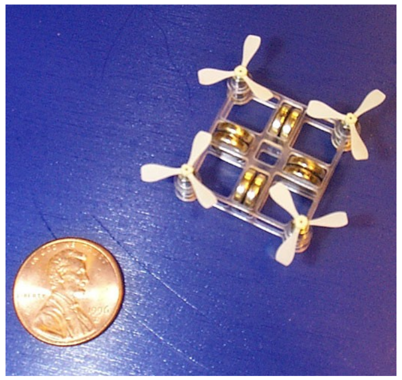
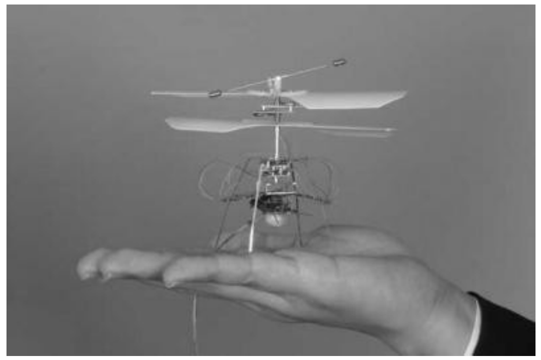
Sapienza Università di Roma — Corso di Laurea in Ingegneria Elettronica
Corso di Fondamenti di Automatica

Control of a quadrotor UAV

(slides prepared by M. Cognetti)

Unmanned Aerial Vehicles (UAVs)

autonomous/semi-autonomous vehicles of variable size rotary wing
(e.g. quadrotors, coaxials)


fixed wing (aeroplanes)


mainly used in repetitive or risky operations:

– surveillance/data acquisition (area monitoring, patrolling, meteorology, geology, traffic/pollution monitoring)

– risky/disaster scenarios (search and rescue, fire-fighting, volcanology)

– service/entertainment (transportation and delivery, cinematography)

Fixed vs rotary wings UAVs

fixed wings:

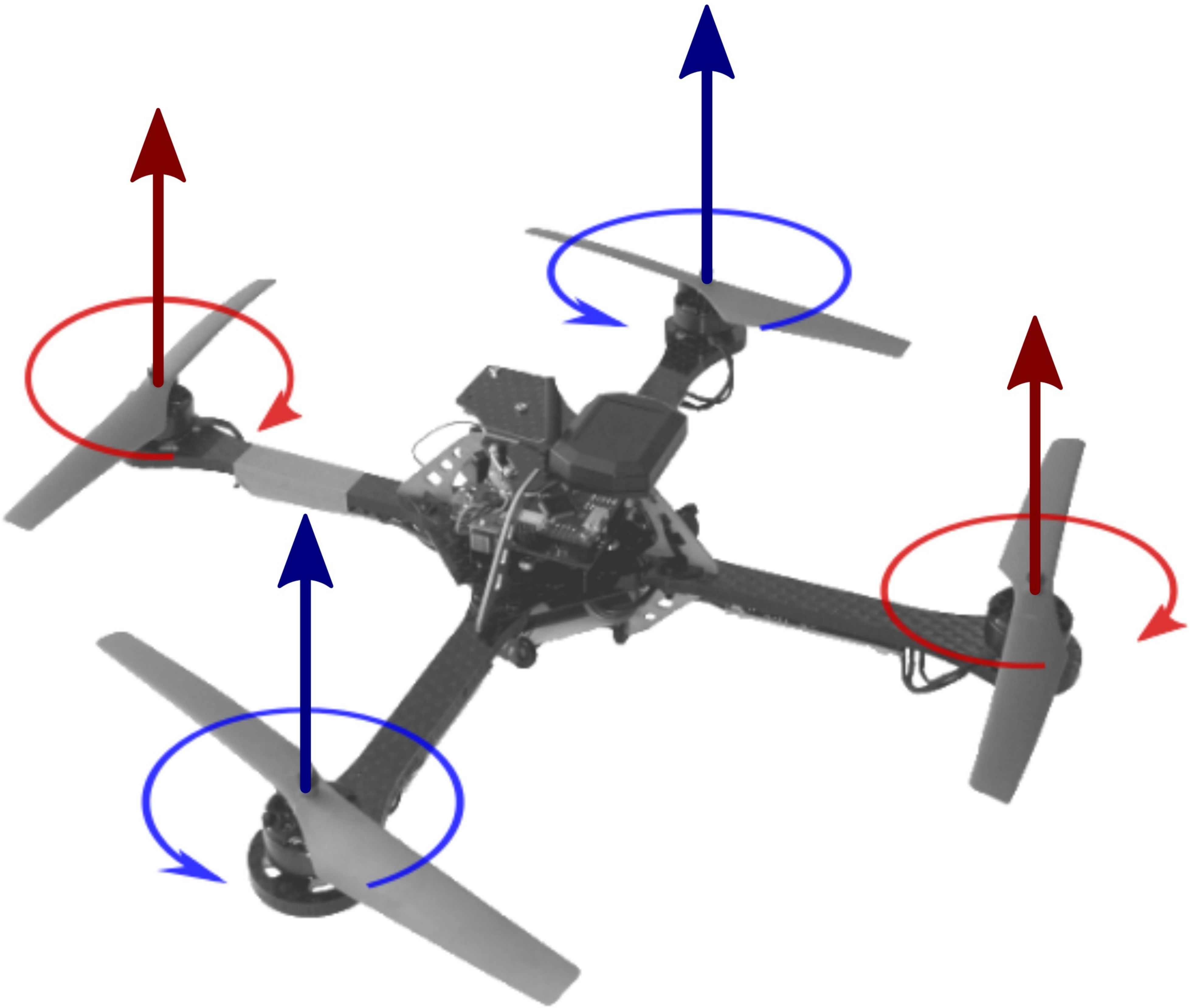
- high endurance (time of flight can be long), high payload capabilities (e.g. more sensors, more computational power)
- a runway is needed to take off and land (small models can be launched/caught)
- non-zero forward velocity is needed to fly (due to aerodynamic constraints)

rotary wings

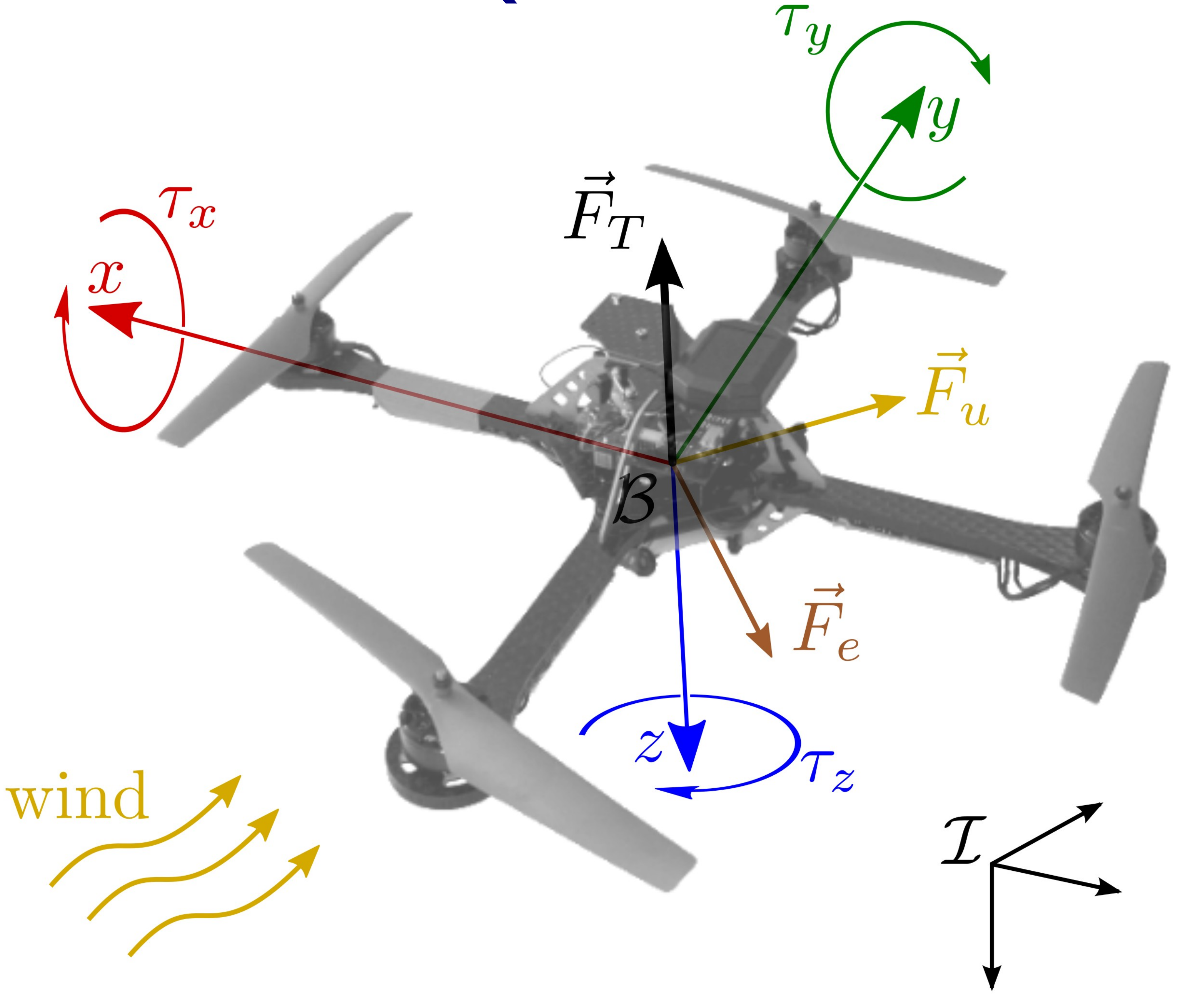
- high manoeuvrability
- vertical Take Off and Landing (can land on very small areas)
- able to perform stationary/slow flight (useful to perform long time tasks in the same position)
- can easily fly in small and cluttered environment (e.g. by performing hovering and slow motion)

Quadrotor

Quadrotor

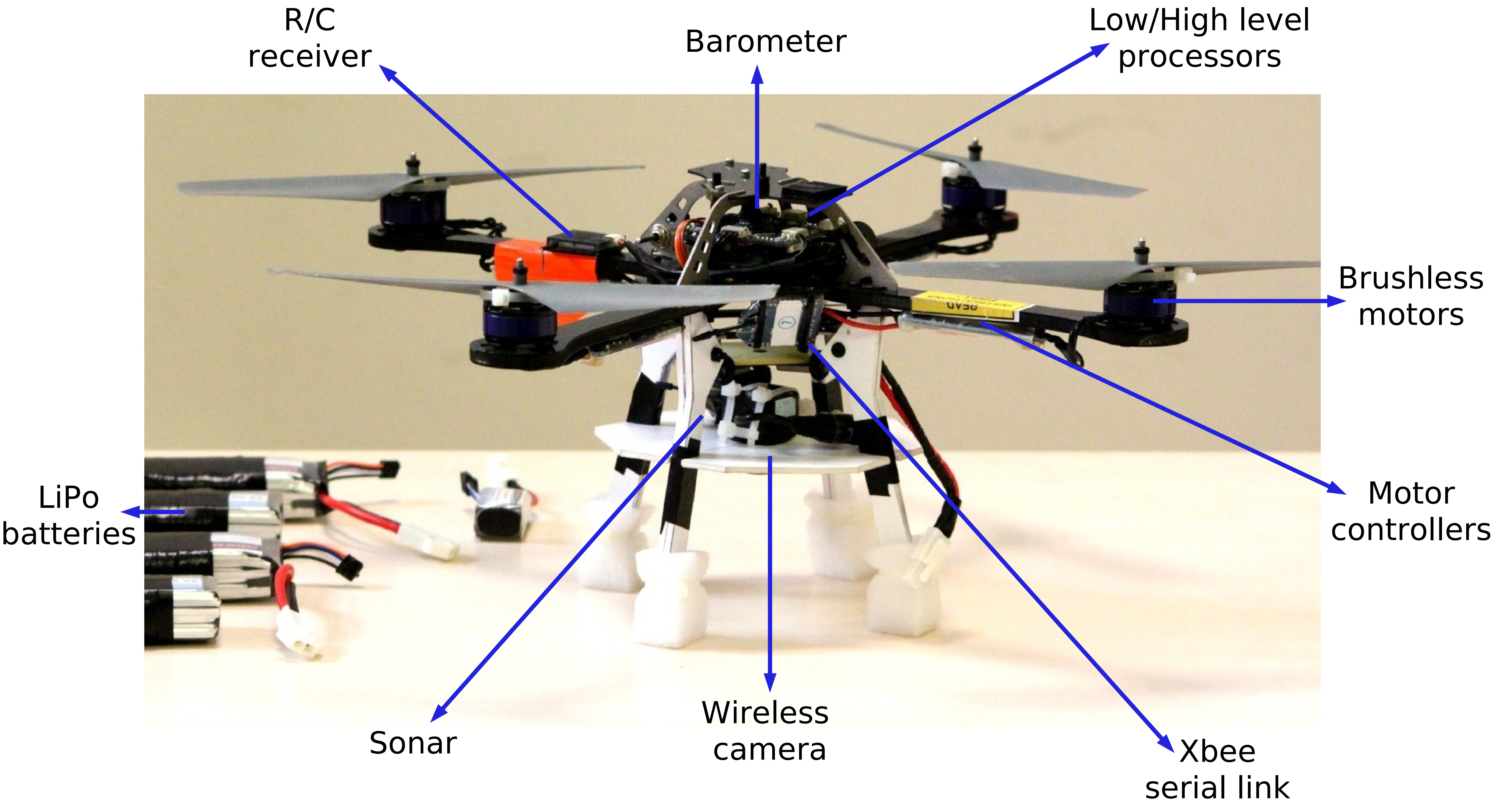


Quadrotor



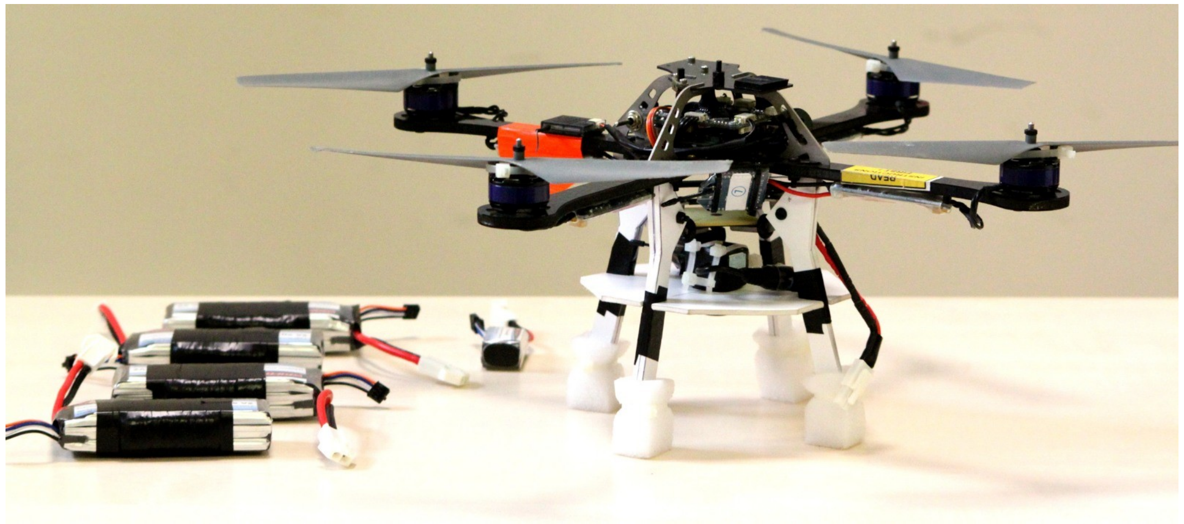
τ_y
y
$\vec{F}_T$
τ_x
x
$\vec{F}_u$
$\mathcal{B}$
$\vec{F}_e$
z
τ_z
wind
$\mathcal{I}$

Overview



R/C receiver
Barometer
Low/High level processors
Brushless motors
Motor controllers
LiPo batteries
Sonar
Wireless camera
Xbee serial link

Overview



Original equipment:

- brushless motors with microcontrollers
- XBee wireless serial link
- R/C radio controller
- barometer (altitude measurements)
- IMU (linear/angular accelerations)
- two onboard CPUs
- GPS

