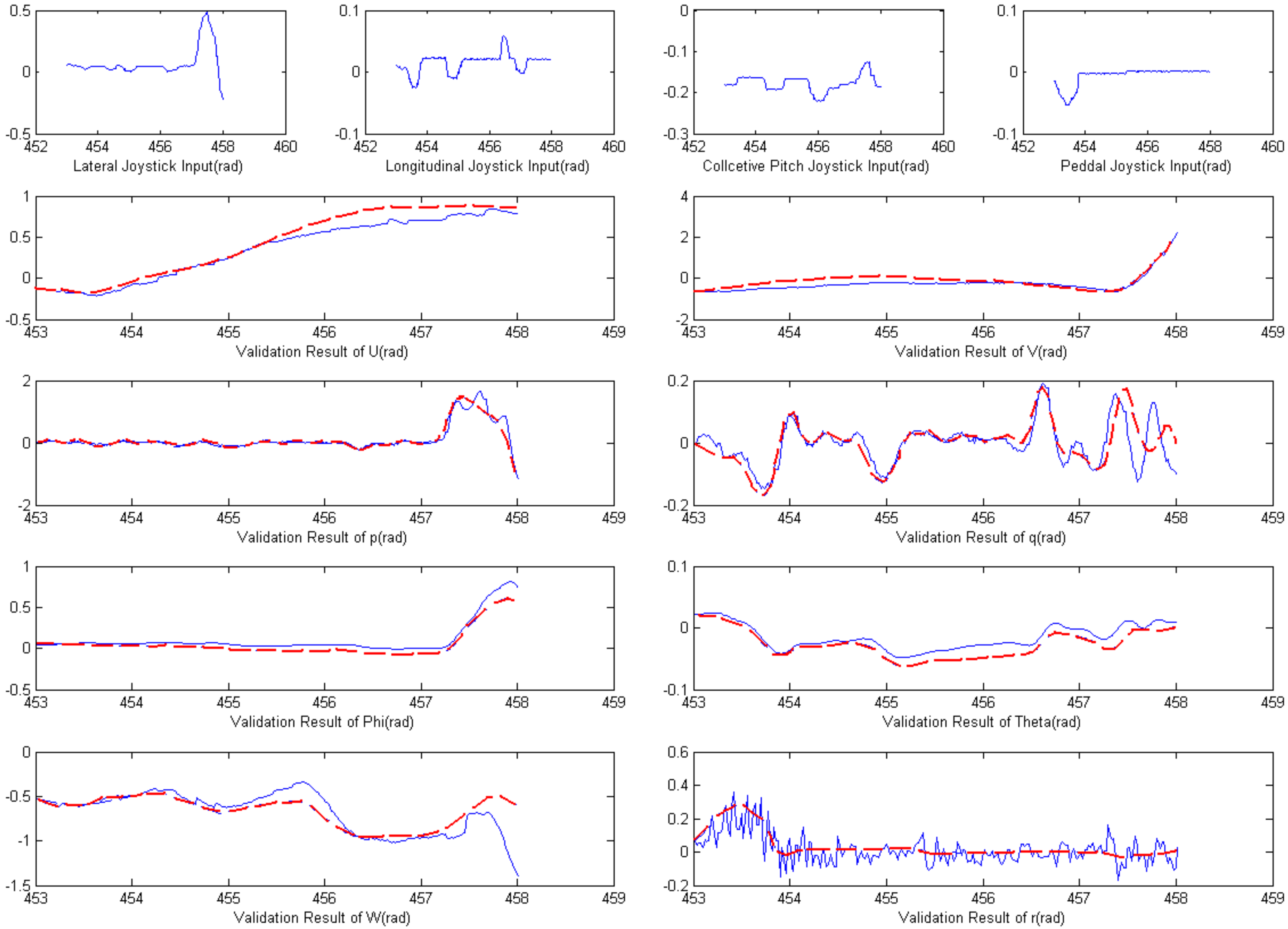
$$B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.022 & 3.314 & 0 & 0 \\ 3.121 & 0.365 & 0 & 0 \\ 0 & 0 & 20.033 & 0 \\ 0 & 0 & 2.081 & -74.364 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

