Camera Drones
Lecture 2 – Flight mechanics, Control and Sensors

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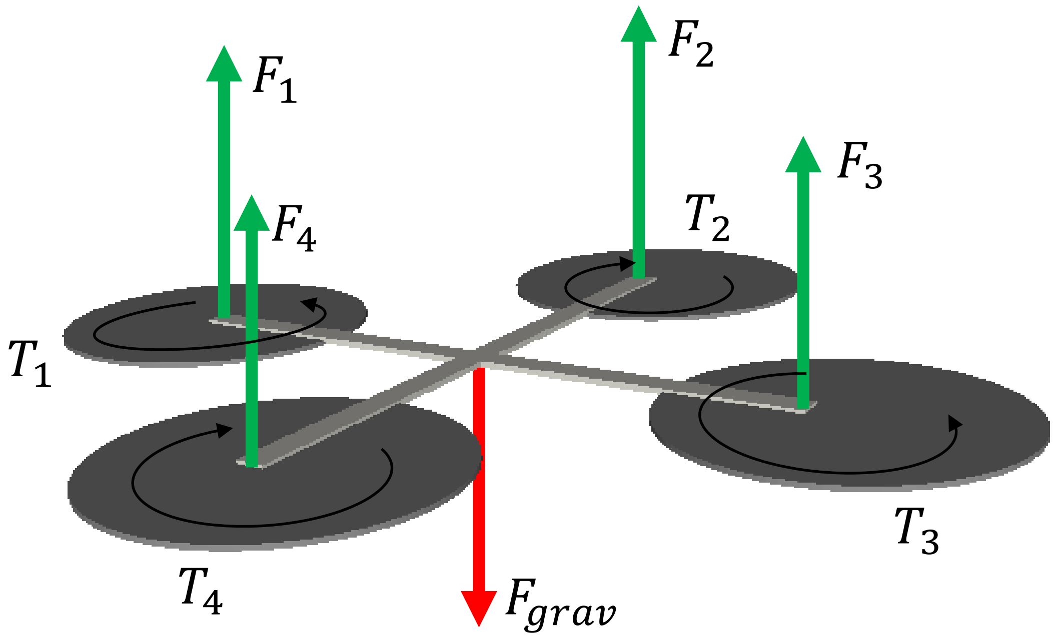
WS 2019

Outline

- Quadrotor flight mechanics
- Quadrotor control principles
- Sensors

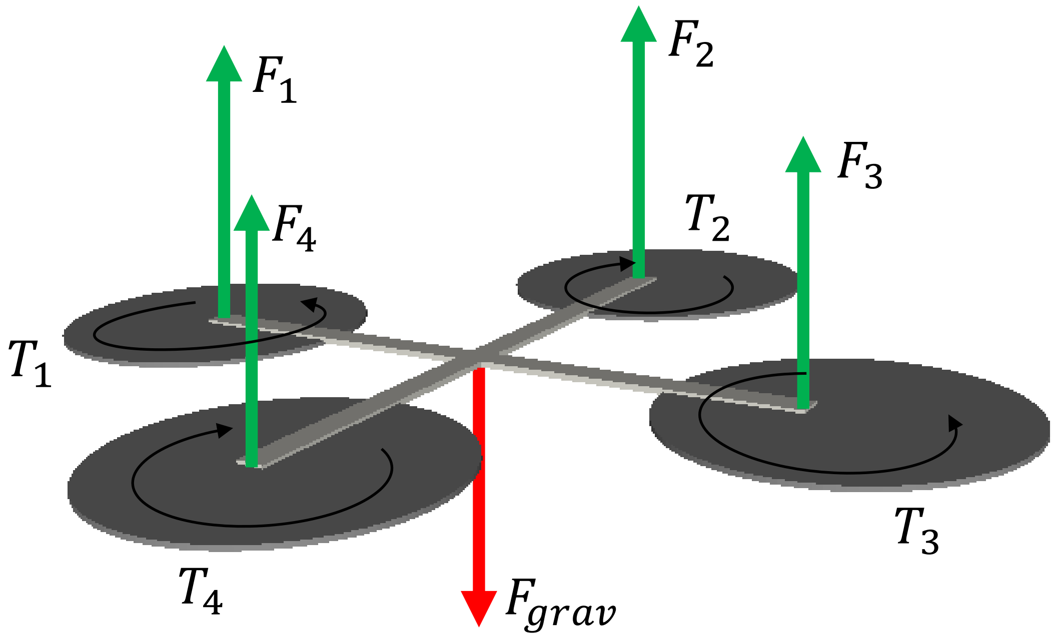
Quadrotor dynamics

- Each rotor produces force/lift and torque by accelerating air
- Gravity pull quadrotor downwards



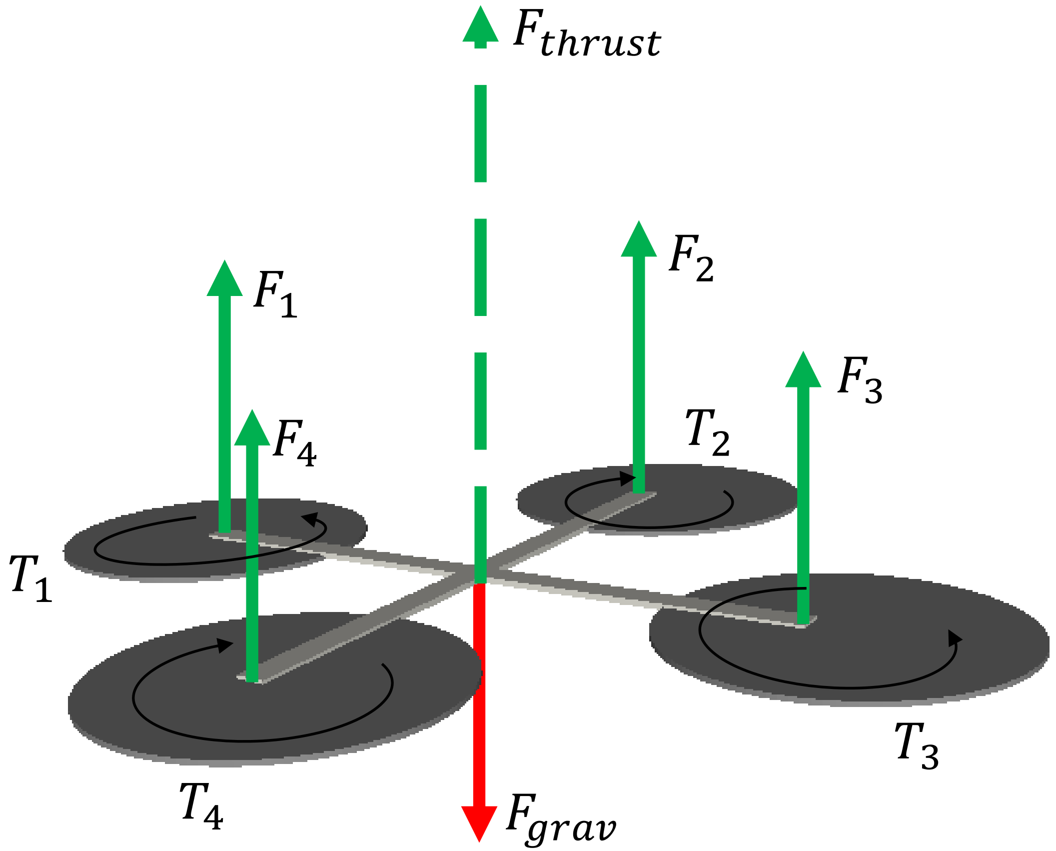
Quadrotor hovering

- Hovering when the lift exactly balances the gravity and when the torque is precisely canceled
- Torque is canceled by counter-rotating rotors