Main features:

200g paylod

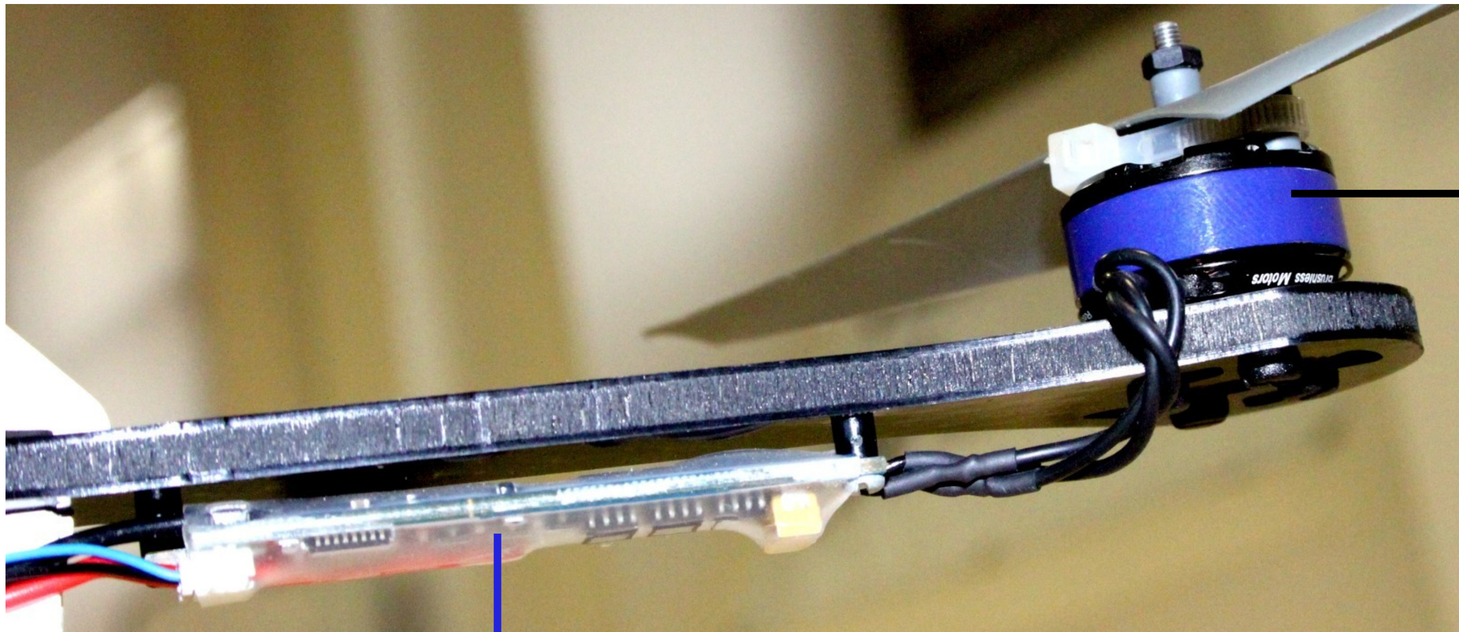
1KHz inner control loop (attitude)

1KHz high level control loop

Add-ons:

- wireless camera
- sonar sensor (height measurements)

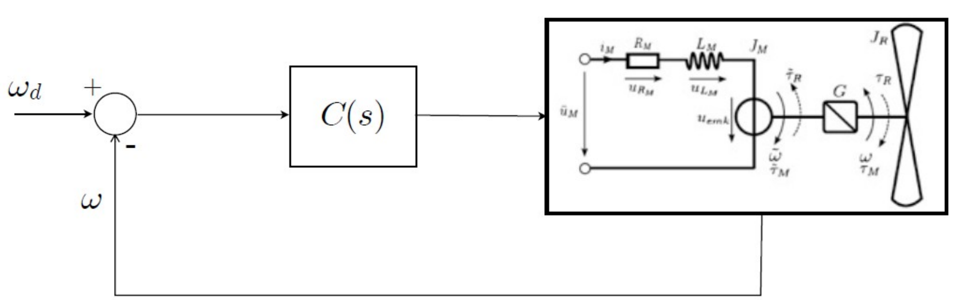
Motors/Batteries



Brushless motors with angular speed control (rpm)

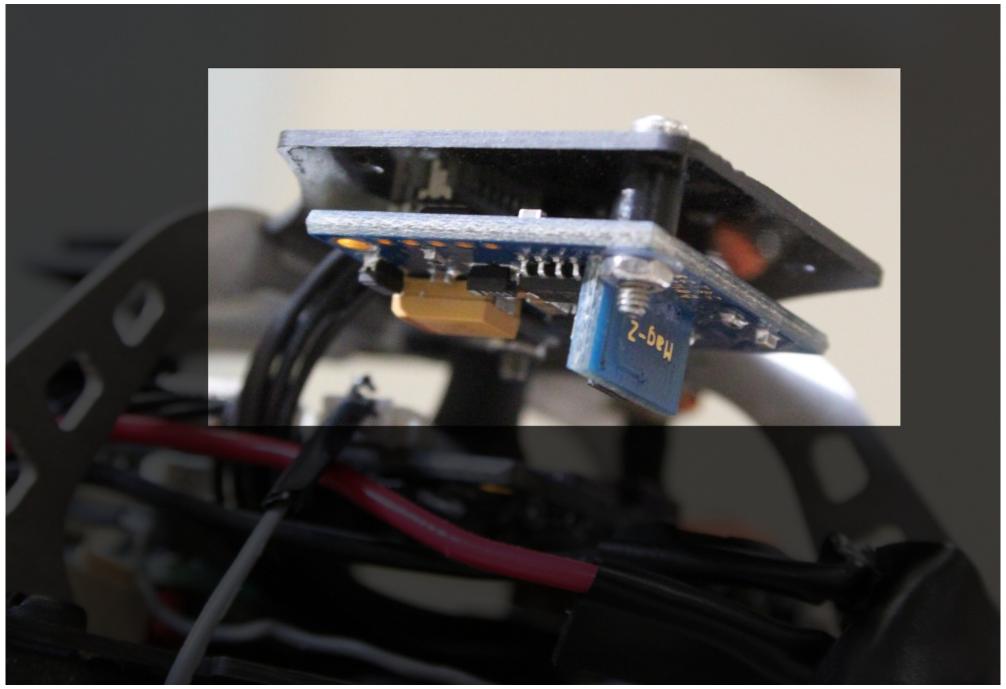
Quadrotor attitude control needs fast change in angular velocities

Motor controllers provide low level feedback control to track angular speed references



Lithium Polymer batteries (LiPo) provides about 15 min. of flight time (with payload, in hovering)

Heading - Barometer



ASCTEC 3D-MAG: heading measurements

- triple axial magnetic compass measuring earth magnetic field
- gives measurements about the orientation of the vehicle w.r.t. north pole (rad: $0-2\pi$)
- the heading can be used to perform hovering control by GPS measurements

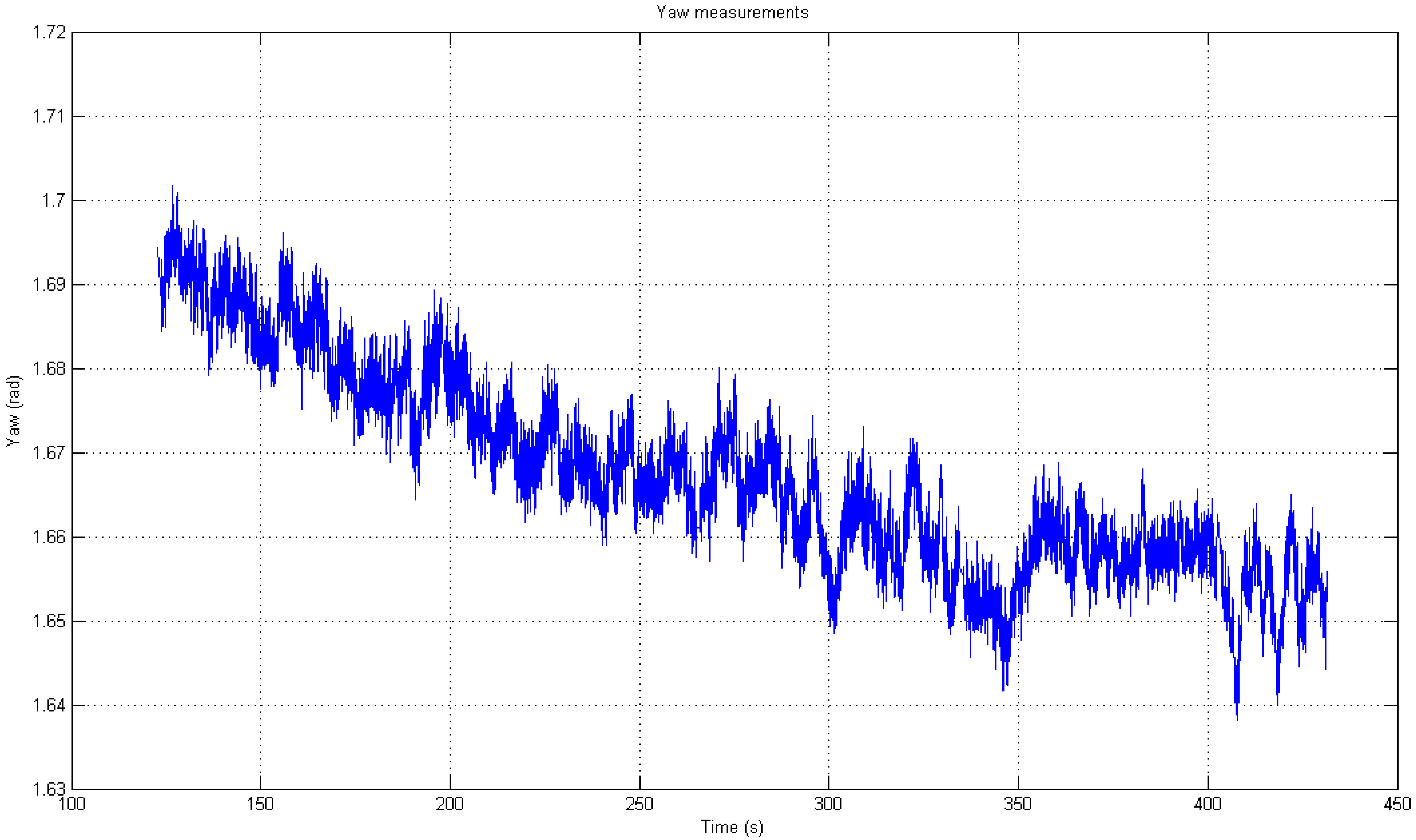
Barometer: altitude measurements

- measures air pressure
- gives measurements about the height of the vehicle (m) above the ground and its variation (m/s)
- can be used to perform height control

Note:

- highly noisy
- unusable indoor (air conditioning, rapid temperature variations)