- **Validation for the identified Model:**

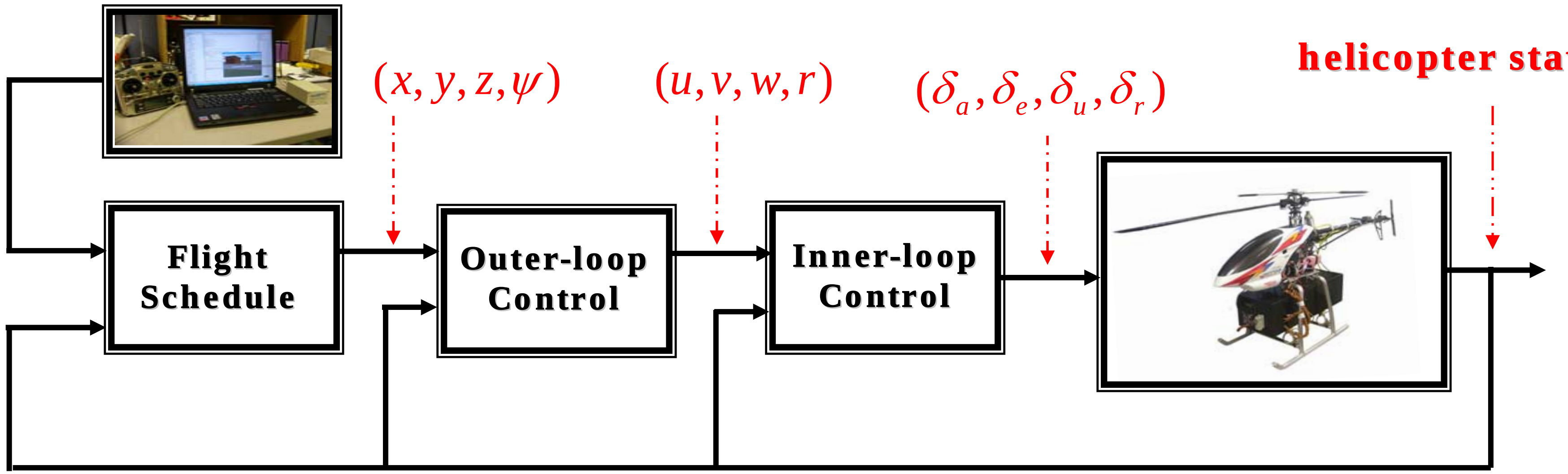
Eigenvalue	Damping Ratio and Natural Frequency	Mode Description
$0.1095 \pm 0.3187i$	$\xi = -0.3249, \omega = 0.337(rad/s)$	Unstable, damped, long period oscillatory, phugoid type mode
$-0.6155 \pm 0.3239i$	$\xi = 0.8849, \omega = 0.6955(rad/s)$	Stable Damped, long period oscillatory, phugoid type mode
$-2.8986 \pm 18.2199i$	$\xi = 0.1578, \omega = 18.37(rad/s)$	Short period roll mode
$-4.3865 \pm 13.1964i$	$\xi = 0.3154, \omega = 13.9(rad/s)$	Short period pitch mode
-0.5399		Damped heave mode
$-8.3347 \pm 9.6487i$	$\xi = 0.6523, \omega = 12.78(rad/s)$	short period yaw mode