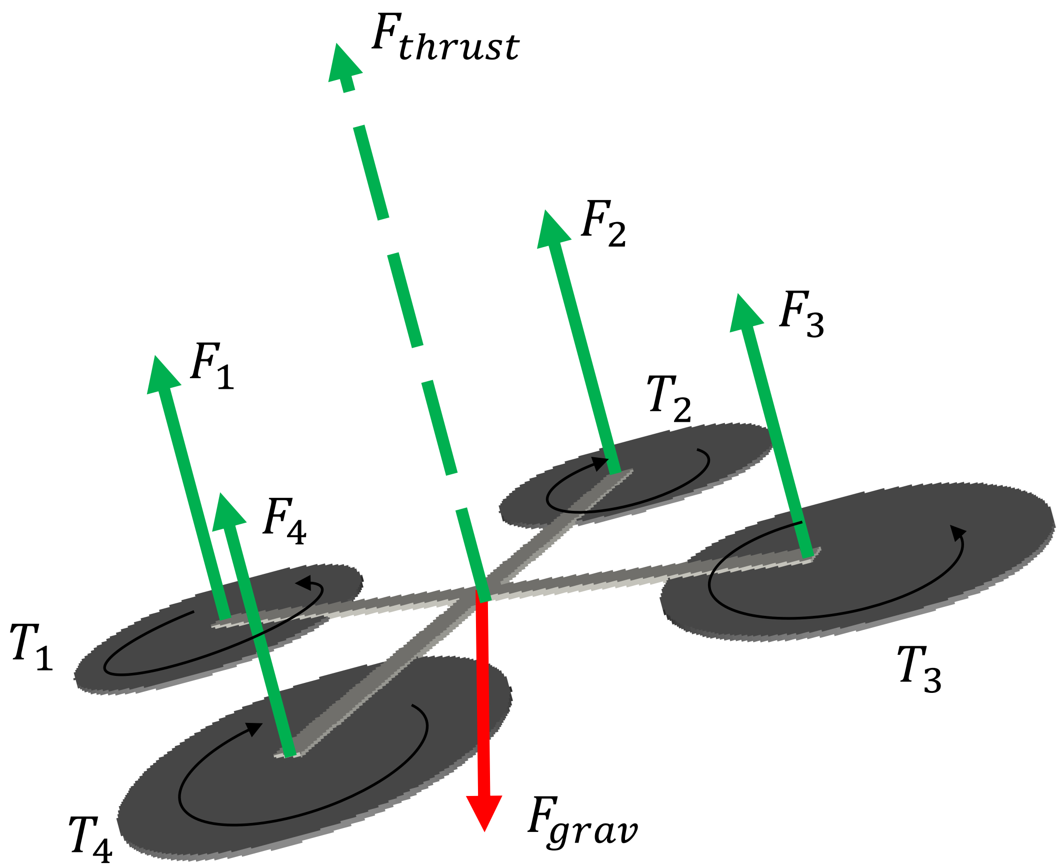
Quadrotor vertical acceleration

- Thrust $F_{thrust} = F_1 + F_2 + F_3 + F_4$



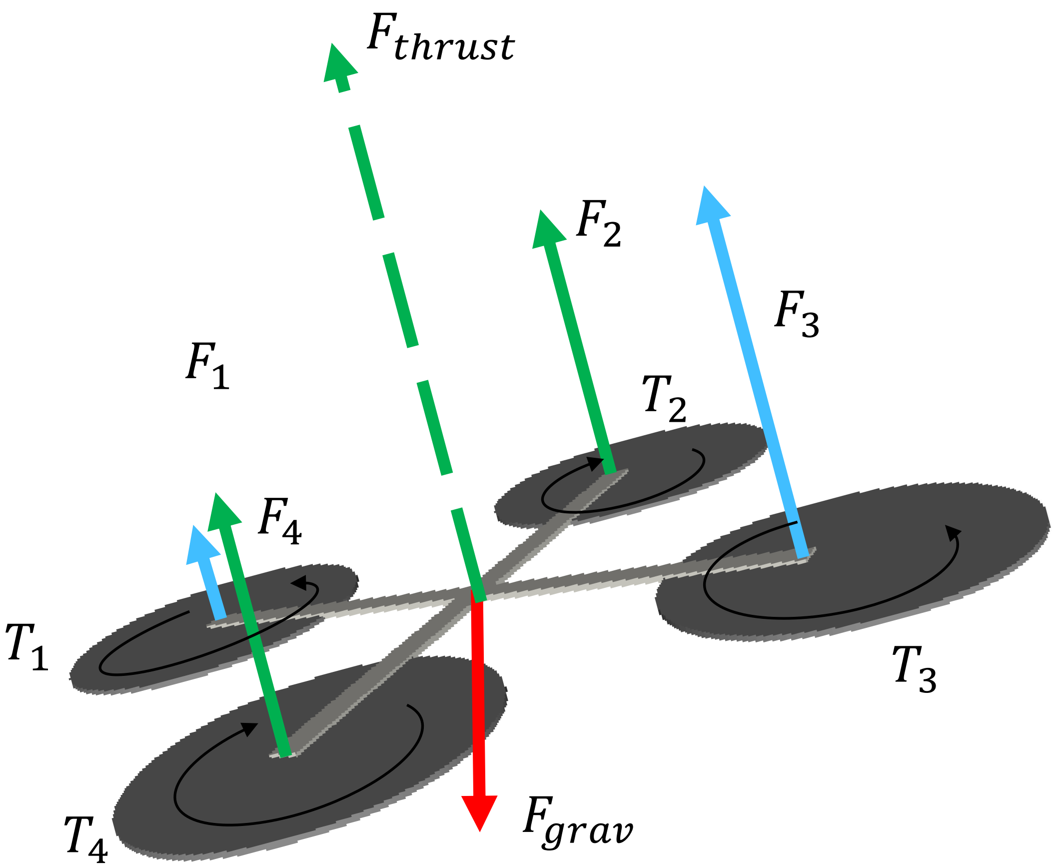
Quadrotor vertical and horizontal acceleration

- Thrust $F_{thrust} = F_1 + F_2 + F_3 + F_4$



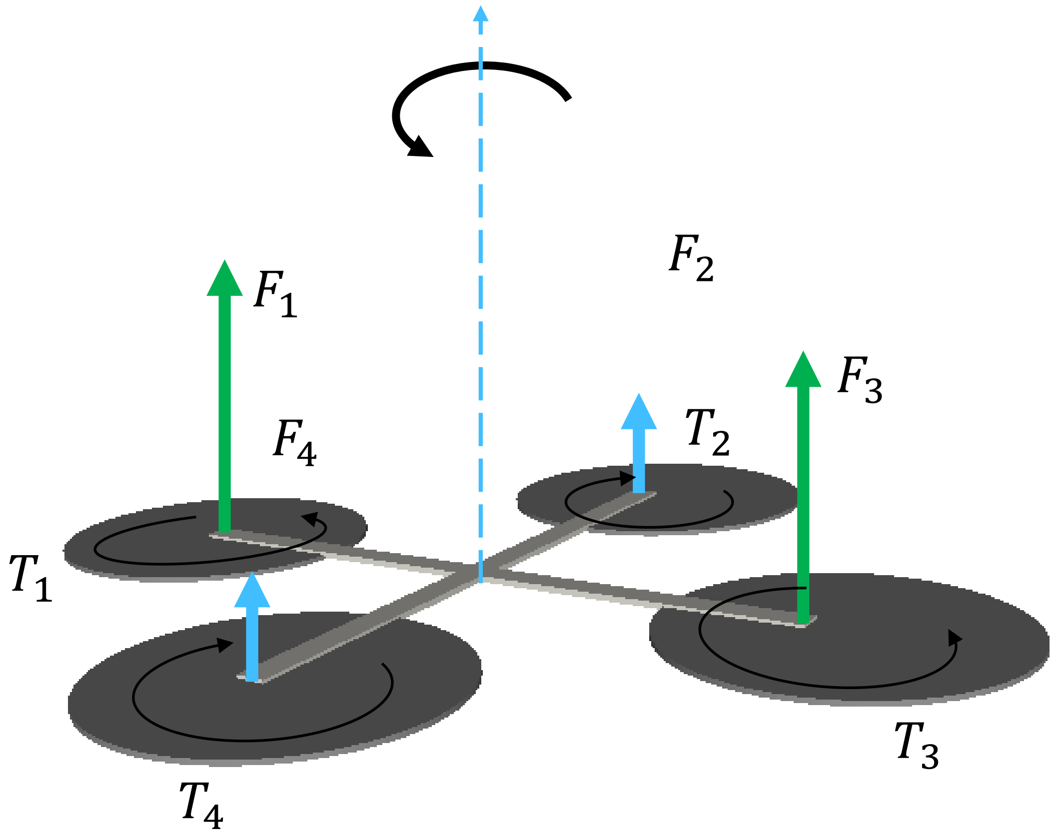
Quadrotor pitch and roll

- To pitch or roll the forces produces by the rotors need to be out of balance
- However, pure pitching and rolling not possible. Every pitch or roll induces also a horizontal acceleration



Quadrotor yaw

- Out-of balance torque is used to produce yaw rotation
- Torque $T = T_1 - T_2 + T_3 - T_4$
- Change rotor spin of pairs of rotors to keep the lift constant, but create imbalanced torque