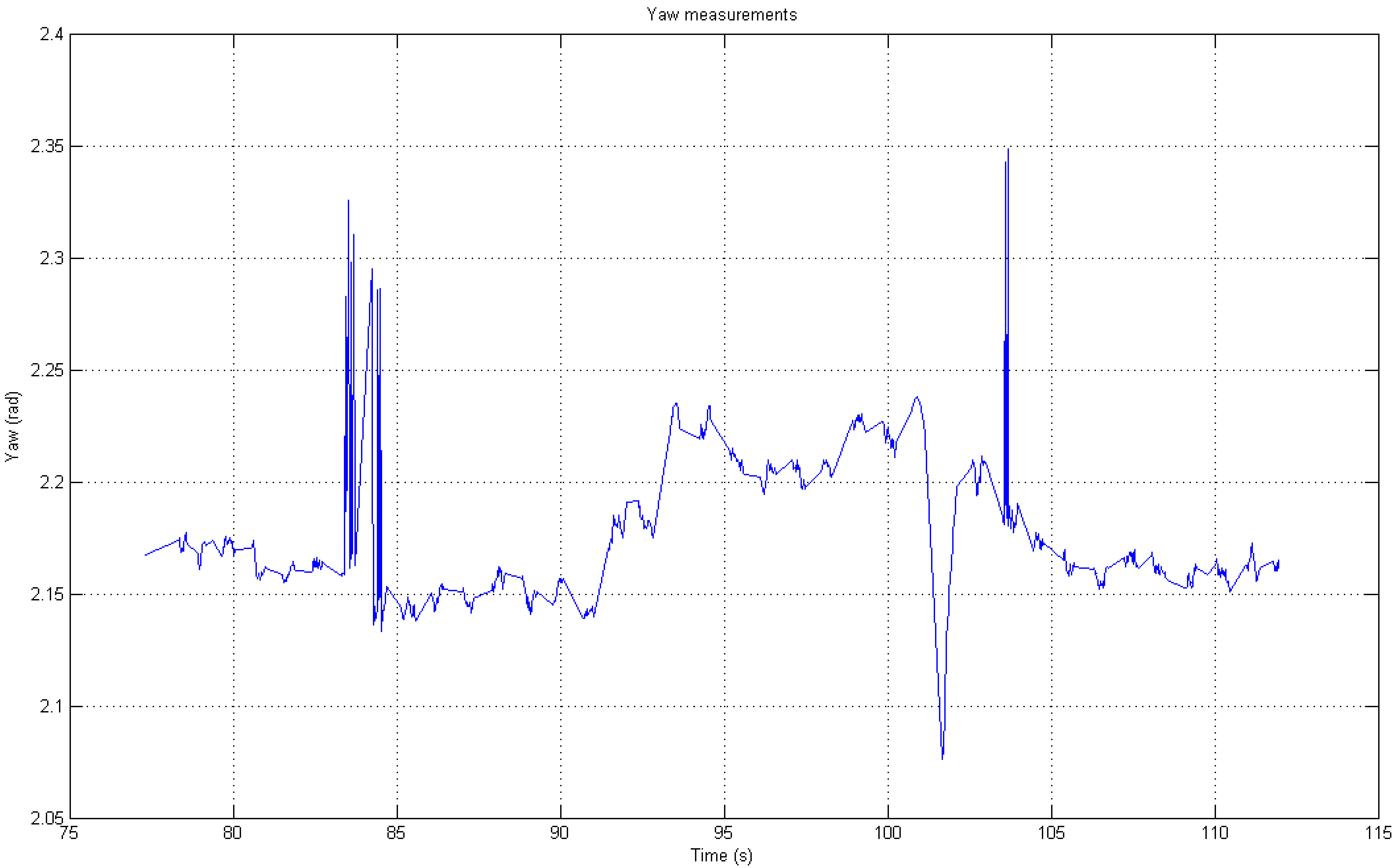
Heading measurements



Yaw angle measurements, vehicle still on the ground

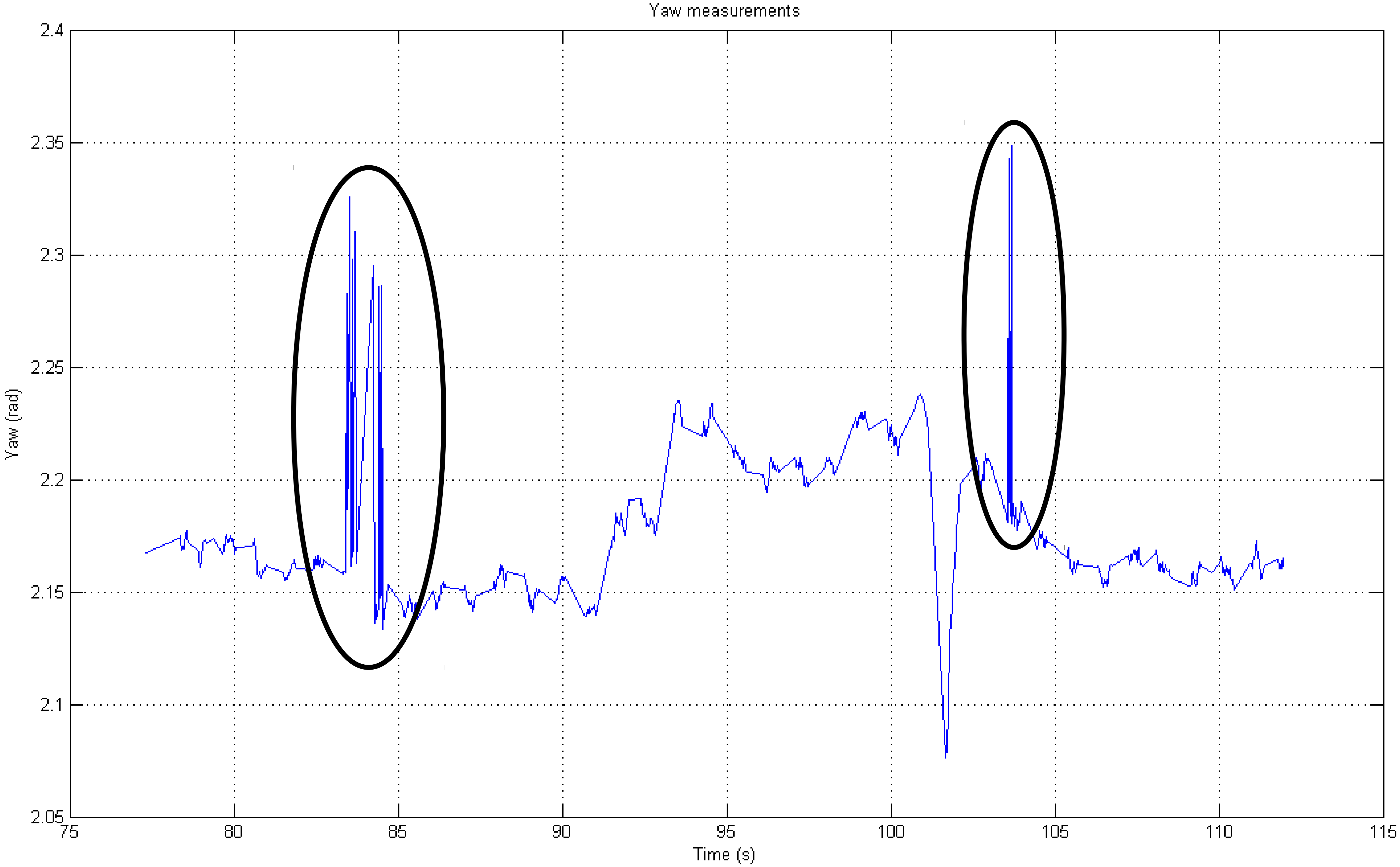
Mean: 1.6671   Variance: 1.4240e10− 4

Heading measurements



Yaw angle measurements, short flight at about 1.5m above ground

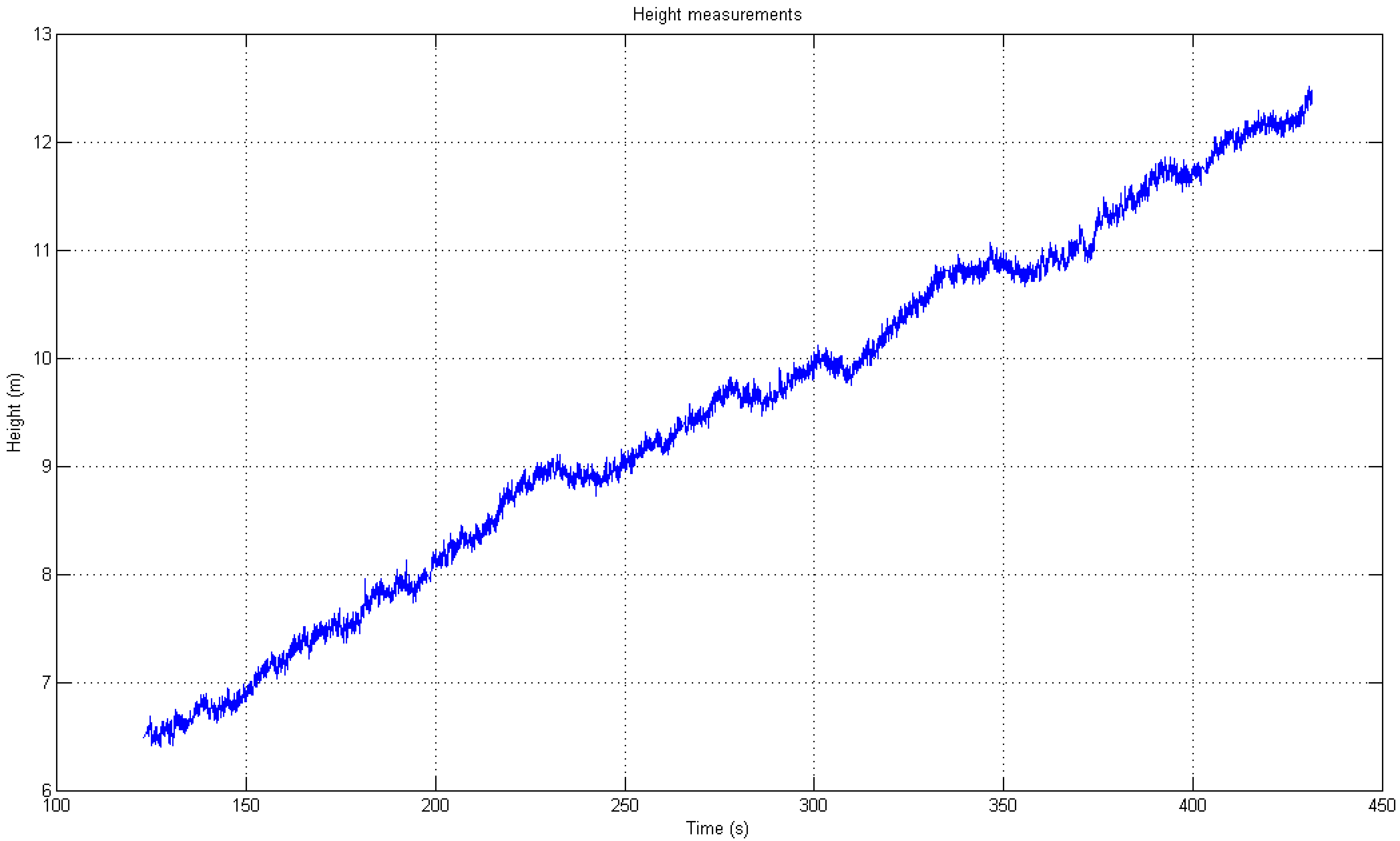
Heading measurements



Yaw angle measurements, short flight at about 1.5m above ground

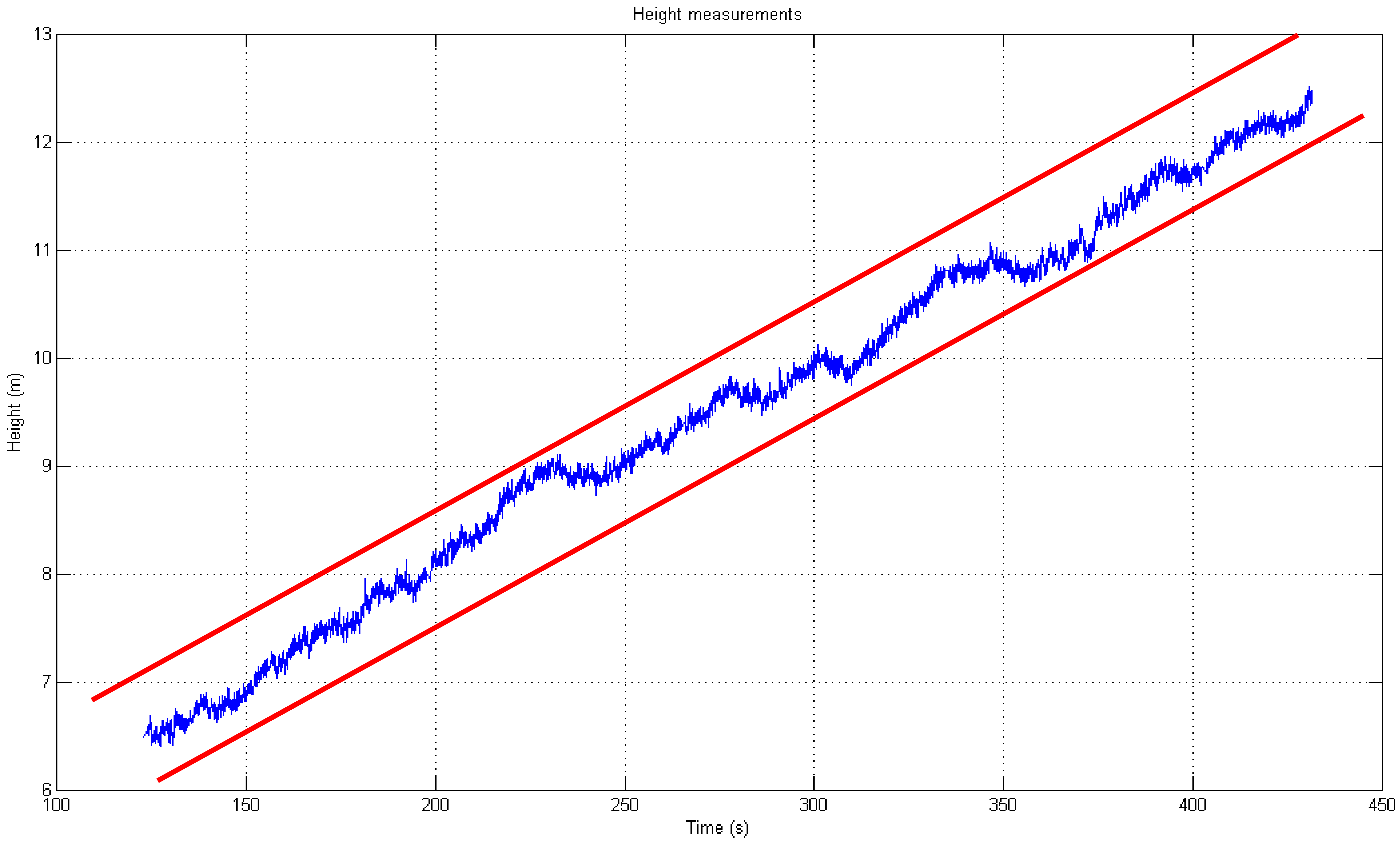
Note: take-off and landing operation results in useless measurements

Barometer measurements



Barometer output, vehicle still on the ground, indoor

Barometer measurements



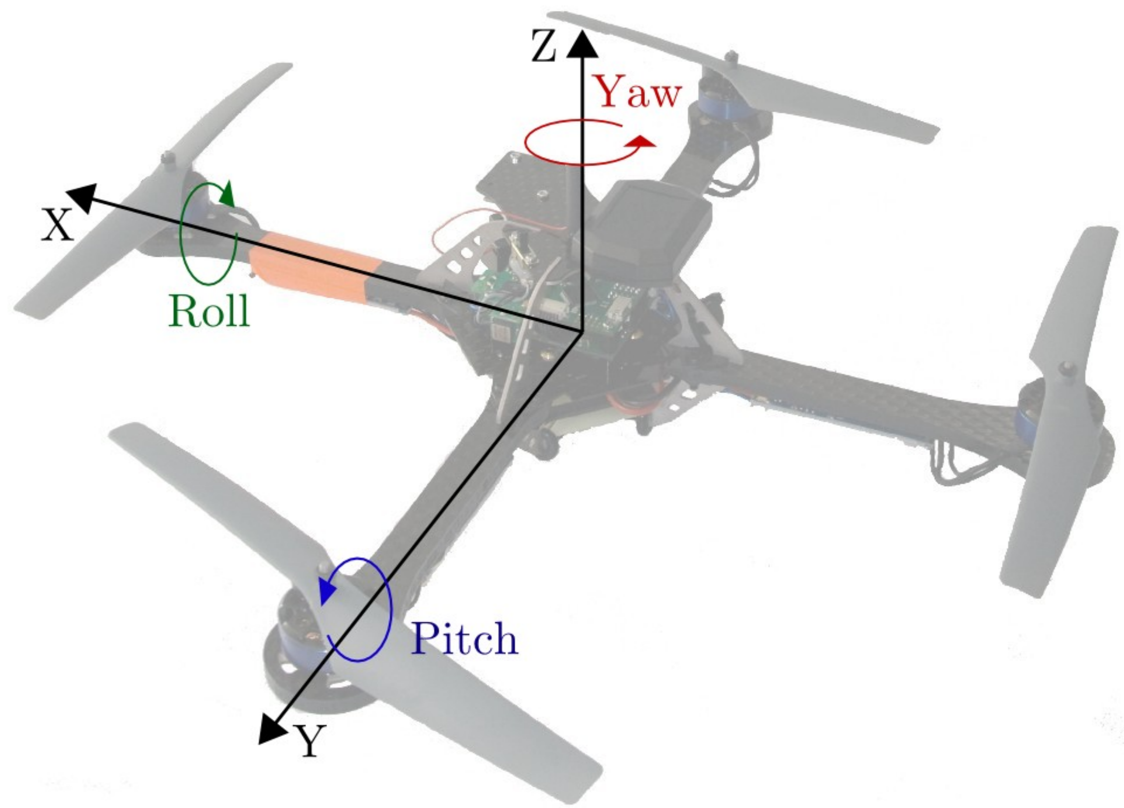
Barometer output, vehicle still on the ground, indoor

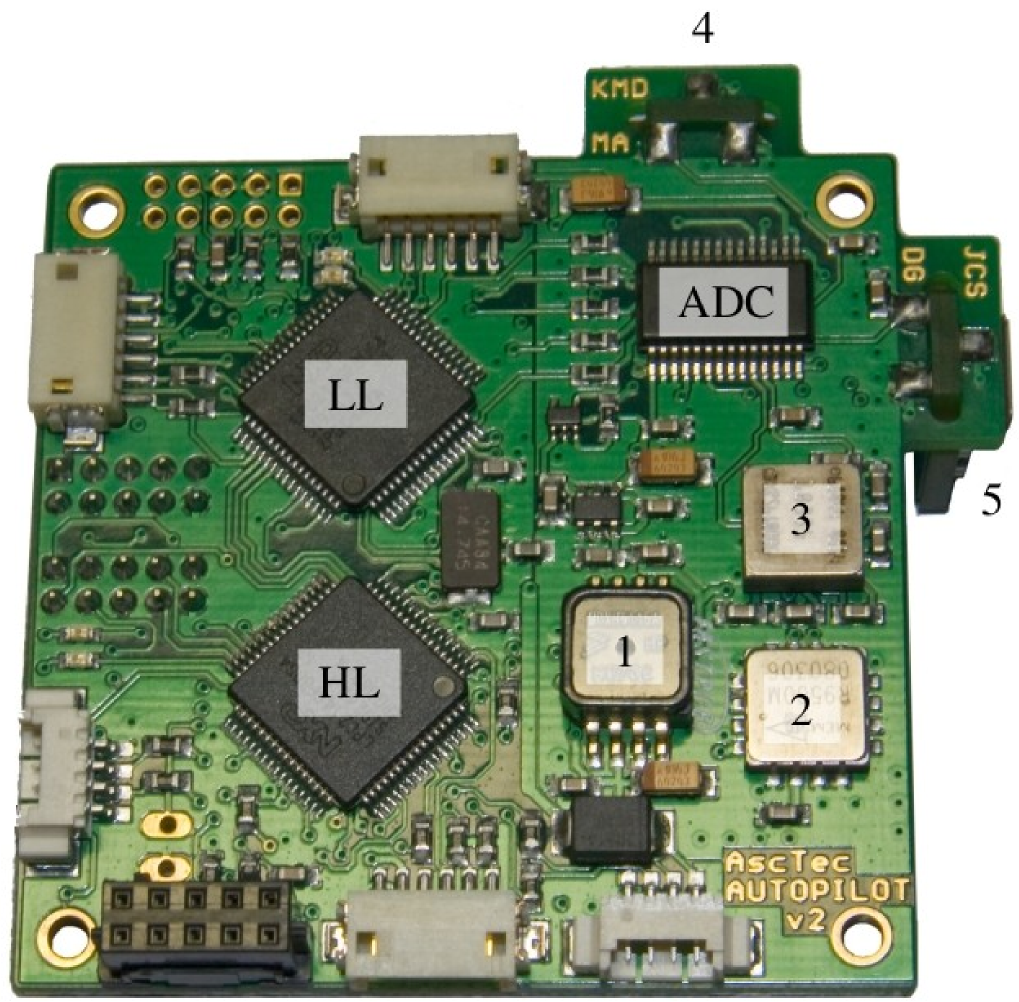
Note: measurements are diverging even if the vehicle is still

