Engineering Lab: Exp. 8 (AE1)

Introduction

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LECTURE 1

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Contents

Introduction

- An unmanned aerial vehicle (UAV) is known by various names, such as a remotely piloted aircraft (RPA), unattended air system (UAS), unmanned aerial systems (UAS) or simply a drone.

- Essentially, a UAV is considered an aircraft without a human pilot.

- All functions can be controlled either by the onboard sensors or by a human operator in a ground control location or by the deployment of autonomous electronic systems.

- The most basic functions of a UAV: Intelligence, Reconnaissance, and Surveillance (IRS).

- An unmanned combat air vehicle (UCAV) has to meet combat-related functions in addition to IRS, *e.g.* target tracking and deployment of defensive and offensive weapon systems against targets.

Introduction (Cond…)

- A UAV can be equipped with simple electronic and physical sensors such as a barometer, global positioning system (GPS) receiver, and altimeter device.

- Sophisticated UAVs can be equipped with photographic, television, infrared (capable of measuring the heat being emitted by an object and detecting motion), and acoustic equipment, compact synthetic aperture radar (SAR) (to create two-dimensional images or three-dimensional reconstructions of objects), and light detection and ranging (LIDAR) (for measuring the exact distance of an object on the earth's surface) laser along with radiation, chemical, and other special sensors to measure pertinent parameters to accomplish critical missions. Navigation and control sensors are of critical importance.

- The onboard sensors can be controlled by the ground-based operator, by preprogrammed sensors, or by automated remote operating mode.

Introduction (Cond…)

- For UCAV, mission requirements can be changed by the ground operator.

- The UAVs can perform a wide range of missions, such as intelligence gathering, surveillance, reconnaissance, aerial mapping, antiterrorist activities, agricultural activities, and emergency operations with remarkable speed.

- The development of compact inertial navigation equipment, exotic software and algorithmic maintenance for equipment calibration, filtering, rapid and accurate processing of navigational information will enable UAV operators to perform important tasks with great accuracy and speed.

- Engineers are deeply involved in specific development of onboard software and hardware of next generation of computer vision and pattern recognition for navigation and UAV orientation.

Civil Applications

Area	Applications
Aerial photography	Filmmaking, Real Estate, Marketing, video, still photo, etc.
Agriculture	Crop monitoring and spraying; herd monitoring and driving
Coastguard	Search and rescue, coastline and sea-lane monitoring
Conservation	Pollution and land monitoring
Customs and Excise	Surveillance for illegal imports
Electricity companies:	Powerline inspection, Wind Turbine Inspection, Tower/Antenna Inspection
Fire Services and Forestry	Fire detection, incident control
Fisheries	Fisheries protection

Civil Applications (Contd…)

Area	**Applications**
Gas and oil supply companies	Land survey and pipeline security
Information services:	News information and pictures, feature pictures, e.g. wildlife
Lifeboat Institutions	Incident investigation, guidance and control
Local Authorities	Survey, disaster control
Meteorological services	Sampling and analysis of atmosphere for forecasting, etc
Traffic agencies	Monitoring and control of road traffic

Civil Applications (Contd…)

Area	Applications
Oil companies	Pipeline security
Police Authorities	Law Enforcement, Search and Rescue, security and incident surveillance
Rivers Authorities	Water course and level monitoring, flood and pollution control
Survey Organizations	Geographical, geological and archaeological survey, Hazardous Material Detection
Water Boards	Reservoir and pipeline monitoring

Military Applications

- **Navy**
  - Shadowing enemy fleets
  - Decoying missiles by the emission of artificial signatures
  - Electronic intelligence
  - Relaying radio signals
  - Protection of ports from offshore attack
  - Placement and monitoring of anti-submarine warfare

- **Army**
  - Reconnaissance (military observation of a region)
  - Surveillance of enemy activity
  - Monitoring of nuclear, biological or chemical (NBC) contamination
  - Electronic intelligence
  - Target designation and monitoring
  - Location and destruction of land mines

Military Applications (Contd…)

- **Air Force**
  - Long-range, high-altitude surveillance
  - Radar system jamming and destruction
  - Electronic intelligence
  - Airfield base security
  - Airfield damage assessment
  - Elimination of unexploded bombs

Classification of Unmanned Aerial Vehicles

- There is no one standard when it comes to the classification of UAS or UAV.
- Defense agencies have their own standard, and civilians have their ever-evolving loose categories for UAV.
- Regardless of the type and purpose of the UAVs, some of the most important performance characters of drones are:
  - Weight,
  - Endurance and flight range,
  - Maximum altitude,
  - Wing loading,
  - Engine type and
  - Power source
- Therefore, drones have been frequently classified using the above characters as criteria.