Eigenvalues and corresponding mode description

Model Validation



Structure of Automatic Flight Control System

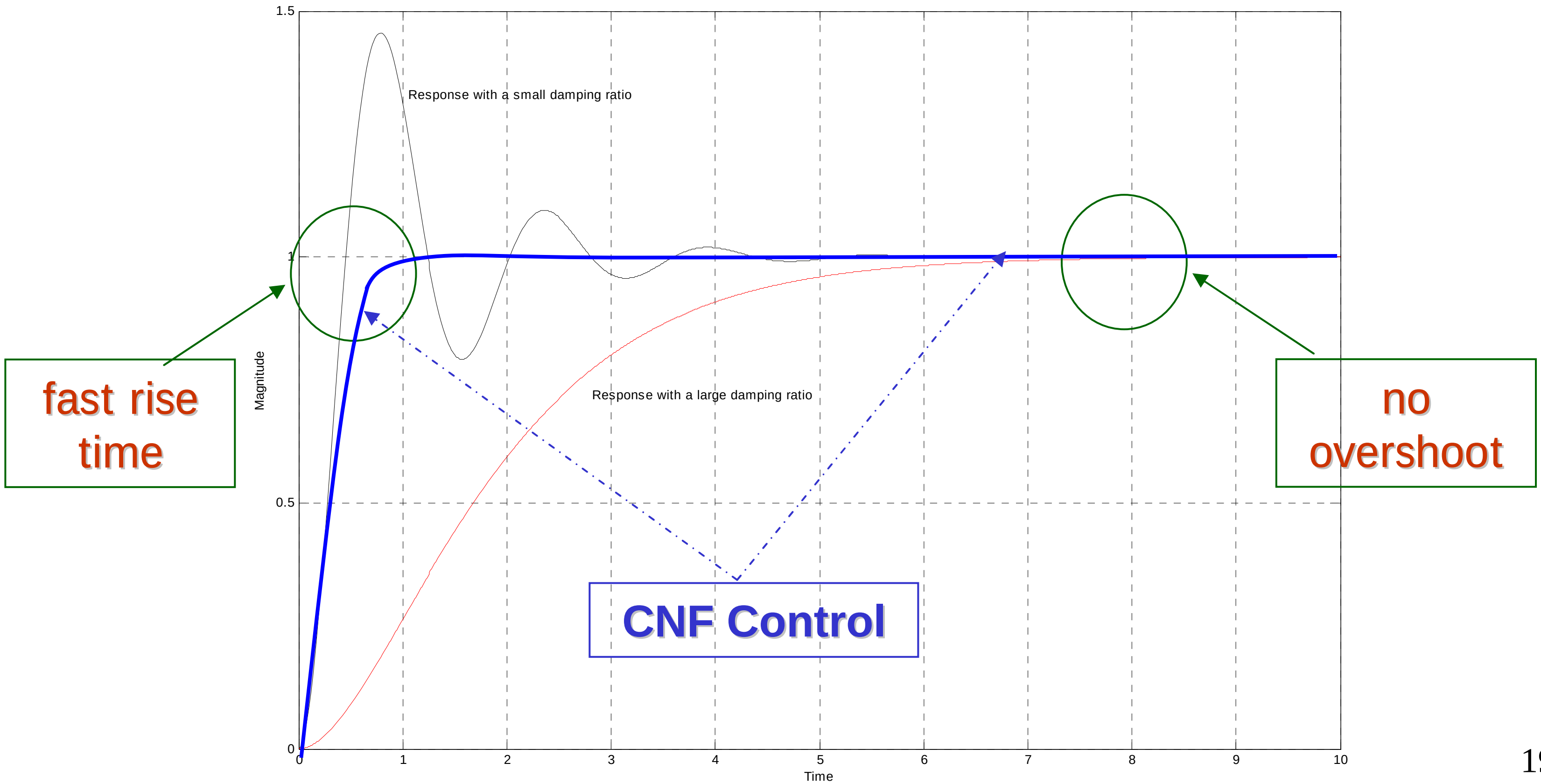


x, y, z	–	position of the helicopter respective to ground frame (North-East-Down frame)
u, v, w	–	velocity of helicopter along axis in body frame
ϕ, θ, ψ	–	roll, pitch and heading angle of helicopter (NED frame)
p, q, r	–	roll, pitch and yaw rate of helicopter along axis in body frame
$\delta_a, \delta_e, \delta_u, \delta_r$	–	control signal for aileron, elevator, collective pitch and rudder

helicopter state – $(x, y, z, u, v, w, \phi, \theta, \psi, p, q, r)$

Automatic Inner Loop Control Using CNF Control Technique

The newly developed CNF (**composite nonlinear feedback**) control technique is capable of tracking a target reference with fast settling time and with small or zero overshoot. It has many advantages compared to conventional approaches...