Inertial Measurement Unit

IMU unit and MEMS gyro sensors:

- measure linear acceleration along body axes (linear accelerometers)
- measure angular speed around body axes (gyroscopes)





(2) accelerometer (x,y,z)

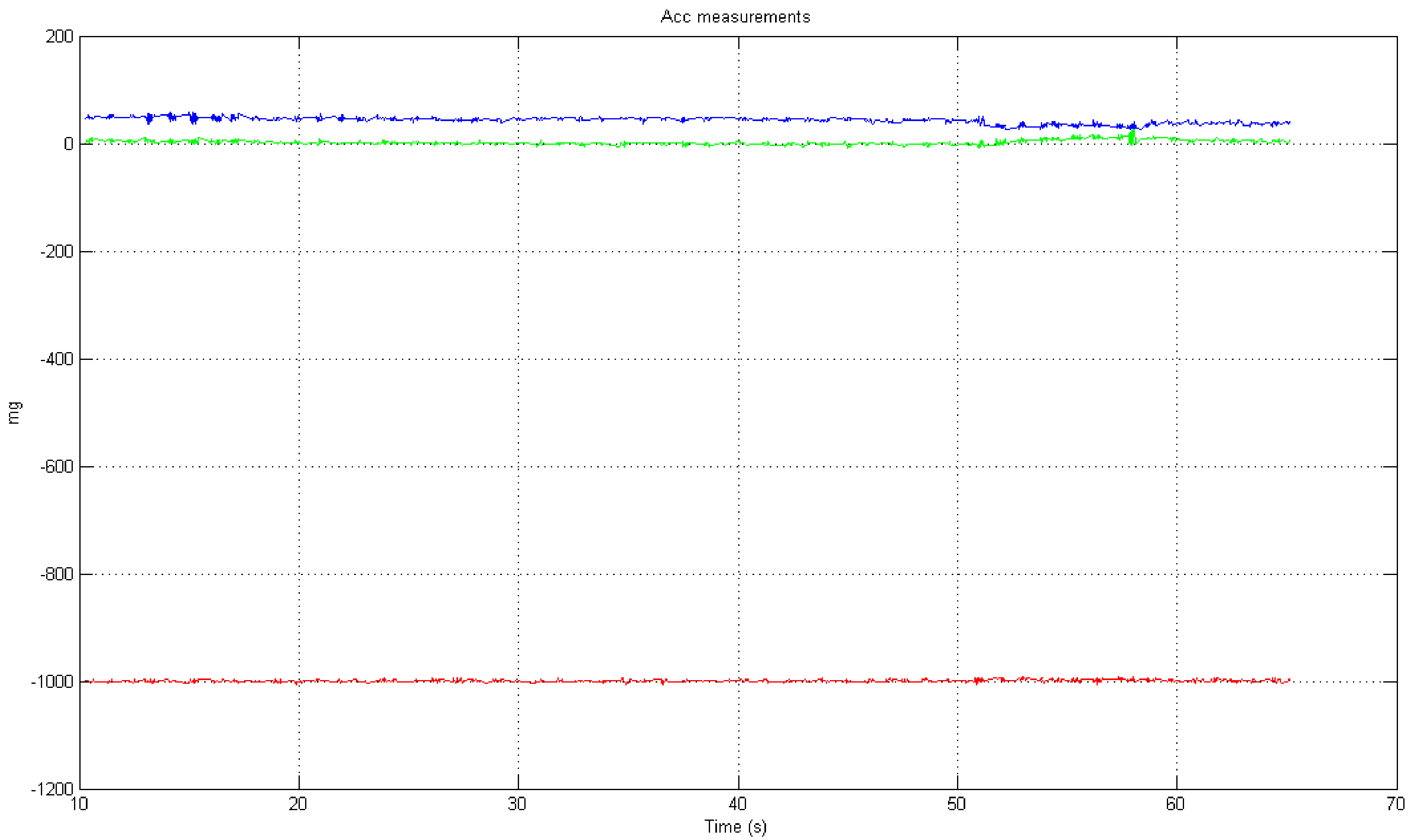
(3) yaw gyroscope

(4) pitch gyroscope

(5) roll gyroscope

We can use a ZYX set of Euler angles to describe vehicle orientation

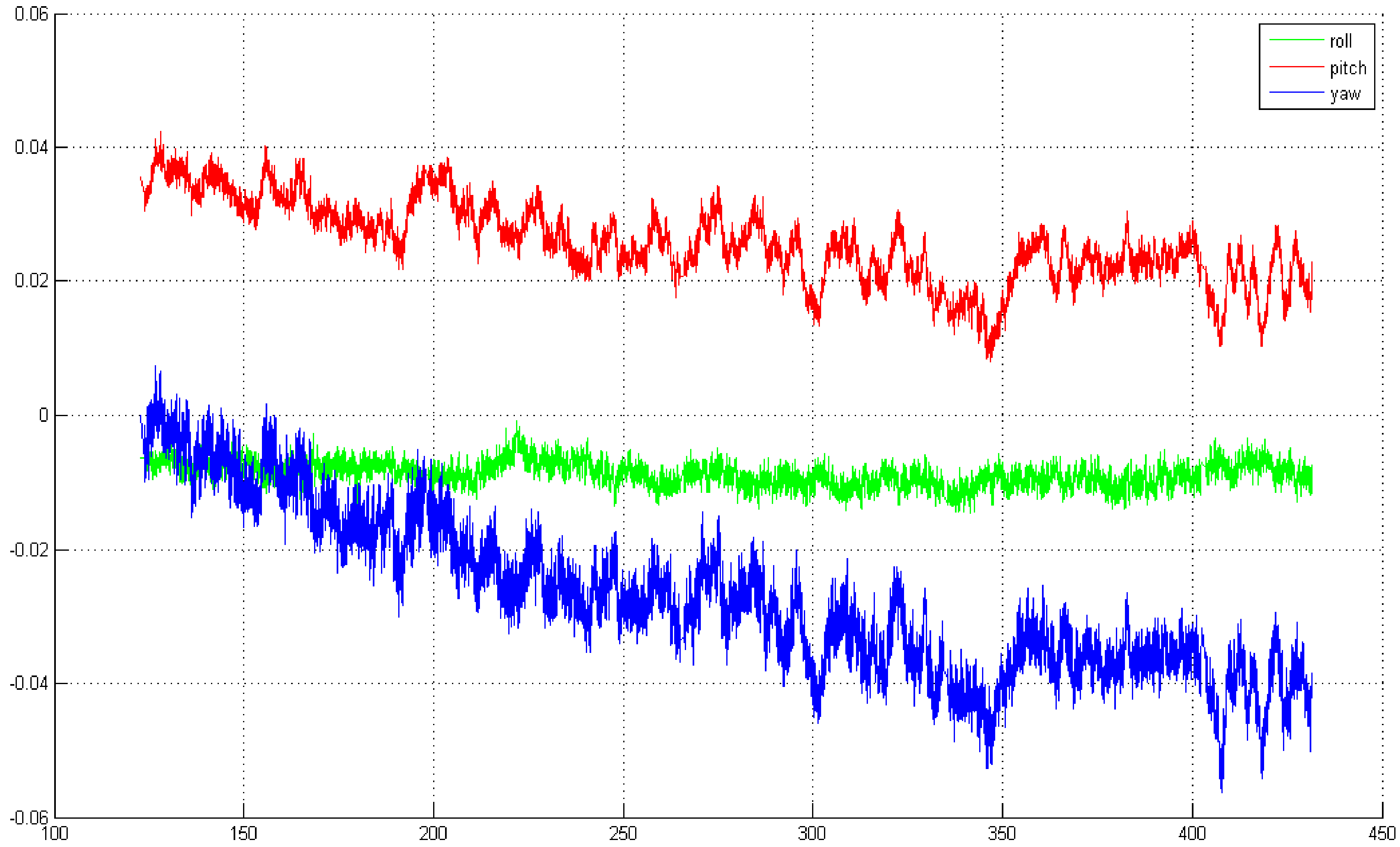
Inertial Measurement Unit



IMU measurements, vehicle still on the ground

Axis	Mean		Variance
x	42.7909	$(mg/1000)$	30.3650
y	2.1791	$(mg/1000)$	20.8219
z	-998.9522	$(mg/1000)$	4.8663

Inertial Measurement Unit



Gyroscopes measurements, vehicle still on the ground

Angle	**Mean**	**Variance**
Roll	-0.0087	$3.3233e10^{-}6$
Pitch	0.0257	$3.5767e10^{-}6$
Yaw	1.6671	$1.4240e10^{-}4$

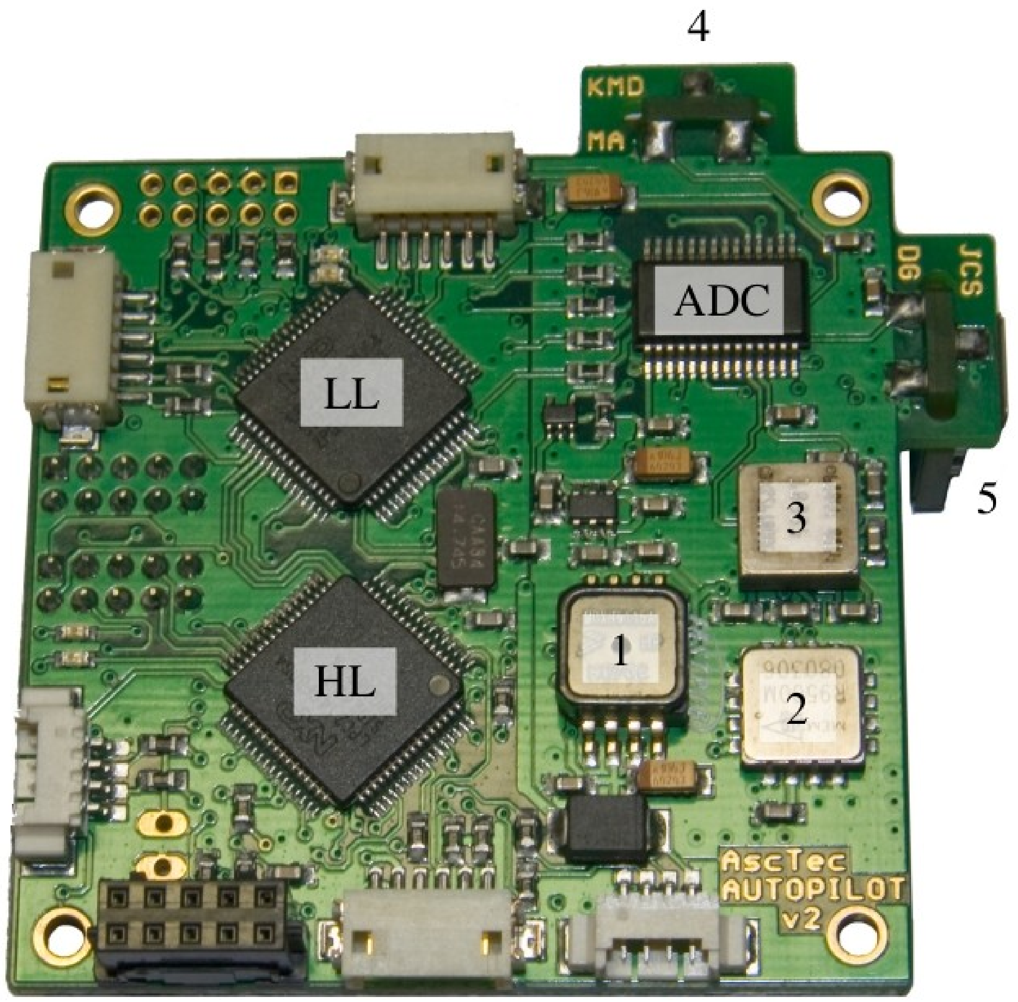
Mainboard

Two ARM7 (LPC2146) microcontrollers:

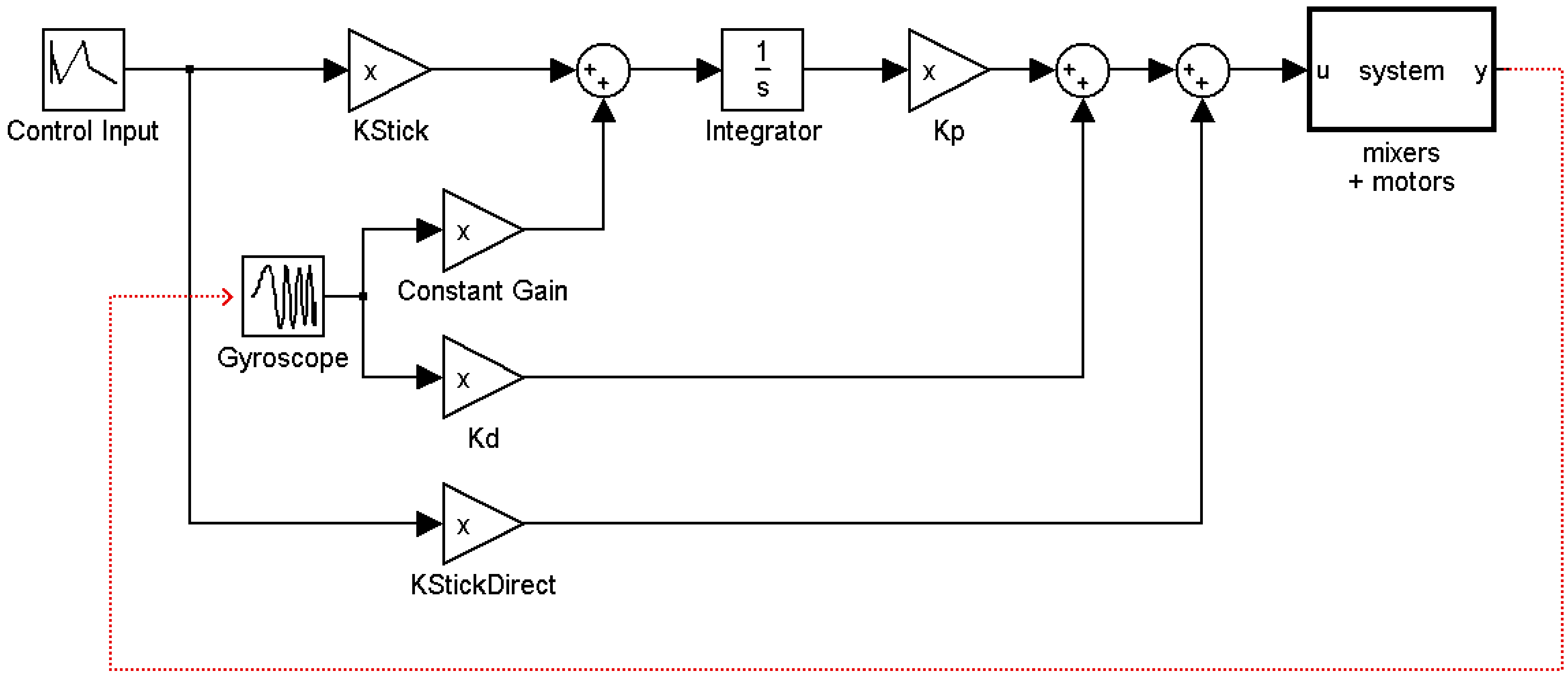
- CPU clock up to 60MHz
- running at 1Khz
- performing different tasks simoultaneously

- Low Level (LL) processor:
  - collects and elaborates data from sensors (black-box)
  - provides attitude stabilization
  - can provide pose stabilization (using GPS data)
  - can provide height stabilization
  - can manage data transmission and reception

- High Level (HL) processor:
  - receive sensor data (from LL processor)
  - can manage data transmission and reception
  - can mange GPS data
  - <u>programmable</u>

