EE5110/6110 Special Topics in Automation and Control

Autonomous Systems: Unmanned Aerial Vehicles

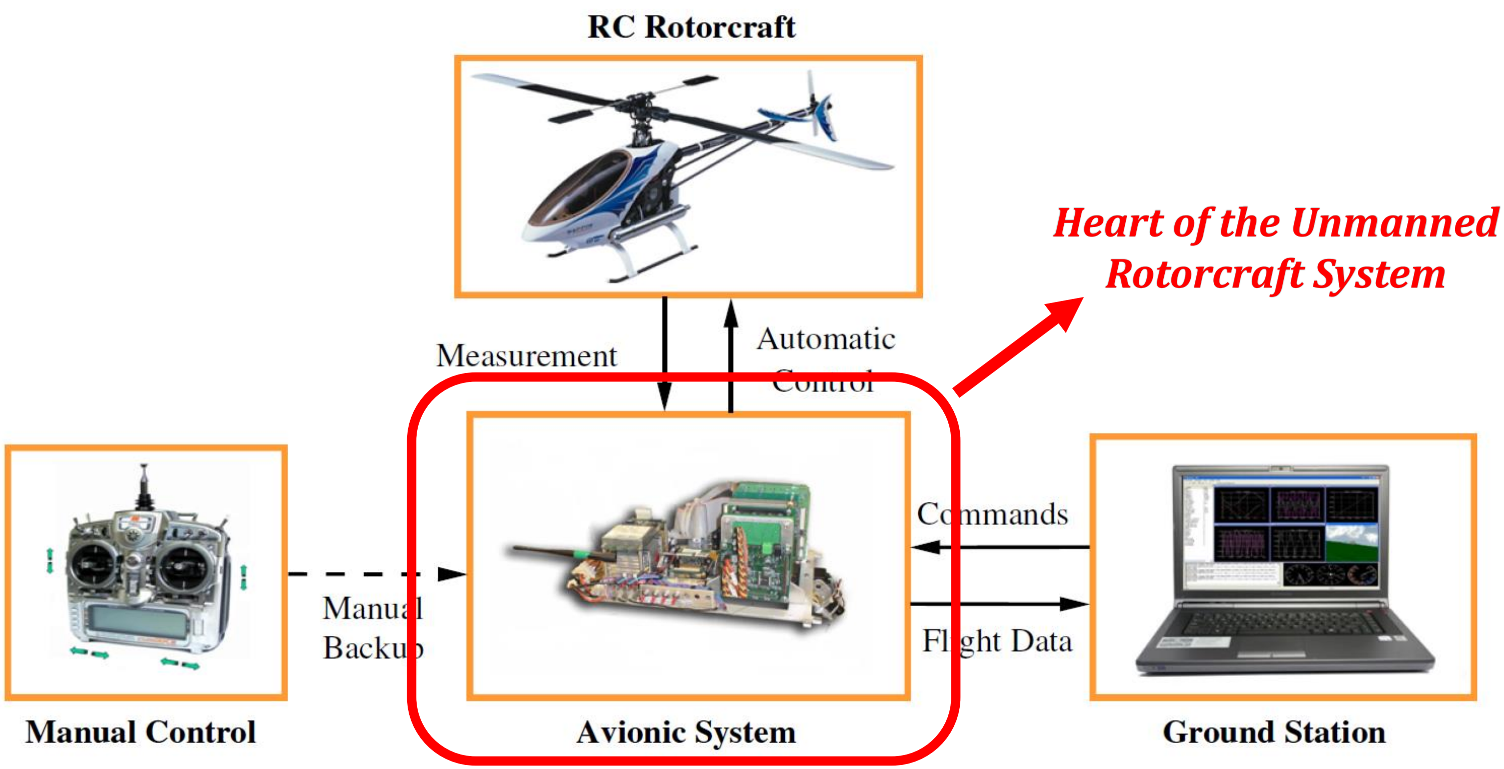
UAV Platform Design

Dr. Lin Feng (tsllinf@nus.edu.sg)

Unmanned Systems Research Group, Dept of Electrical & Computer Engineering
Control Science Group, Temasek Laboratories
National University of Singapore

Key components of an unmanned rotorcraft system

1. A radio-controlled (RC) rotorcraft
2. An avionic system for collecting inflight data, performing automatic control laws, executing mission-oriented tasks, and communicating with the ground station
3. A manual control system consisting of a pilot and a wireless joystick
4. A ground station system for monitoring the flight states of the UAV and communicating with the avionic system



General introduction

- A reliable unmanned aerial platform is the foundation of the subsequent work (e.g., flight dynamics modeling and control system design)
- Essential issues in platform construction:

  1) What components should be included?

  2) How to achieve a reliable assembly?

  3) How to minimize construction time and avoid iterations?

  4) How to verify the reliability of a constructed UAV platform?

Answers will be provided in this presentation!

Bare aircraft selection

How to choose a platform?

Multi rotor

Mini coaxial helicopter

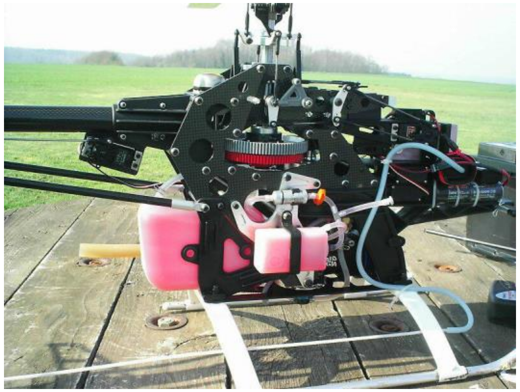
CopterWorks

Raptor 90

Bare aircraft selection

Bare Helicopter: Raptor 90

Full Length of fuselage: 1410mm (55.50")
Full width of fuselage: 190mm (7.50")
Total height: 465mm (18.25")
Main rotor dia: 1640mm (64.75")
Tail rotor dia: 260mm (10.25")
Gear ratio: 1:8.45:4.65
Full equipped weight: 4800g (10.5 lbs)



Bare aircraft selection

- UAV Hardware System
  - » Quad-rotor
  - » Sensor
    - IMU + GPS
    - Monocular camera
    - Two processor solution: flight control + vision processing
- UAV Software System
  - » Flight control system: Gumstix processor to realize real-time, measurement reading, flight control, servo driving and wireless communication (run in 50 Hz)
  - » Vision guidance system: Mastermind processor to realize camera image capture, intensive image processing (run in 5 Hz, the vision algorithm will cost about 120ms for each image)

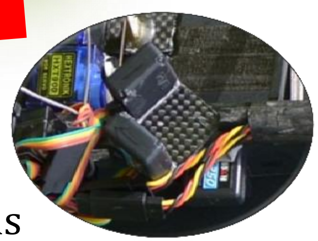
Unconventional UAV

Gimballed vector thrust

- Roll and pitch controlled by the gimbal system
- Yaw controlled by the rotational speed difference

Retractable wings

- 3 control modes available
- Enable VTOL, hovering, cruise flight

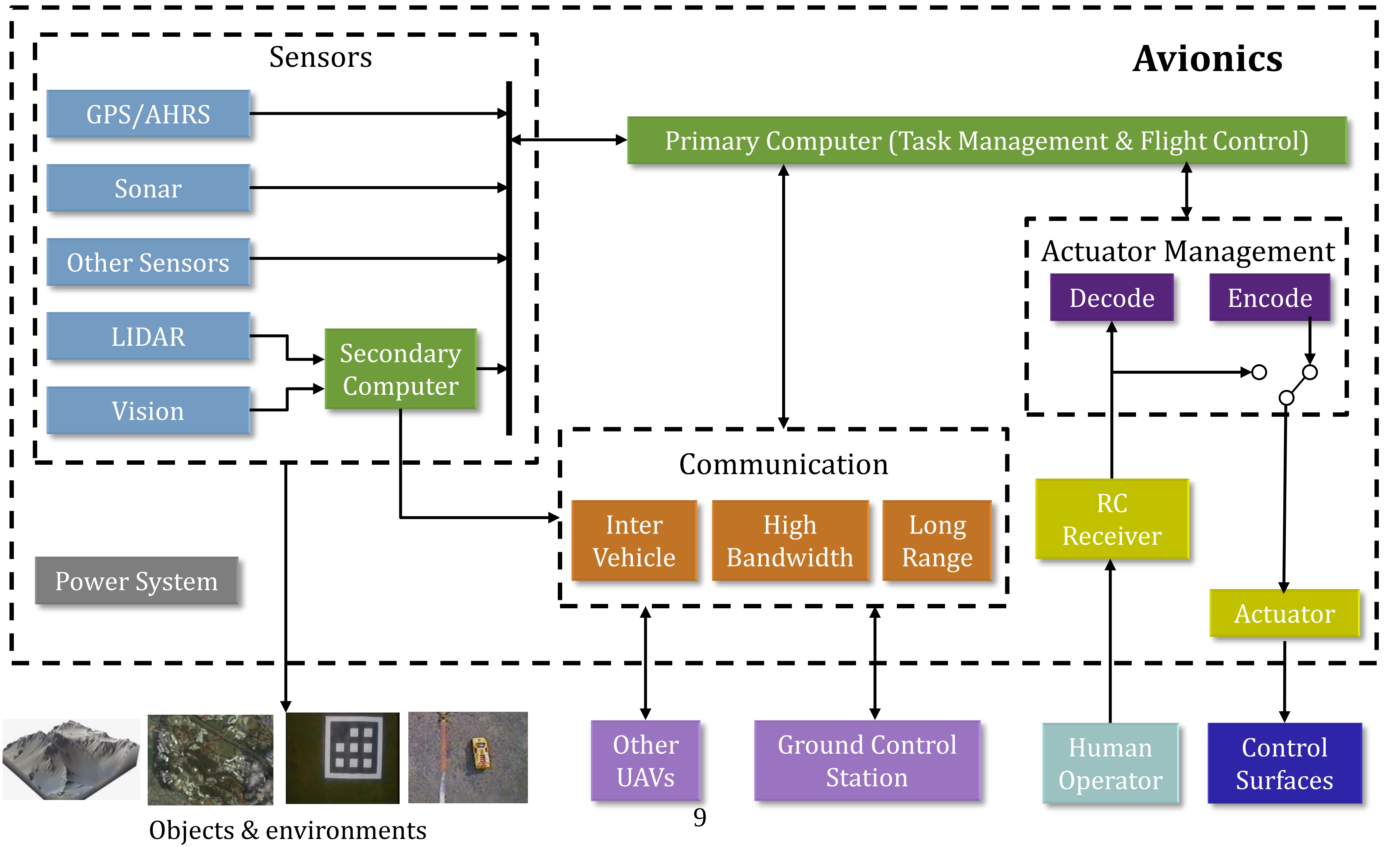


Gyro Stabilizer

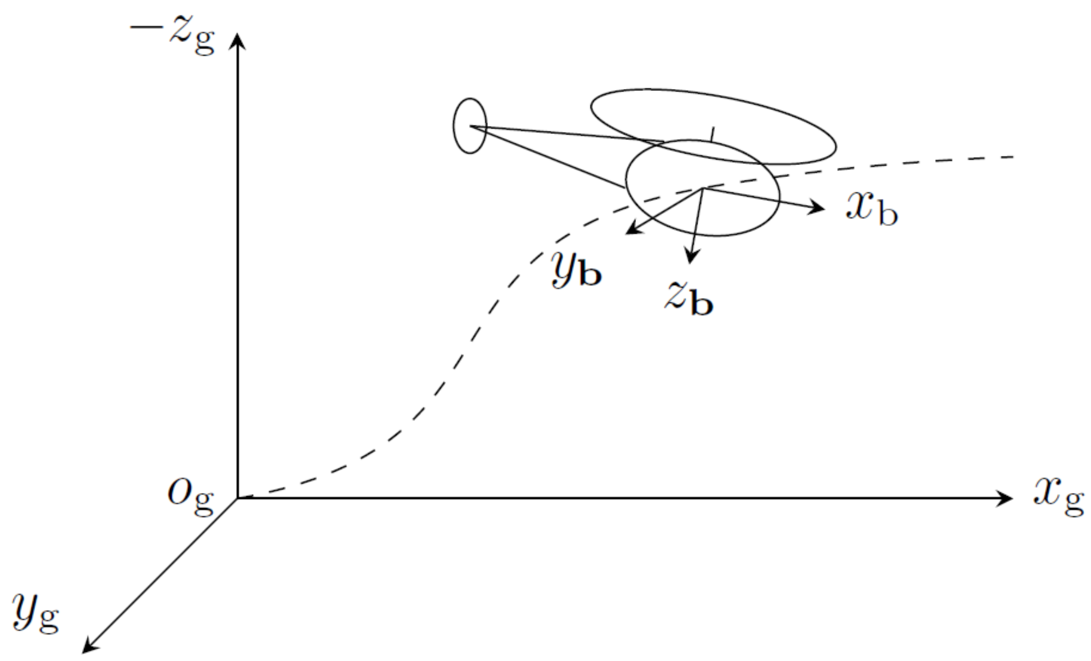
- 5 gyros to stabilize 3-axis orientation
- Works on both hovering and cruising modes

a new design

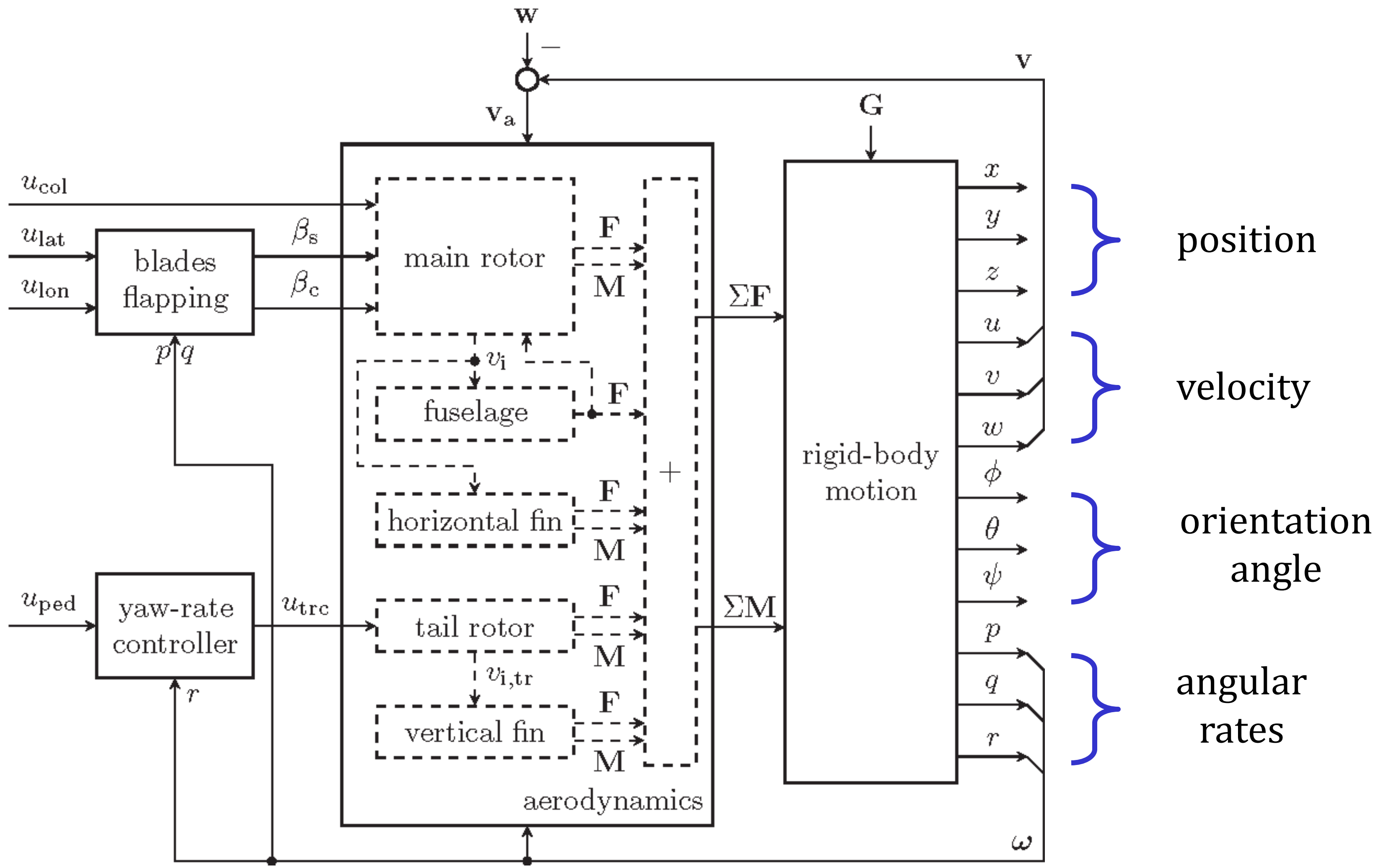
Essential hardware components of avionics



From time to time, the vehicles recognize where they are and compare their actual position with where they should be according to their assigned path, and the pilots make appropriate maneuvers to bring the vehicles back to the correct path.



Required navigation information for an aircraft



How to get navigation information

Forms of Navigation

- Landmarks
  - Recognized by human pilots
- Celestial Navigation
- Radio Navigation
  - Ground-based navigation
  - Satellite navigation
- Inertial Navigation
  - Gimbaled INS
  - Strapdown INS
- Visual Navigation

Inertial Navigation System

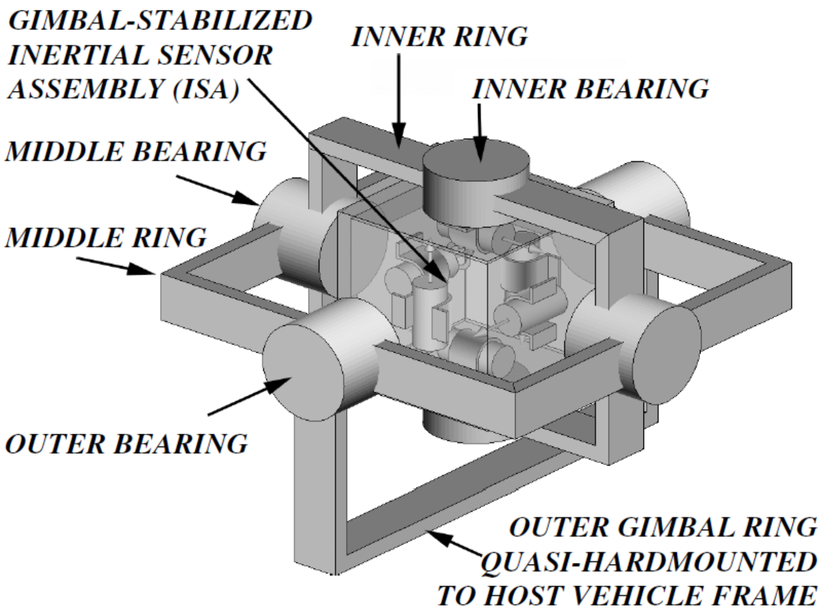
A group of sensors and computing devices that observes the position, velocity, acceleration, orientation, angular rates of the vehicles with respect to an inertial frame of reference

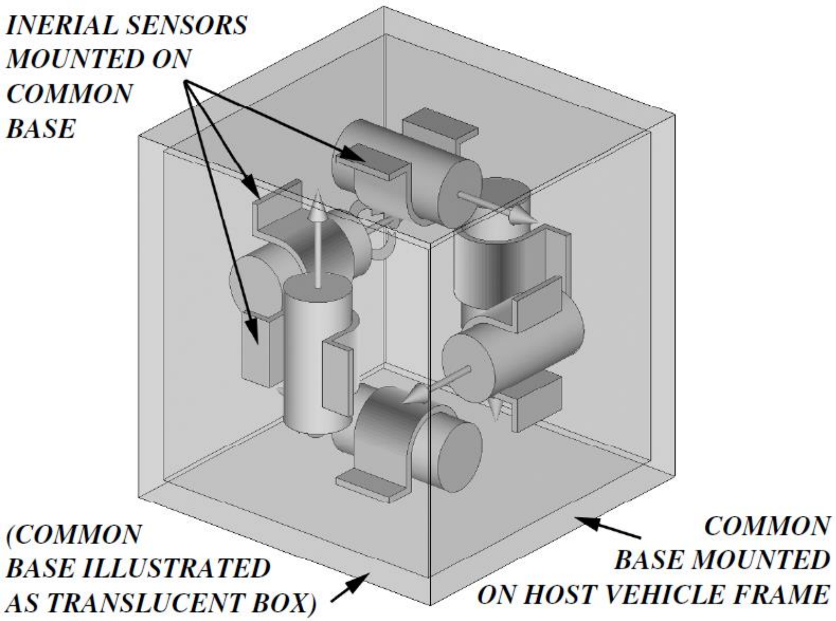
sensors → algorithms →

Inertial measurement unit (IMU)

Gimbaled IMU

Strapdown IMU



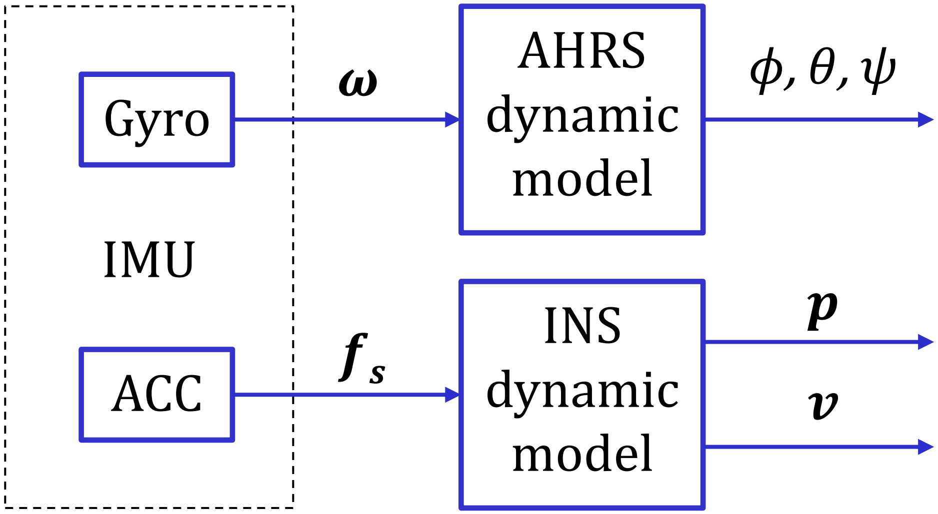


MEMS-based strapdown IMU

IMU

- Gyroscopes
- Accelerometers
- Temperature
- Magnetometer
- Barometer

Basic idea for strapdown INS



- What are the models?
- Are the other sensors needed?
- Does the framework work properly?