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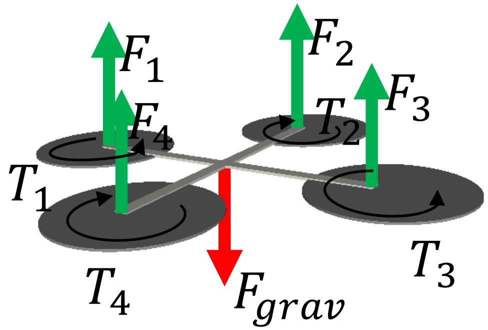
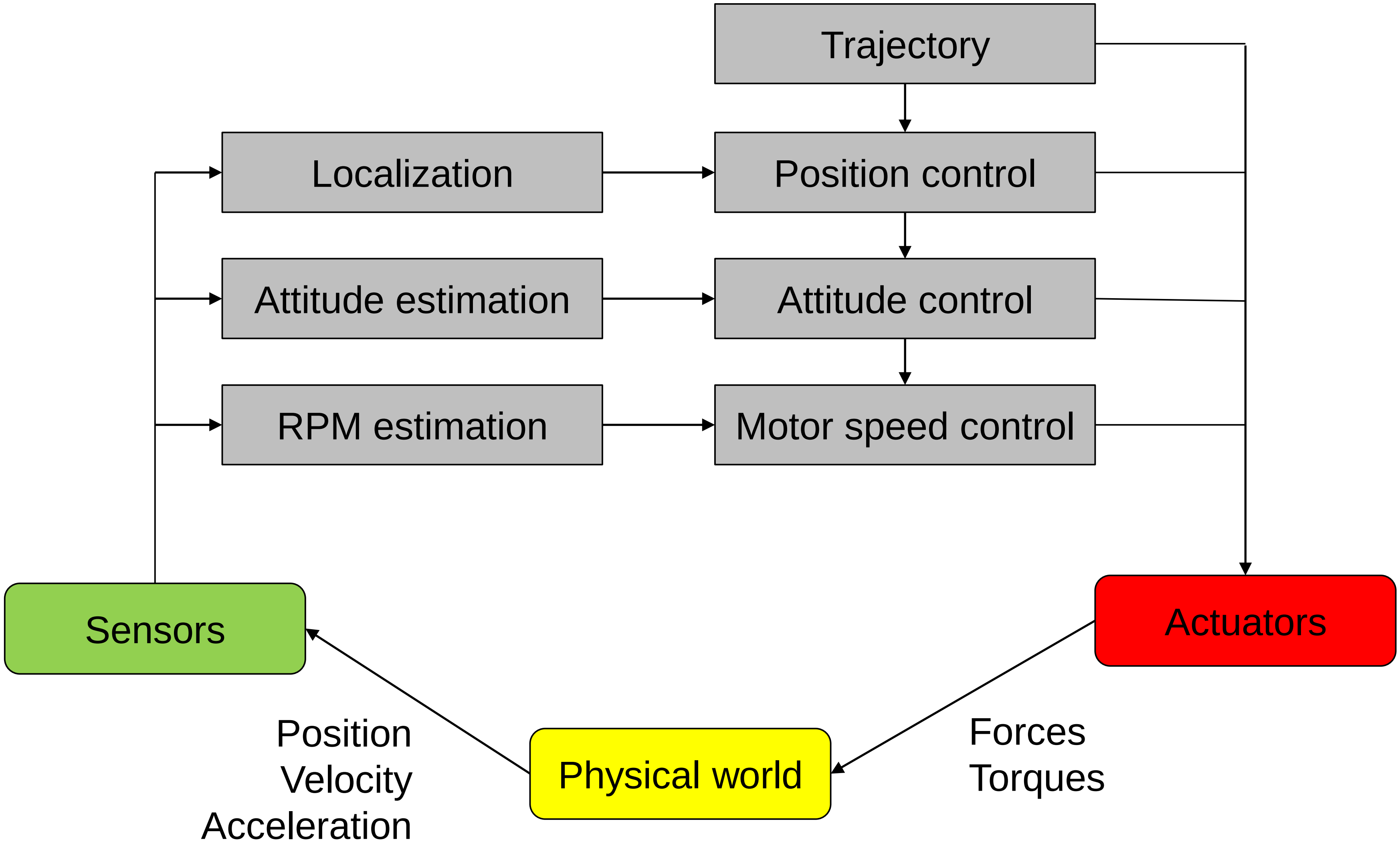
Quadrotor control - Hovering

- Hovering means quadrotor needs to hold position
- Requirement:
  - Each rotor produces exactly the same thrust
    (if there is a slight imbalance, a movement occurs)

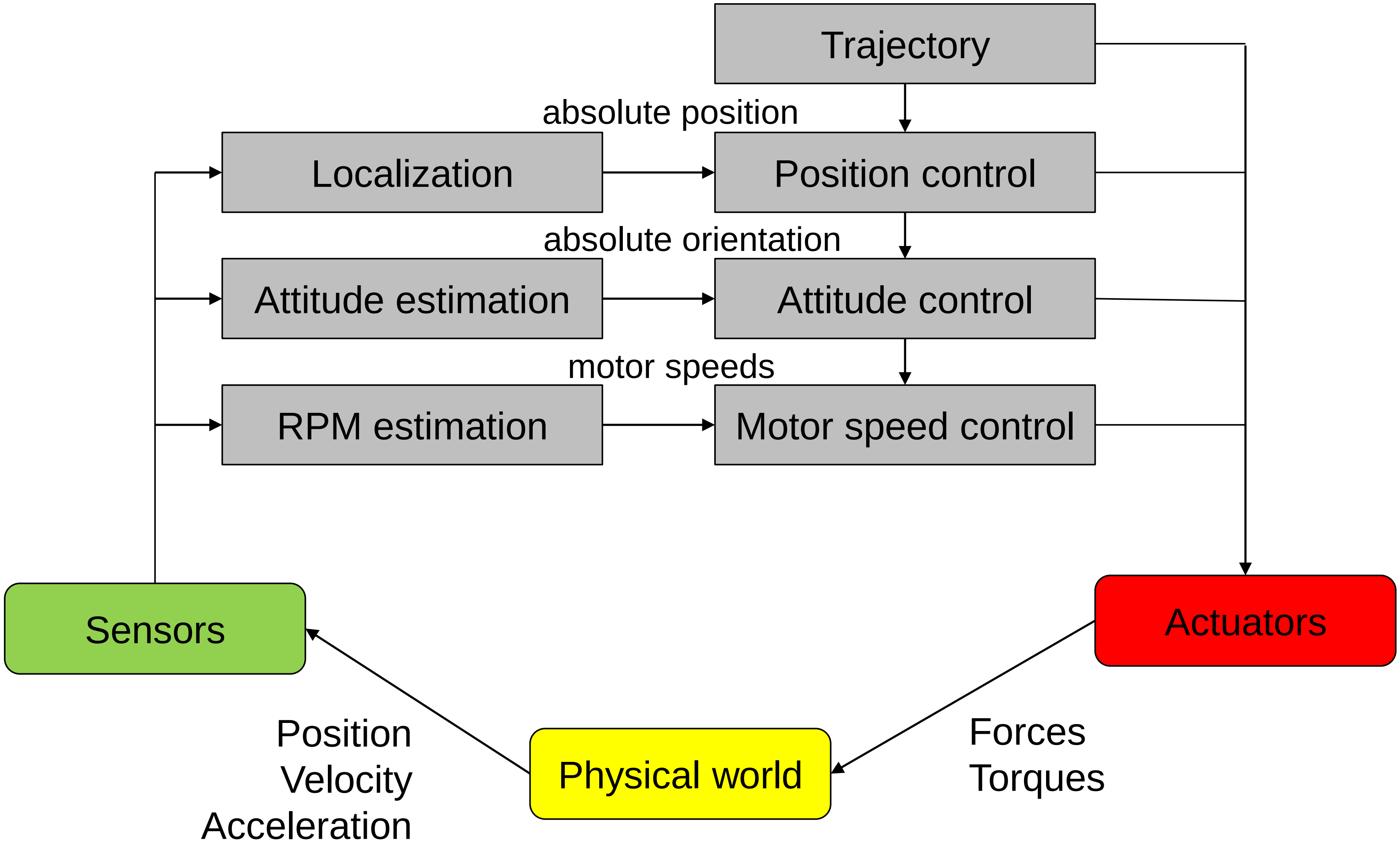


- Practically infeasible – control loop necessary
- Control loop means measuring deviation from hover position and then act against deviation
- What needs to be measured for this?
  - Is attitude/orientation enough? – If attitude is perfect zero than there is no movement

Elements of quadrotor control



Measurements needed for quadrotor control



Control timings

- Motor control happens on motor boards (controls every motor tick)
- Attitude control implemented on micro-controller with hard real-time (at 250Hz-1000Hz)
- Position control (at 4-250Hz)
- Trajectory (waypoint) control (at 0.1-1Hz)