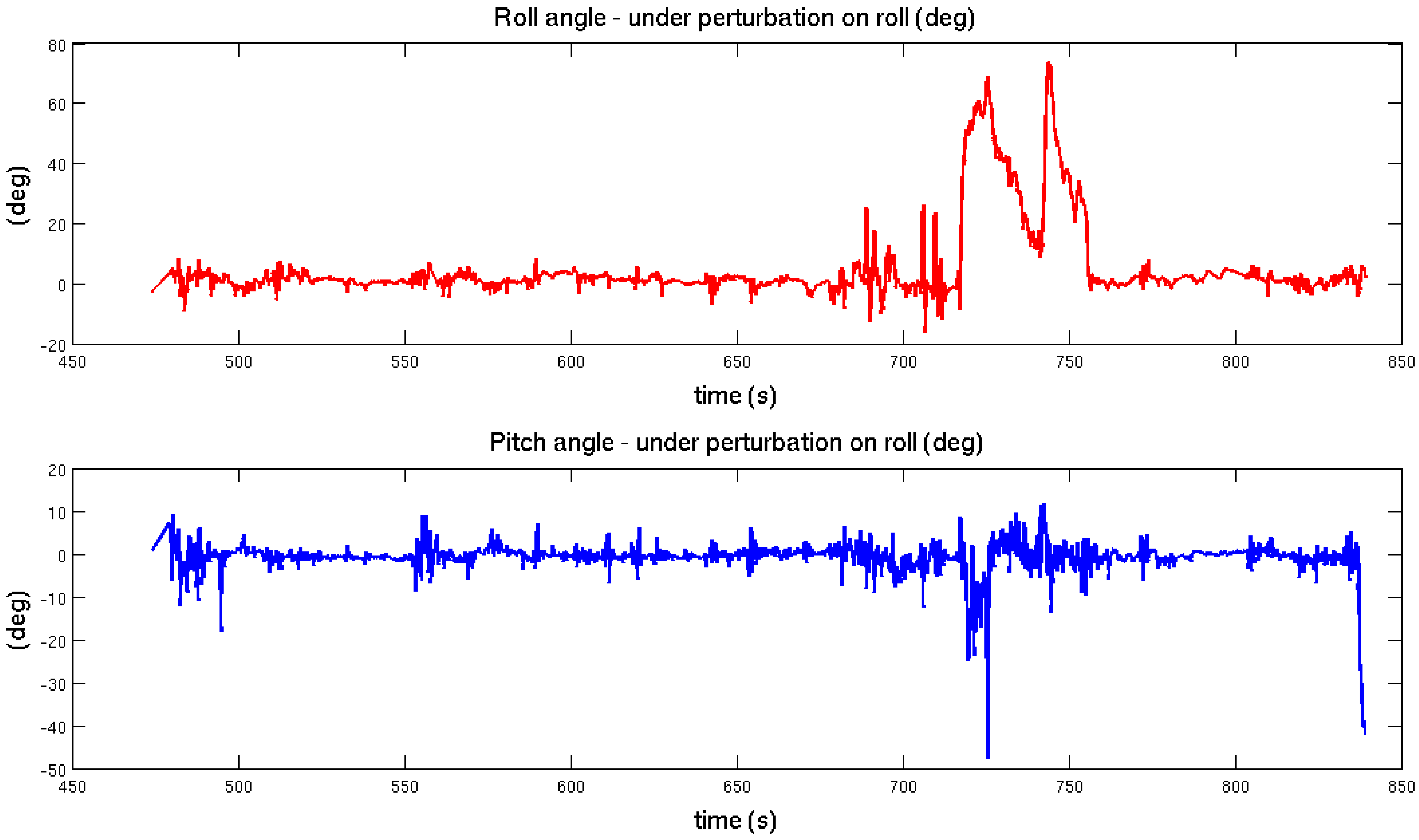


Attitude control



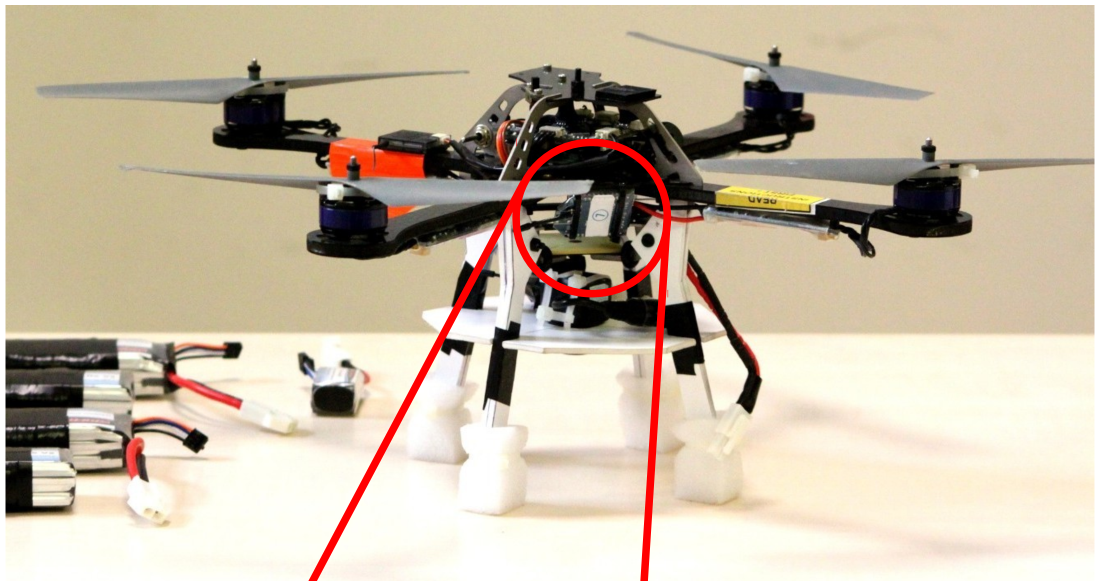
From: D. Gurdan, J. Stumpf, M. Achtelik, K.-M. Doth, G. Hirzinger, D. Rus,
Energy-efficient Autonomous Four-rotor Flying Robot Controlled at 1 kHz,
International Conference on Robotics and Automation (ICRA) 2007

Attitude control



Vehicle airborne, with height control and “perturbations” on roll angle

Communication module



Xbee-PRO 802.15.4 OEM RF Module (wireless serial link)

- indoor/Urban range up to 30 m
- outdoor range up to 90 m
- interface data rate: up to 115.2 Kbps
- operating frequency 2.4 GHz

Actual data transmission rate up to 100Hz sending IMU, gyro, barometer and sonar data

The same channel is used to transmit control packets (minimum rate 10Hz)

Some redundancy or/and data check is needed

Common Issues

Transmission channels are noisy:

- data packets may be corrupted (slower transmission rate, incomplete data)
- images from camera may be unusable
- the small size of the vehicle implies that radio links are close each other

Security:

- if remote control fails, the vehicle may perform unsafe motion
- when battery charge is low motors receive less power

Limitations:

- small cpu performance $\longrightarrow$ onboard data processing is limited
- limited number of communication ports

Distance sensors

Sonar

- Reliable
- Reflection of the beam depends on the surface
- Beam is influenced by environment (e.g. wind)
- Cheap

Laser

- Reliable and accurate
- Typically gives multiple scan
- Can be used to reconstruct environment
- Can be used for navigation

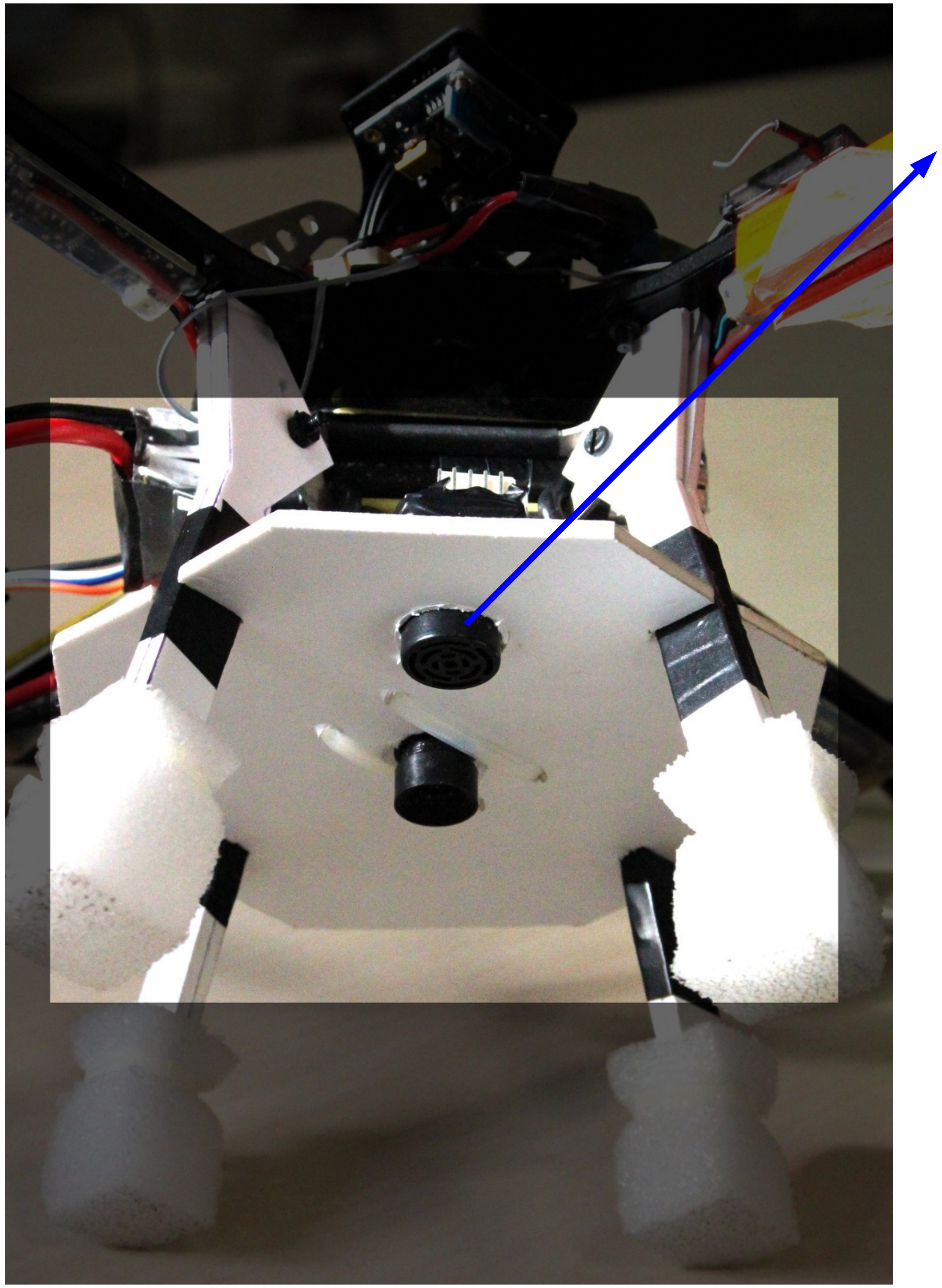
Stereo camera

- Needs elaboration to reconstruct distance data
- High information content

Kinect (or PrimeSense)

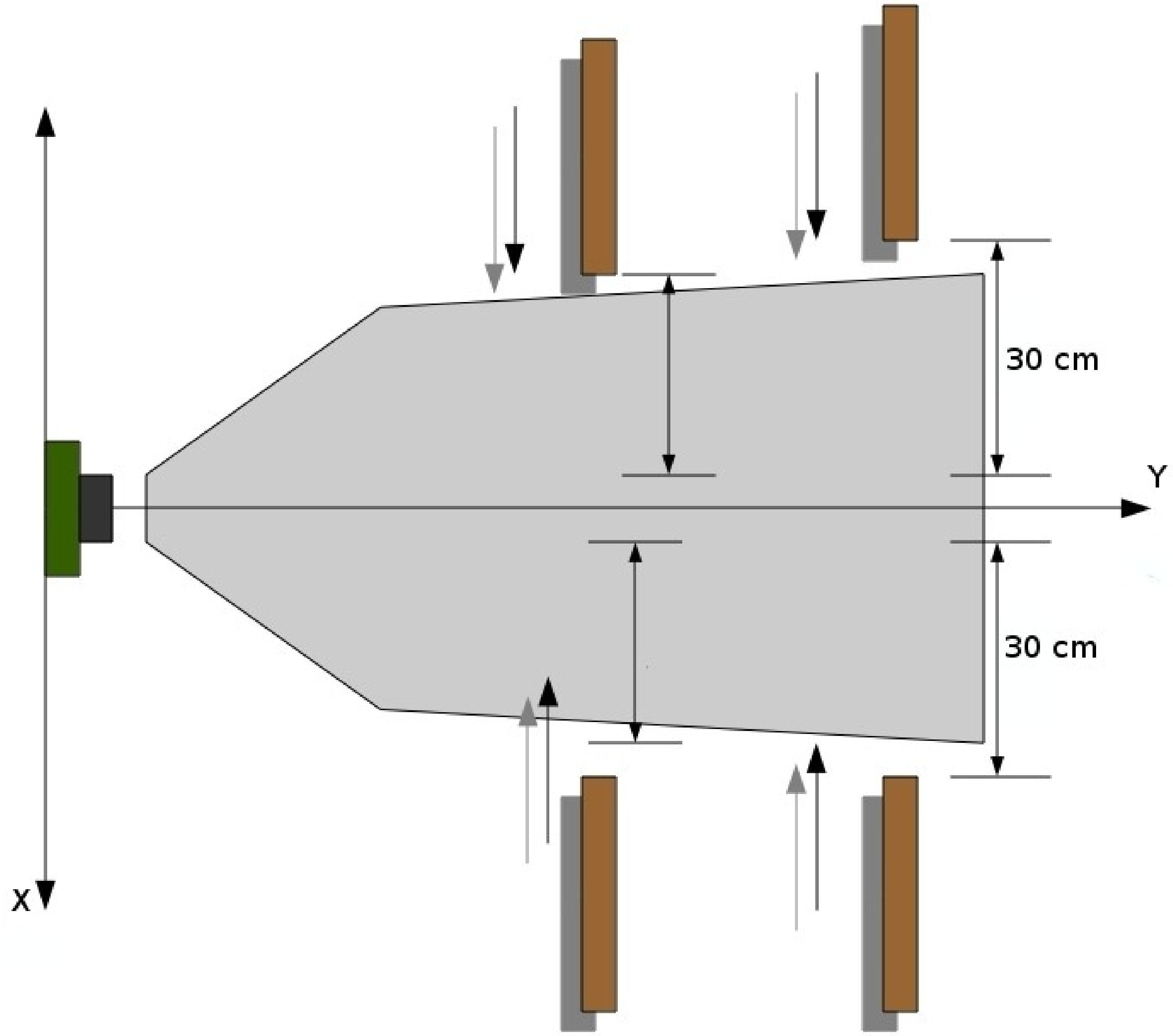
- Projects a set of markers (near-IR light)