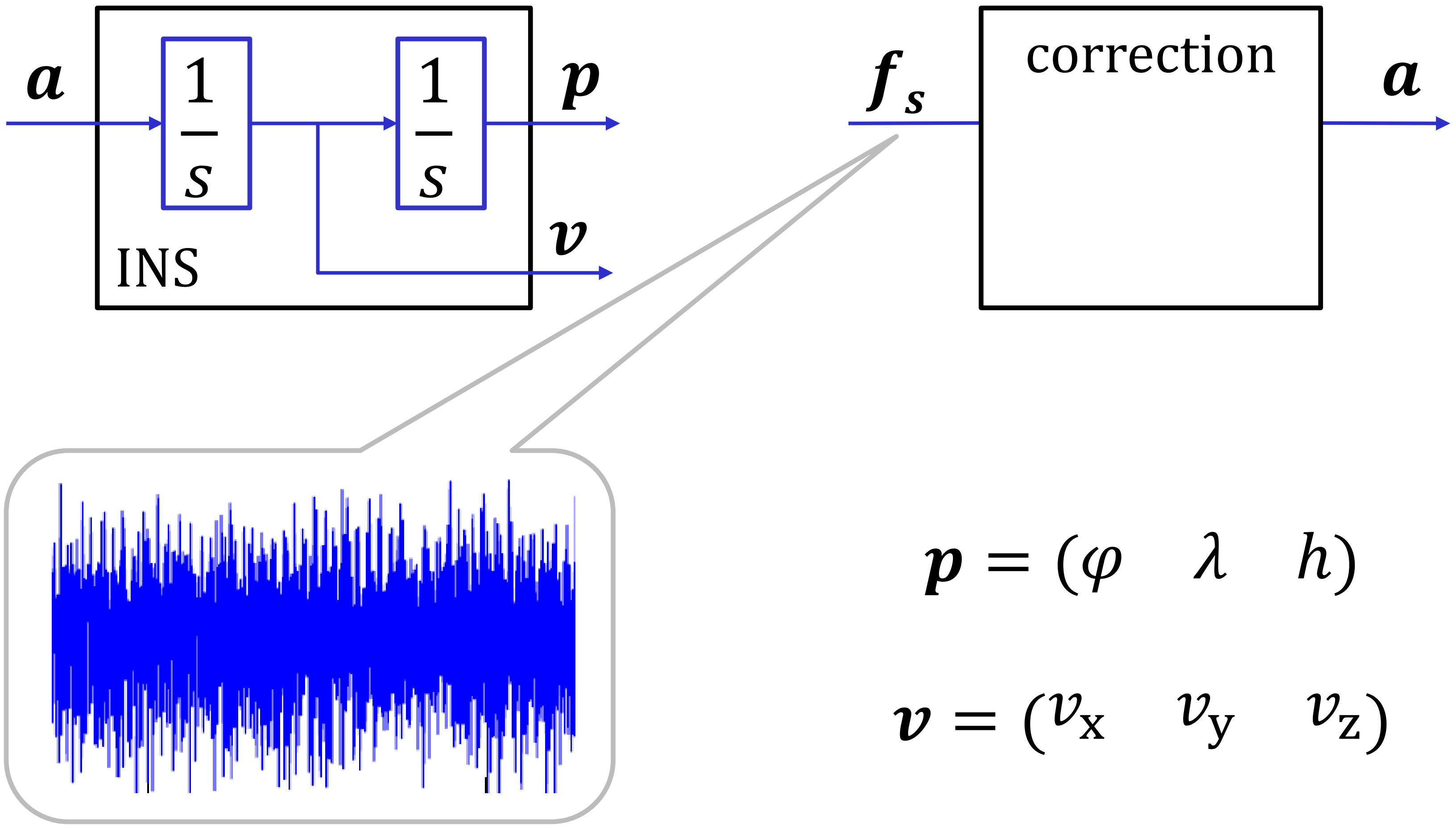
AHRS dynamic model

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$\dot{\mathbf{\Phi}} = \mathbf{H}\boldsymbol{\omega}$$

$$\mathbf{\Phi}(t_k) = \mathbf{\Phi}(t_{k-1}) + \int_{t_{k-1}}^{t_k} \mathbf{H}\boldsymbol{\omega}\mathrm{d}t$$

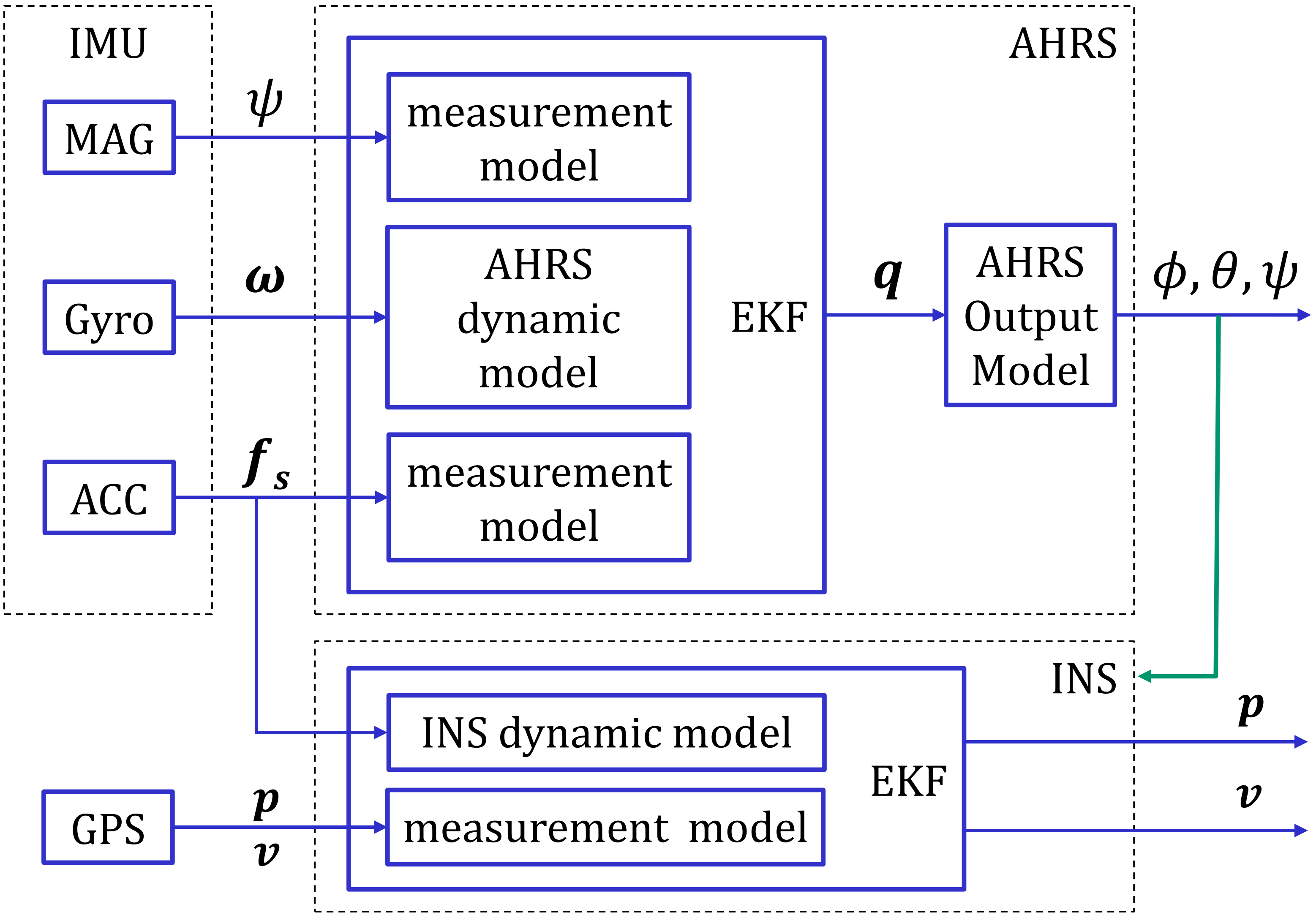
INS dynamic model



$$\boldsymbol{p} = (\varphi \quad \lambda \quad h)$$

$$\boldsymbol{v} = (v_{\mathrm{x}} \quad v_{\mathrm{y}} \quad v_{\mathrm{z}})$$

GPS-aided INS by EKF



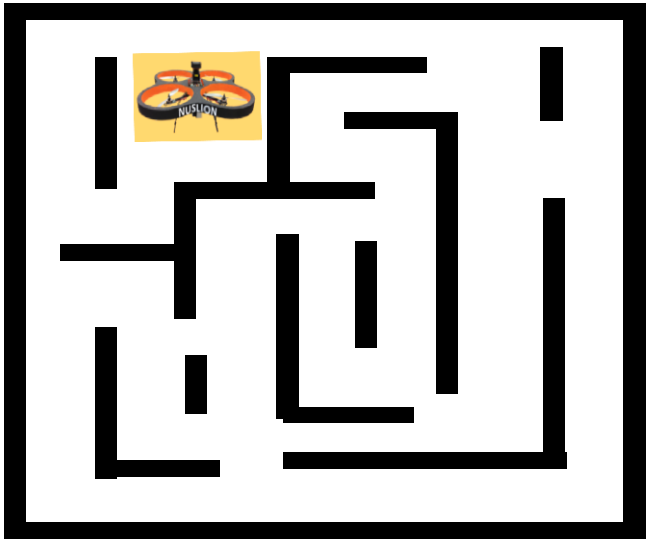
IMU grades

The navigation accuracy of the INS is significantly affected by the IMU used which can be roughly divided into four performance categories: marine & aviation grade, tactical grade, industrial grade, and automotive & consumer grade.

IMU Grade	Marine & Aviation	Tactical	Industrial	Automotive
Cost (USD)	100k – 1M	10 – 30k	0.5 – 3k	< 500
Gyro Type	Laser / Fiber Optic	Fiber Optic / MEMS	MEMS	MEMS
Gyro Bias ($°/\mathrm{h}$)	0.001 – 0.01	0.01 – 1	1 – 100	> 100
Gyro Random Walk ($°/\sqrt{\mathrm{h}}$)	< 0.005	0.005 – 0.5	0.5 – 5	> 5
Accelerometer Bias (mg)	0.01 – 0.1	0.1 – 1	1 – 10	> 10
Example	Honeywell HG9900	Honeywell HG1900	Crossbow IMU440	ArduIMU
	Honeywell HG9848	Spatial FOG	Microstrain GX2	Razor IMU
			SBG IG500A	
			Vectornav VN-100	

Relative sensing

- Why the UAV need the relative sensing?
- How to navigate in a clutter environment?

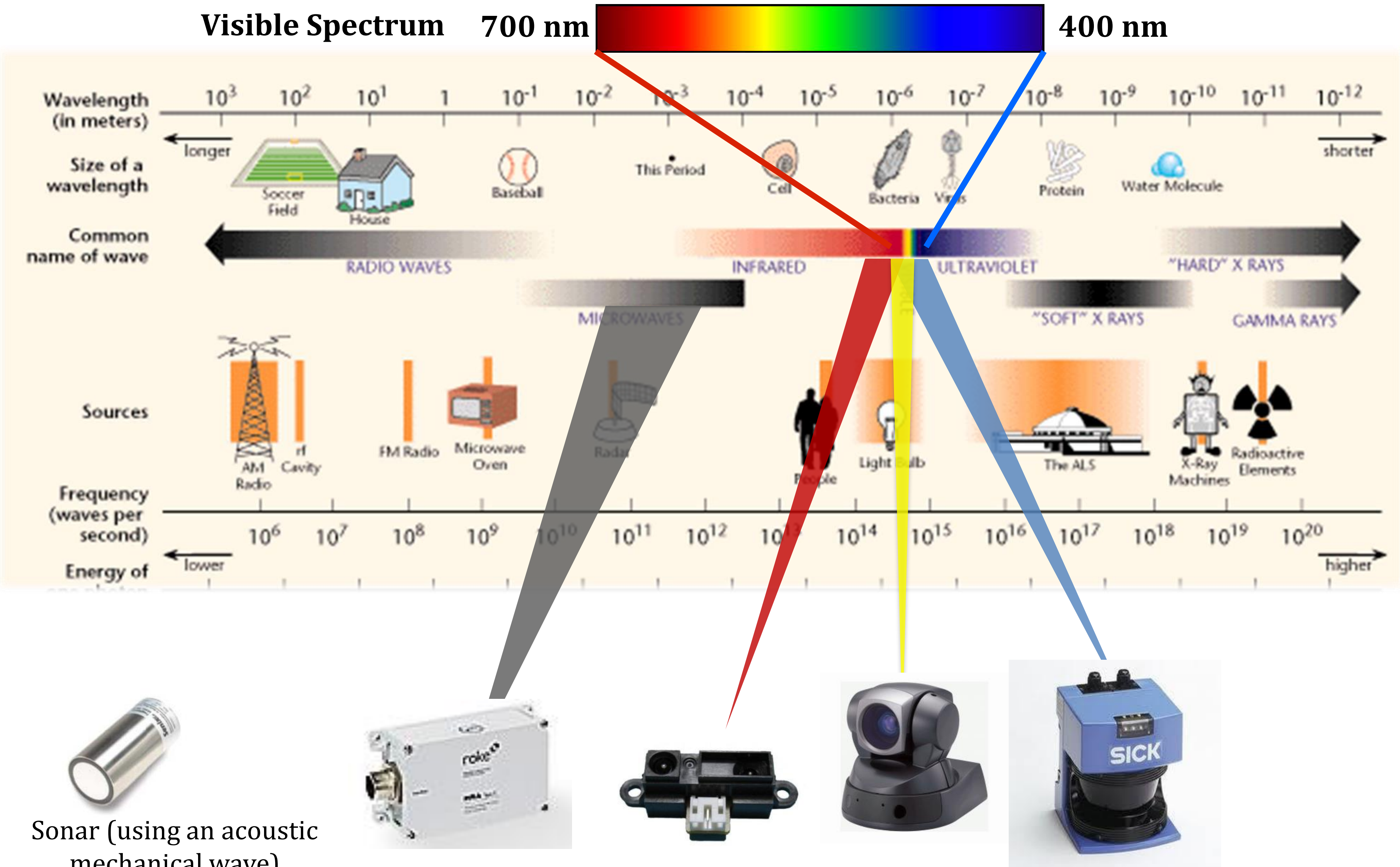


Localization

Obstacle avoidance

Adopted from "Conflict-Free Navigation in Unknown Urban Environments" by D. H. Shim, H. Chung and S. S. Sastry

Electromagnetic spectrum & range sensors



Sonar (using an acoustic mechanical wave)

Miniature radar

Infrared sensor

Camera

Laser scanner

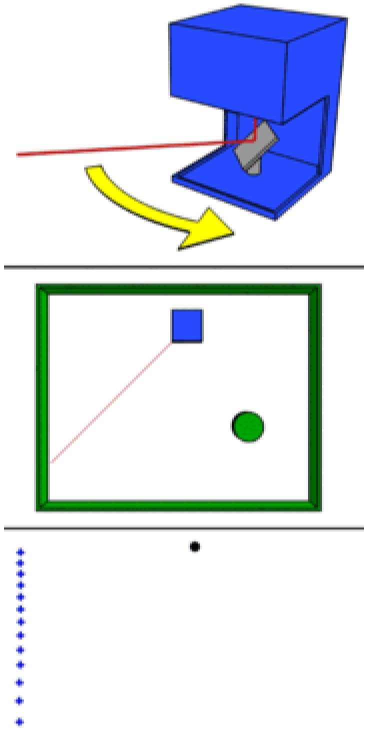
LIDAR

LIDAR (**Li**ght **D**etection **a**nd **R**anging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.

The prevalent method to determine distance to an object or surface is to use laser pulses. Like the similar radar technology, which uses radio waves instead of light, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal.

The acronym LADAR (Laser Detection and Ranging) is often used in military contexts.

A **laser rangefinder** is a device which uses the technology of **LIDAR.**



The illustration of LIDAR

NUS National University of Singapore

Selected manufacturer and specification of laser range scanners

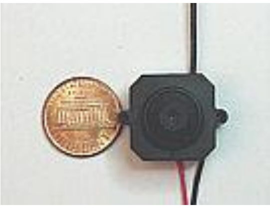
	SICK: LMS 200	SICK: LMS400	SICK: LD-LRS1000	Hokuyo: URG-04LX	Hokuyo: UHG-08LX Laser	Hokuyo UTM-30LX Laser
						
Field of	180 °	70 °	360 °	240°	270°	270°
Angular resolution:	0.25 °	0.1 °	0.125 °	.0.36° (360° /1,024 steps)	0.36° (360° /1,024 steps)	0.25°
Response time:	13 to 53 ms	5 to 2 ms	66.6 to 200 ms	100ms/scan	67ms/scan	25ms/scan
Resolution:	10 mm	1 mm	3.9 mm	±10mm	3% of distance	±50mm
Scanning range:	80 m	3 m	250 m	60 to 4095mm	0.03 to 11m	0.1 to 30m
Supply voltage:	24 V DC ± 15%	24 V DC ± 15%	24 V DC ± 15%	5VDC±5%	12 VDC ±10%	12 VDC±10%
Data interface:	RS-232, RS-422	Ethernet, RS-232, RS-422	Ethernet, RS-422/RS-232	USB, RS-232C	USB2.0	USB2.0
Power	20 W	20 W	36 W	4W	10W	8 W
Weight:	4.5 kg	2.3 kg	3.2 kg	160g	500g	210g(w/ocable)
Price:	---	---	---	$2375.00	$3950.00	$5590.00

Drawback

The main drawback of laser sensing is the weight and high power consumption due to the nature of active sensing. Although a 3D LIDAR is able to provide one more dimensional measurement than a 2D LIDAR, it is hard to be carried by a small-scale UAV with limited payload and power supply. Therefore, in localization and navigation applications, the combination of two 2D LIDAR is a feasible solution balancing the quality of 3D measurement against total weight.

Vision sensor

To enhance the performance of navigation systems of UAVs in unknown environments, the vision augmented system become a possible solution. The core issue is vision-aided motion estimation techniques.



- Stereo vision
- Optical flow
- Model-to-data correspondence

Stereo vision

Optical flow

Model correspondence

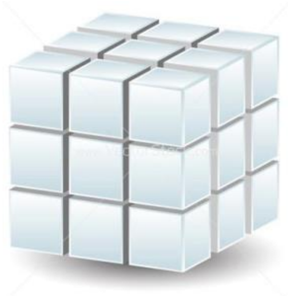
Vision sensor

Why Integrating Vision with Unmanned Aircrafts?

- **Rich Information**

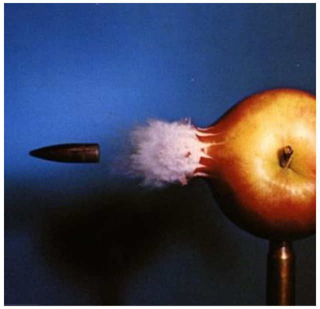
"The reason is that sight, more than any of other sensors, gives us knowledge of things and classifies many difference among them."

– Aristotle



Geometry

Photometry



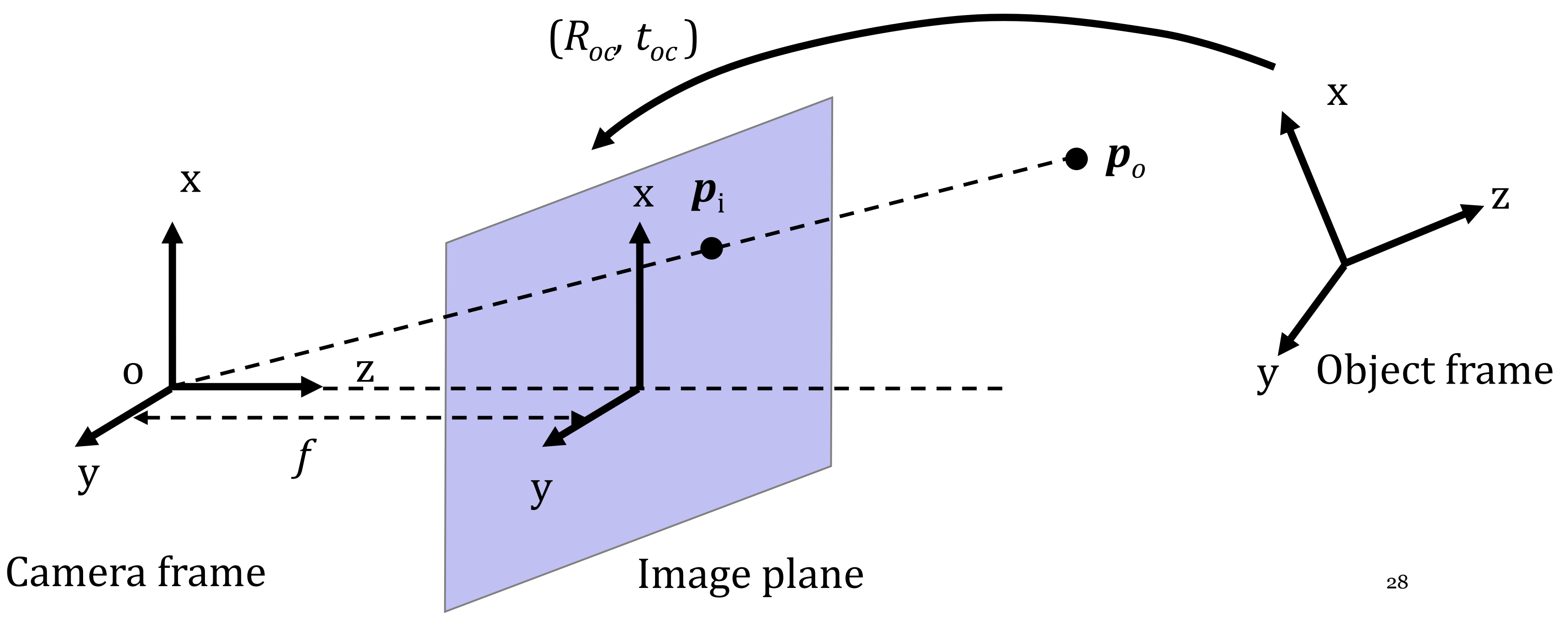
Dynamics

- **Low cost, light weight, and sometime we do not have other choices.**

Vision sensor - pose estimation

Pose estimation is to determinate the geometric transformation that relates the camera to the known scene structure.

$$\lambda \begin{pmatrix} \mathbf{p}_{\mathrm{i}} \\ 1 \end{pmatrix} = \begin{bmatrix} f_x & s_\theta & o_x \\ 0 & f_y & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{R}_{\mathrm{oc}} & \mathbf{t}_{\mathrm{oc}} \\ 0 & 1 \end{bmatrix} \begin{pmatrix} \mathbf{p}_{\mathrm{o}} \\ 1 \end{pmatrix},$$

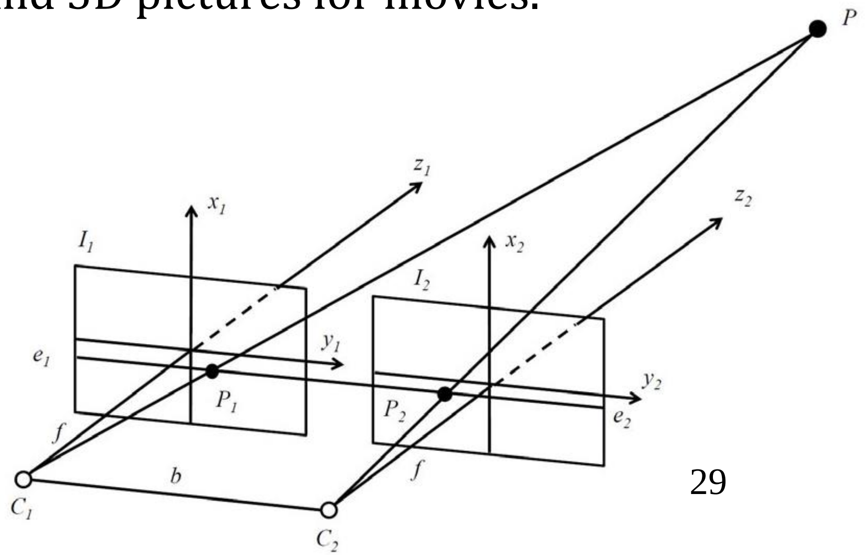


Vision sensor

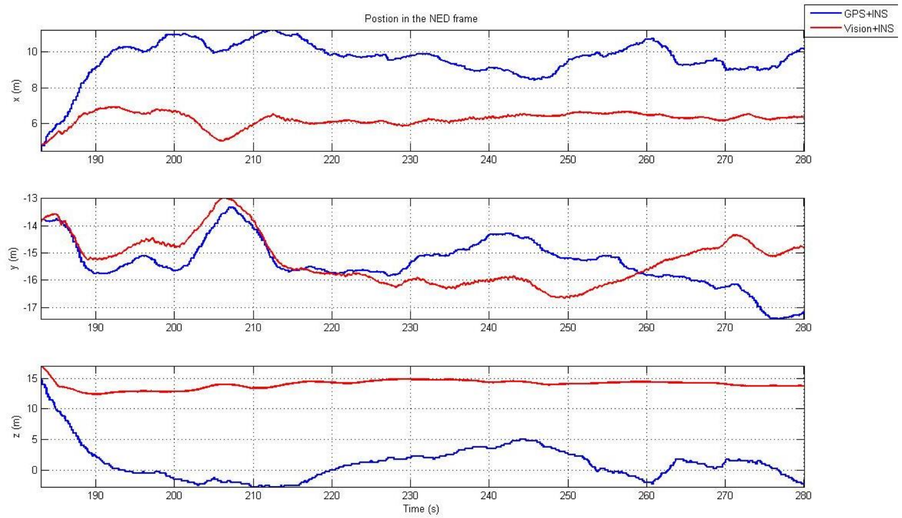
A **single camera** is able to handle applications of vision-aided target identification and tracking. When it comes to the situations that relative distance measurement is required, the recommended reliable solution is to utilize stereo vision that is able to provide complete 3D information.