CNF Control Law

$$u = Fx + Gr + \rho B'P(x - G_e r)$$

$$G_e = \begin{bmatrix} 1.0000 & -0.0000 & 0 & 0 \\ 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.0011 & 0.0306 & 0 & 0 \\ -0.0175 & -0.0021 & 0 & 0 \\ -0.0007 & 0.0021 & 0 & 0 \\ 0.0011 & 0.0011 & 0 & 0 \\ 0.0000 & 0 & 1.0000 & 0 \\ 0.0000 & 0.0000 & 0 & 1.0000 \\ 0.0000 & 0.0000 & -0.0000 & 0.2474 \end{bmatrix}$$

$$G = \begin{bmatrix} 0.0028 & 0.0199 & 0 & 0 \\ -0.0408 & 0.0027 & 0 & 0 \\ 0.0002 & -0.0022 & 0.1003 & 0.0054 \\ 0.0000 & -0.0001 & -0.0010 & -0.0434 \end{bmatrix}$$

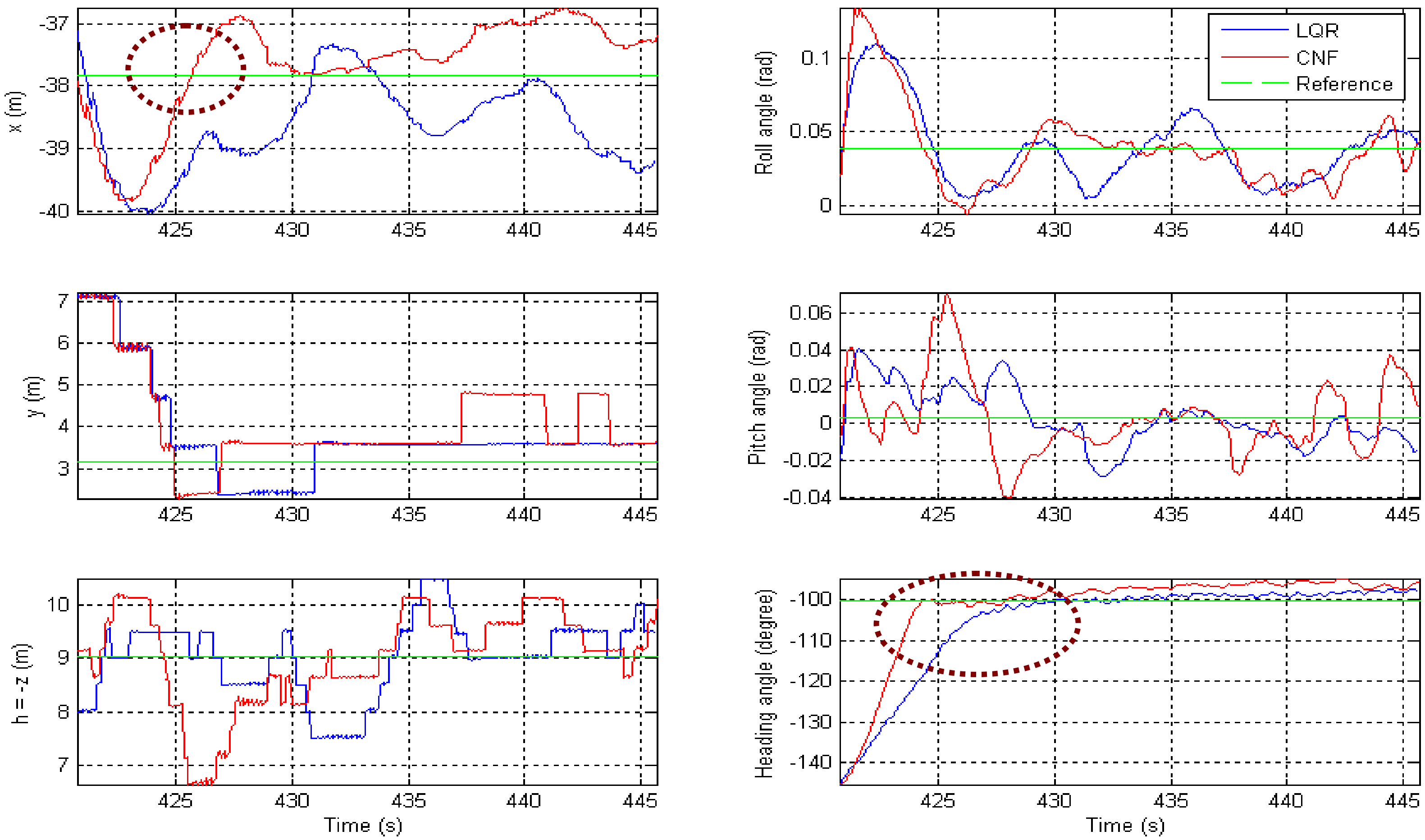
$$F = \begin{bmatrix} 0 & -0.0128 & 0.2641 & 0 & -0.1492 & 0 & 0 & 0.1048 & 0 & 0 & 0 \\ 0.0322 & 0 & 0 & 0.1720 & 0 & -0.3006 & 0.0599 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0661 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.1757 & 0.0912 \end{bmatrix}$$