Sonar

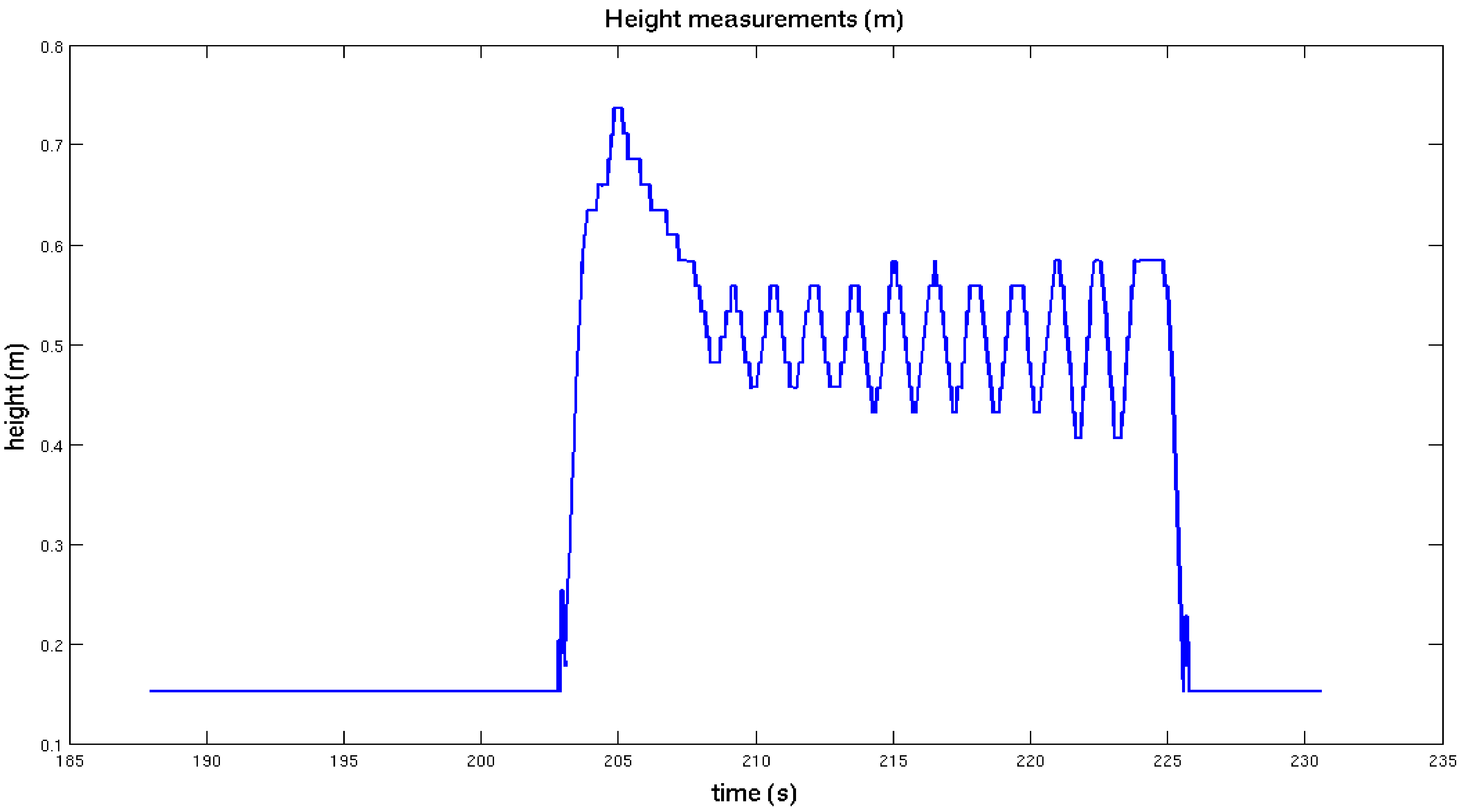


MaxBotix LV-MaxSonar-EZ4

- range 6 to 256 inch (~15cm to 6.5m)
- resolution 1 inch (2.54 cm)
- voltage supply 5V
- 20 Hz data rate
- provides precise distance measurements



Sonar



Sonar measurements (airborne)

- Note the quantization of the measurements

Height control

Actual implementation

- Height measurements from sonar
- Angles measurements from IMU

Issues

- Sonar measurements are quantized
- Needed filtering/dirty derivative

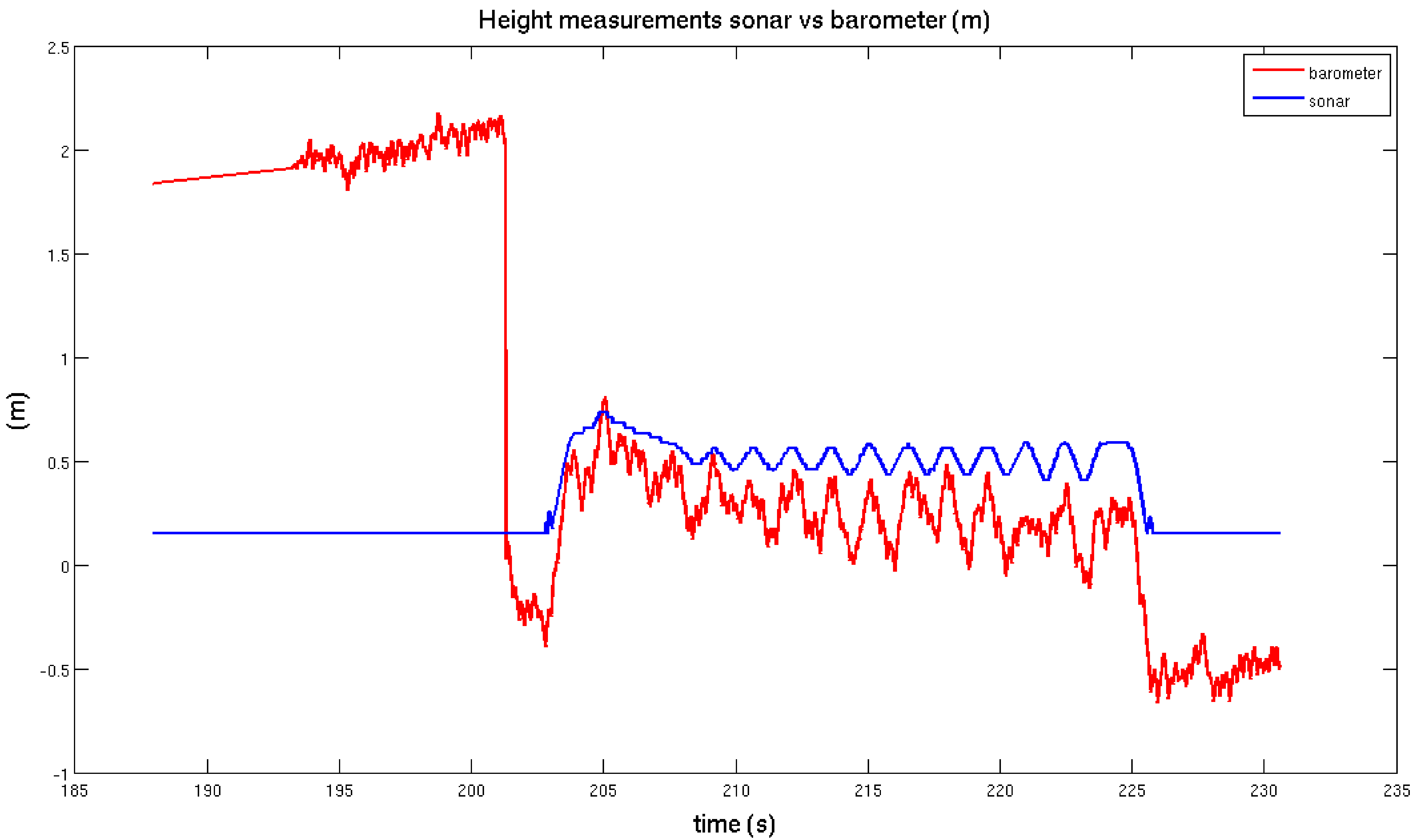
$$T = \frac{m}{\cos(\vartheta)\cos(\varphi)}[g - K_{zp}(z_d - z) - K_{zd}(\dot{z}_d - \dot{z})]$$

From IMU
(small noise)

From sonar
(quantized)