A **stereo camera** is a type of camera with two or more lenses. This allows the camera to simulate human binocular vision, and therefore gives it the ability to capture three-dimensional images, a process known as stereo photography. Stereo cameras may be used for making stereoviews and 3D pictures for movies.

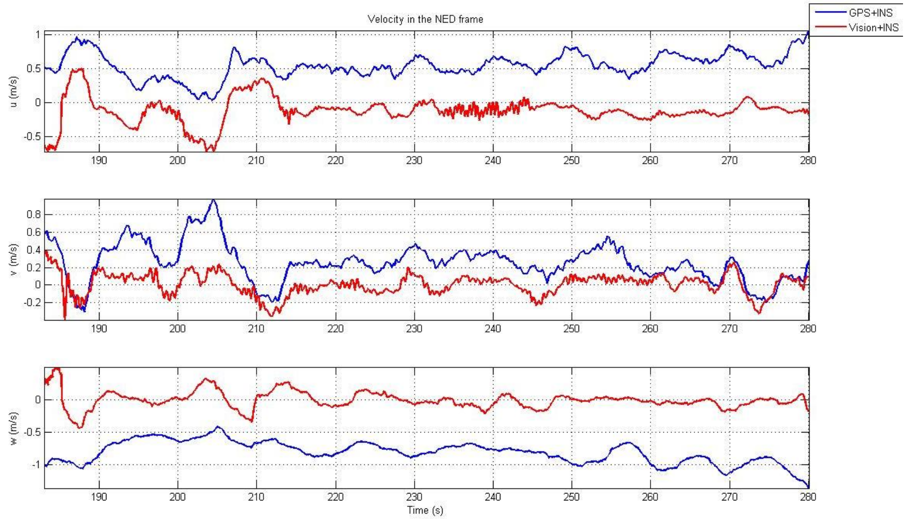
Point Grey: Bumblebee



Vision aided flight control



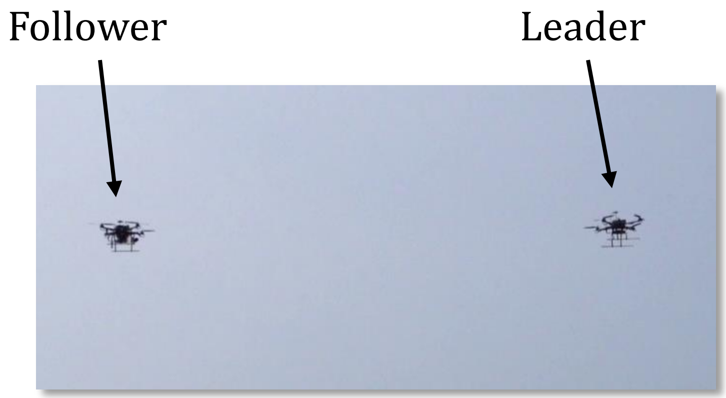
Vision-based position estimation (GPS/INS vs Vision/INS)



Vision-based velocity estimation (GPS/INS vs Vision/INS)

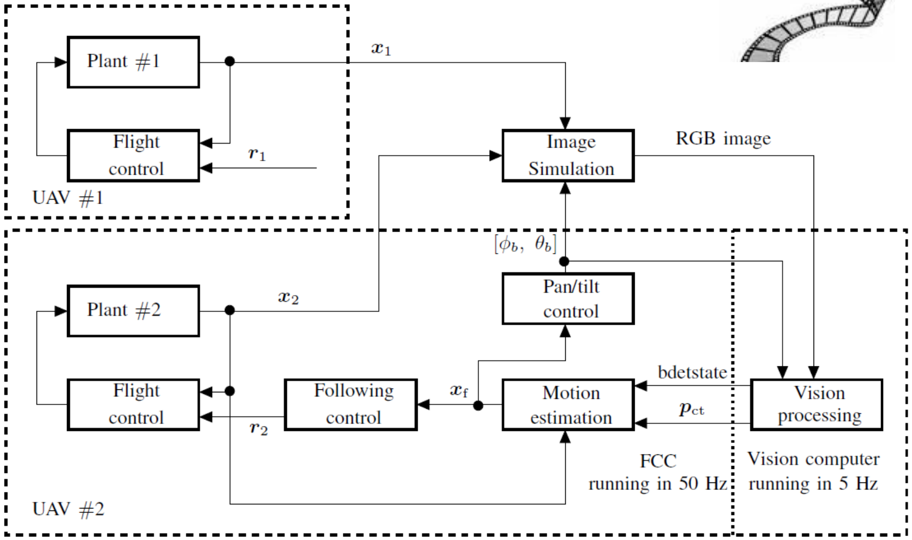
Vision-aided Leader-follower Formation

To realize leader-follower formation using vision-aided relative sensing and motion estimation.

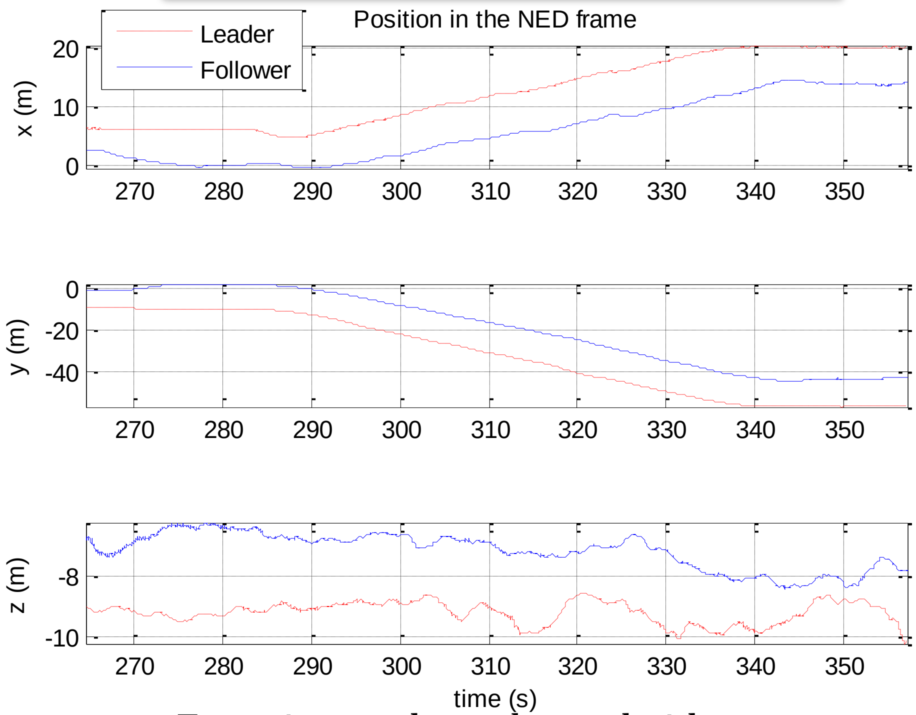


Key Features:

- Vision-based relative displacement measurement
- Motion estimation under assumption of the quasi steady states.
- Robust following control using the dynamic inversion and the robust perfect tracking.
- No inter-vehicle communication
- Real-time onboard processing



The block diagram of the integrated simulation



Experimental results and video

RGB-D camera

Despite the common usage of monocular camera or stereo camera on UAV platforms, the depth camera is a more advanced vision sensor, which can also be used to solve UAV navigation and environmental mapping problems.

	PMD[vision] CamCube 3.0	Mesa Imaging SR4000	Microsoft Kinect	Asus Xtion PRO LIVE
Type	ToF	ToF	Projected-light	Projected-light
Range (m)	7.5	0.1–10	0.8–4	0.8–3.5
Resolution	200×200 or 160×120	176×144	640×480	640×480 or 320×240
Frame rate	40 or 80	50	30	30 or 60
FOV (deg)	40×40	43.6×34.6	57×43	58×45
Weight (g)	1438	470	440	228
Dimension (cm)	Not published	$65 \times 65 \times 68$	$24.9 \times 6.6 \times 6.7$	$18 \times 3.5 \times 5$

Sensors

A sound gets emitted, then you 'see' your surroundings based on the sound coming echoing back. This is because sound takes time to travel distances. Farther the distance, the longer it takes for the sound to come back.

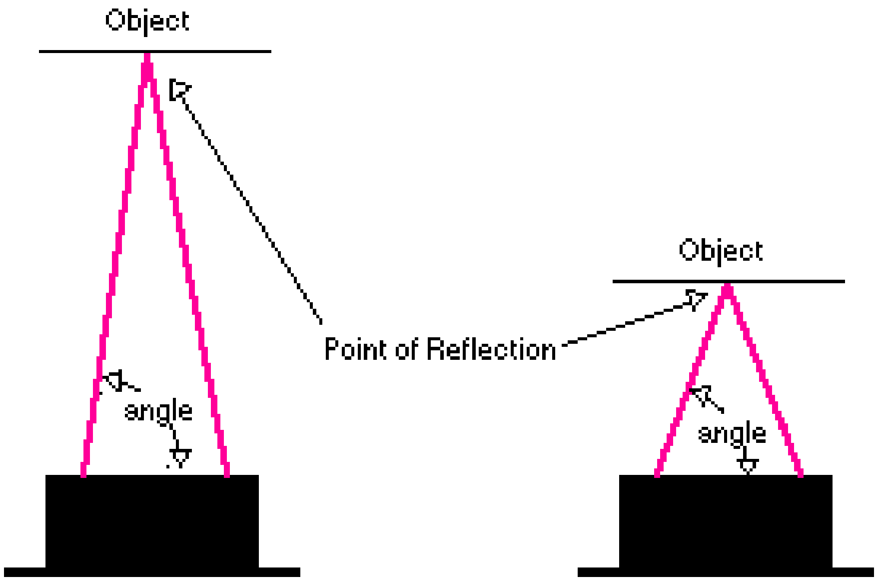
Devantech SRF08
Range Finder

Voltage	5v
Current	15mA Typ. 3mA Standby
Frequency	40KHz
Maximum Range	6 m
Minimum Range	3 cm
Max Analogue Gain	Variable to 1025 in 32 steps
Connection	Standard IIC Bus
Light Sensor	Front facing light sensor
Timing	Fully timed echo, freeing host computer of task
Echo	Multiple echo - keeps looking after first echo
Units	Range reported n uS, mm or inches
Weight	0.4 oz.
Size	43mm w x 20mm d x 17mm h

SICK: UM30

Switching outputs:	Analogue output
Length:	135.5 mm
Thread size:	M30 x 1.5
Supply voltage min ... max:	DC 12 ... 30 V
Resolution:	1 mm
Analogue output	4 ... 20 mA/0 ... 10 V
Accuracy:	=< 2% of final value
Ripple:	10 %
Power consumption:	<= 70 mA
Response time:	180 ms
Standby delay:	2 s
Connection type:	Connector, M12, 5-pin
Scanning range min ... max:	350 ... 5.000 mm

The **Sharp IR Range Finder** is probably the most powerful sensor available to the everyday robot hobbyist. It is extremely effective, easy to use, very affordable ($10-$20), very small, good range (inches to meters), and has low power consumption.



Sharp IR Range Finder

How to collect and analyze the information from different sensors?

The primary functions of onboard computers include analyzing and processing various data delivered by onboard sensors, executing missions, communicating with the ground station and other UAVs, and logging flight data for post-flight analysis.

ADLQM87BC SBC – PC/104

Gumstix DuoVero™ Zephyr COM

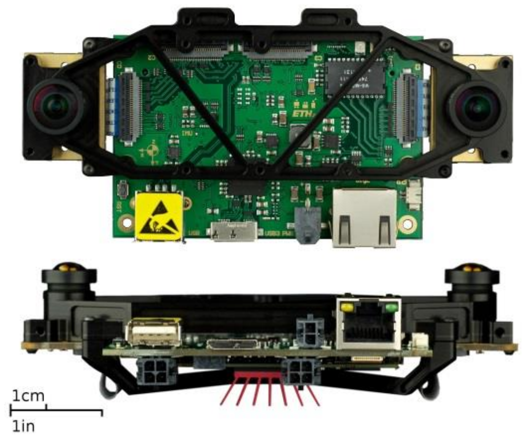
AscTec Mastermind

A single board computer (SBC) is still the first choice for UAV systems, which has compact size and complete features of a fully functional computer, including microprocessor(s), memory, input/output, storage, and so on.

Hardware acceleration

Types of Hardware Accelerator

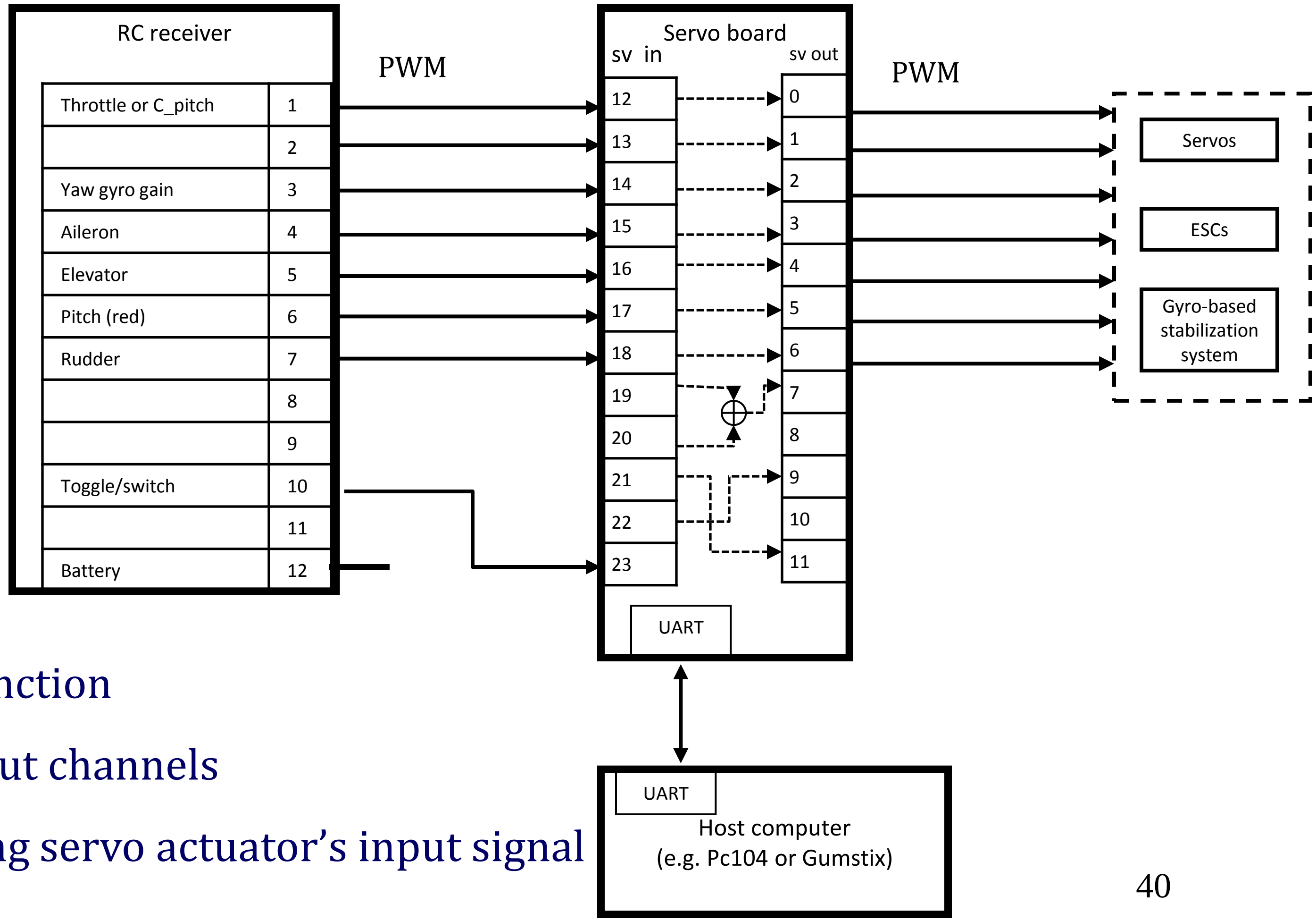
- GPU : Graphics Processing Unit
  - Many-core - 30 SIMD processors per device
  - High bandwidth, low complexity memory – no caches
- MPPA : Massively Parallel Processor Array
  - Grid of simple processors – 300 tiny RISC CPUs
  - Point-to-point connections on 2-D grid
- FPGA : Field Programmable Gate Array
  - Fine-grained grid of logic and small RAMs
  - Build whatever you want



FPGA based SLAM sensor unit adopt from "A Synchronized Visual-Inertial Sensor System with FPGA Pre-Processing for Accurate Real-Time SLAM" by J. Nikolic, J. Rehder, M. Burri, et al.

Actuator Management

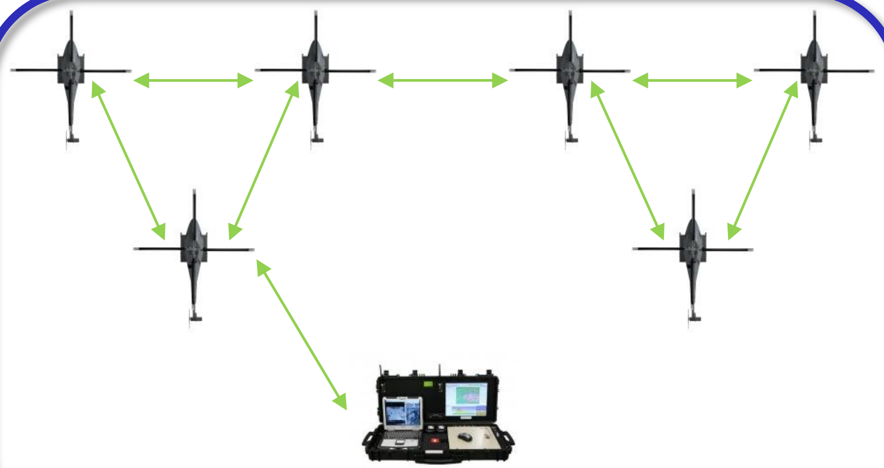
Actuator management is to realize smooth switching between the manual control mode and the automatic control mode. The requirements for the actuator management are listed as follows.



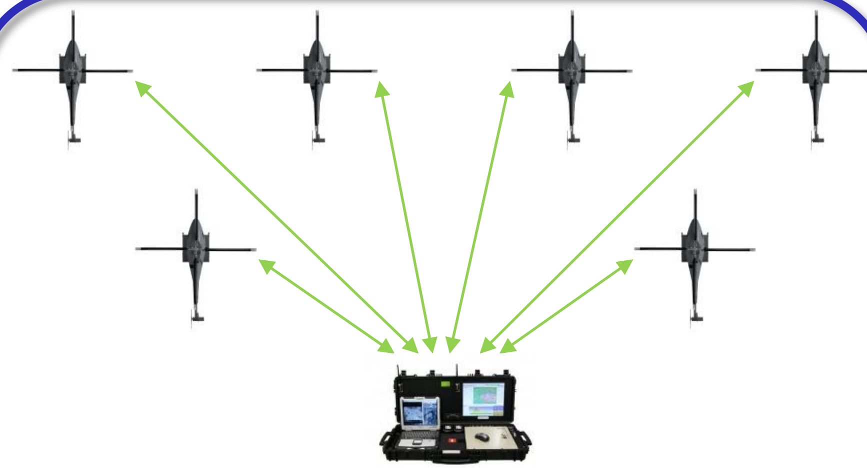
- Reliable switching function
- Sufficient input/output channels
- Capability of recording servo actuator's input signal
- High resolution

Communication unit

The communication units in the UAV system framework are deployed as interfaces between the UAV entity itself and external entities. The external entity can be the GCS for the ground operator, or another UAV entity for information exchange. With UAV to GCS communications, the operator can remotely control and monitor UAVs in operation. With inter-UAV communications, the UAV team can multiply their capability and effectiveness in cooperative tasks.