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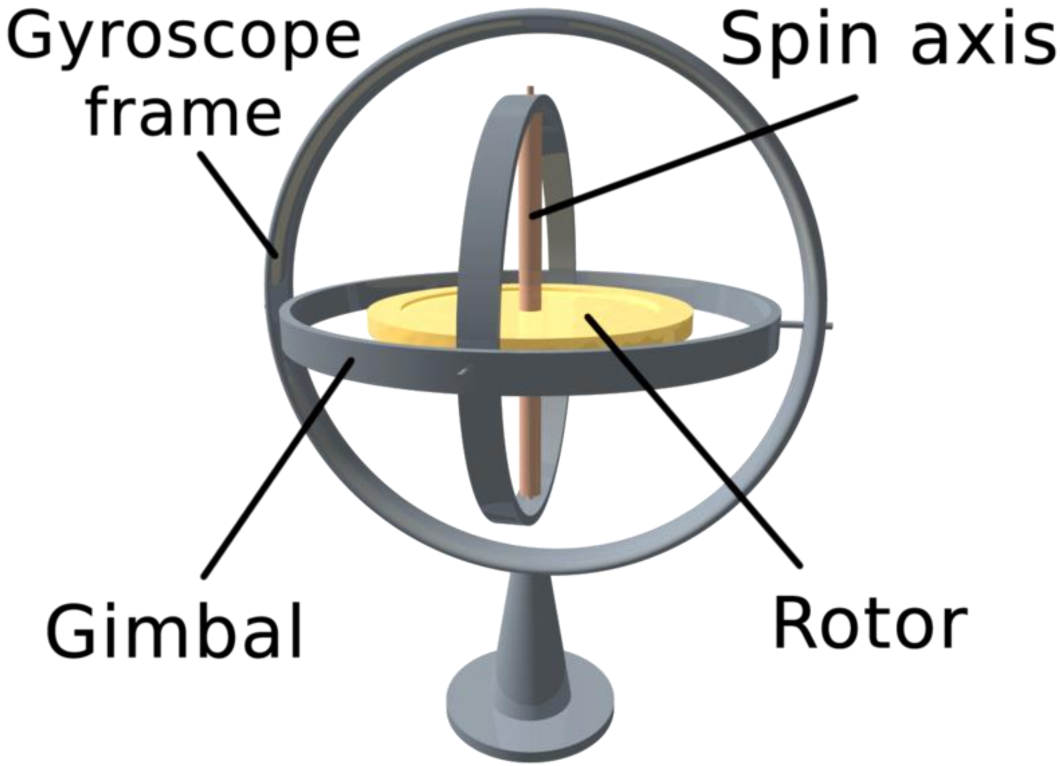
Sensors

- Gyroscope
- Accelerometer
- Magnetic field sensor (Digital compass)
- Inertial measurement Unit (IMU)
- GPS
- Inertial navigation system (INS)
- Air pressure sensor
- Ultrasound sensor
- Infrared sensor
- Laser distance sensor
- Laser range finder
- Depth camera
- Digital camera
- Optical flow sensor
- Optical flow camera (PX4Flow)

Gyroscope

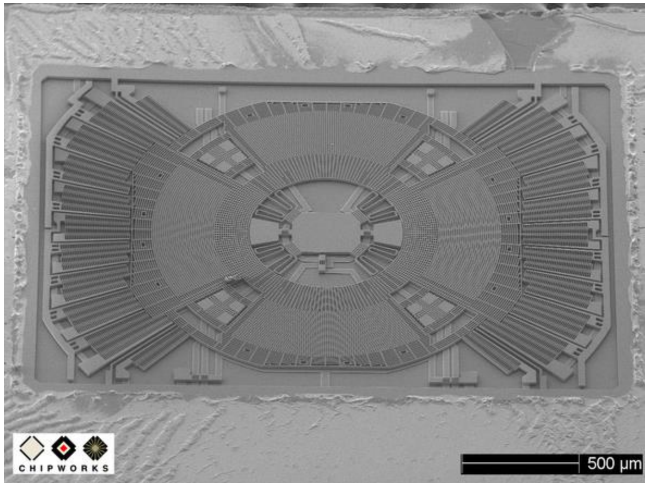
- Measures orientation (standard gyro) or angular velocity (rate gyro)
- Mechanical gyro: Spinning wheel mounted in a gimbal device (can move freely in 3 dimensions)



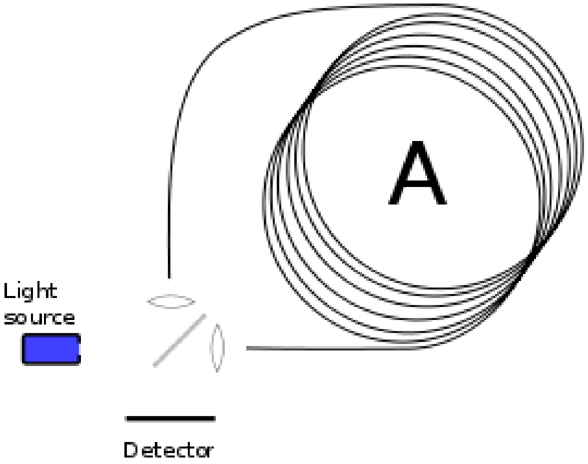
[Image source: Wikipedia, PD]

Gyroscope

- Modern gyros are micro electro-mechanical systems (MEMS) or fiber optic gyros
- MEMS:
  - Vibrating structures (vibration keeps its direction under rotation)
- Fiber optic:
  - Interference between counter-propagating laser beams is measured, changes with rotation
  - Fiber length e.g. 5km!



[Image source: Amber Case, CC BY-NC 2.0]



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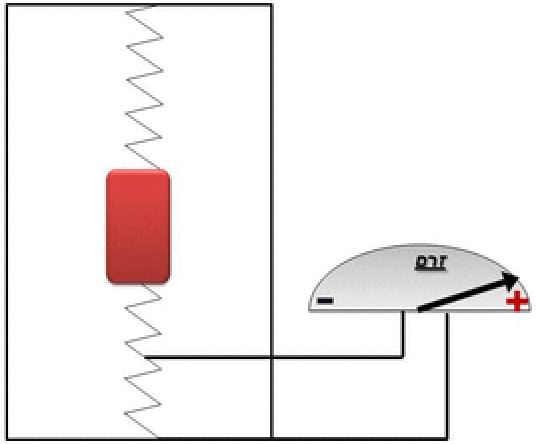
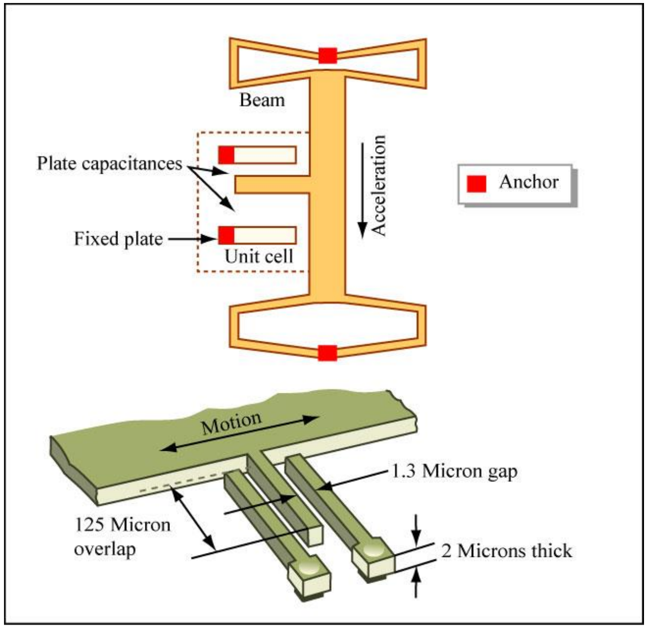
Accelerometer

- Measures all external forces acting upon it (e.g. gravity)
- Acts like a spring-damper system
- To obtain inertial acceleration (due to motion alone), gravity must be subtracted



Accelerometer

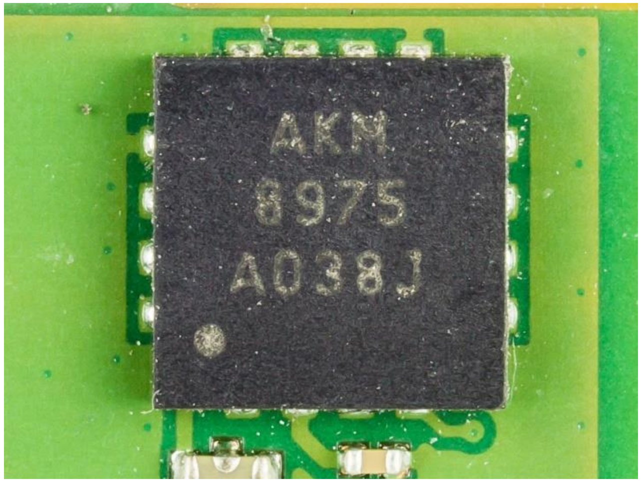
- Implementation as micro electro-mechanical system (MEMS)
- Spring-like structure with a proof mass
- Damping results from residual gas
- Measurements using capacitive or piezoelectric elements



[Image source: MIT OpenCourseWare, CC BY-NC-SA 2.0]

Magnetic field sensor (Digital compass)

- Measures **absolute** orientation in one axis
- Much less accuracy than gyroscope for relative orientation
- Easily affected by metal (door frames etc.)