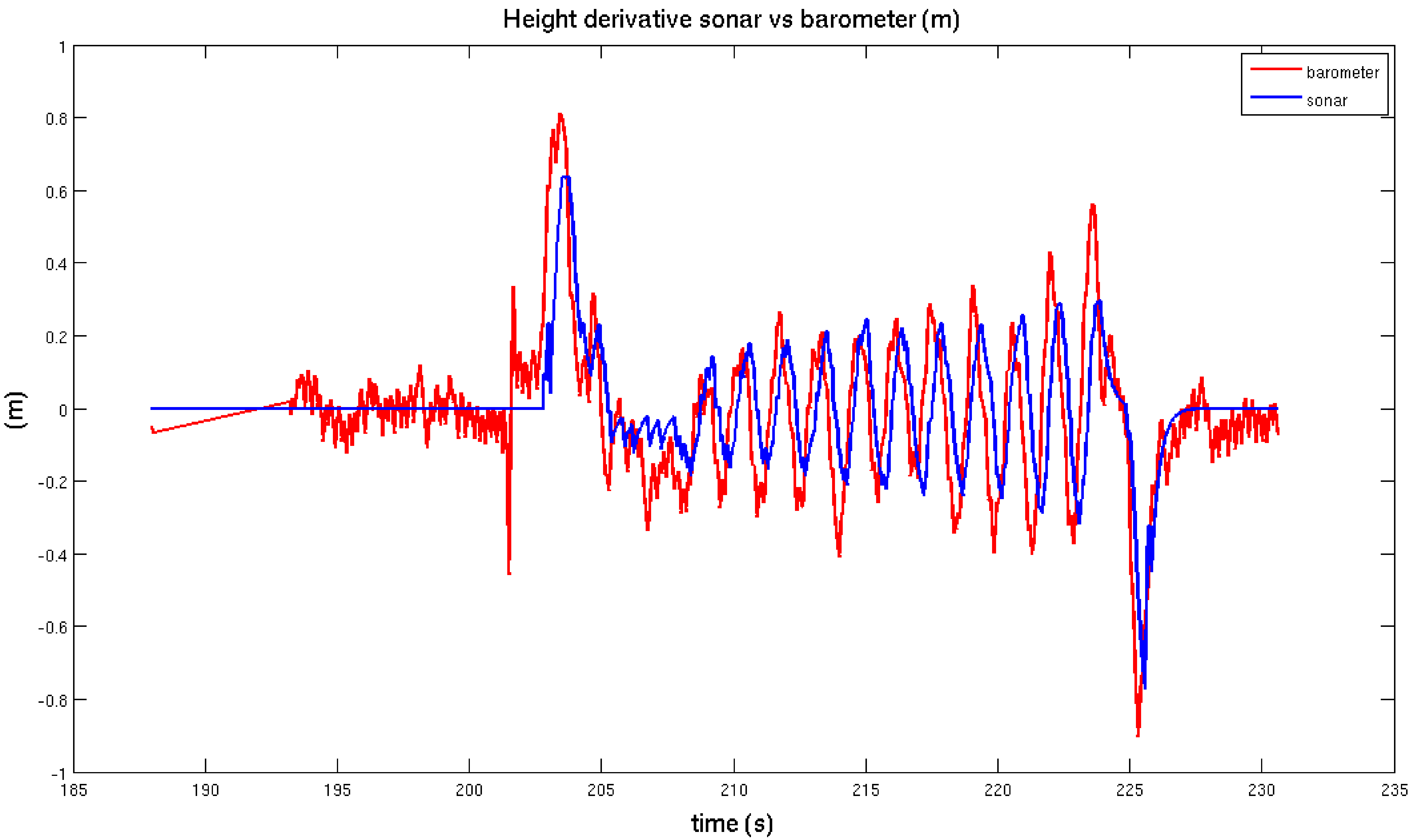
Filtered
derivative

Height control



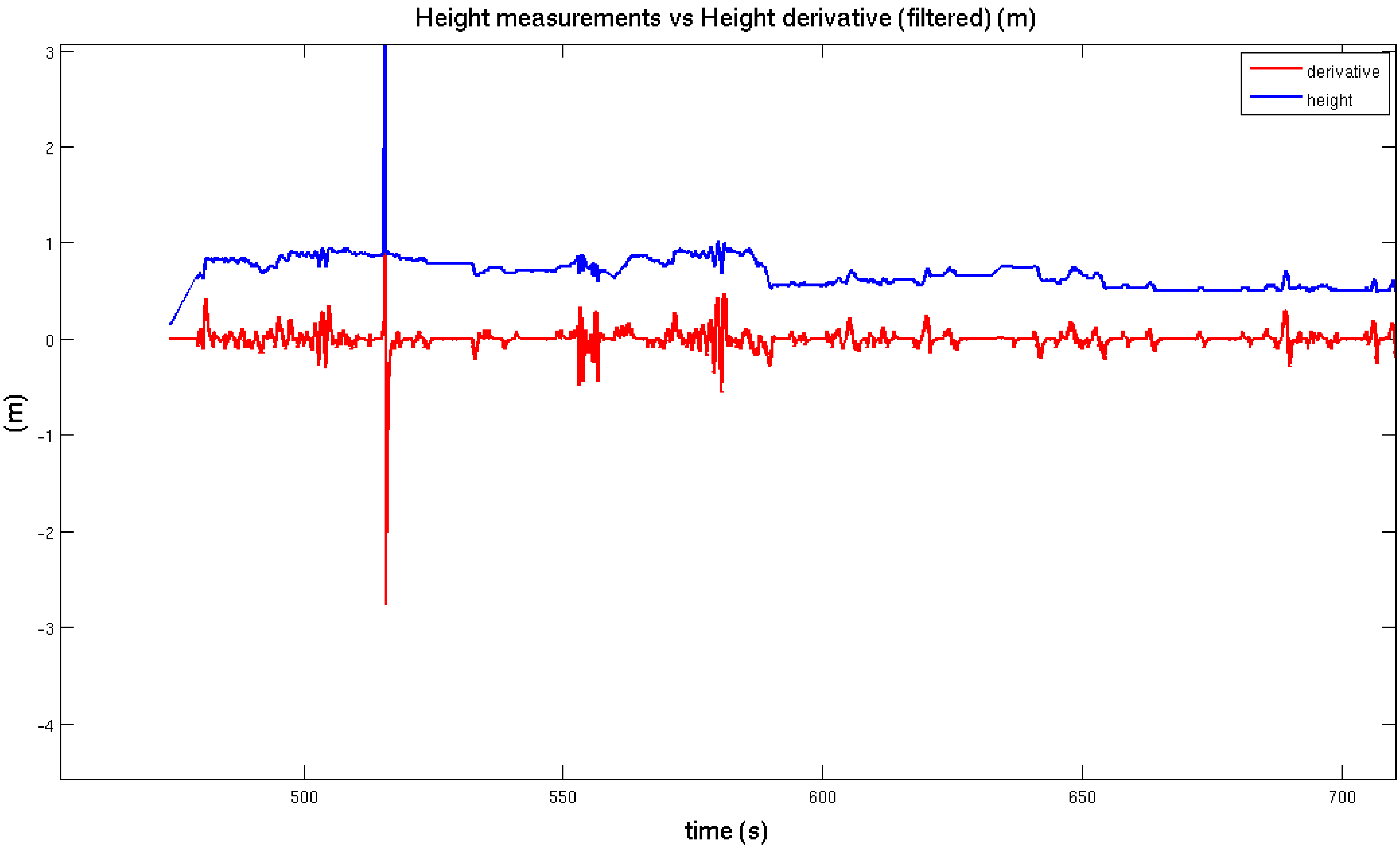
Indoor flight with height control

Height control



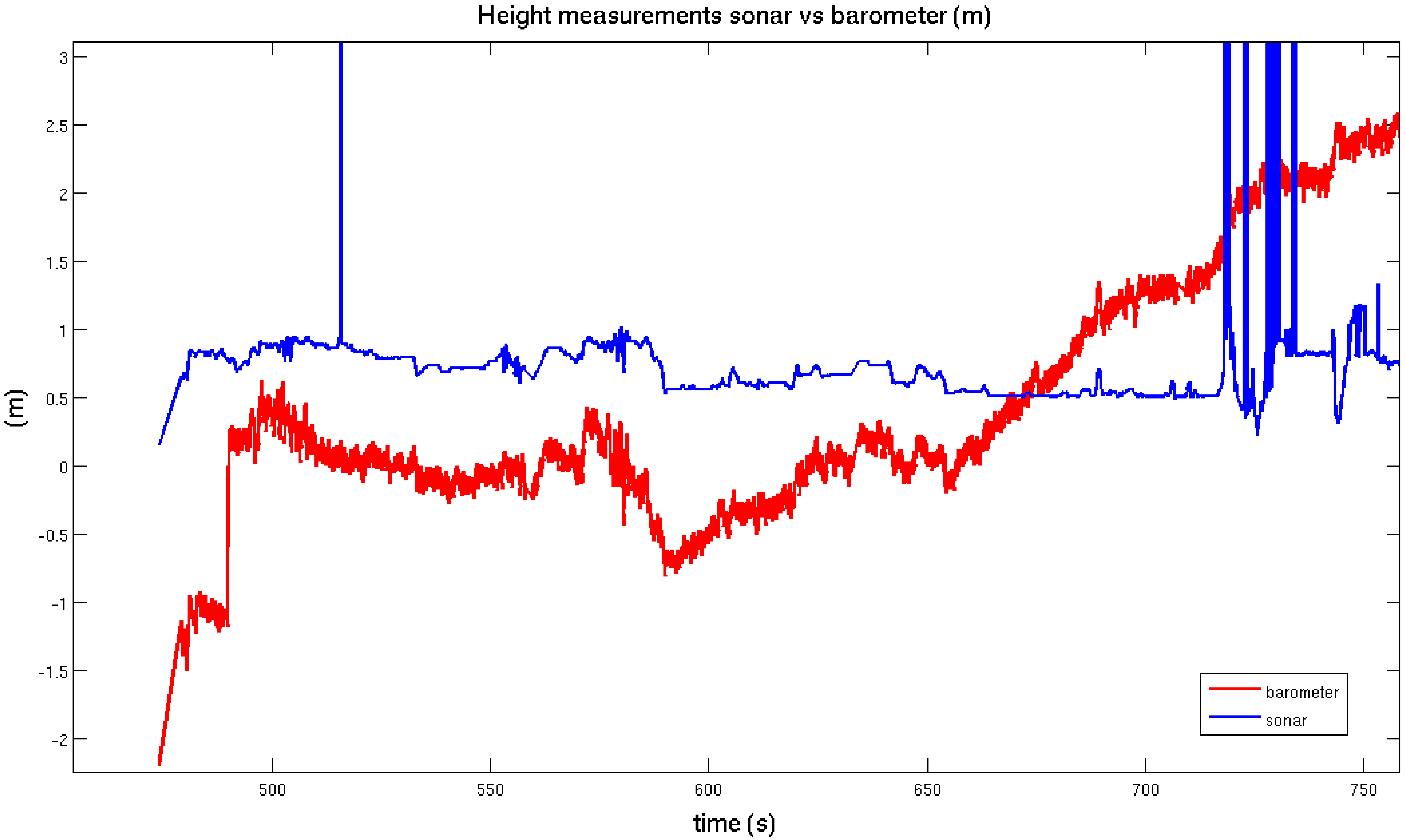
Indoor flight with height control

Height control



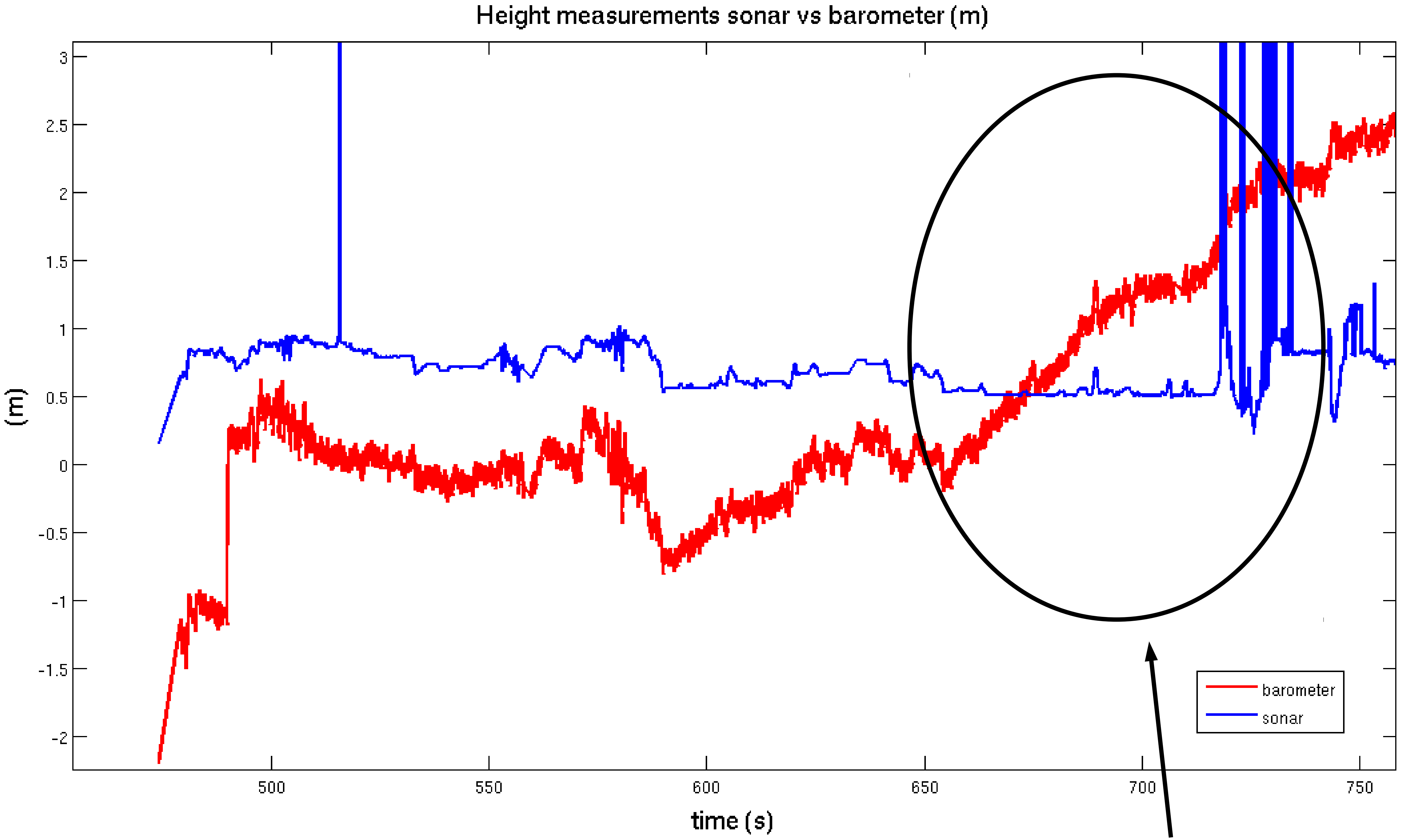
Outdoor flight with height control

Height control



Outdoor flight with height control

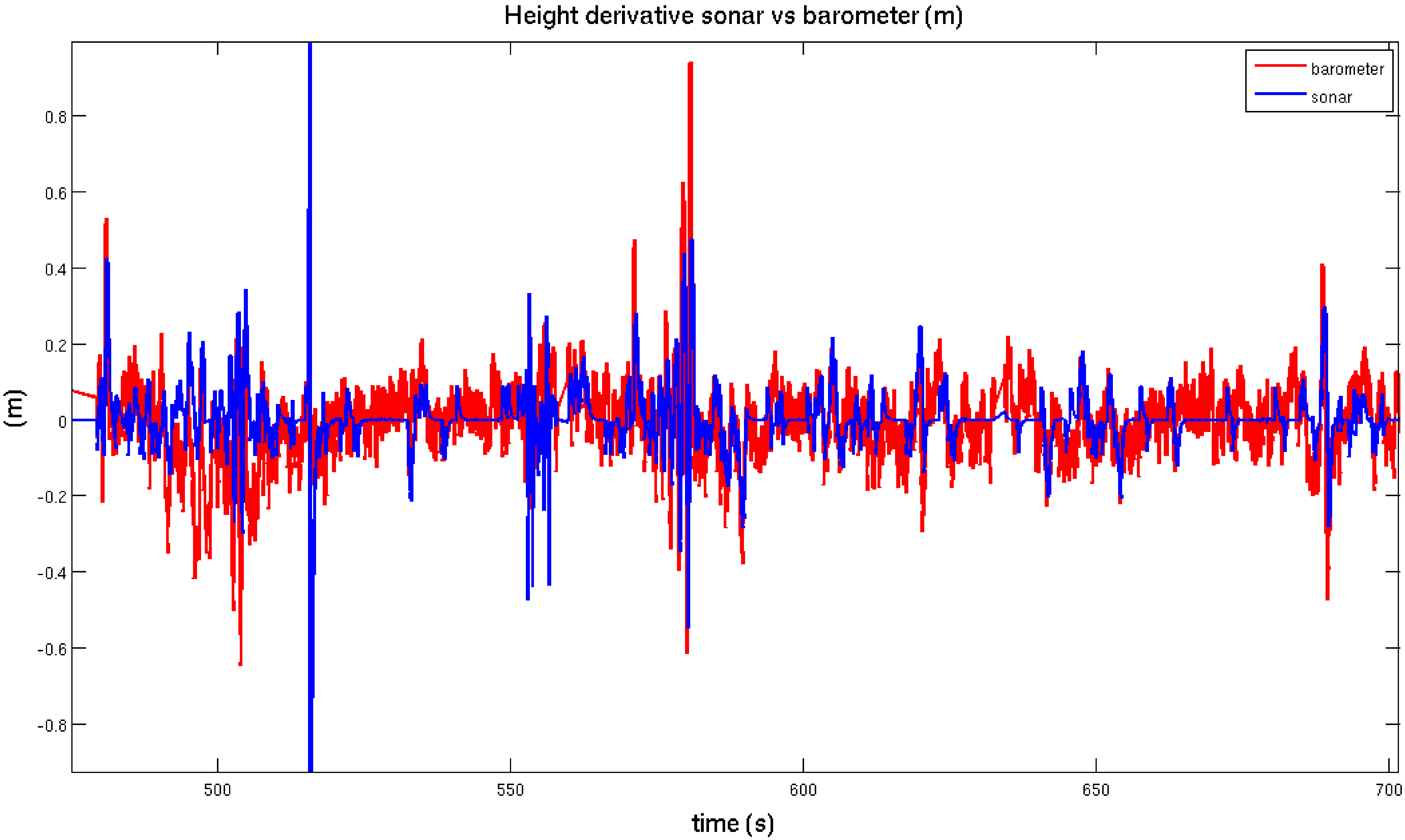
Height control



Outdoor flight with height control

Whom would you trust?

Height control



Outdoor flight with height control

Vision Systems

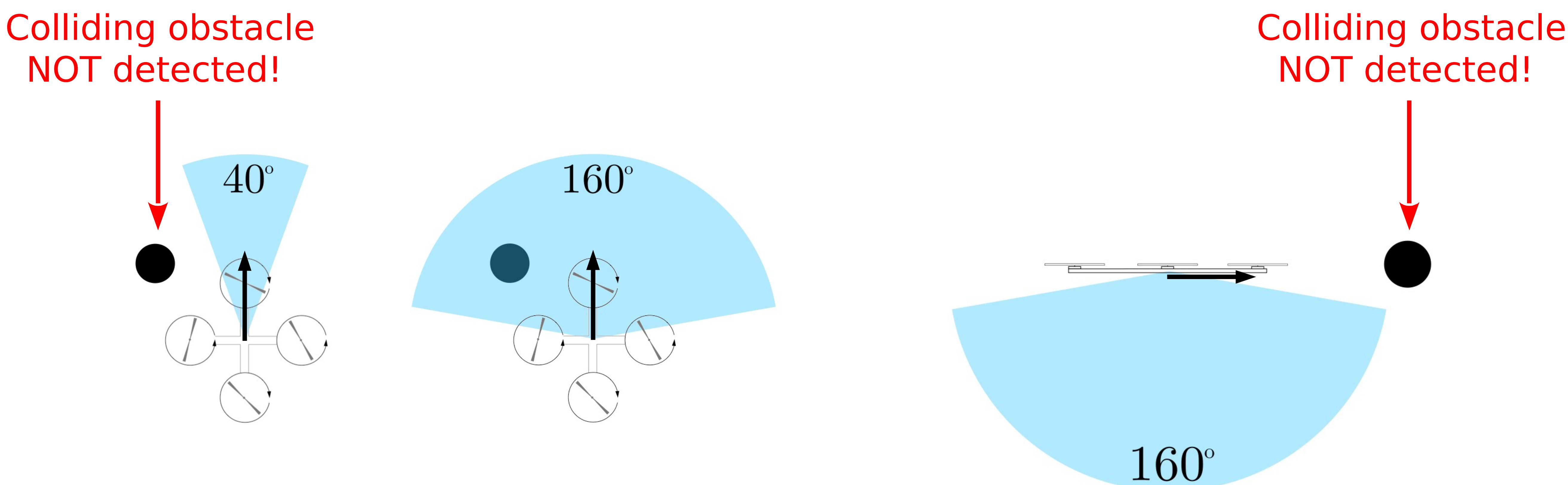
Front mounting:

- Recovering data for navigation
- Environment exploration
- Area monitoring
- Field of view is a critical parameter

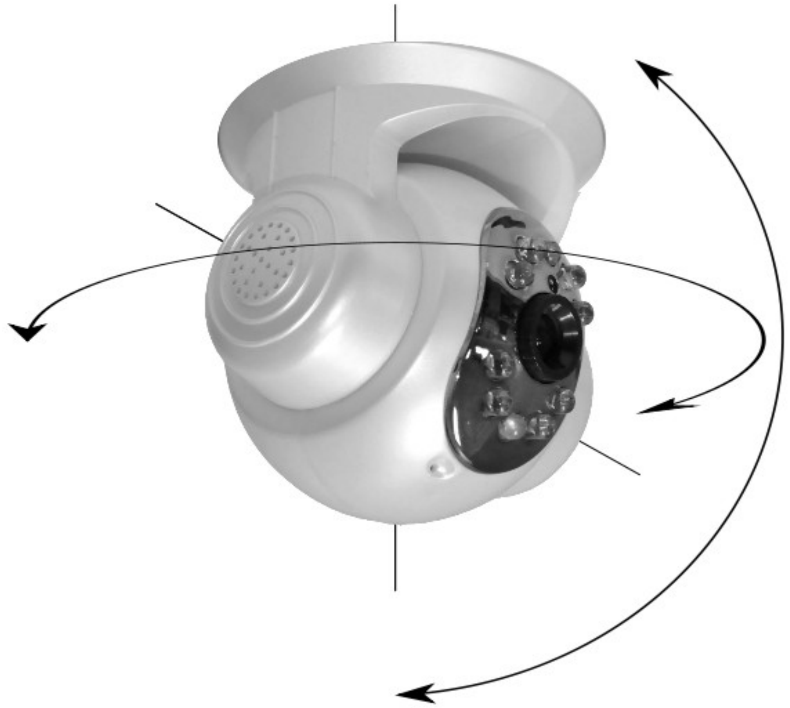
Bottom mounting:

- Navigation (e.g. with markers)
- Sourveillance (by hovering)
- Simultaneous Localization and Mapping (SLAM)
- Optic Flow (Velocity estimation)