Decentralized Control



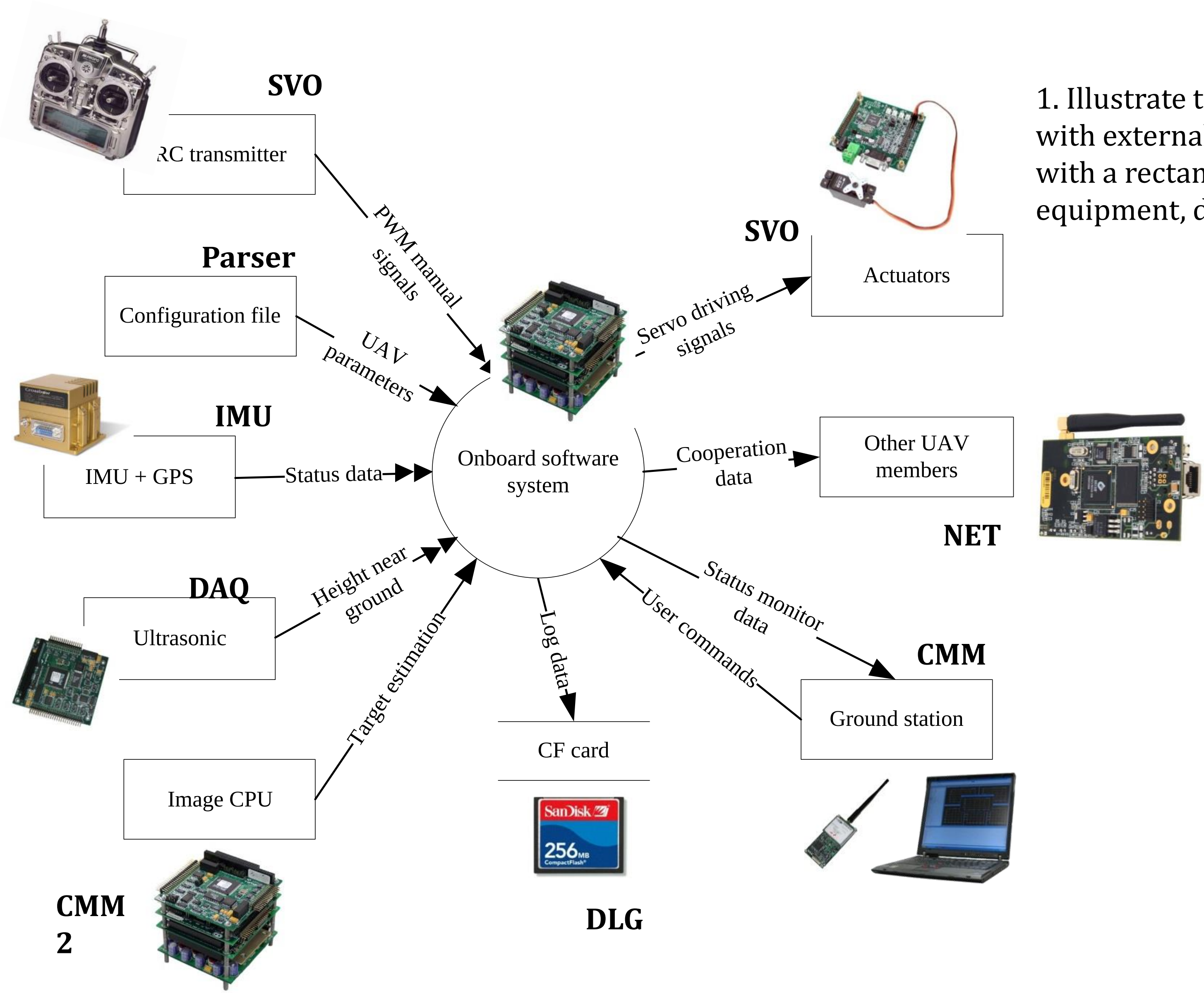
Centralized Control

Communication unit

The typical values of data bandwidth and communication range of those communication devices are summarized

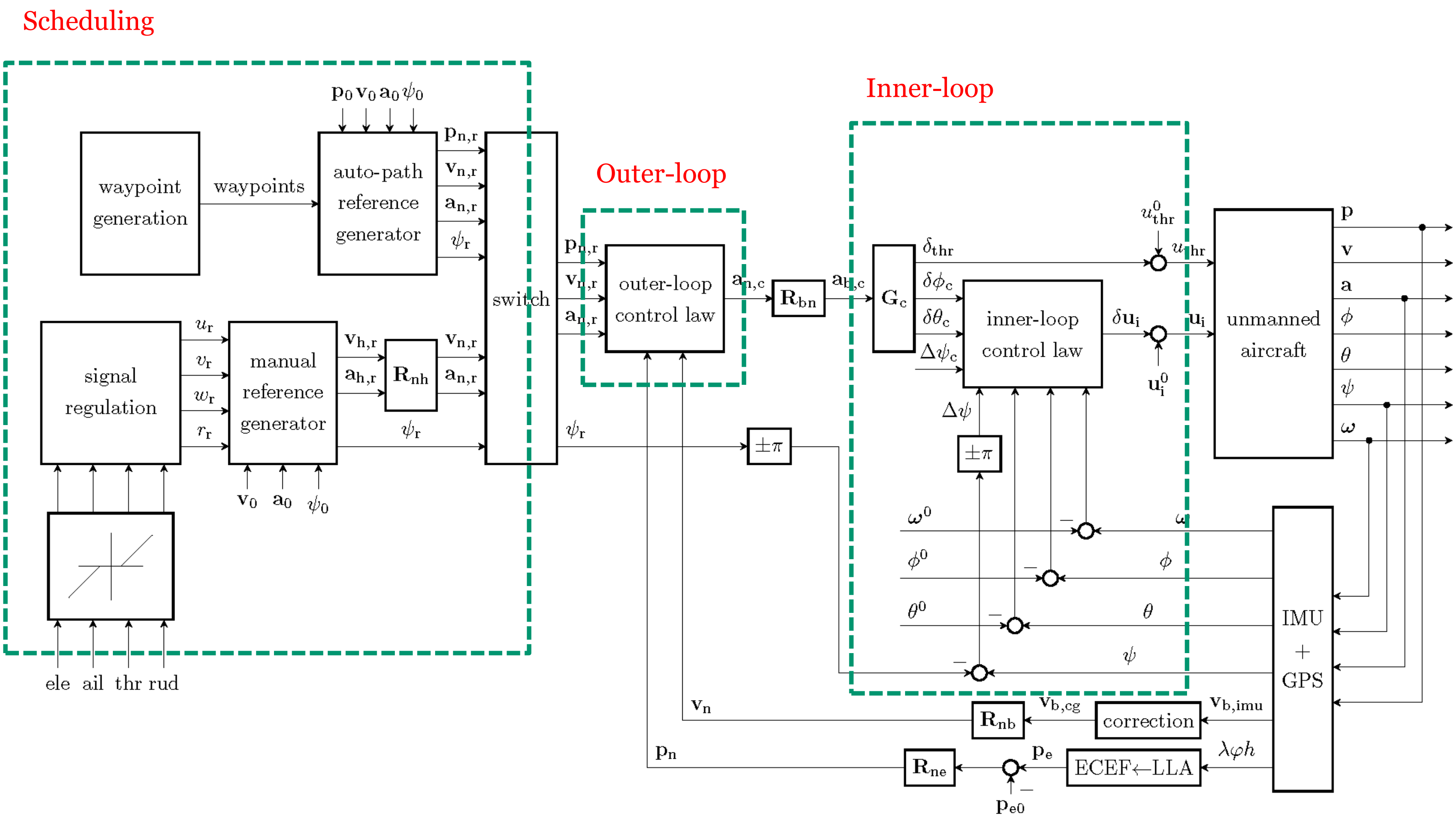
Communication module	Data bandwidth	Range	Protocol
UART interface	115200 bps	32 km	UART
802.11g	54 Mbps	250 m	TCP/IP
3G modem	300 kbps	Hundred km	TCP/IP
4G modem	5 Mbps	Hundred km	TCP/IP

Onboard software – data flow

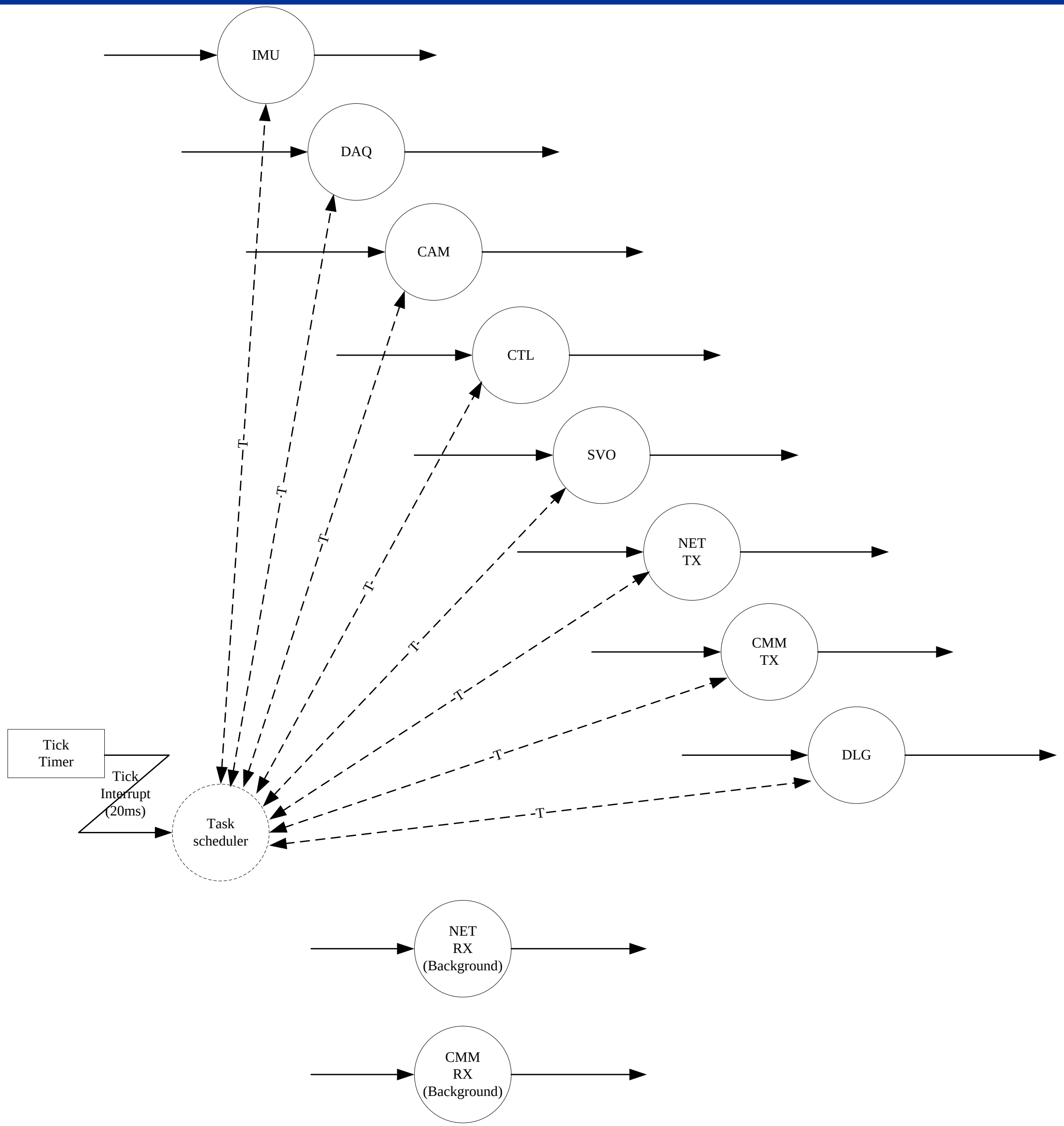


1. Illustrate the overall functionalities with external entities (represented with a rectangle box), such as users, equipment, data stores

Onboard software – control flow structure



Onboard software – task scheduling



1. Multitasking (Multithreading) is necessary for reliable real-time software

2. Task synchronization is realized via signal, IMU -> DAQ -> CAM -> CTL -> SVO -> NET -> CMM -> DLG

3. Background tasks are scheduled by the RTOS scheduler, will be activated once no other threads are working

4. Each working thread represents a state in the whole system behaviors

5. task scheduler manages the state transitions

Onboard software system – performance test

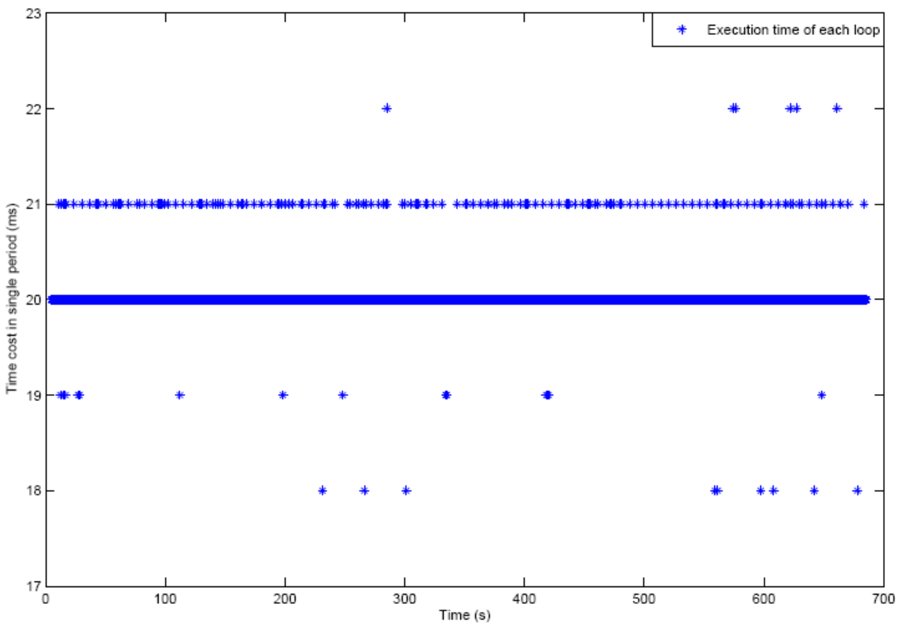


Figure 3.15: Time intervals between each loop.

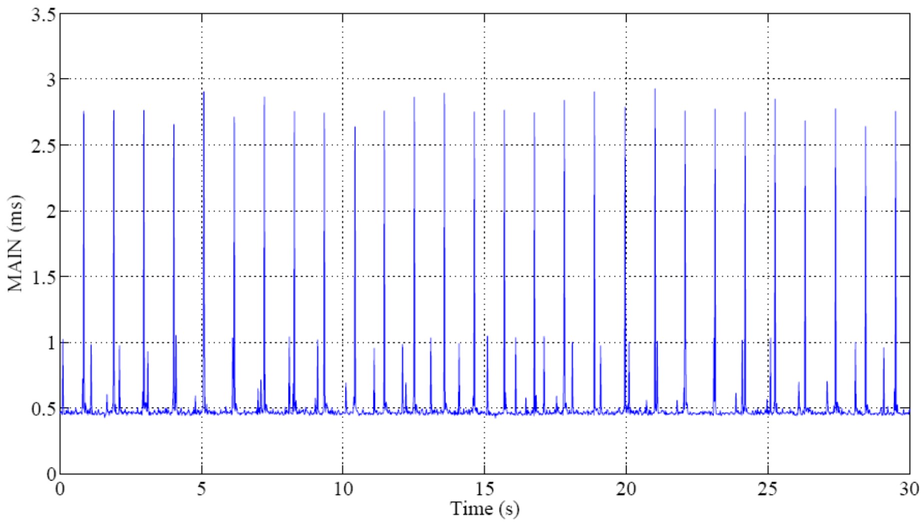
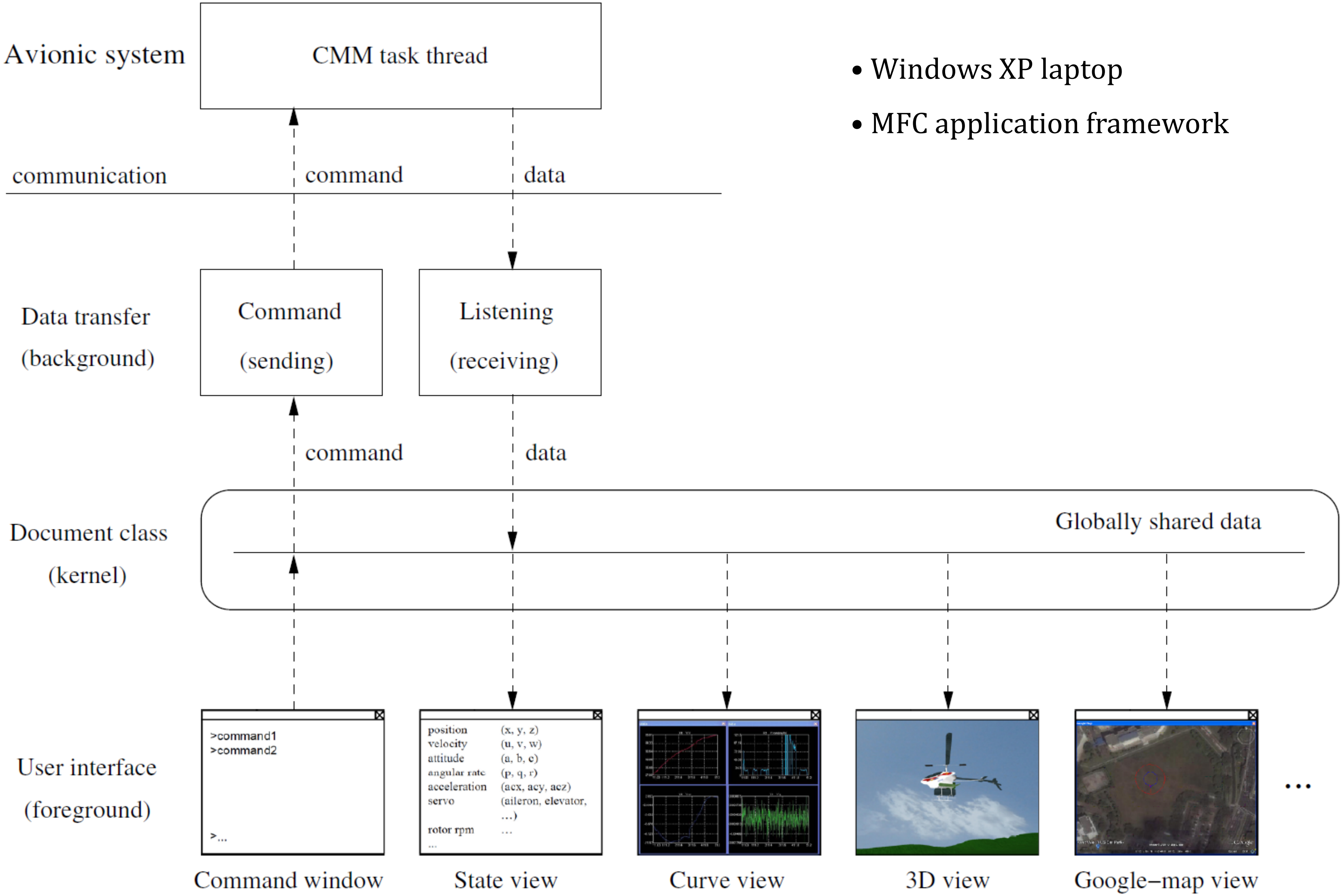


Figure 3.16: Time consumption statistics for main loop.

CPU maximum working load

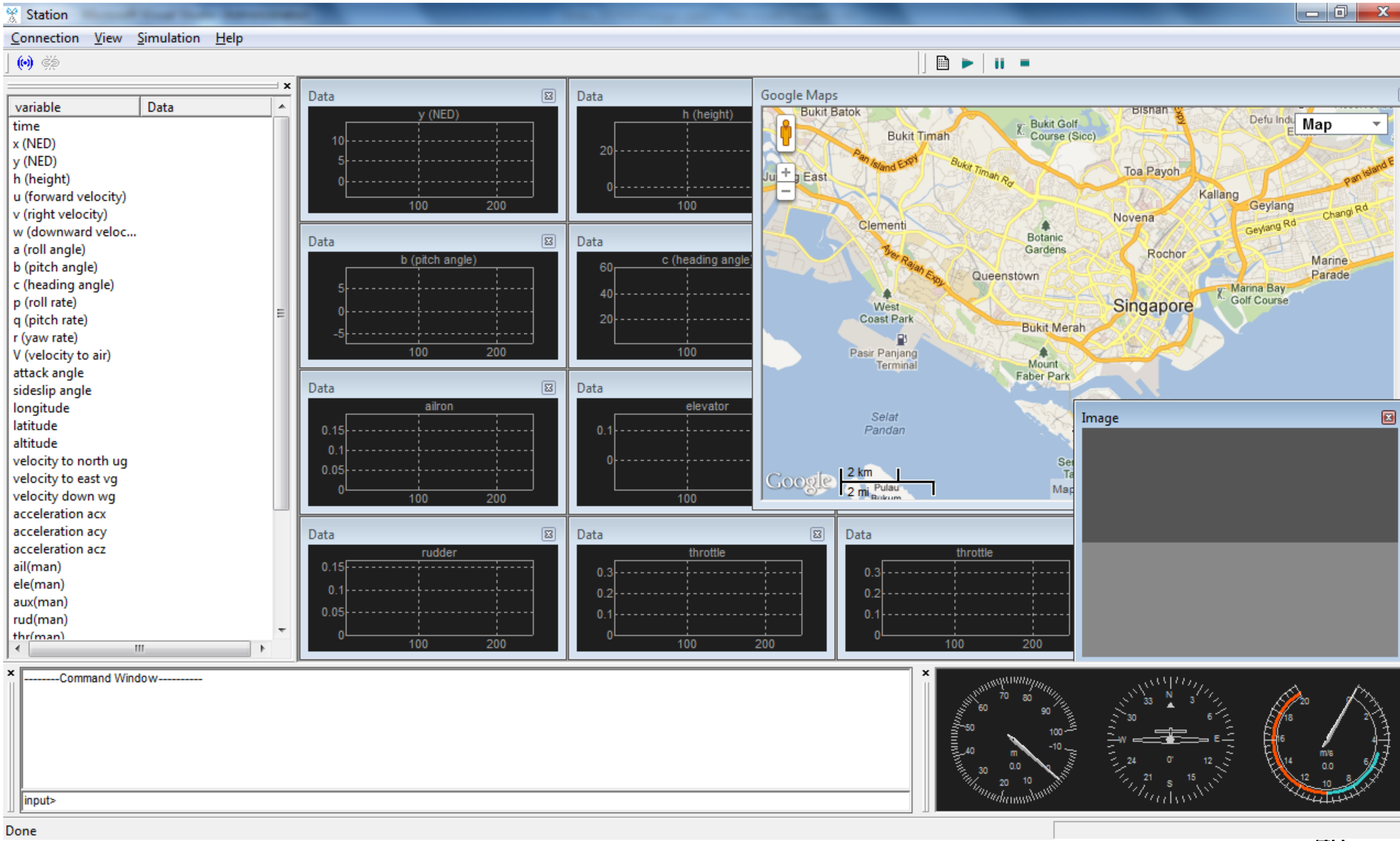
$$\text{usage}_{\max} = \tau_{\max}/T_{\text{cyc}} = 2.93/20 = 14.65\%$$

Ground control software system - framework



- Windows XP laptop
- MFC application framework

Ground control system – information monitoring



Construction of avionic system… introduction

- For ease of understanding, we in this section use one of our UAV platforms, named HeLion, for illustration.