$$B'P = \begin{bmatrix} 0.0087 & -0.0057 & 0.0383 & -0.0139 & 0.0394 & -0.0629 & 0.9293 & 2.3499 & 0.0243 & -0.0027 & 0.0084 \\ 0.0013 & -0.0015 & 0.0317 & 0.0699 & 0.0662 & 0.0854 & 1.9052 & 1.1038 & 0.0135 & 0.0006 & -0.0055 \\ 0.0027 & 0.0056 & -0.0140 & -0.0391 & -0.0089 & -0.0536 & 0.0707 & 0.1496 & 0.4989 & -0.0138 & 0.0471 \\ 0.0008 & 0.0005 & -0.0008 & -0.0076 & -0.0032 & -0.0130 & -0.0178 & 0.0635 & 0.0569 & -0.0505 & 0.1537 \end{bmatrix}$$

$$\rho = \mathrm{diag}\{\,\rho_1 \quad \rho_2 \quad 0 \quad \rho_4\,\}, \qquad \rho_i = -1.582\beta_i\left|e^{\alpha_i|y(i)-r(i)|} - 0.3679\right|, \qquad i = 1, 2, 4.$$

$$\beta_1 = 0.9, \quad \beta_2 = 1.6, \quad \beta_4 = 2 \qquad \alpha_1 = 2, \quad \alpha_2 = 2, \quad \alpha_4 = 3$$