NOTE: rigid transformation from camera to body must be considered



Vision Systems

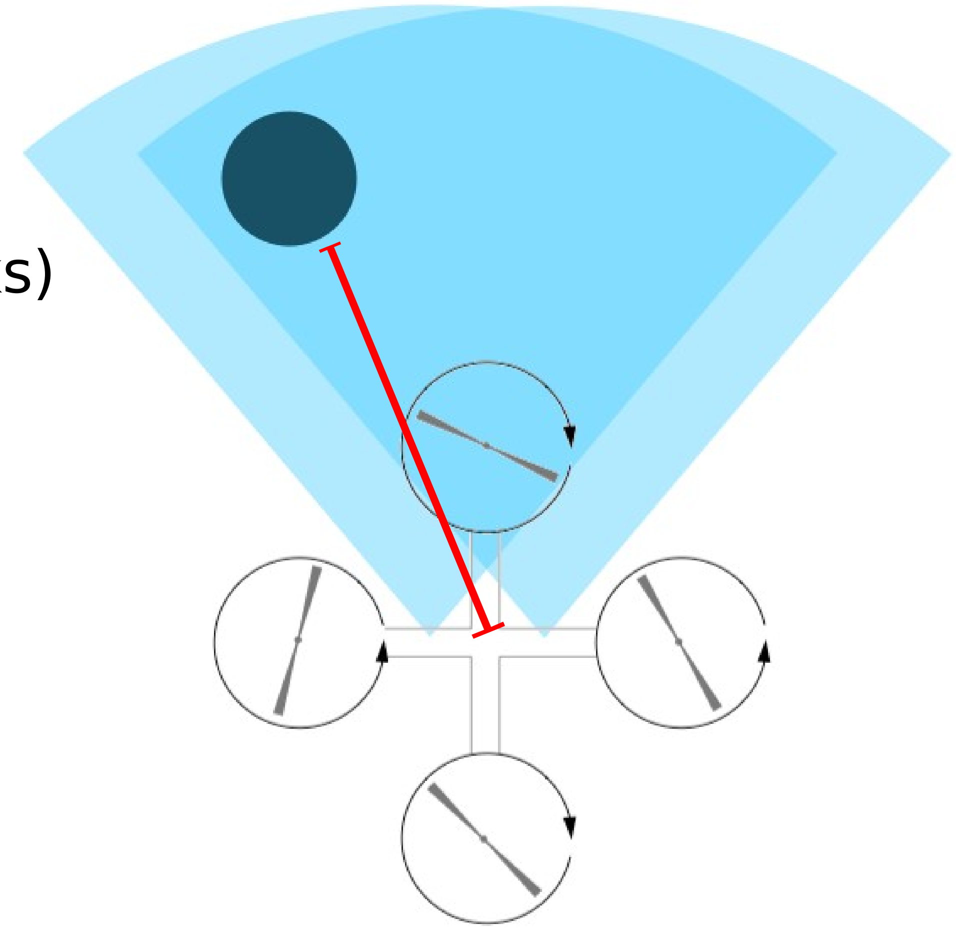


Pan-Tilt platforms can be used

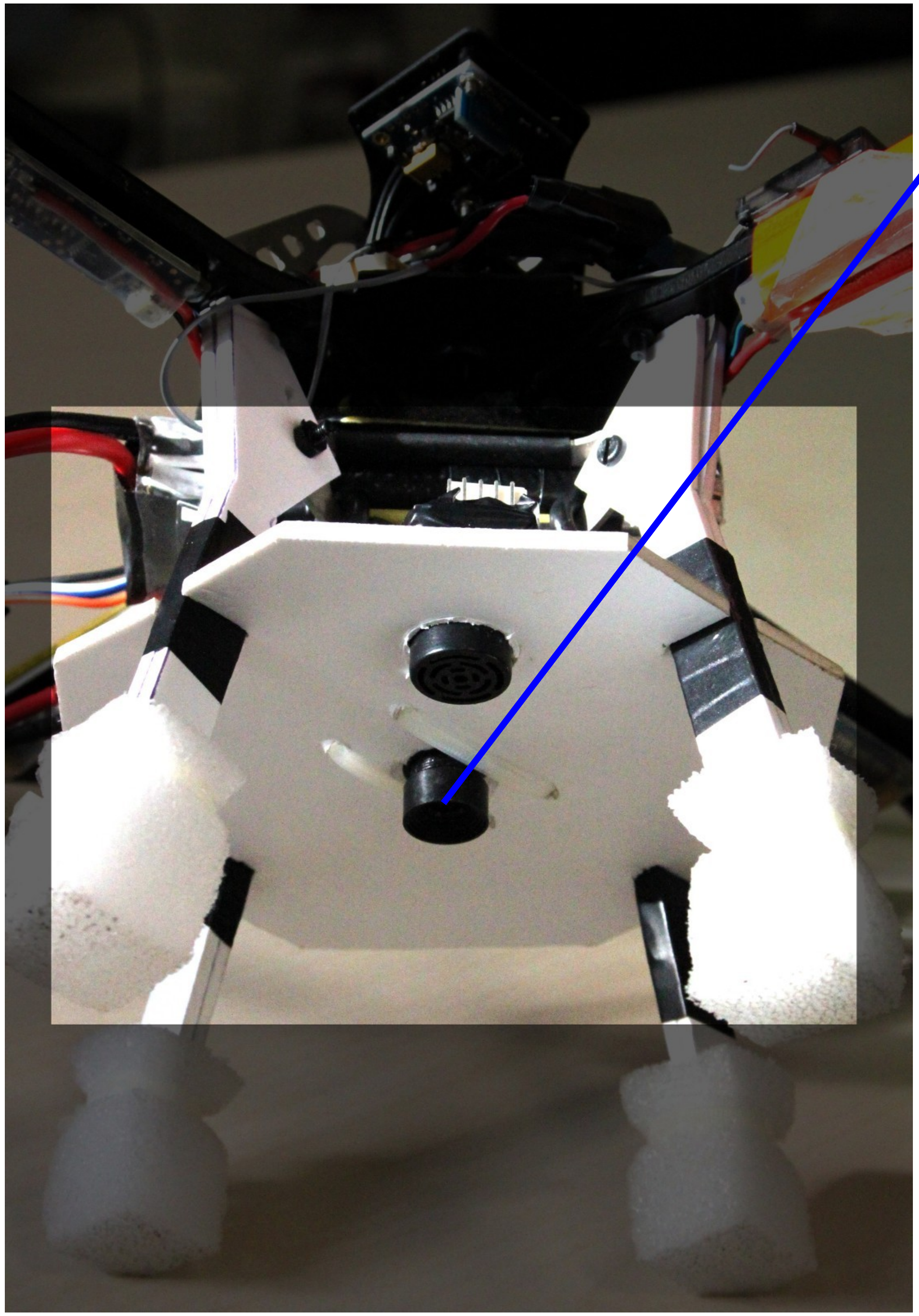
- Compensating vehicle motion
- Decoupling vision task from motion
- Adapting camera view to the task

Multiple cameras

- Multiple views (top + bottom, e.g. for different tasks)
- Stereo vision:
  - Recovering distance informations
  - 3D reconstruction of the scene
  - High computational cost
    (can't be done onboard for small vehicles)



Camera (onboard)



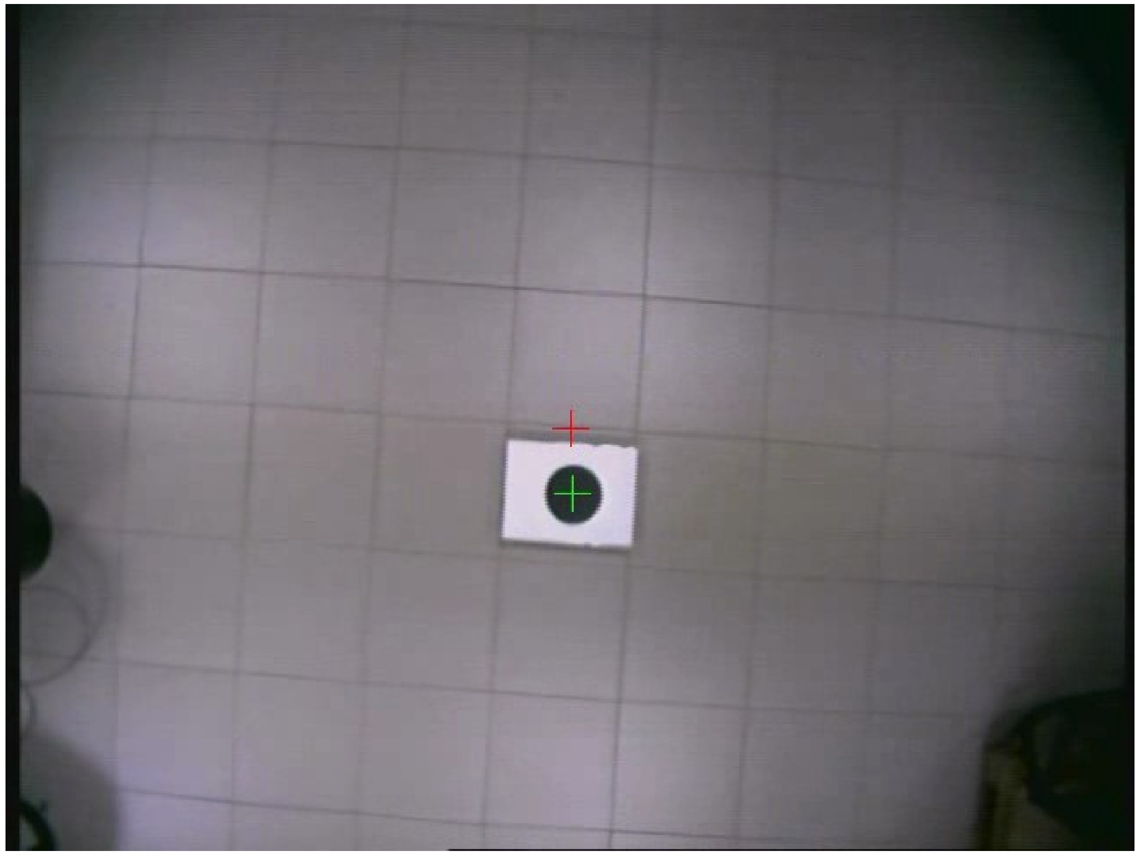
Wireless camera

- 640x480 (or 320x240)
- 30 fps
- operating frequency 2.4 Ghz
- voltage supply 6V

Camera link may fail

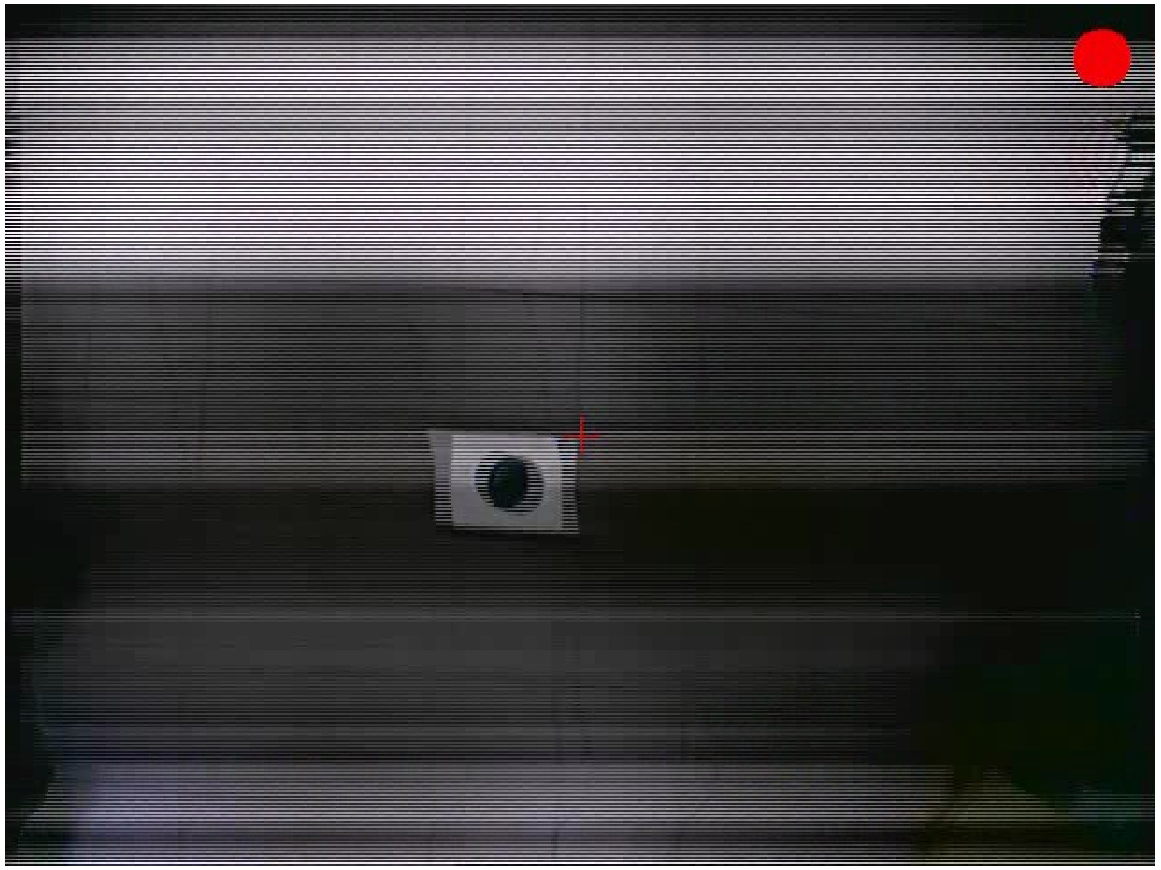
- Images can be unusable
  (slower frame rate / incomplete data)
- Wireless link interferes each other
- More power is needed
  (less flight time / more payload)

Camera (onboard)



Camera view

- Task maybe IBVS
  (target tracking is needed)
- Task maybe surveillance
  (continuous monitoring)
- Field of view ~60°



Noisy link

- Tracking of target fails!
  (target recovery is needed)
- Images are distorted / unusable
- Information data is lost!

Common Issues

Payload, endurance and hardware

- Reducing sensor number is convenient
- Some tasks need more sensor data (e.g. navigation)
- Sensor data may need computational power
- Some sensors need fast / large data link (e.g. camera)

Security

- Is the system really autonomous?
- What if software / hardware fails?

Data logging is desirable to perform performance analysis / debugging

Future works

Pelican quadrotor
(also from Asctec)

Augmented payload (500 g.)

↓

Augmented cpu capability
(AtomBoard 1.6 GHz)

↓

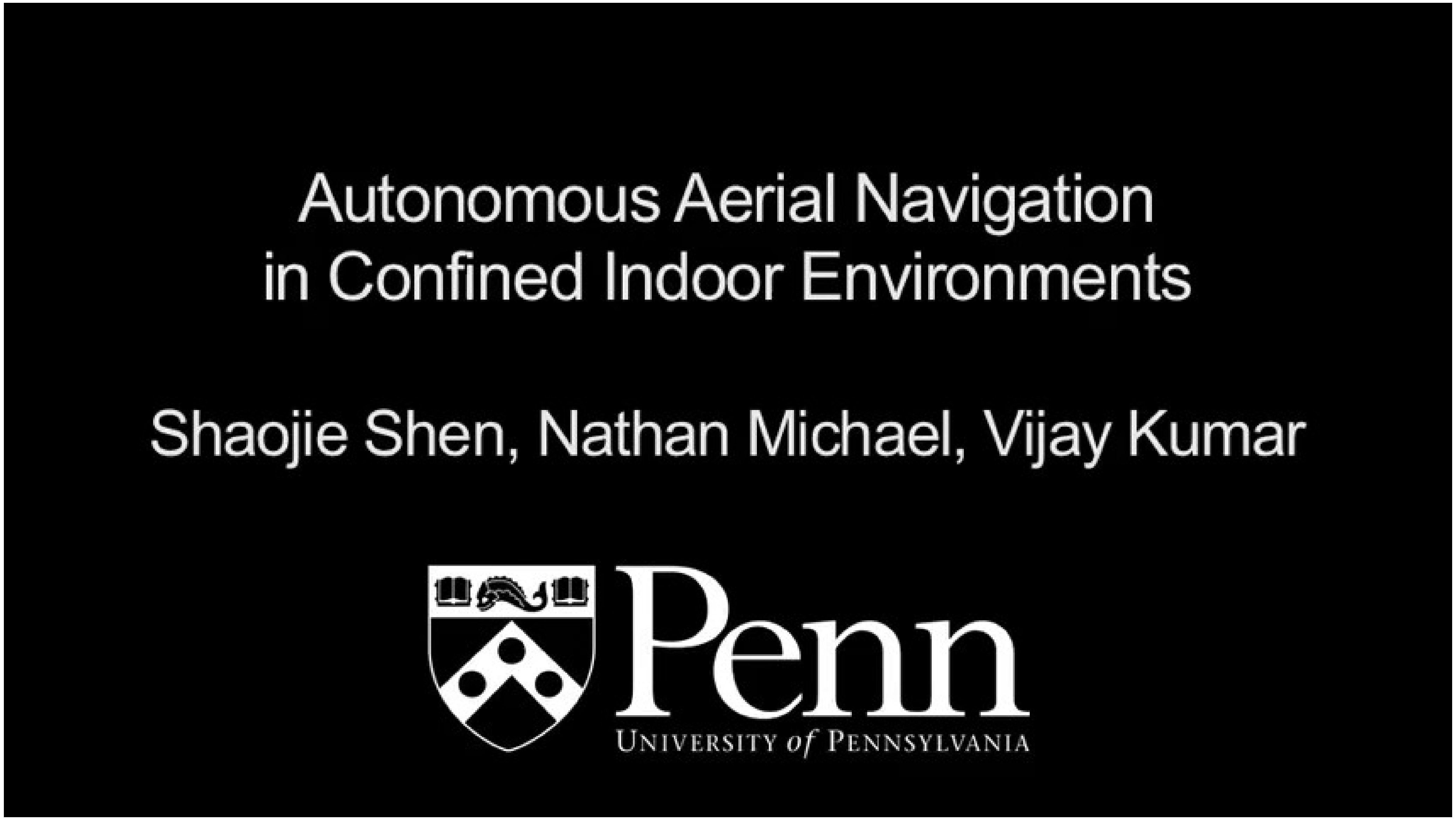
Removing communication problems
(WiFi tcp/ip board)

Kinect sensor (depth map)

↓

Navigation system

Examples of navigation



(Taken from youtube)

Example of interaction

(Taken from youtube)