- The methodology we proposed consists of four key steps:

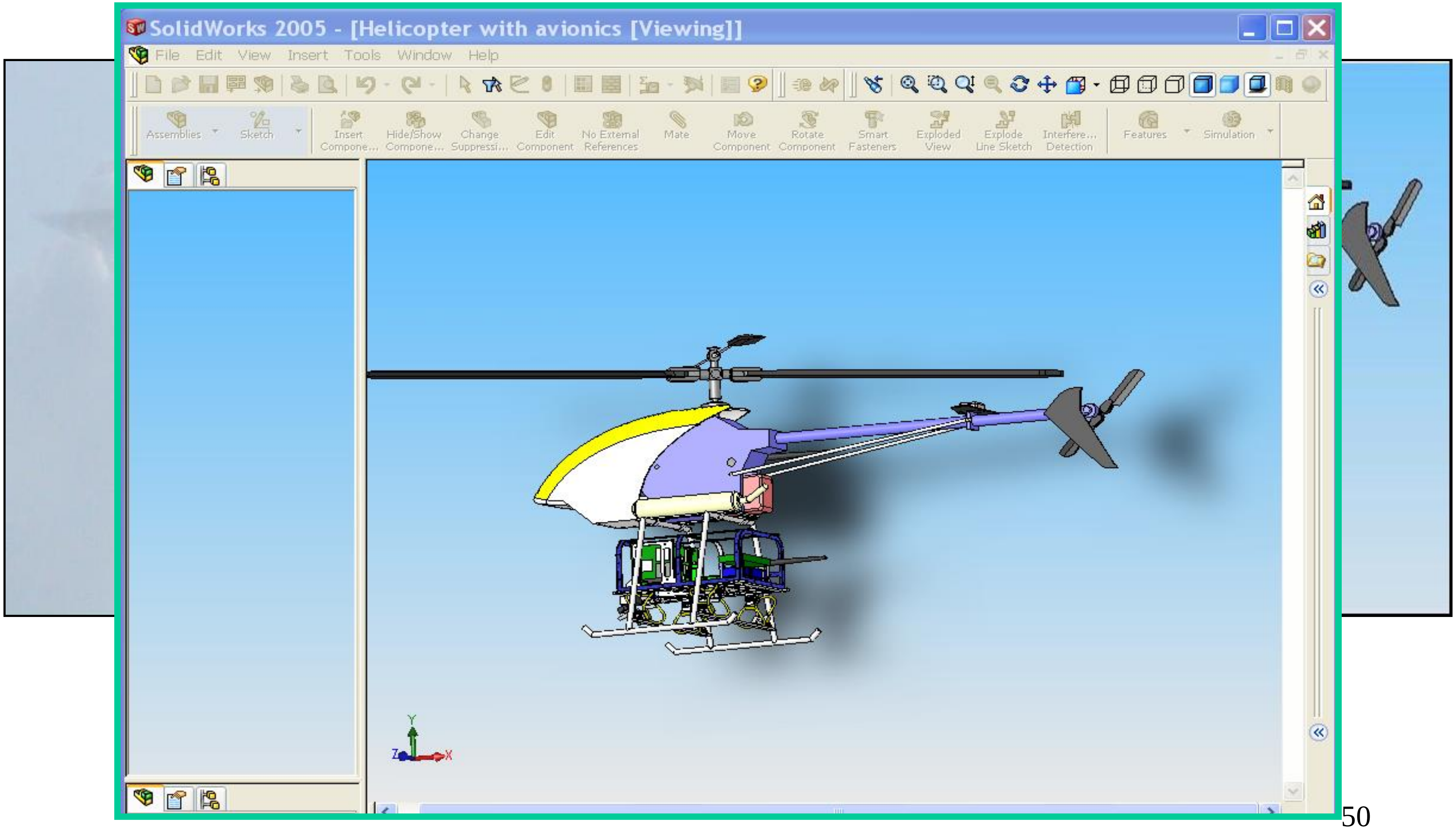
  1) Virtual Design Environment Selection

  2) Hardware Components Selection

  3) Layout Design and Integration

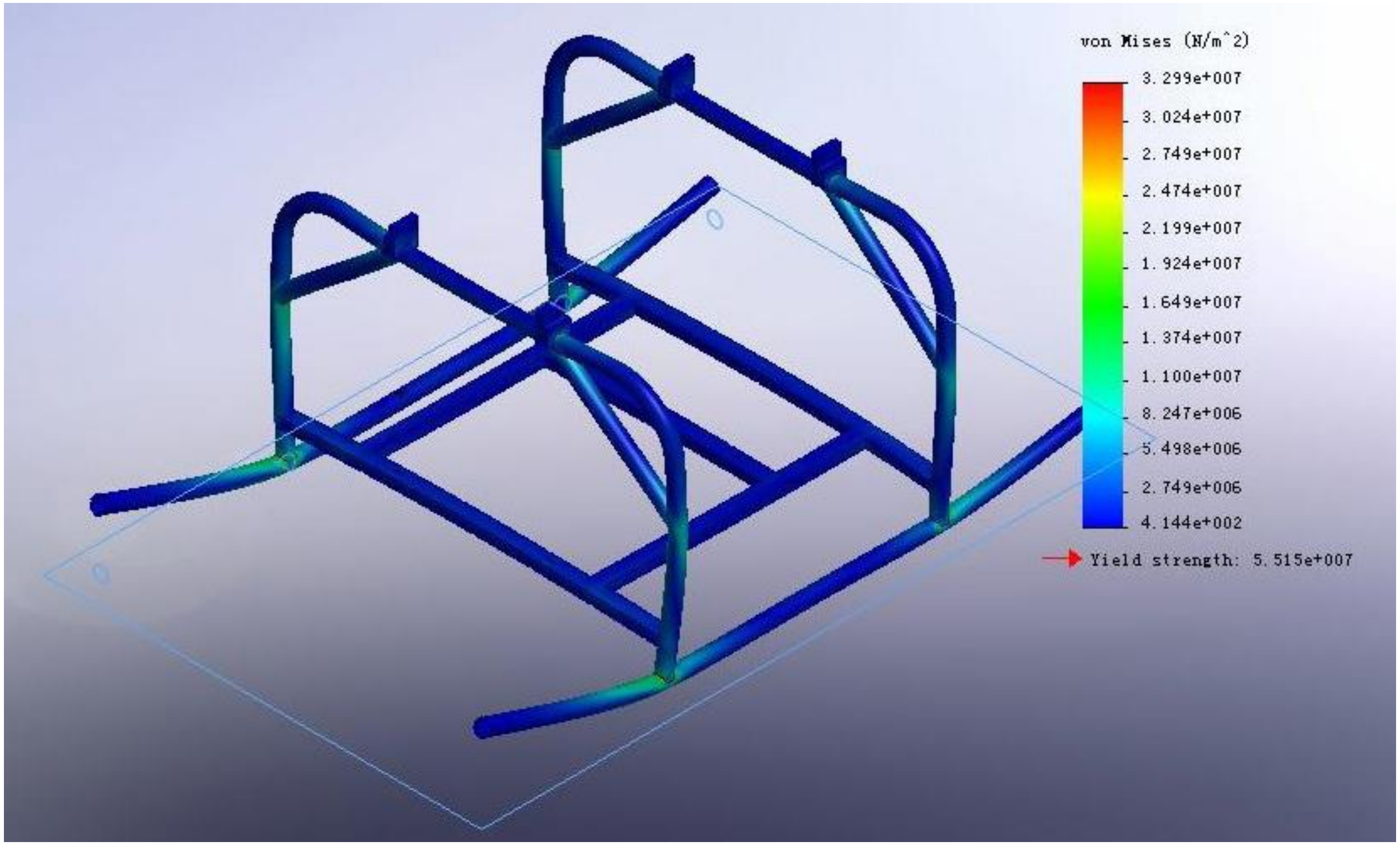
  4) Reliability Evaluation

Step 1: Virtual design environment (VDE) Selection: SolidWorks



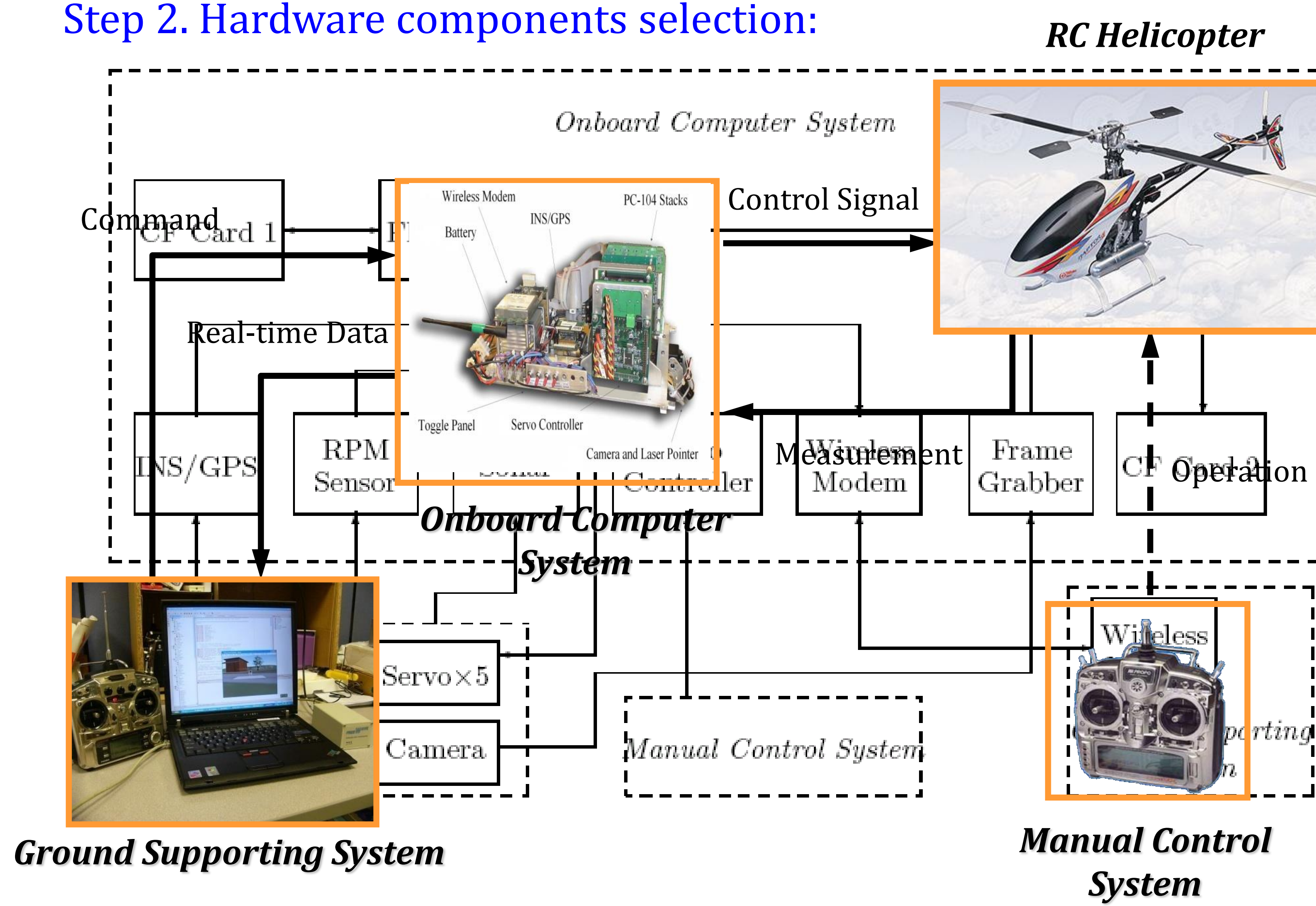
Construction of avionic system… VDE selection

Mechanical structure design and modeling



Construction of avionic system… components selection

Step 2. Hardware components selection:

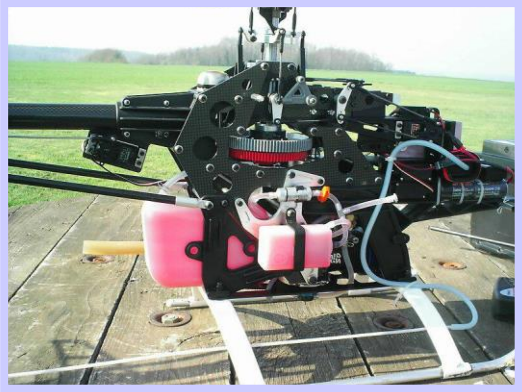


Construction of avionic system… components selection

Step 2. Hardware components selection:

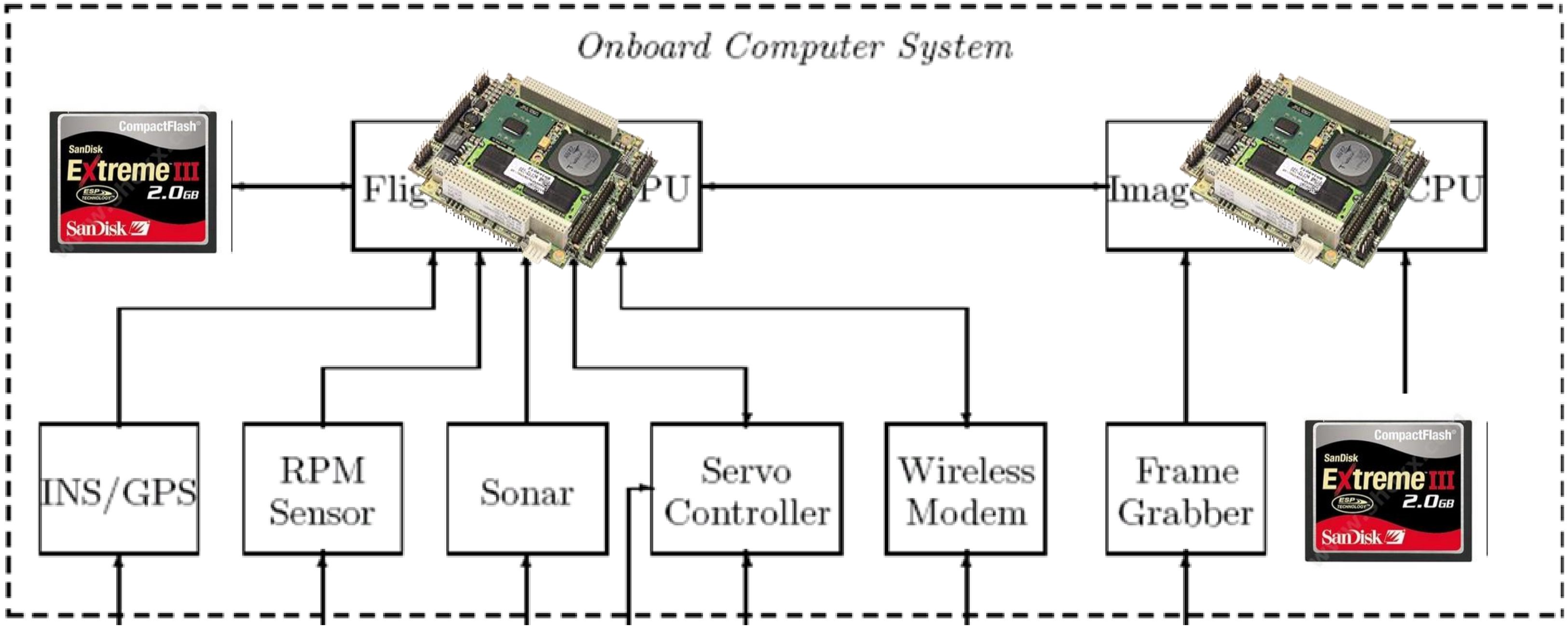
RC helicopter: Raptor 90 SE

- Rotor Span - 1.52 m
- Max Payload - 5 kg
- Max Flight Endurance - 15 minutes
- Maneuverability - 3D acrobatic flight
- Reliable design



Construction of avionic system… components selection

Step 2. Hardware components selection:

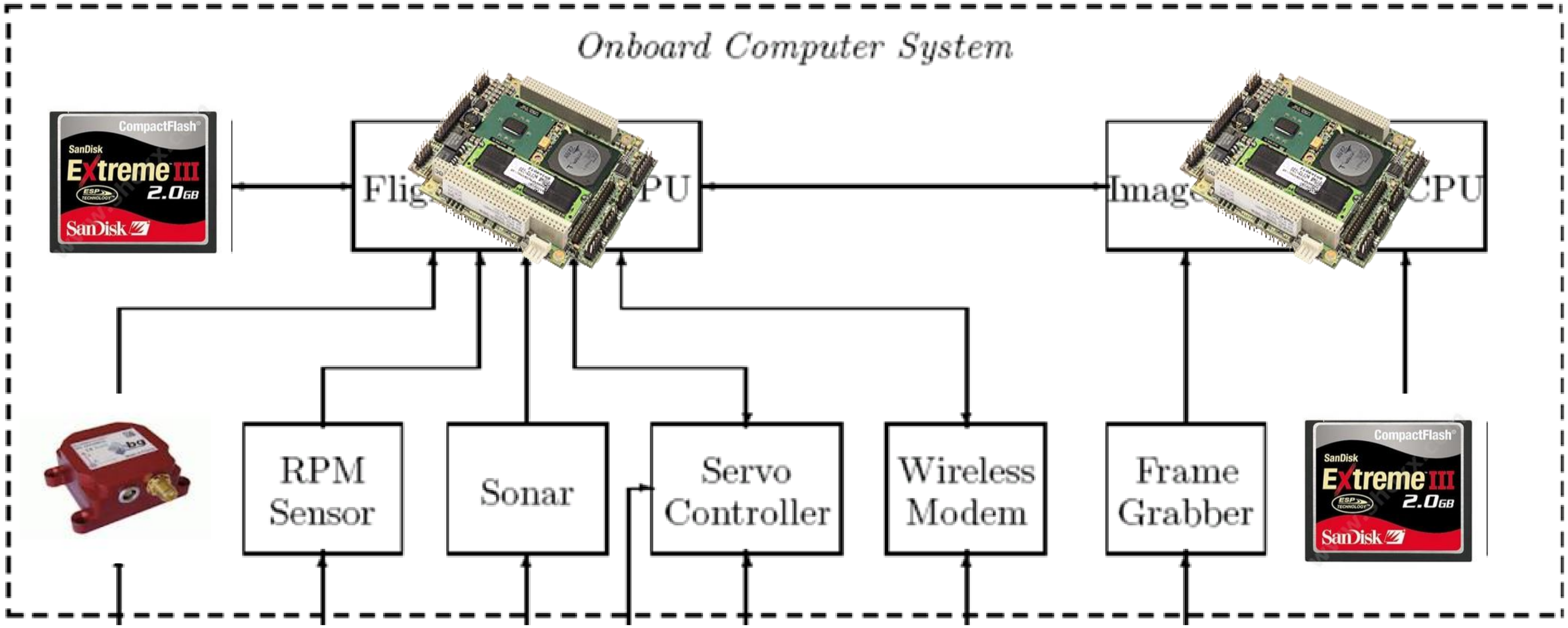


Reason for selection:

1. Industry/military level reliability
2. Sufficient computational power
3. Small and standard size
4. Good expendability
5. Drive support for real-time OS

Construction of avionic system… components selection

Step 2. Hardware components selection:

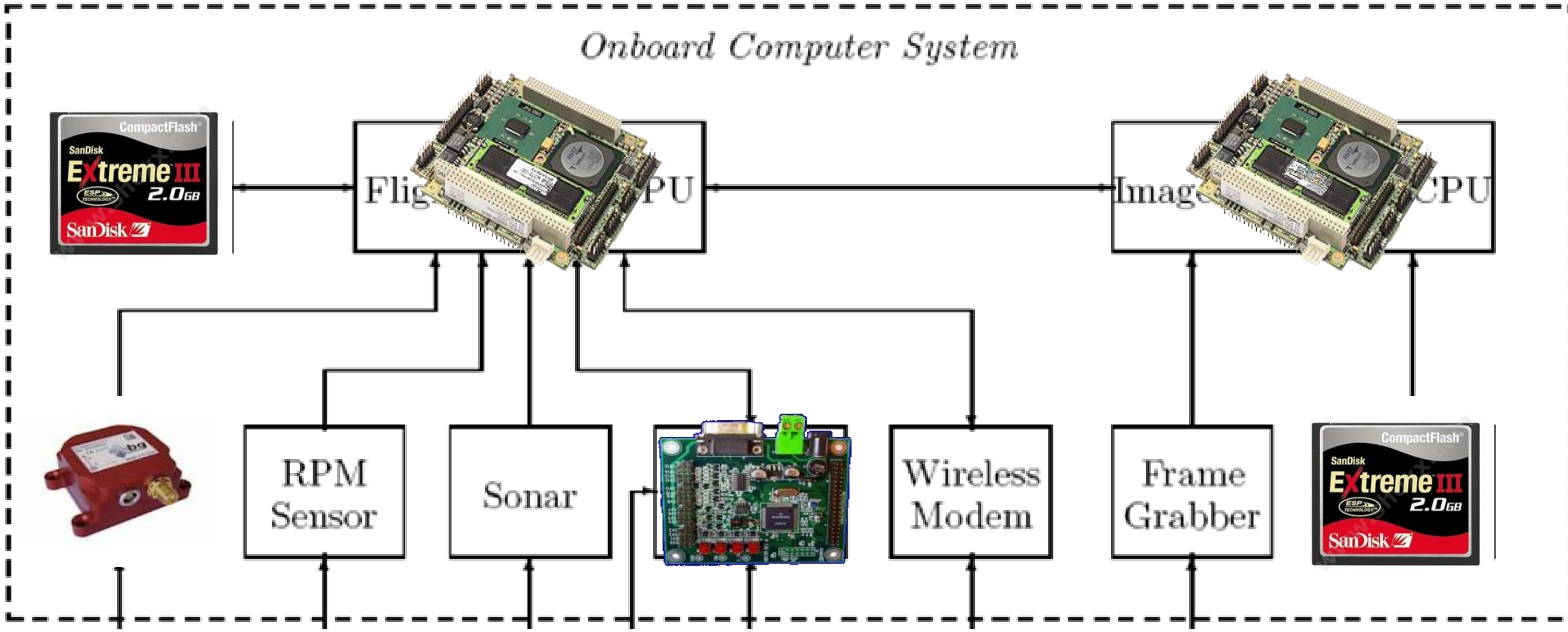


Reason for selection:

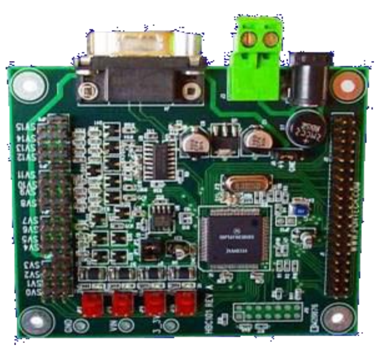
1. Complete data package for modeling and control
2. Precise calibration for raw sensors
3. Extended Kalman filter design
4. Sufficient update rate up to 100 Hz
5. Anti-vibration and EMI design

Construction of avionic system… components selection

Step 2. Hardware components selection:



HBC-101 Servo Ctrl Bd

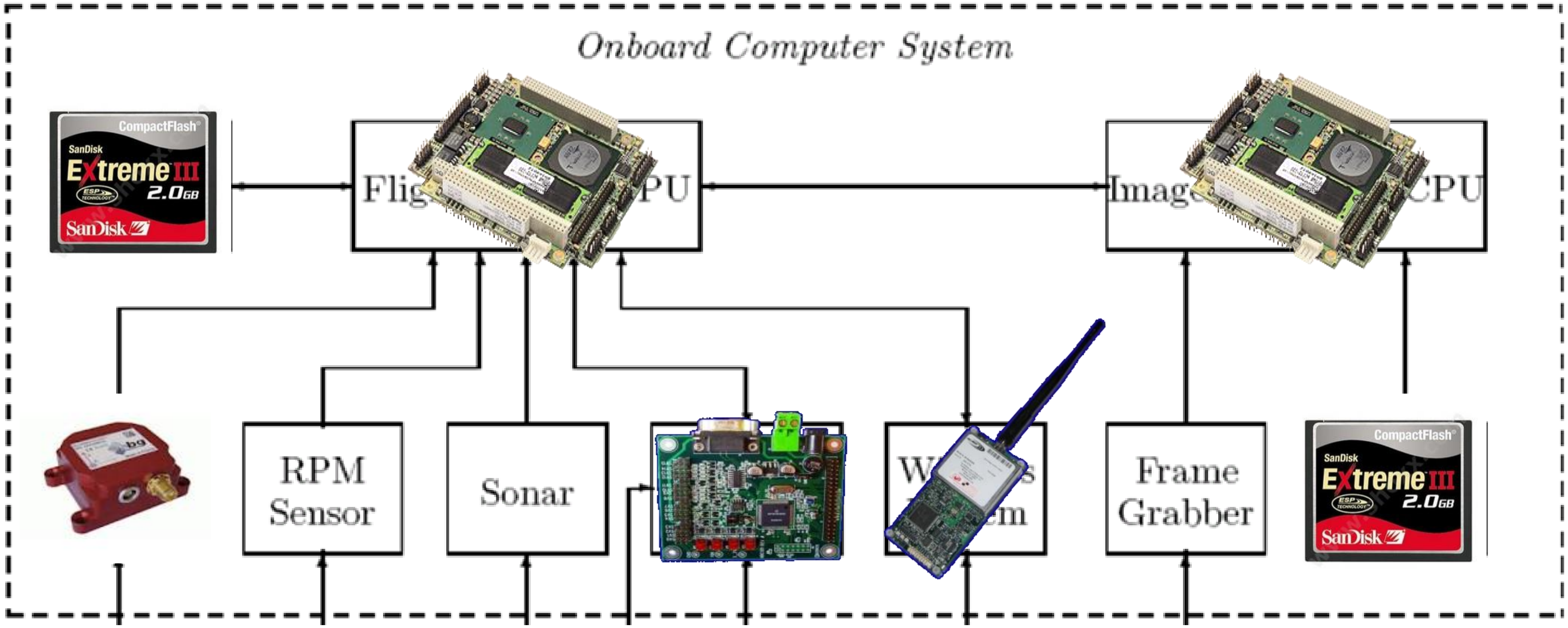


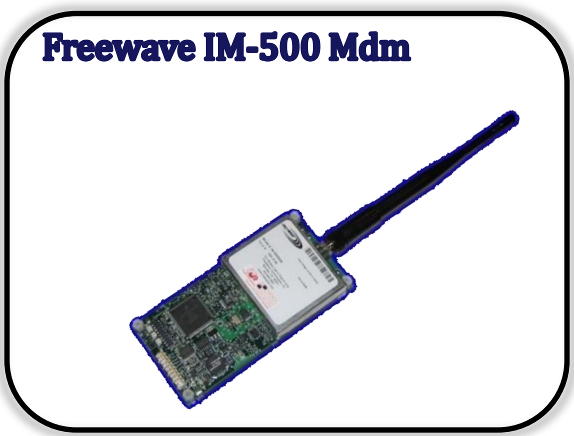
Reason for selection:

1. Input signal recording for modeling and control
2. Reliable manual/auto switching function
3. Sufficient input/output channels for extension
4. High A/D resolution (16-bit)

Construction of avionic system… components selection

Step 2. Hardware components selection:



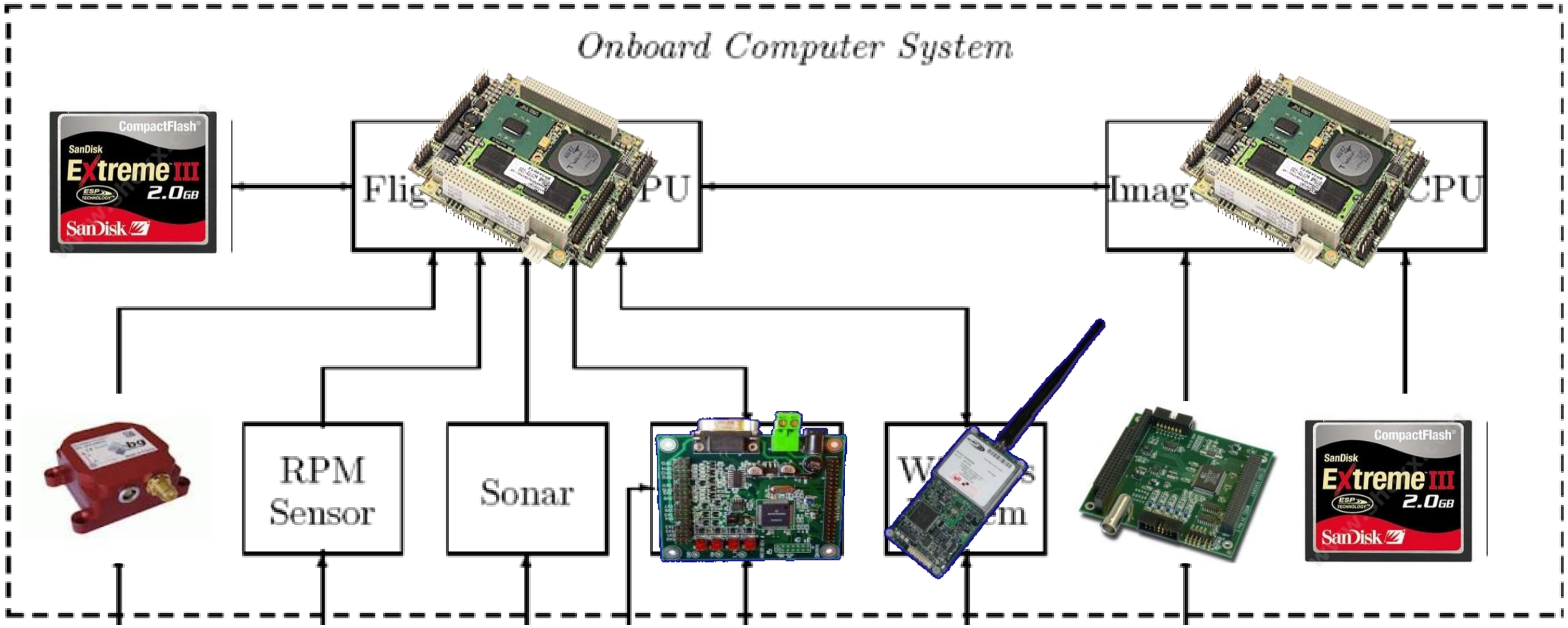


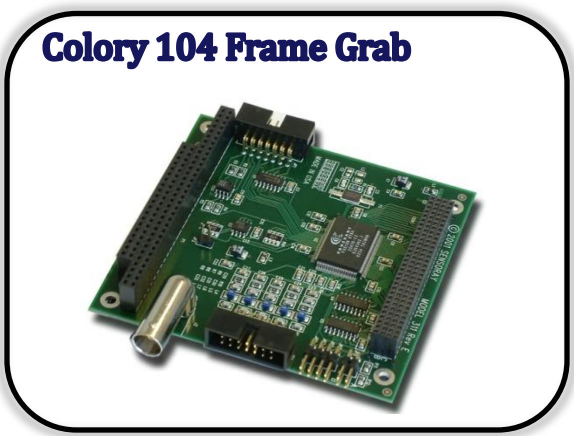
Reason for selection:

1. Extremely long range up to 32 km
2. Small size and ultra light weight
3. Plug-in-and-play configuration
4. Sufficient throughput rate

Construction of avionic system... components selection

Step 2. Hardware components selection:



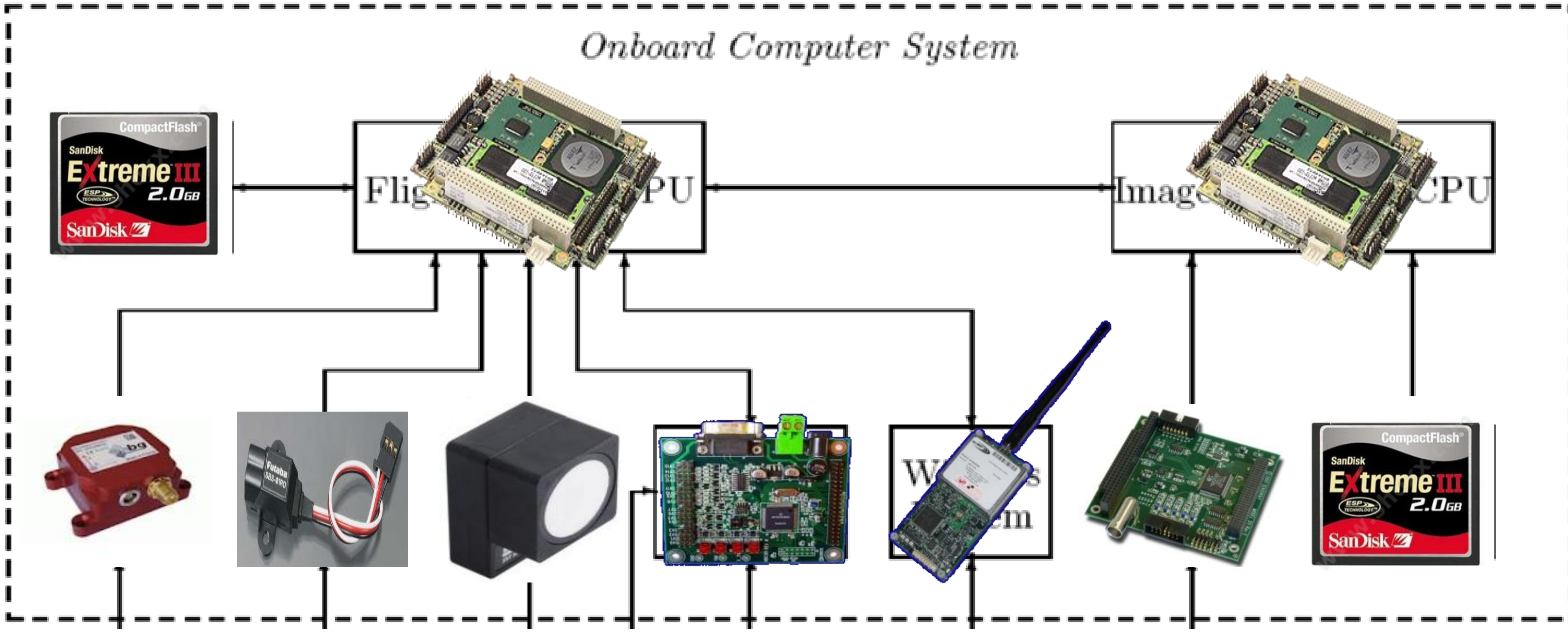


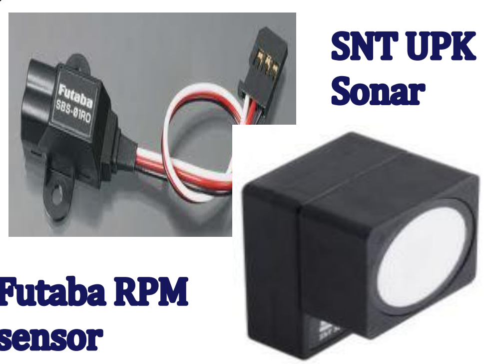
Reason for selection:

1. Sufficient resolution up to 720*576 pixels
2. Processing rate up to 30 FPS
3. Plug-in-and-play configuration
4. Parallel image processing to 2 formats

Construction of avionic system… components selection

Step 2. Hardware components selection:





SNT UPK Sonar

Futaba RPM sensor

Reason for selection:

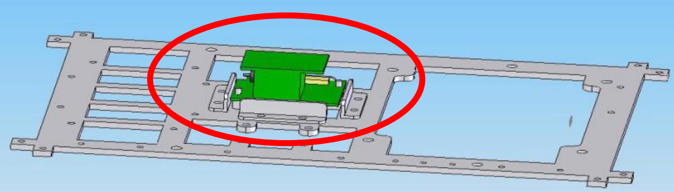
1. Light weight and small size
2. Sufficient precision
3. Easy for customization and mounting

Construction of avionic system… layout design

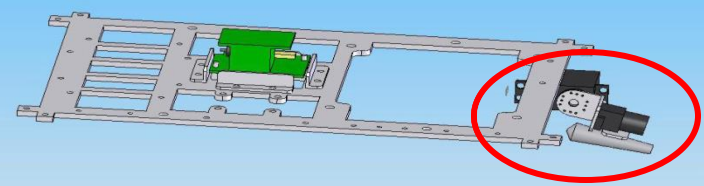
Step 3. Layout Design and Integration:

Onboard layout design

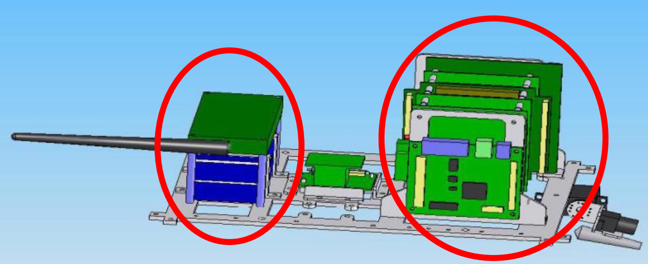
Determining the location of INS/GPS



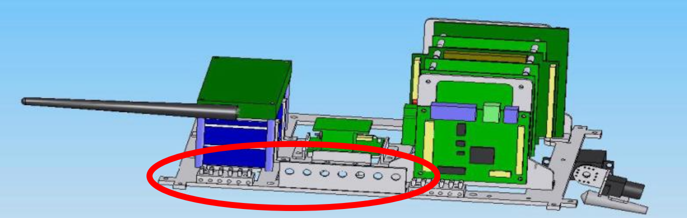
Determining the location of the camera and laser pointer



CG balancing

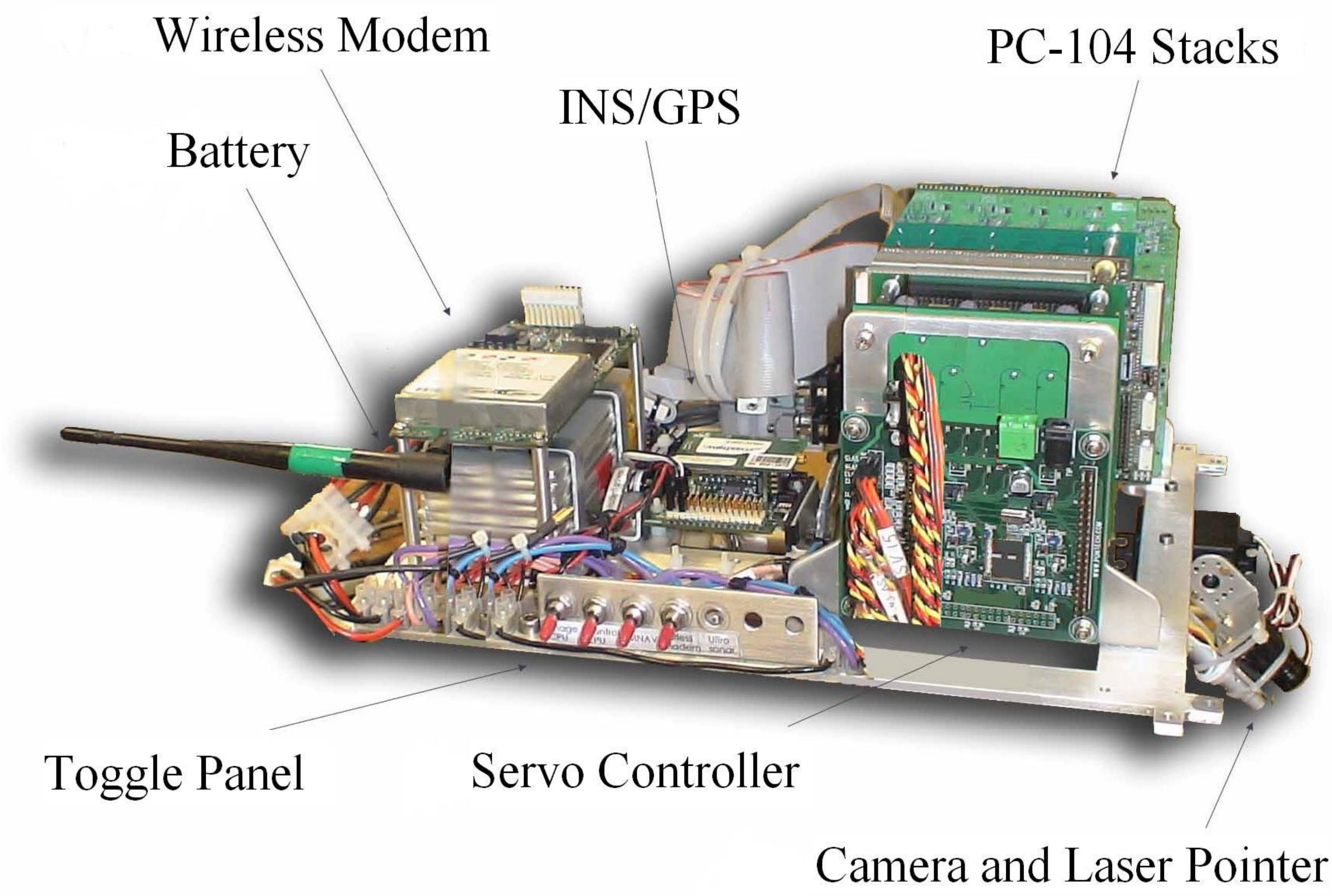


Locating the remaining components

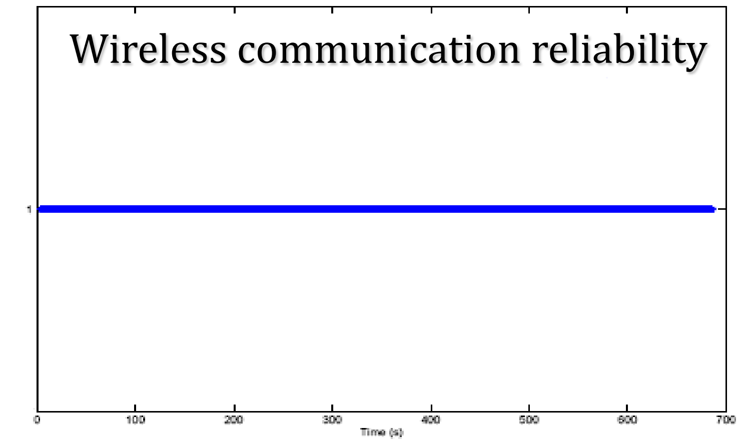


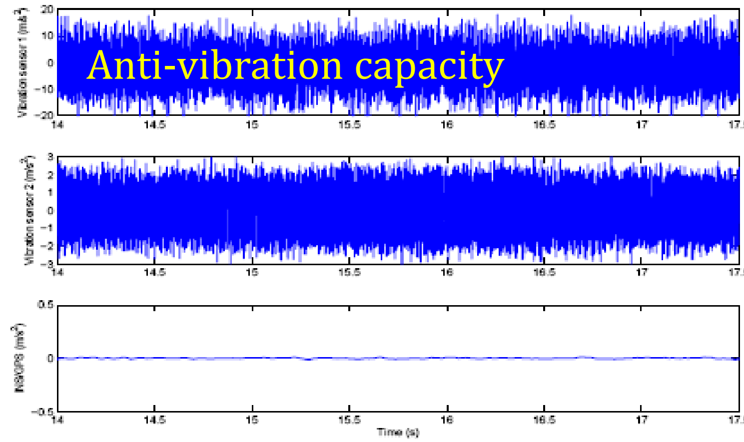
Construction of avionic system… layout design

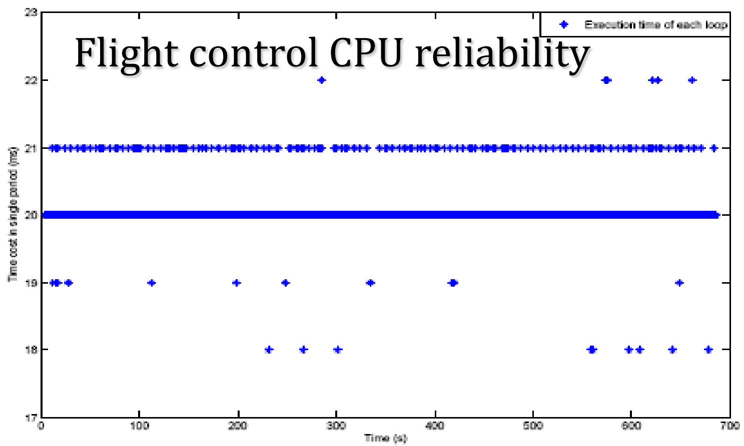
Step 3. Layout Design and Integration:

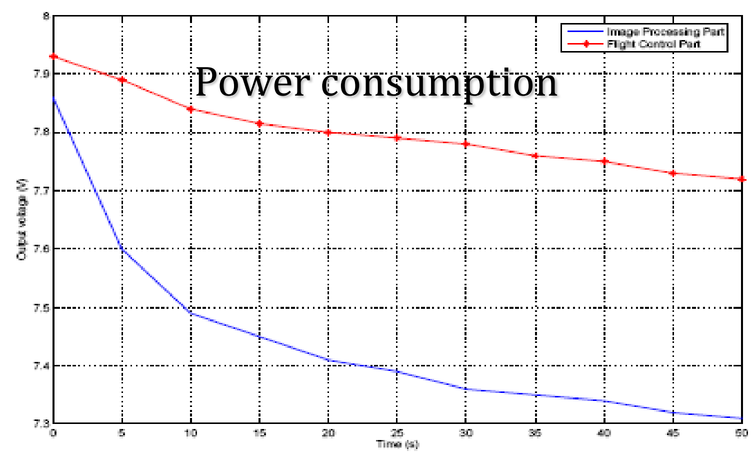


Step 4. Reliability Evaluation:



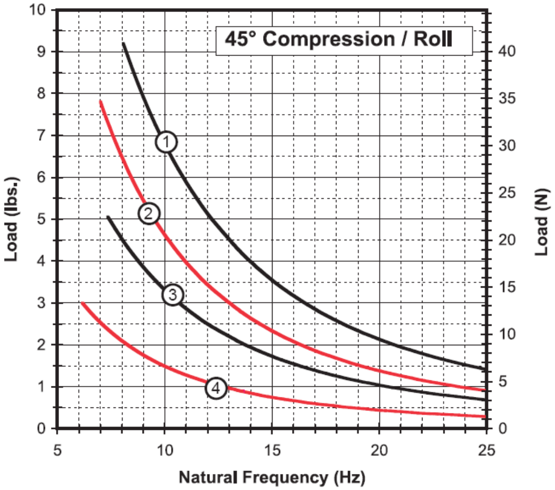


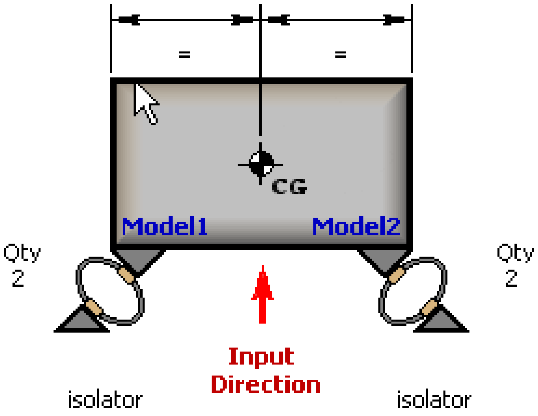


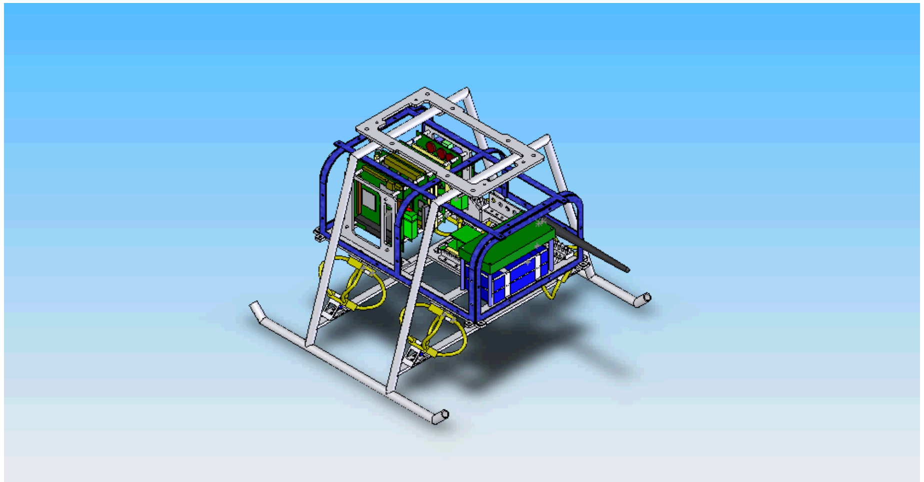


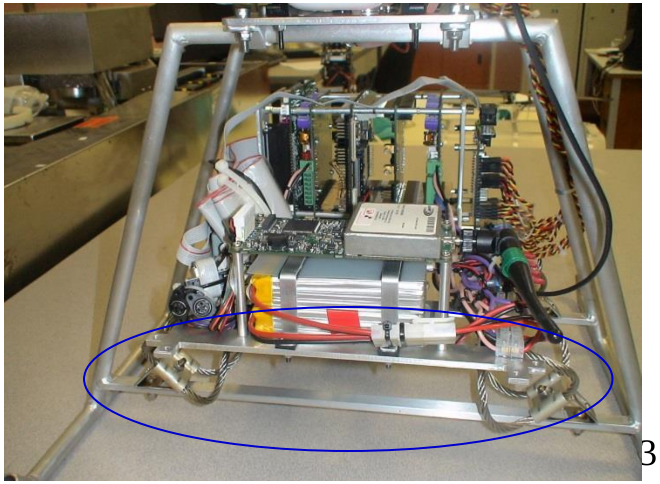
Construction of avionic system… reliability evaluation

Vibration isolation mount

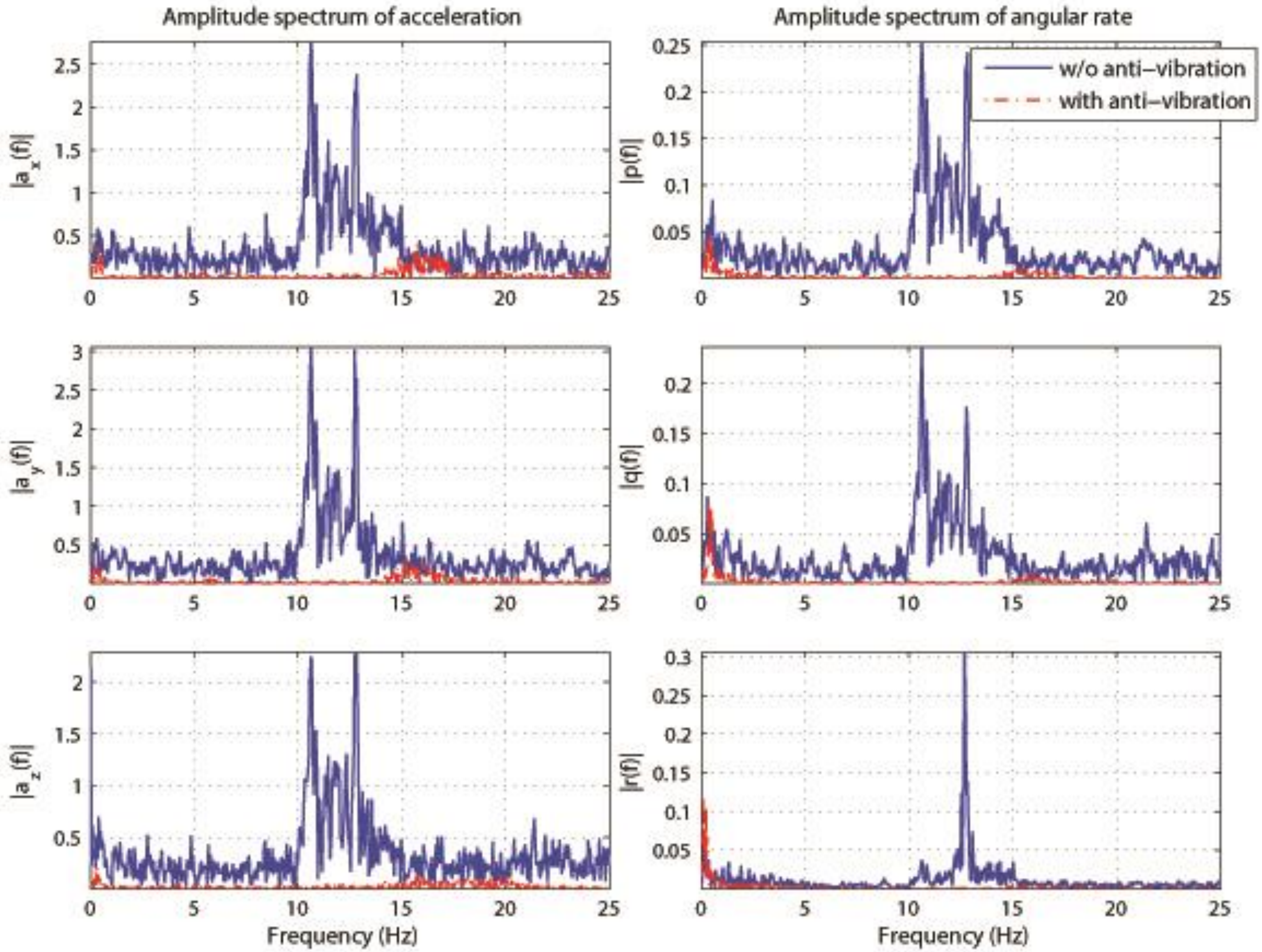








Anti-vibration test



GPS-less, map-less vision-based navigation

- Motivation:
  - Low-cost INS with MEMS sensors
  - GPS-denied and unknown environments (without reference map)
  - Assume relatively flat ground

Inertial Measurement Units (IMUs) are widely used for navigation of various vehicles.

- Measure acceleration *a* and angular rate *ω*.
- To estimate position *p*, velocity *v* and attitude *ρ*:

$$\int a \Longrightarrow v, \quad \int v \Longrightarrow p, \quad \int \omega \Longrightarrow \rho$$

Pure inertial navigation drifts rapidly for low-cost and light-weight IMUs due to measurement noises and biases.

GPS-less, map-less vision-based navigation

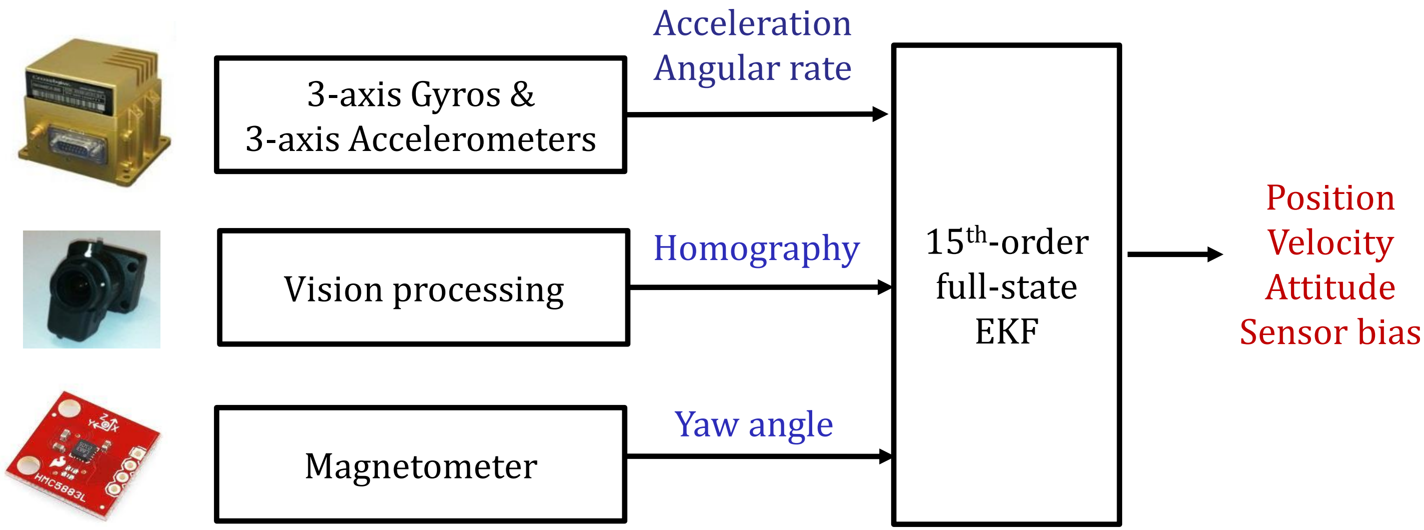
Problem statement:
- Navigation of small-scale unmanned aerial vehicles (UAVs)
- Very limited computational resources
- Low-cost IMU with unknown measurement biases
- GPS-denied environments, unmapped environments

Objective: use a minimal sensor suite with an IMU as the core sensor to obtain
- Unknown measurement bias: estimate and compensate
- Attitude and velocity: drift-free
- Position: reduce drift significantly

We choose visual odometry because
1) Very limited onboard computational resources
2) Low-definition images
3) Near homogenous environment
4) Mapping is not required

Sensor fusion structure

- The structure of our vision-aided inertial navigation system is shown as follows:



Measurements:

- UAV acceleration: $\mathbf{a}_{\mathrm{nb,IMU}} \in \mathbb{R}^3$
- UAV angular rate: $\boldsymbol{\omega}^{\mathrm{b}}_{\mathrm{b/n,IMU}} \in \mathbb{R}^3$
- Homography: $\mathbf{H}_{\mathrm{vis}} \in \mathbb{R}^{3\times 3}$
- UAV altitude: $p_{\mathrm{n},z} \in \mathbb{R}$
- UAV heading angle: $\psi \in \mathbb{R}$

States to be estimated:

- UAV position: $\mathbf{p}_{\mathrm{n}} \in \mathbb{R}^3$
- UAV velocity: $\mathbf{v}_{\mathrm{n}} \in \mathbb{R}^3$
- UAV attitude: $\boldsymbol{\rho} \in \mathbb{R}^3$
- IMU acceleration measurement bias: $\mathbf{b}_a \in \mathbb{R}^3$
- IMU angular rate measurement bias: $\mathbf{b}_\omega \in \mathbb{R}^3$

EKF: process model

The IMU measurements enter the system as inputs.

$$\mathbf{a}_{\mathrm{nb,IMU}} = \mathbf{a}_{\mathrm{nb}} - \mathbf{b}_a - \mathbf{w}_a,$$
$$\boldsymbol{\omega}^{\mathrm{b}}_{\mathrm{b/n,IMU}} = \boldsymbol{\omega}^{\mathrm{b}}_{\mathrm{b/n}} - \mathbf{b}_\omega - \mathbf{w}_\omega,$$

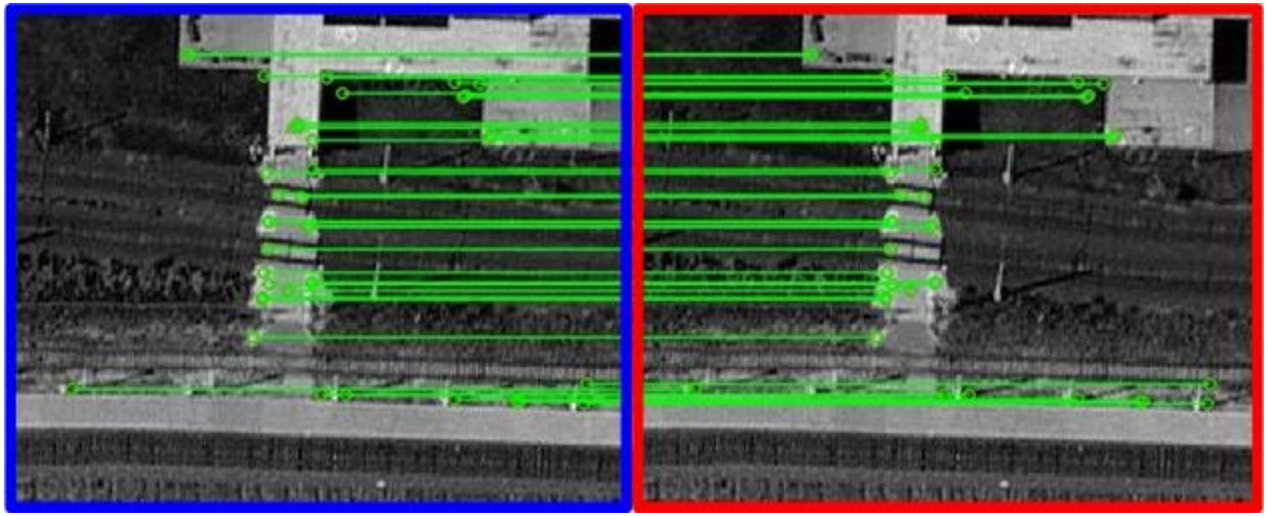
where $\mathbf{b}_a \in R^3$ and $\mathbf{b}_\omega \in R^3$ are unknown but constant measurement biases; and $\mathbf{w}_a \in R^3$ and $\mathbf{w}_\omega \in R^3$ are zero-mean Gaussian white noises.

- The 6-DOF motion equation of the UAV is

$$\begin{bmatrix} \dot{\mathbf{p}}_{\mathrm{n}} \\ \dot{\mathbf{v}}_{\mathrm{n}} \\ \dot{\rho} \\ \dot{\mathbf{b}}_a \\ \dot{\mathbf{b}}_\omega \end{bmatrix} = \begin{bmatrix} \mathbf{v}_{\mathrm{n}} \\ \mathbf{R}_{\mathrm{n/b}}(\mathbf{a}_{\mathrm{nb,IMU}} + \mathbf{b}_a + \mathbf{w}_a) + g\mathbf{e}_3 \\ \mathbf{L}_{\mathrm{n/b}}(\boldsymbol{\omega}^{\mathrm{b}}_{\mathrm{b/n,IMU}} + \mathbf{b}_\omega + \mathbf{w}_\omega) \\ \mathbf{0}_{3\times 1} \\ \mathbf{0}_{3\times 1} \end{bmatrix}$$

EKF: measurement model

- How to compute homography from two images?



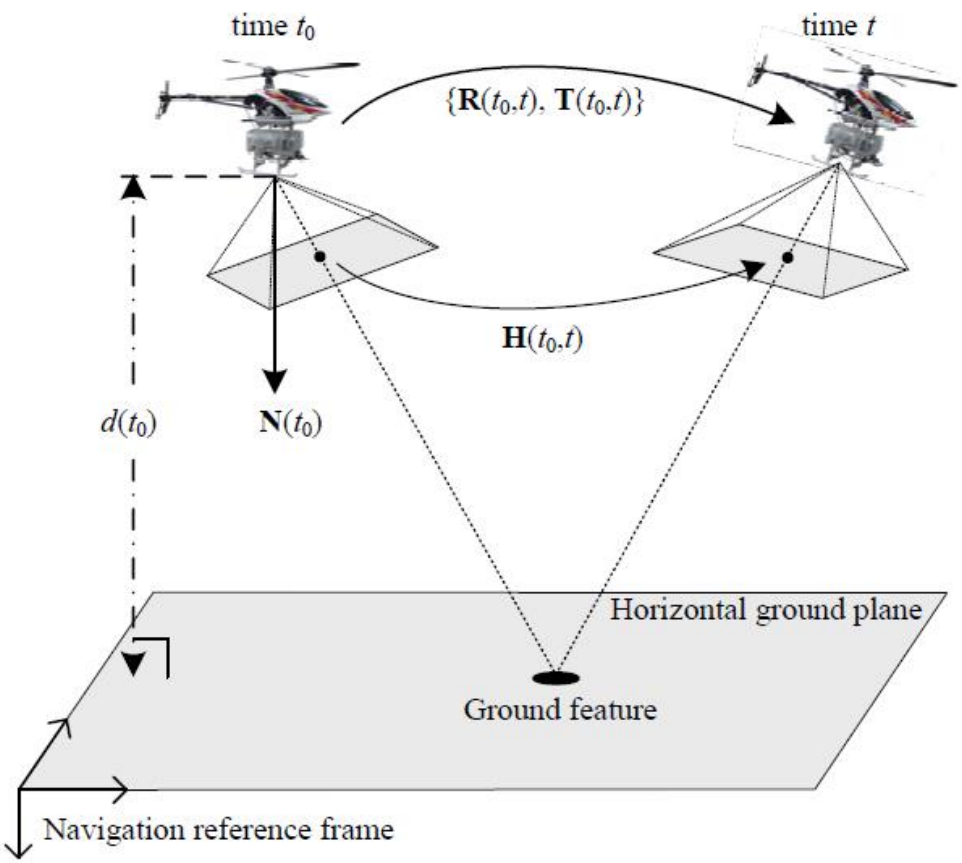
Two Images → Feature extraction → Feature matching → Homography matrix $H \in R^{3x3}$

If two images are identical, $H = I_{3x3}$

Assumption: horizontal ground This assumption is usually valid for indoor environments and outdoor environments when UAV flies at a high altitude.

EKF: measurement model

- What information does a homography have?



Homography contains rich motion information of the UAV:

$$\mathbf{H}(t_0, t) = \mathbf{R}(t_0, t) + \frac{1}{d(t_0)}\mathbf{T}(t_0, t)\mathbf{N}(t_0)^{\mathrm{T}}$$

EKF: measurement model

Measurement model for vision:

$$\mathbf{y}_{\text{vis}} = \text{vec}\mathbf{H}_{\text{vis}} = \text{vec}\mathbf{H} + \mathbf{n}_{\text{vis}}$$

Measurement model for compass:

$$y_{\text{comp}} = \psi + n_{\text{comp}}$$

Measurement model for barometer:

$$y_{\text{baro}} = p_{\text{n},z} + n_{\text{baro}}$$

- The vision measurement model is highly nonlinear in the UAV states.
- With the above process and measurement models, we can apply the EKF. The procedure is standard and omitted here.

Observability analysis

- **Recall our aim**: obtain drift-free velocity and attitude estimates.
- **Question**: can the proposed navigation system achieve that aim?
- **Answer**: YES by observability analysis.