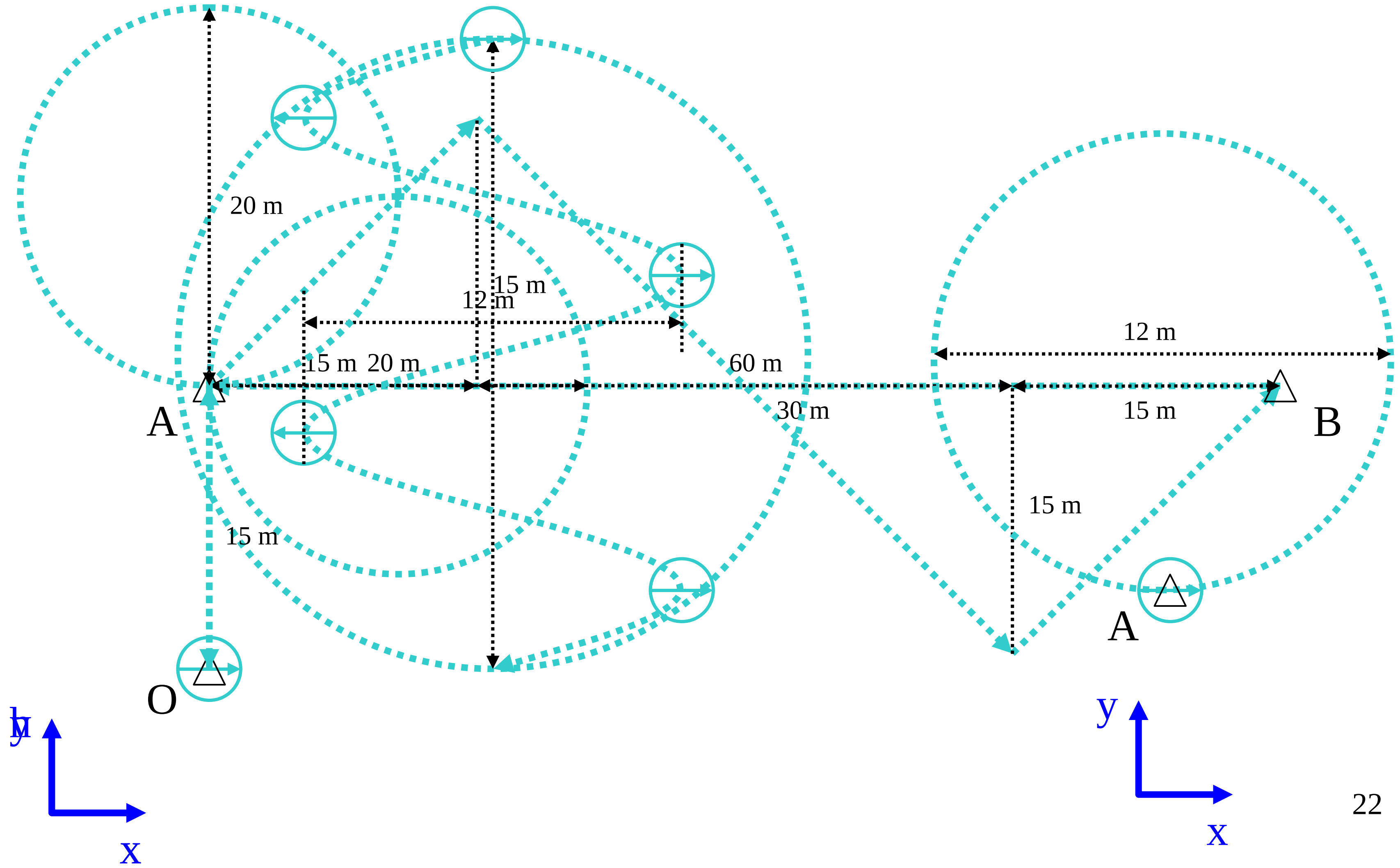
Comparison with Conventional LQR Technique



Results were obtained from actual flight tests...

Full Envelop Flight Paths – Illustration

1. standby 2. takeoff 3. hovering 4. slithering 5. head turning 6. pirouette
7. wheeling 8. backward down spiraling 9. hovering 10. landing 11. standby