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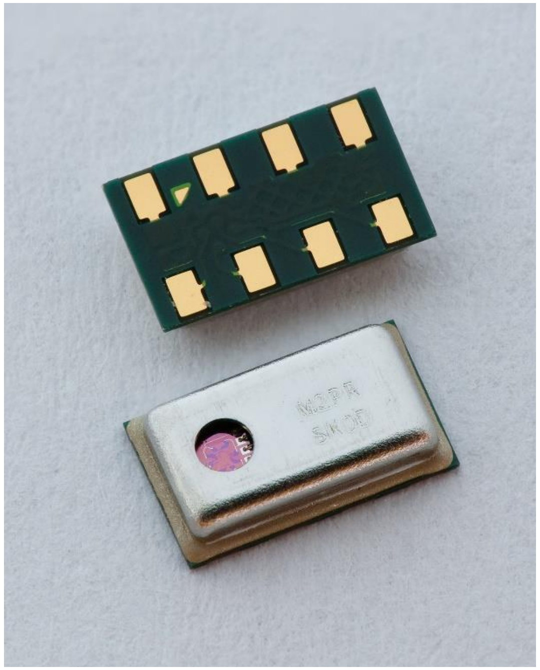
Air pressure sensor

- Measurement of air pressure can be used to measure altitude
- MEMS implementation
- Measurement depends highly on weather changes (temperature)
- Environment changes (open/closing doors or windows changes the measurement)

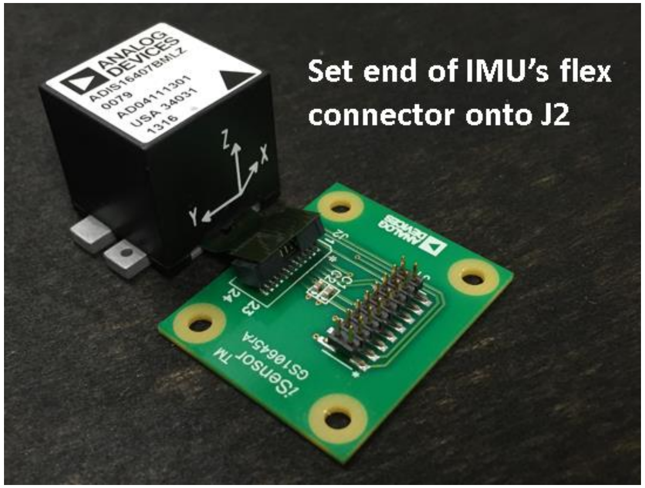


[Image source: Wikipedia, CC BY-SA 3.0]

Inertial measurement unit (IMU)

- Combines gyroscopes and accelerometers
- MEMS gyroscopes and accelerometers only give measurement in one axis
- An IMU therefore contains gyroscopes and accelerometers for each axis
- 3-axes gyroscope
  - Measures angular velocity
  - Integration necessary for angular position (orientation)
  - Problem: Integration leads to slow drift
- 3-axes accelerometer
  - Measures accelerations in 3 directions (includes gravity)
  - Problem: Rotation as well as linear accelerations are combined in the measurements
- Sometimes also contain air pressure sensor and digital compass

Inertial measurement unit (IMU)



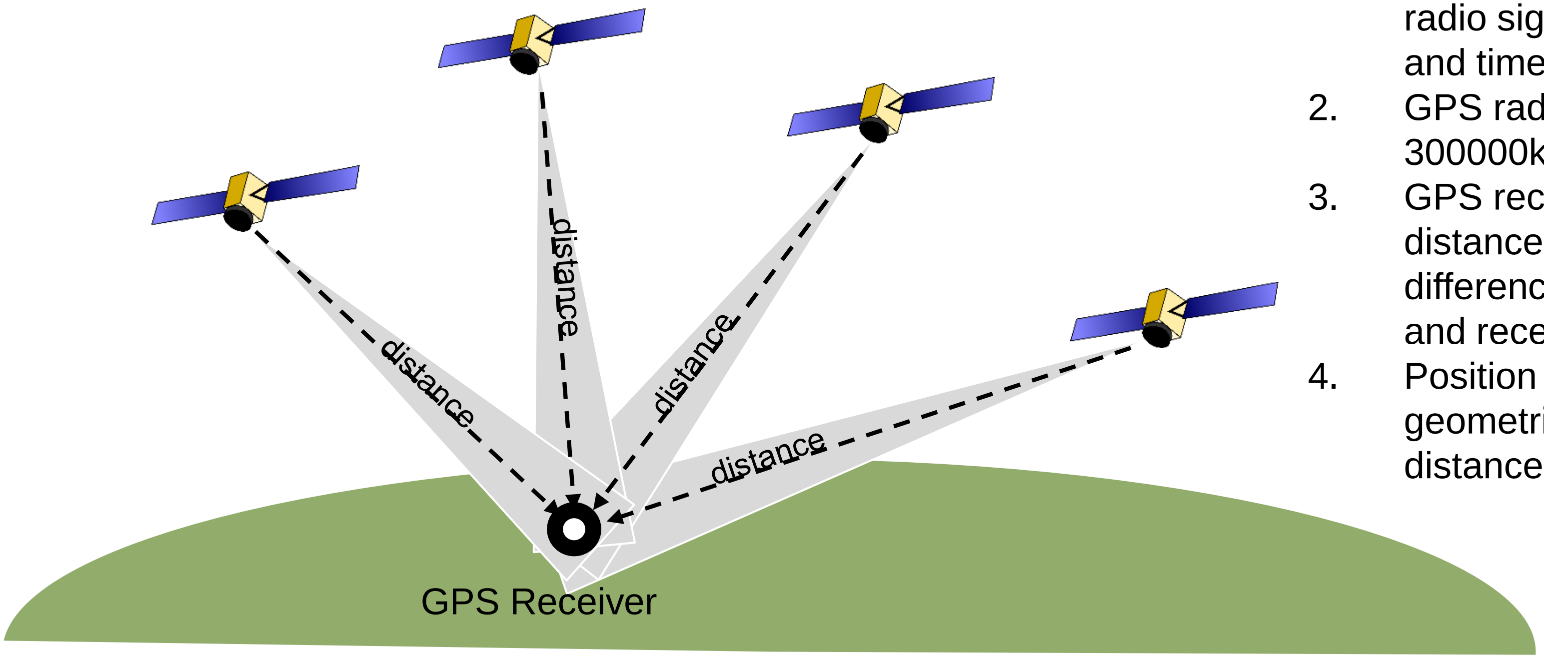
ADIS16407, 16g, MEMS

Crossbow NAV 420,
580g, MEMS

Invensense MPU-6000, 0.1 g,
MEMS, 4x4x0.9mm

Global positioning system (GPS)

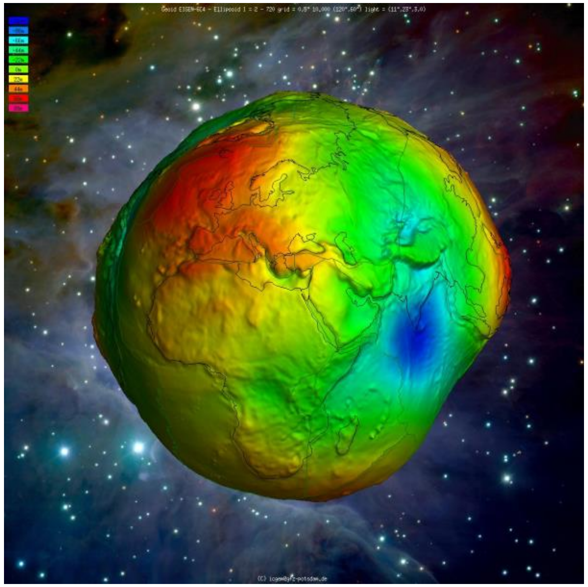
- Measures absolute position in clear outdoor areas
- GPS satellite send position and time



1. Each satellite transmits radio signal with position and time
2. GPS radio signal travels at 300000km/s (speed of light)
3. GPS receiver computes distance from time difference between sending and receiving
4. Position can be computed geometrically from 4 distance measurements

Global positioning system (GPS)

- Accuracy:
  - worst case pseudo-range 7.8m (RMS 4m)
  - horizontal accuracy of less than 3.5 meter measured
- Problem: No or bad reception indoors or urban canyons
- Height measurement
  - GPS provides position in space
  - Height over ground needs to be computed from Geoid model (earth is not a sphere)
  - Height measurement needs to be treated with care



[Image source: http://icgem.gfz-potsdam.de/vis3d/longtime]