Linearize the nonlinear process and measurement models at the following straight and steady level (SSL) flight condition.

$$\phi = \theta = \psi = 0, \quad \boldsymbol{\omega}^{\mathrm{b}}_{\mathrm{b/n}} = \mathbf{0}_{3\times 1}, \quad \mathbf{a}_{\mathrm{nb}} = -g\mathbf{e}_3, \quad \mathbf{v}_{\mathrm{n}} = \kappa \mathbf{e}_1$$

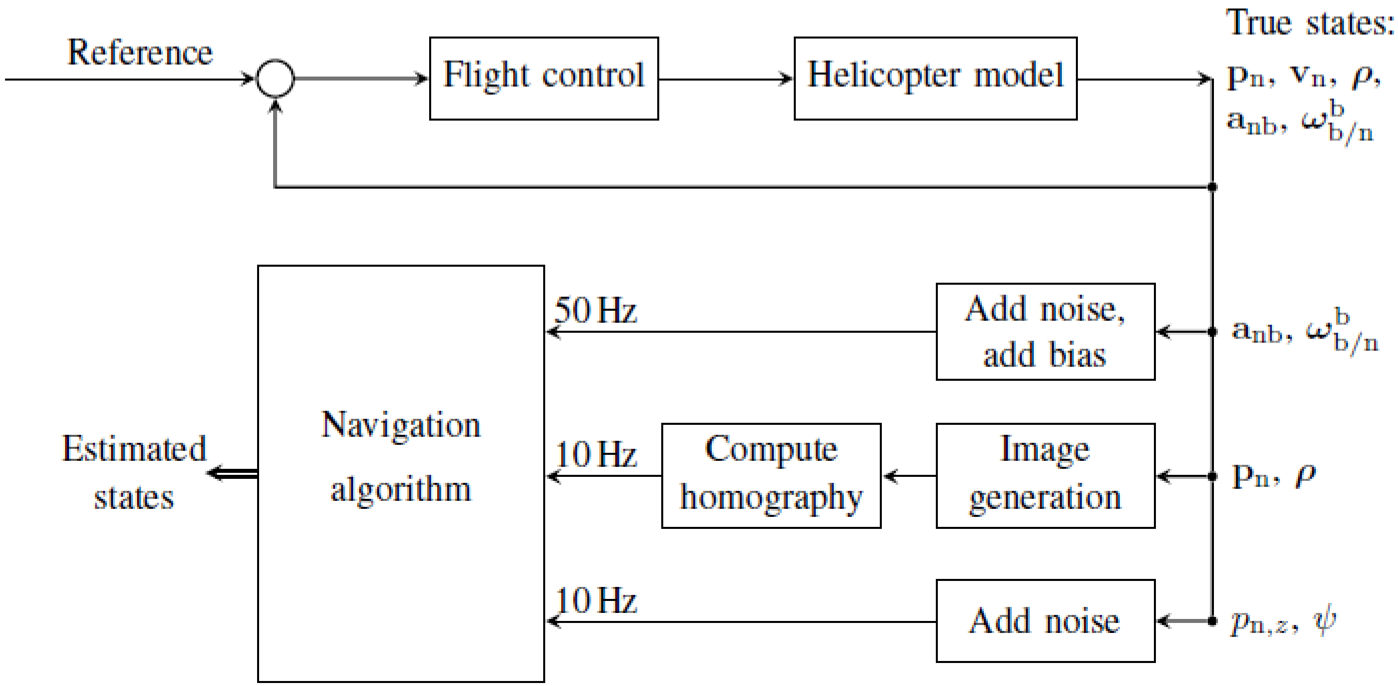
Observability matrix:

$$\mathcal{O} = \left[\mathbf{C}^{\mathrm{T}}, (\mathbf{CA})^{\mathrm{T}}, \cdots, (\mathbf{CA}^{14})^{\mathrm{T}}\right]^{\mathrm{T}}$$

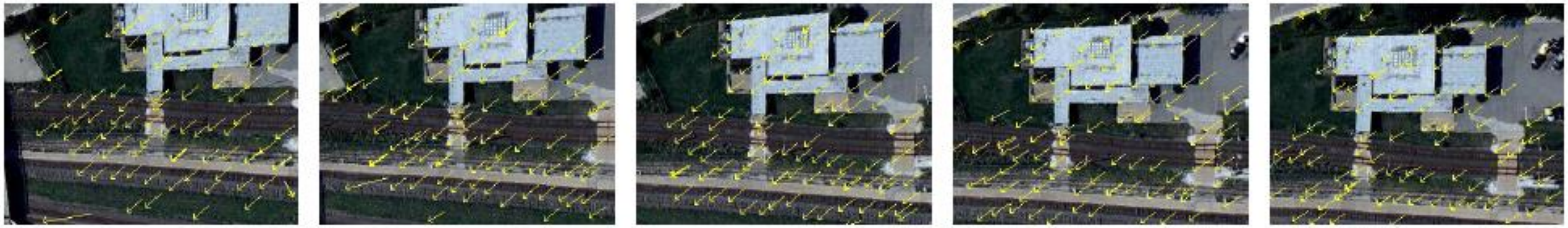
Observability Analysis Conclusions

- The velocity and attitude are observable when the UAV speed is nonzero.
- The position except the altitude is unobservable.

Comprehensive simulation

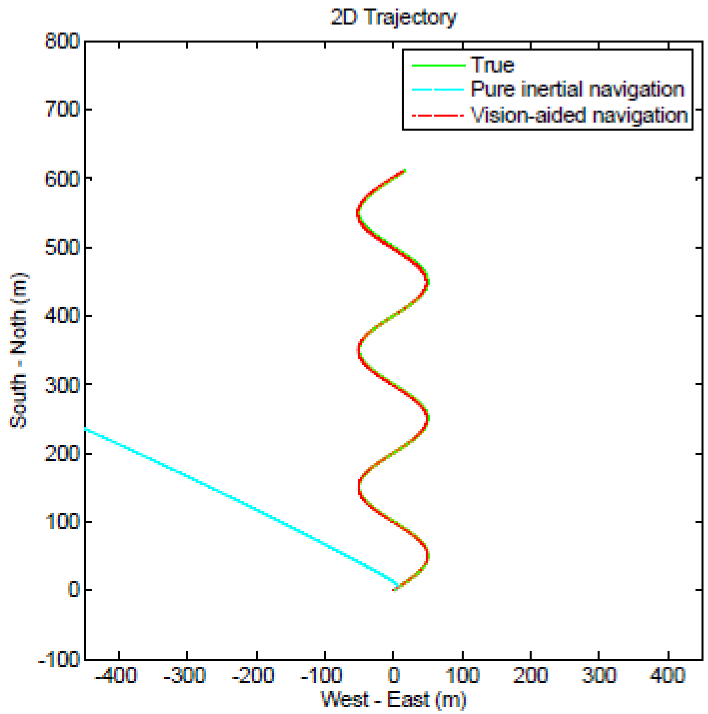


Block diagram of the simulation

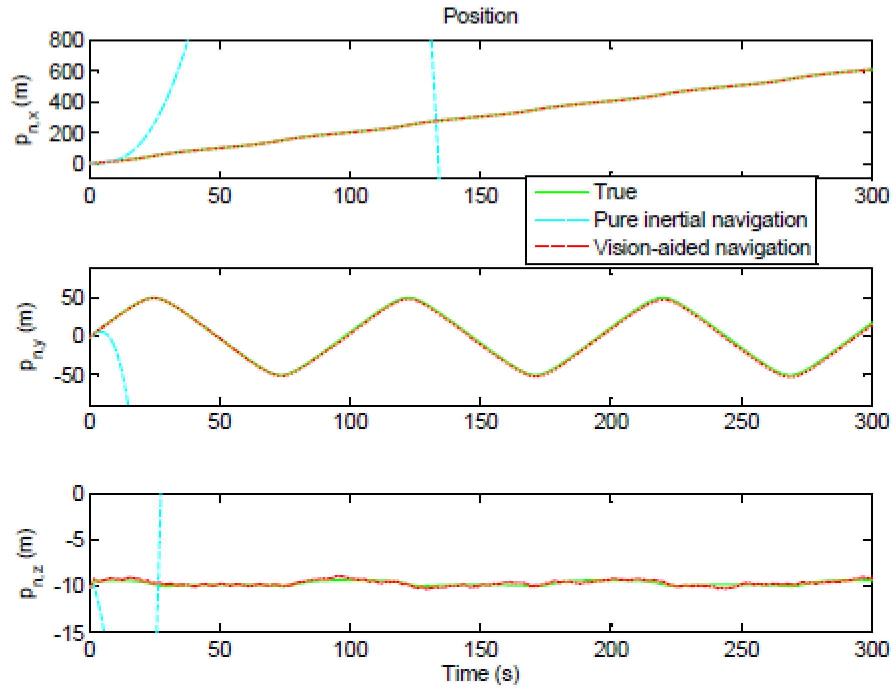


Generated images.

Comprehensive simulation



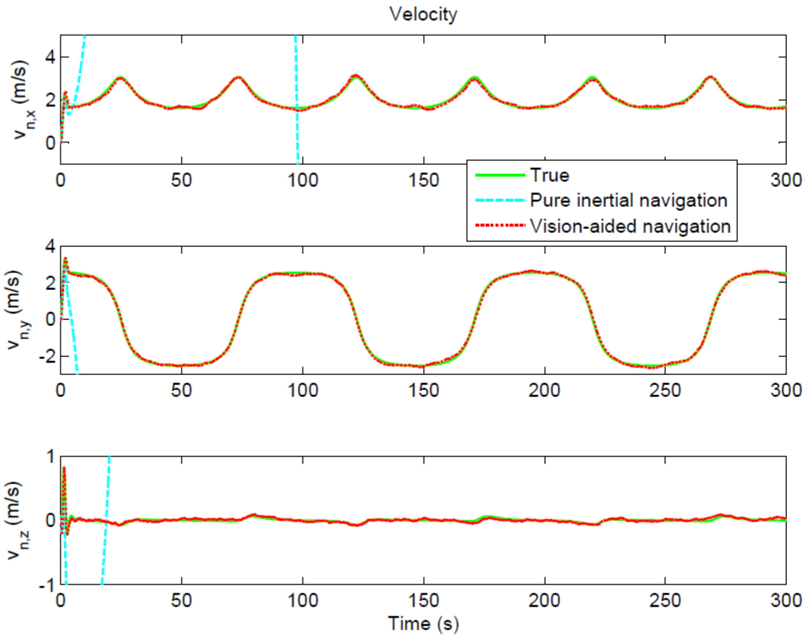
2D trajectory



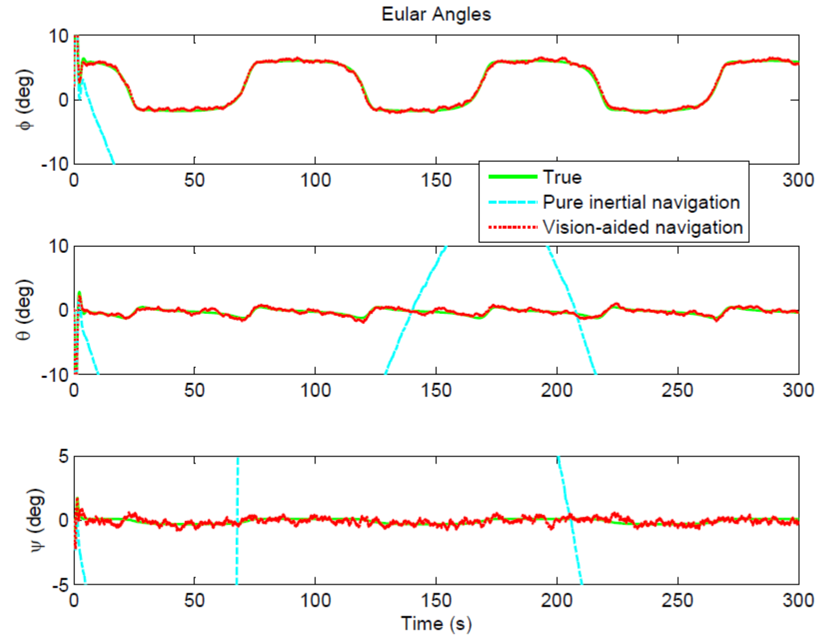
Position

The position estimate is much more accurate than IMU dead reckoning though it still drifts.

Comprehensive simulation



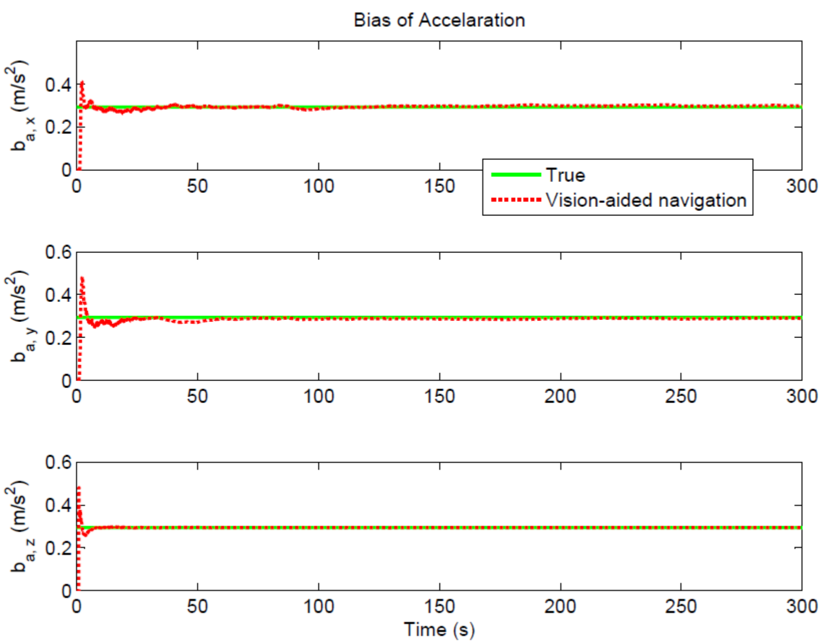
Velocity



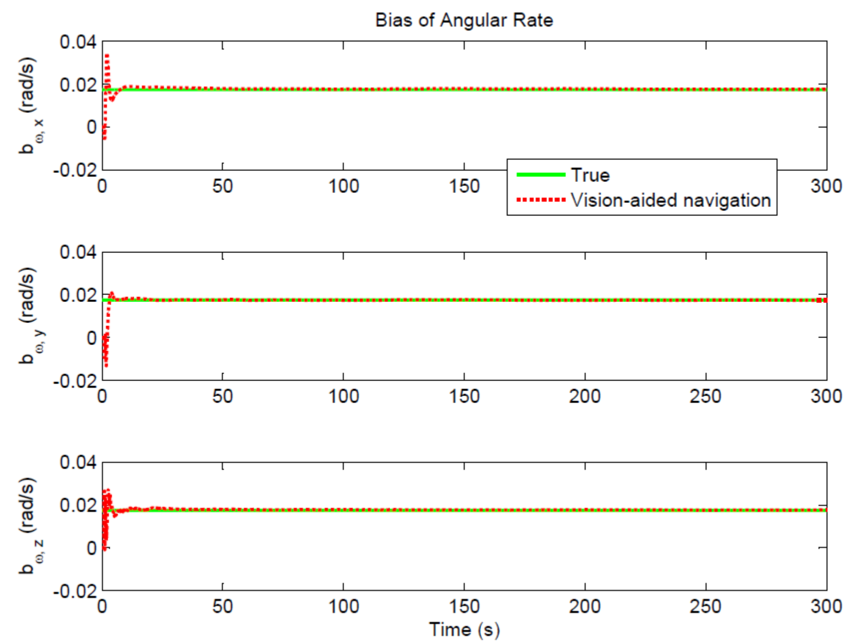
Euler angle

The velocity and attitude estimation is drift-free.

Comprehensive simulation



Bias of acceleration



Bias of angular rate

The IMU measurement biases can be accurately estimated.

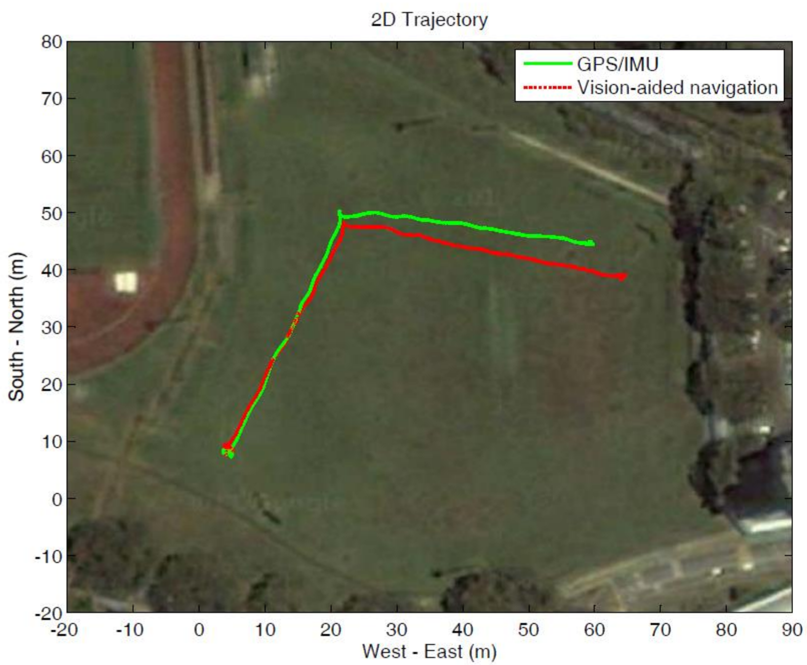
Experimental setup

Experimental platform: a quad-rotor UAV developed by the NUS UAS Research Group.

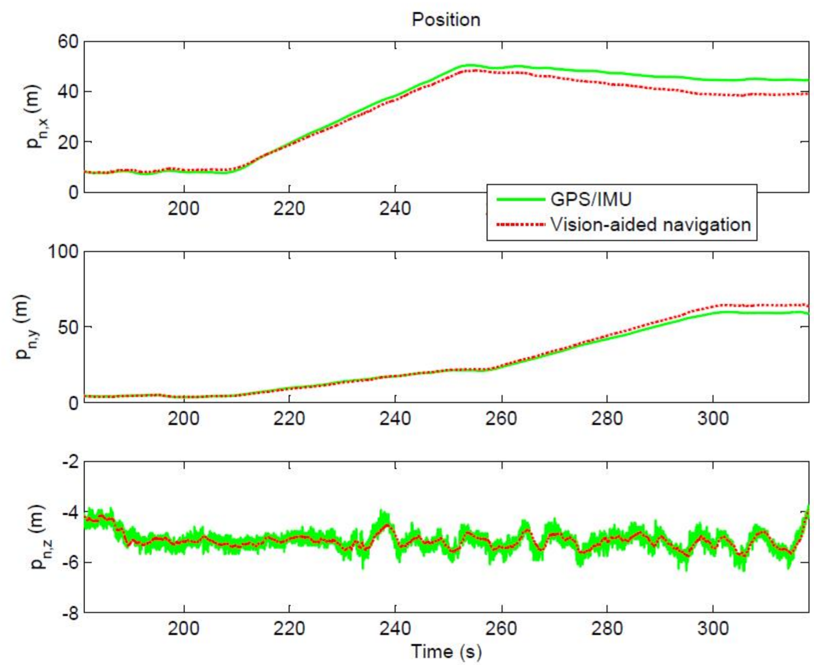
Samples of the consecutive images captured by the onboard camera. The arrows in the images represent the detected optical flow.

Flight experiment

Closed-loop flight test: the flight control is based on the vision-aided navigation system.

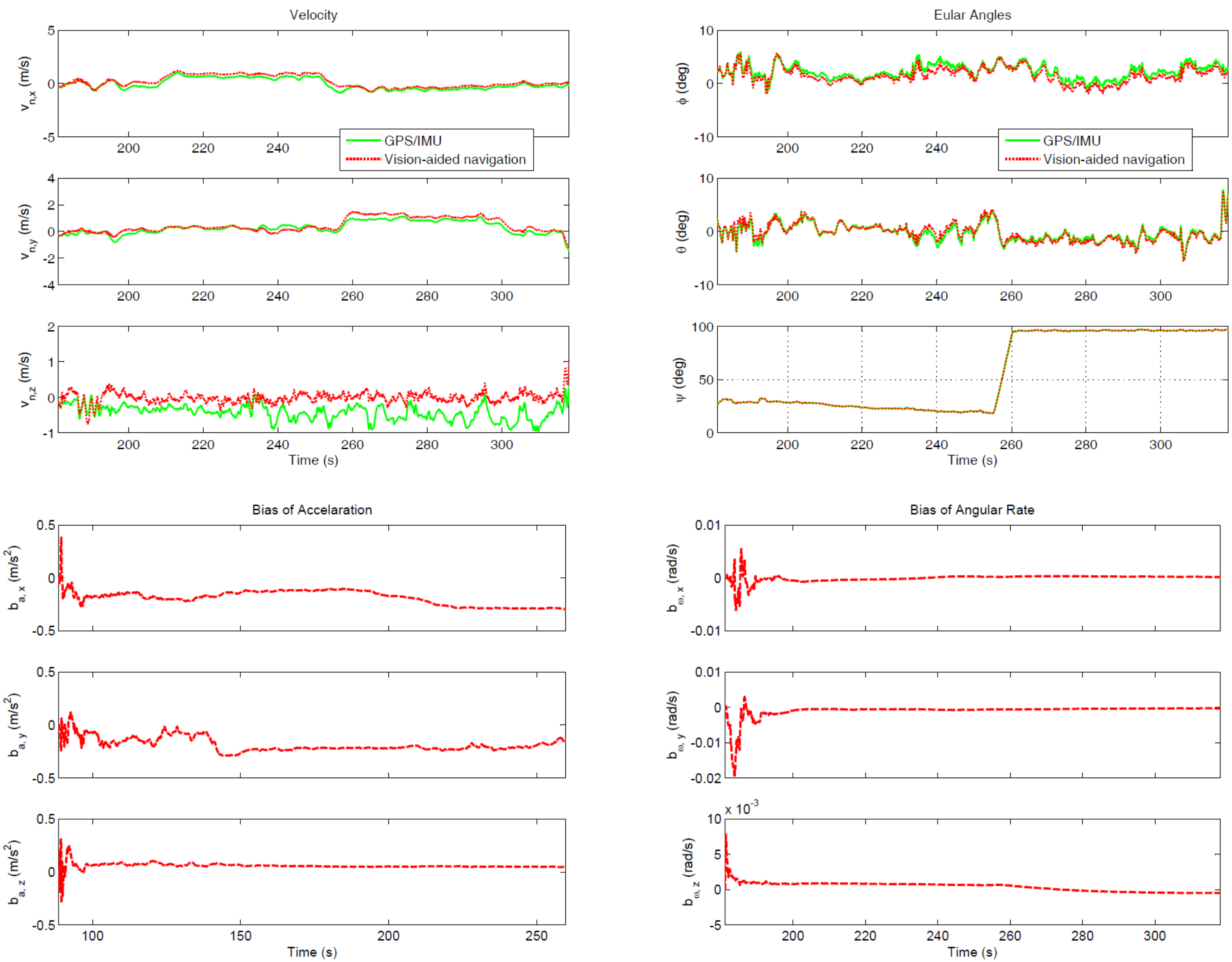


2D trajectory plotted against satellite image



Position

Flight experiment



Summary

- Time-efficient and simple for implementation
  - » A monocular downward-looking camera on a UAV is used
  - » Less computation and storage resources are required compared to SLAM
  - » Data fusion is achieved under the framework of the EKF
- The unique relative position and angular solution
  - » Homography matrix is directly fed into the EKF as measurement
  - » The decomposition of Homography matrix is not required, which always led to noisy results
- Observability guarantees
  - » The velocity and attitude of the UAV are observed, if the yaw angle is measurable
  - » The unknown bias of the accelerometer and rate gyro are observable

Thank You!

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http://uav.ece.nus.edu.sg

for more information on our research activities and published resources…