Video Demo of Full Envelop Flight

Target Aiming Test – Illustration

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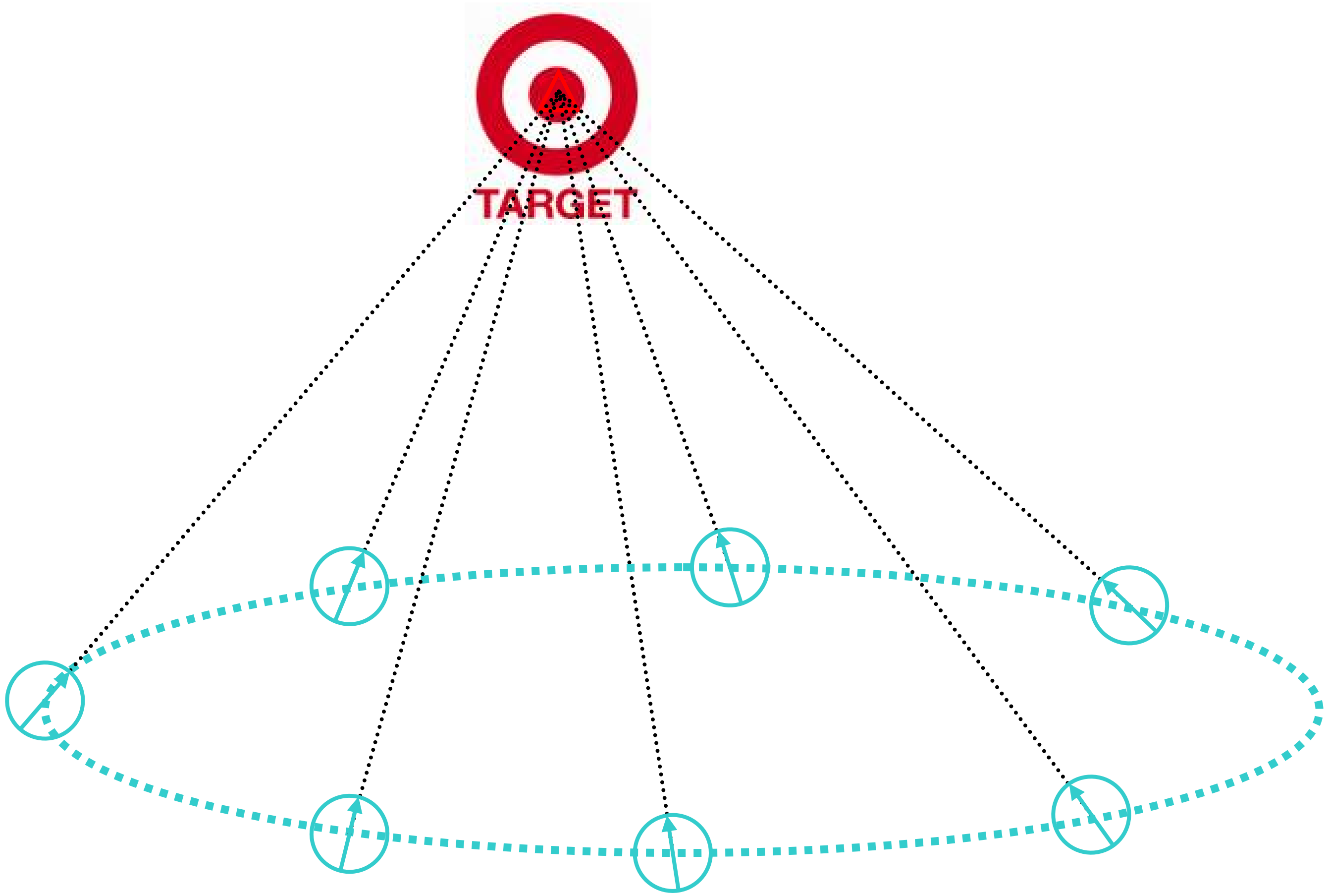

Video Demo of Target Aiming

Current Work – Ground Target Tracking & Attacking

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Experimental Results of Ground Target Detection