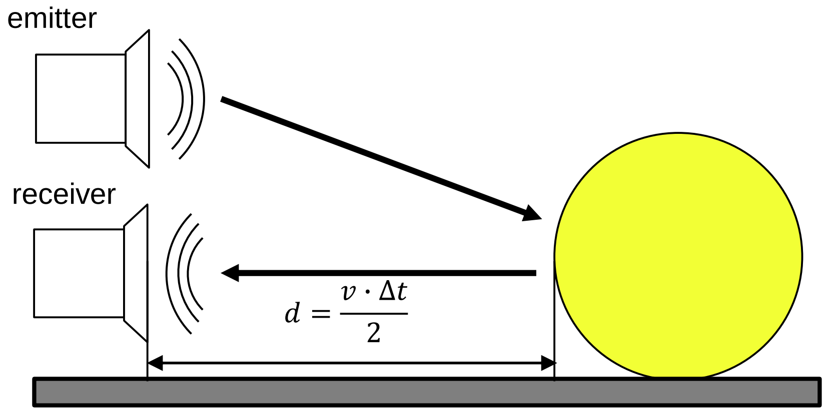
Inertial navigation system (INS)

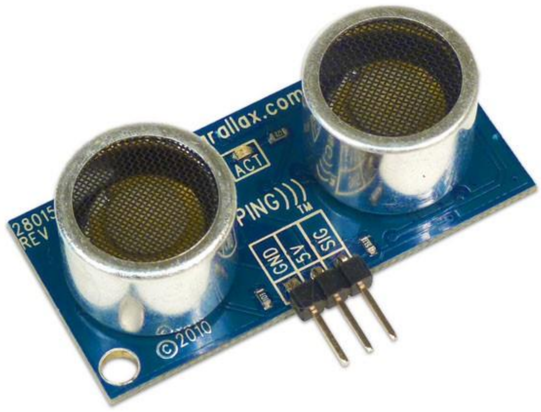
- A system consisting of GPS and IMU
- Integrates IMU measurements to get pose and orientation and corrects these measurement with global GPS positions and/or wheel encoders
- Accuracy:
  - X,Y position: 0.02-0.3m RMS
  - Z position: 0.05-0.5m RMS
  - Roll and pitch: 0.02 degree
  - Heading: 0.05-0.2 degree
- 100 000 $ price tag

[Image source: www.applanix.com]

Ultrasound sensor

- Distance sensor, can be used to measure height above ground
- Range between 12cm and 5m
- Opening angles around 20 to 40 degrees
- Soft surfaces absorb sound (no measurement)

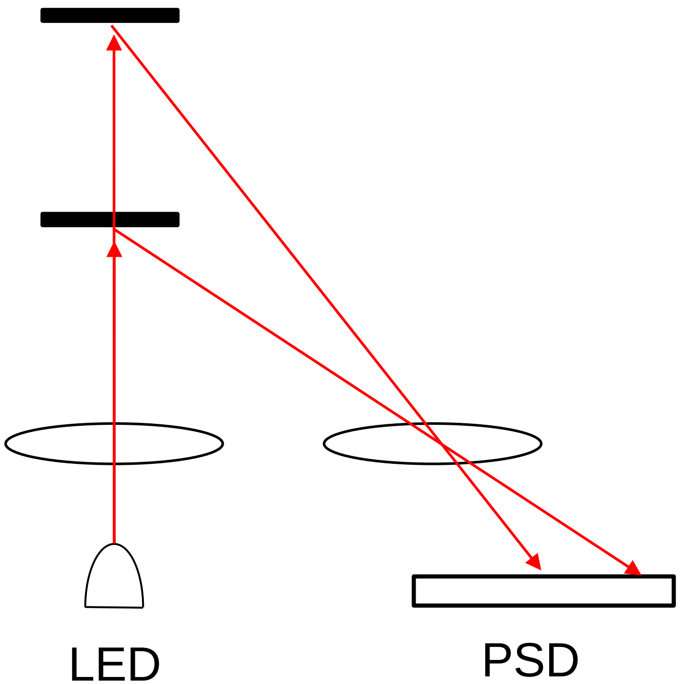




[Image source: http://www.ic0nstrux.com]

Infrared distance sensor

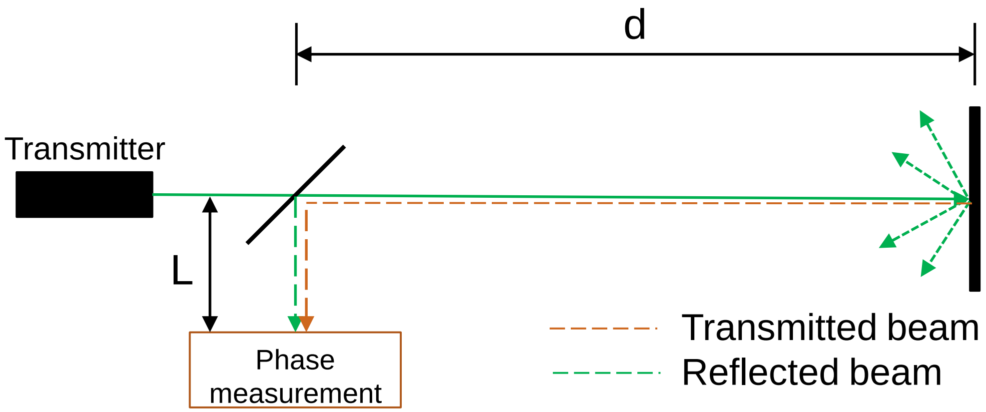
- Distance sensor, can be used to measure height above ground
- Range between 12cm and 5m
- Very similar to ultrasound sensor, but no problems with soft surfaces, but instead with dark surfaces



[Image source: Wikipedia, CC-BY-SA-2.0]

Laser distance sensor

- Distance sensor, can be used to measure height above ground
- Time-of-flight principle (TOF)
- Range between 0.2 and 14m
- Narrow field of view (3 degree)
- 1000Hz measurement frequency
- High precision for distance measurement



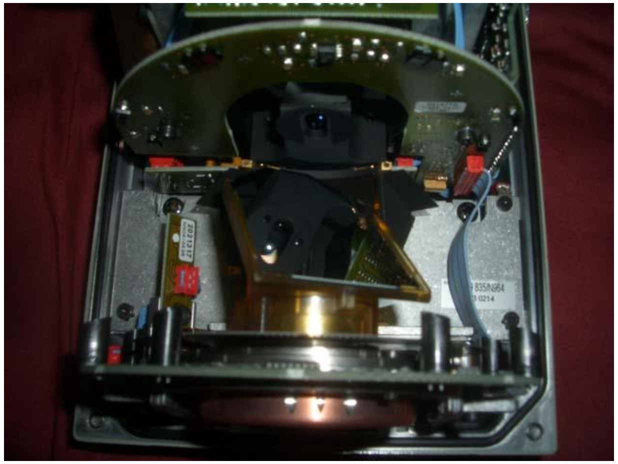
[Image source: www.terabee.com]

Laser range finder (Lidar)

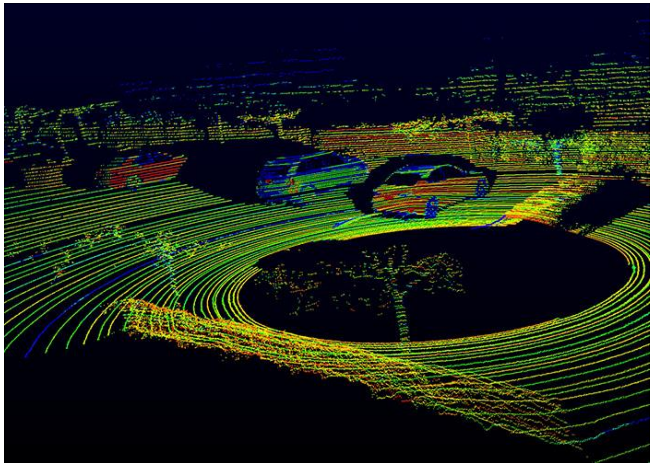
- Rotating laser distance sensor (one axis or multiple axis)
- Line scanner or 3D scanner
- 3D scanner returns complex 3D point cloud

[Image source: Wikipedia, CC BY-SA 3.0 DE]

[Image source: www.hizook.com]



[Image source: Trevis Deyle]

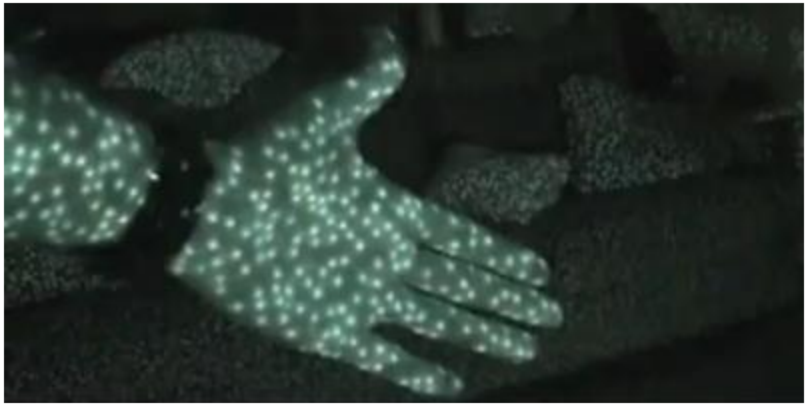


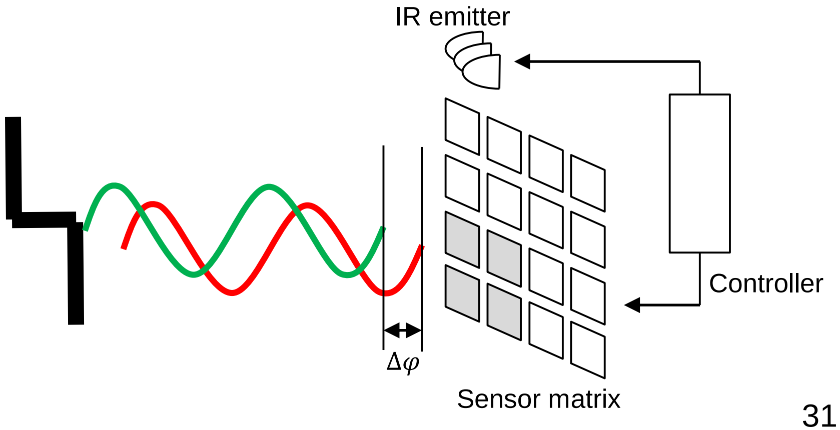
[Image source: Velodyne]

Depth camera

- Two principles structured light or time-of-flight (TOF)
- Measures 3D point cloud in one shot (no rotating elements as Lidar)
- Accuracy and range less than Lidar

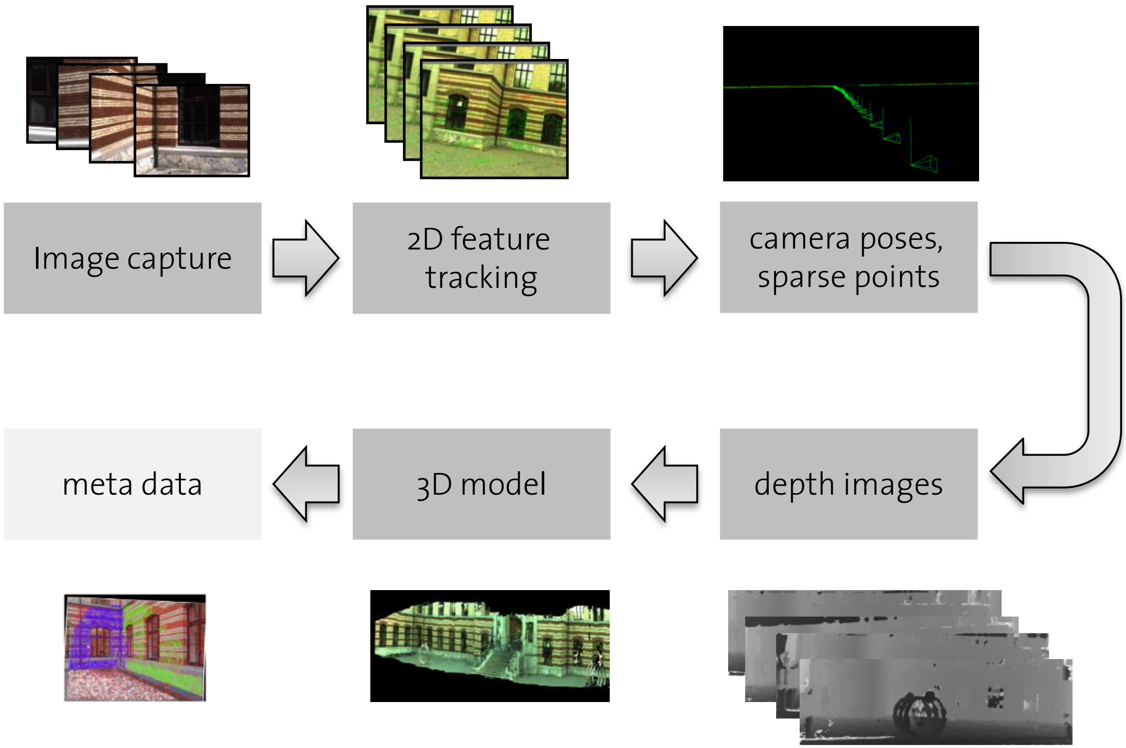
The elements of a depth sensor

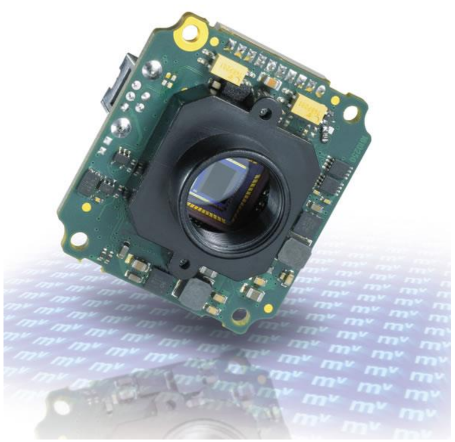




Digital camera

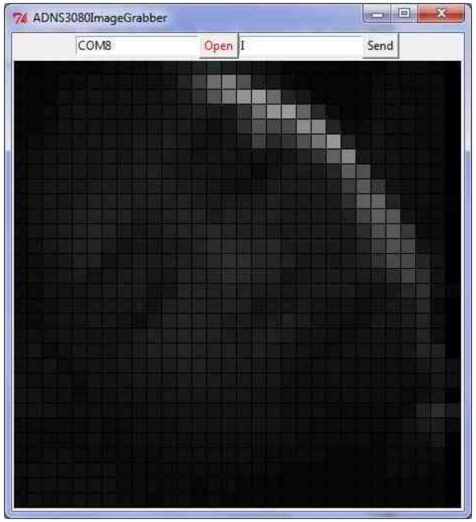
- Versatile sensor
- Possibility to estimate full 6 DOF pose (orientation and position) and to obtain a 3D point cloud
- However, complex image processing algorithms necessary and necessity to take multiple images

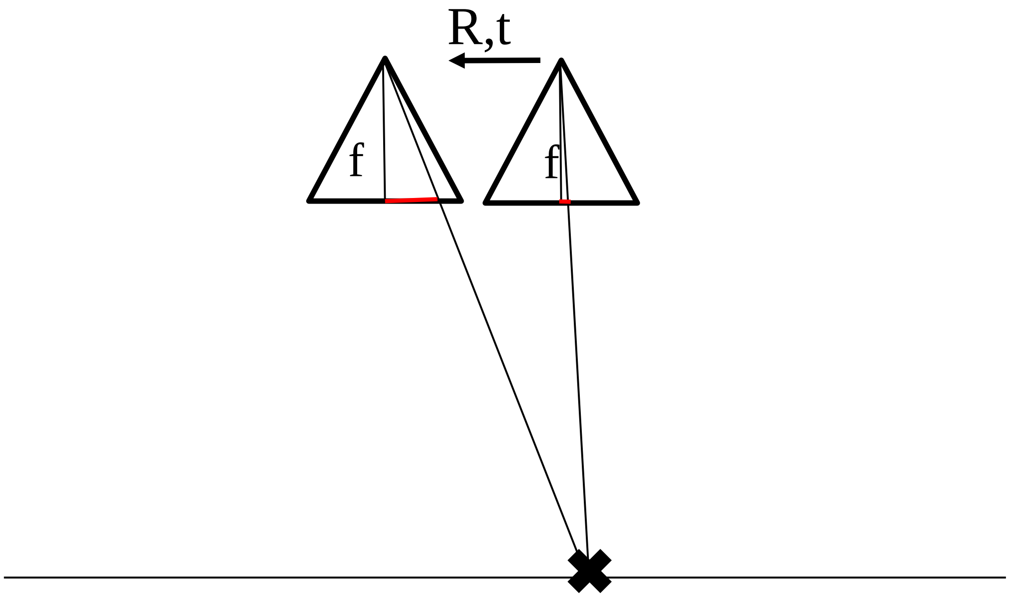




Optical flow sensor

- Sensor used in computer mouse
- Low resolution infrared camera
- Measures x,y shift of infrared image
- Method needs very high update rates (image shift needs to be small)

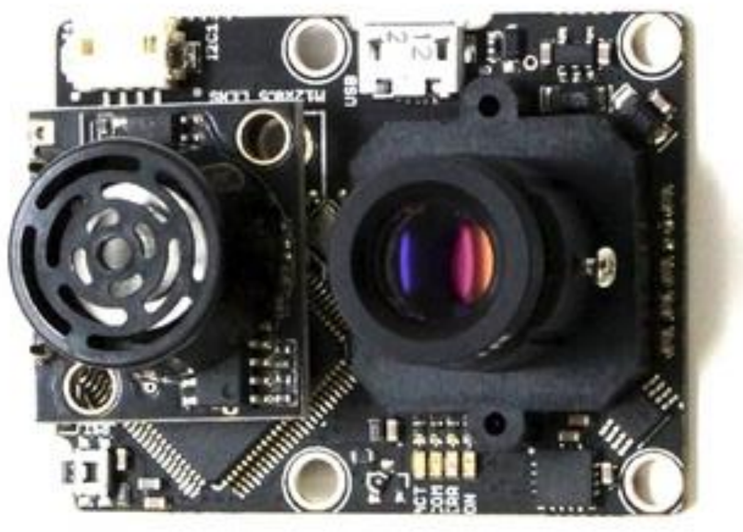




[Image source: http://ardupilot.org]