Single stage pattern recognition

Dual stage pattern recognition

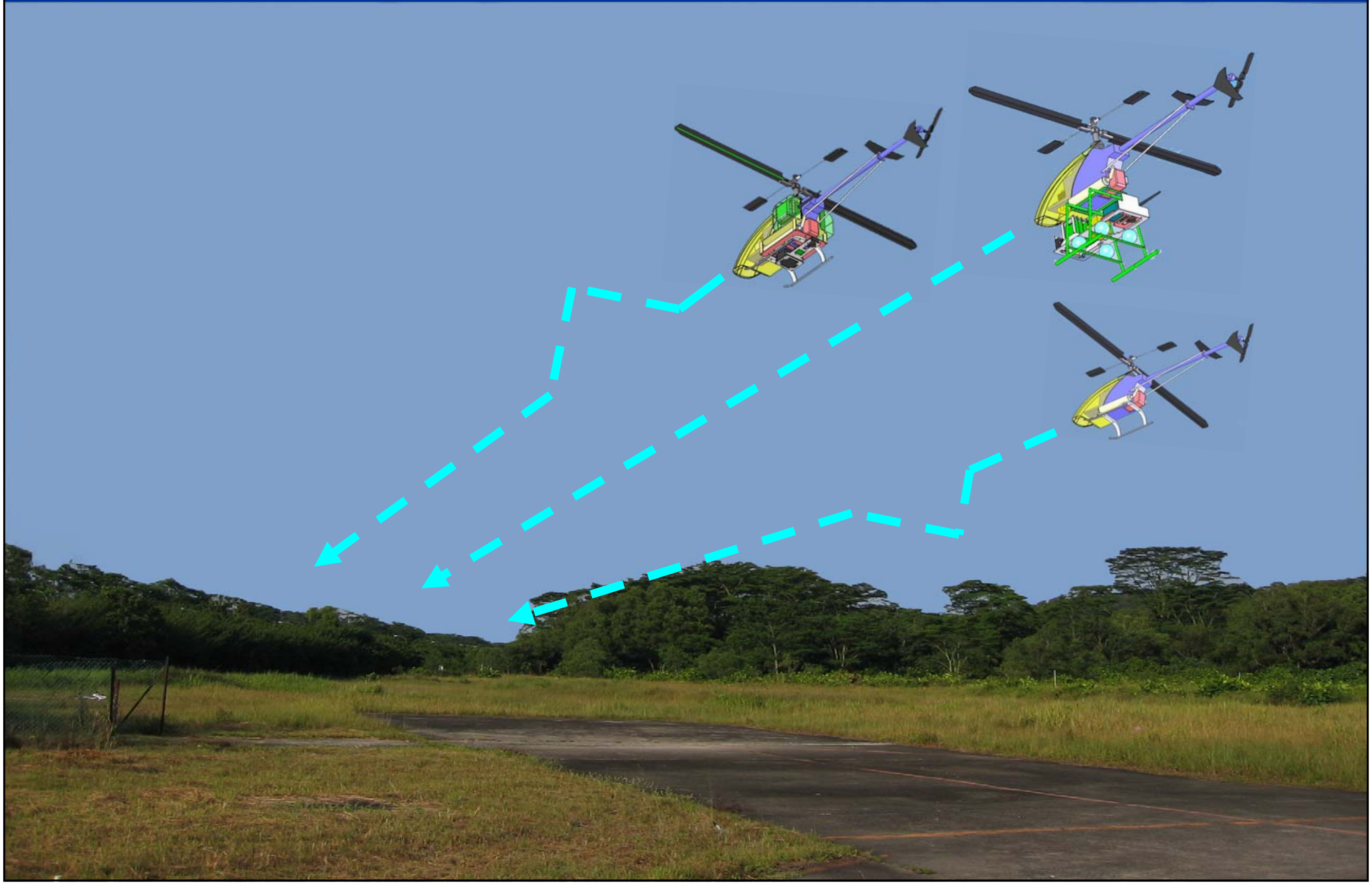
+ : predicted position

⌖ : measured position

Summary of Results for Ground Target Detection

		Number of images	Number of errors	Accuracy
Flying training data	Single stage pattern recognition	175	163	93.2%
	Dual Stage pattern recognition	175	172	98.29%
Flying testing data	Single stage pattern recognition	273	260	95.24%
	Dual stage pattern recognition	273	271	99.27%

Future Work – Formation Flight



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Dr Dong Miaobo, Dr Lan Weiyao

Mr. Cai Guowei, Mr. Lin Feng & Mr. Yun Ben

Acknowledgement

As well as in memory of our first chopper, NUSIX,

which crashed twice on 25 March 2006 and 15 February 2007

Thank you!