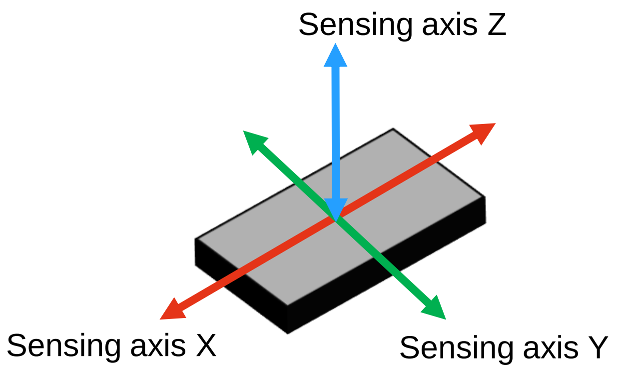
Optical flow camera (PX4Flow)

- Smart camera measuring x,y,z movement in meters
- Combines camera, gyroscope, ultrasound and processor
- Processor computes optical flow from image with 200Hz
- Gyroscope computes optical flow component induced by tilting (to be removed from x,y measurement)
- Ultrasound sensor used to convert pixel measurement into meter
- Parrot AR.Drone has a similar sensor

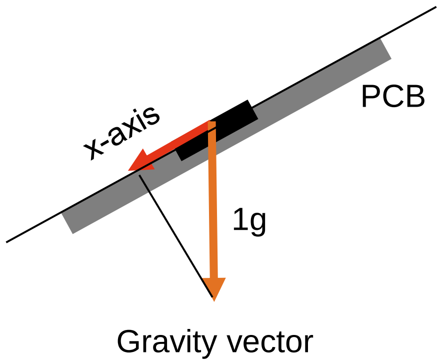


How to measure attitude?

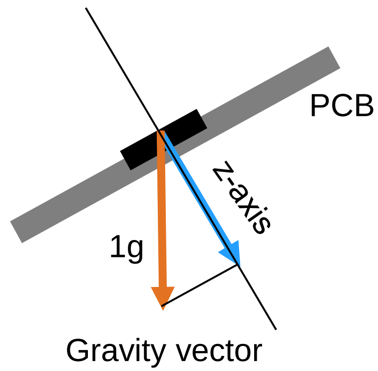
- Definition:
  - Attitude is orientation of drone with respect to the earth gravity vector and yaw as compass direction
- Limitation: Accelerometer can only measure tilt angles when sensor is not moving!



Sensing axis of 3-axis accelerometer



Gravity component of a tilted x-axis accelerometer

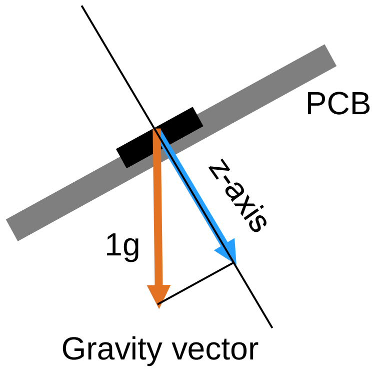


Gravity component of a tilted z-axis accelerometer

How to measure attitude?

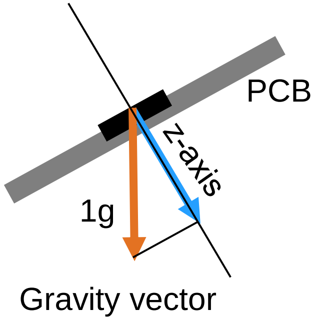
- Gyroscope for attitude estimation
  - Rotational velocities can be integrated over time to get attitude measurements
  - Need for starting condition and leads to drift
  - Toy quadrotors use gyroscopes

- Better: Combination of gyroscope and accelerometer for attitude estimation
  - Accelerometer defines starting condition (quadrotor placed on a flat ground)
  - Attitude estimated by integrating gyroscope values
  - Attitude correction from time to time using accelerometer measurements when quadrotor has zero position (can be measured when Z-acceleration is exactly 1g and all other axis measure 0g)



How to measure position?

- Double integration of linear acceleration gives position!
- But how to measure linear acceleration?
- When moving, accelerometers measure linear acceleration+rotational acceleration+gravity
- Solution:
  - Use gyroscope measurements to subtract rotational acceleration and gravity
  - Differentiating gyroscope measurements gives rotational acceleration to subtract
  - Knowledge of attitude allows to subtract correct amount of gravity
  - Double integration of remaining acceleration gives position
  - However, due to inaccuracies in all previous steps a strong drift occurs.
- Needed: Correction/fusion with position sensor e.g. GPS (can be of low update rate)

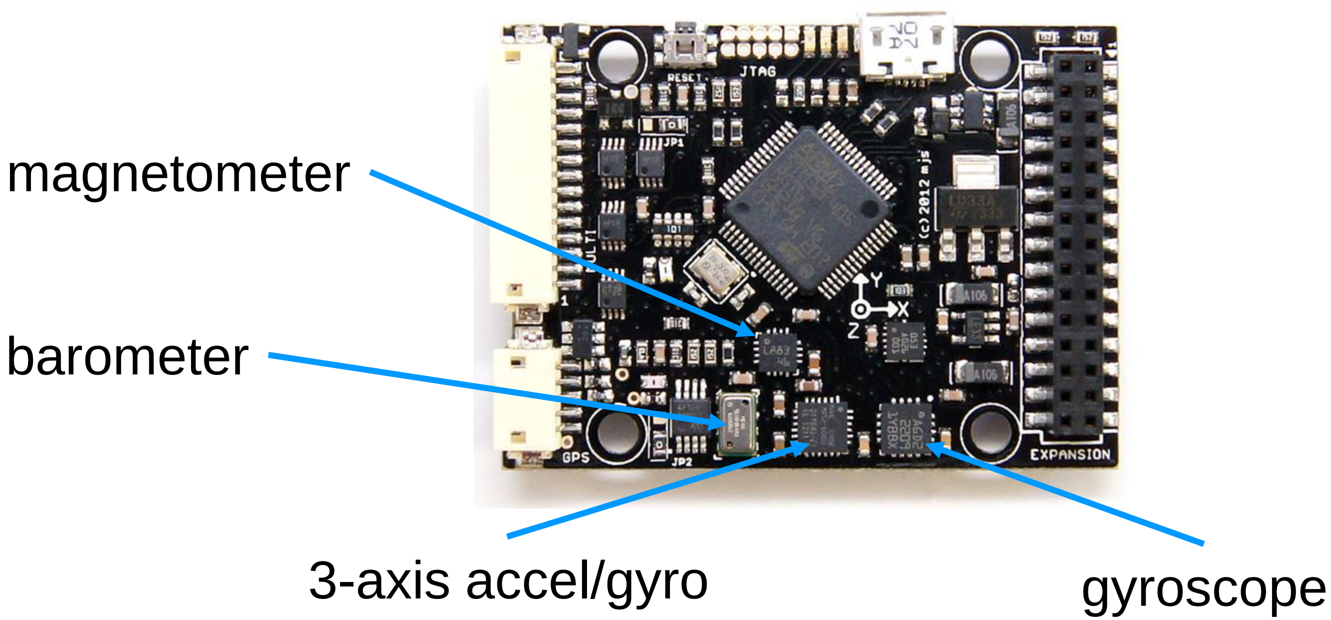


Sensor combinations

- Attitude control:
  - Gyroscope+Accelerometer+Digital compass
- Attitude + height control:
  - Gyroscope+Accelerometer+Digital compass+Pressure sensor/Ultrasound/Infrared/Laser distance
- Position control:
  - Gyroscope+Accelerometer+Digital compass + Integration (drift)
  - Gyroscope+Accelerometer+Digital compass+Pressure sensor/Ultrasound/Infrared/Laser distance + GPS (only outdoors)
  - Gyroscope+Accelerometer+Digital compass+Pressure sensor/Ultrasound/Infrared/Laser distance + Camera/Optical flow

Pixhawk FMU and sensors

- ARM7 Cortex-M4F microcontroller (168MHz,DSP,floating-point hardware acceleration)
- ST Micro L3GD20H 16 bit gyroscope
- ST Micro LSM303D 14 bit accelerometer / magnetometer
- Invensense MPU 6000 3-axis accelerometer/gyroscope
- MEAS MS5611 barometer



Pixhawk control scheme