Category of Drones using Their Weight

- **Very small UAVs**
  - Nano UAVs (<0.25 kg)
  - Micro UAVs (0.25 to 5 kg)
- **Small/ Light-weight drones UAVs** (5 to 50 kg)
  - Mini UAVs
- **Medium UAVs** (50 to 200 kg)
- **Large UAVs** (>200 kg)

Very small UAVs

Mosquito Micro UAV

Skate UAV

Black Hornet Nano UAV

Sky Viper Nano UAV

Small UAVs

RQ-7 Shadow

RS-16 UAV

Thunder B Small Tactical UAV

RQ-11B RAVEN Small UAV

Medium UAVs

Pioneer UAV

Skyeye UAV

Hunter UAV

Watchkeeper UAV

Fire Scout UAV

Eagle Eye UAV

Large UAVs

Predator UAV

Global Hawk UAV

Harfang UAV

Sabrewing Cargo UAV

Category of Drones: Based on Endurance & Range

- According to the **ranges**

- **Very low cost close-range UAVs:** have a range of 5 km, endurance time of 20 to 45 minutes

- **Close-range UAVs:** that have a range of 50 km and endurance time of 1 to 6 hours, usually used for reconnaissance and surveillance tasks.

- **Short-range UAVs:** have a range of 150 km or longer and endurance times of 8 to 12 hours. Like the close range UAV, they are mainly utilized for reconnaissance and surveillance purposes.

- **Mid-range UAVs:** that have super high speed and a working radius of 650 km. They are also used for reconnaissance and surveillance purposes in addition to gathering meteorological data.

- According to their **endurance** in the air without fuel refill:

- **Long-endurance UAVs**:

can stay airborne for 24 h or more and travel 1500–20,000 km without refill.

- **Medium-endurance UAVs**:

can fly for 5–24 h without refill.

- **Low-endurance UAVs**:

can fly for an hour at a stretch and cover 100 km.

Category of Drones: Based on Altitude

- **Low-altitude UAVs:**

  mostly used for close-up imagery of crop fields, fly just up to 100–1000 m above the crop canopy.

- **Medium-altitude UAVs**:

  also utilized in agriculture, particularly in obtaining near-infrared (NIR) and thermal imagery of crops. They fly at about 1000–10,000 m above the crop height.

- **High altitude UAVs**:

  Are commonly used in judging natural resources and for military reconnaissance. They fly at a height above 10,000 m above ground surface.

Category of Drones: Based on Wing Loading

- $$\text{Wing loading} = \frac{\text{total weight of the UAV}}{\text{total wing area of the UAV}}$$

❖ **Low wing loading UAVs:**

wing loading less than 50 kg/m^2

❖ **Medium wing loading UAVs:**

wing loading 50–100 kg/m^2 (e.g. Fire Scout, X-45).

❖ **High wing loading UAVs:**

wing loading of over 100 kg/m^2 (e.g. Global Hawk).

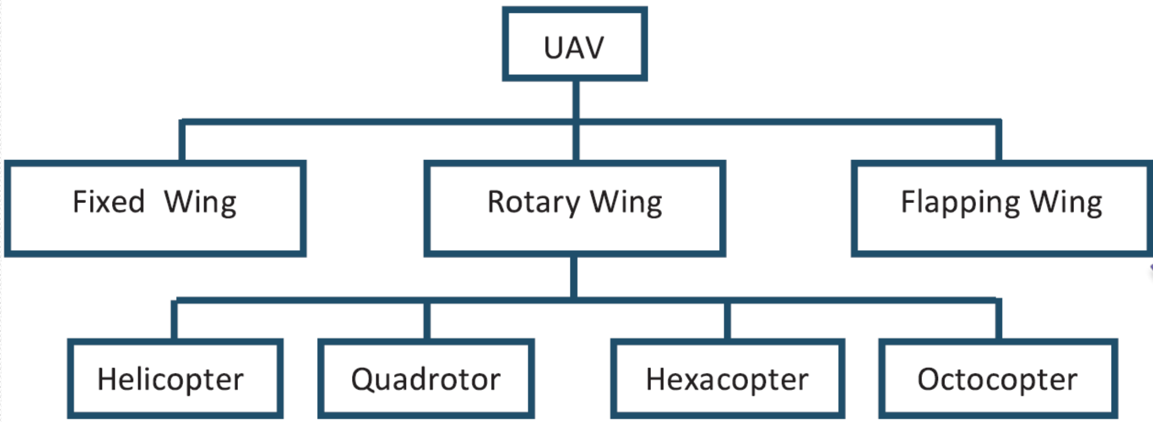
Category of Drones: Other types

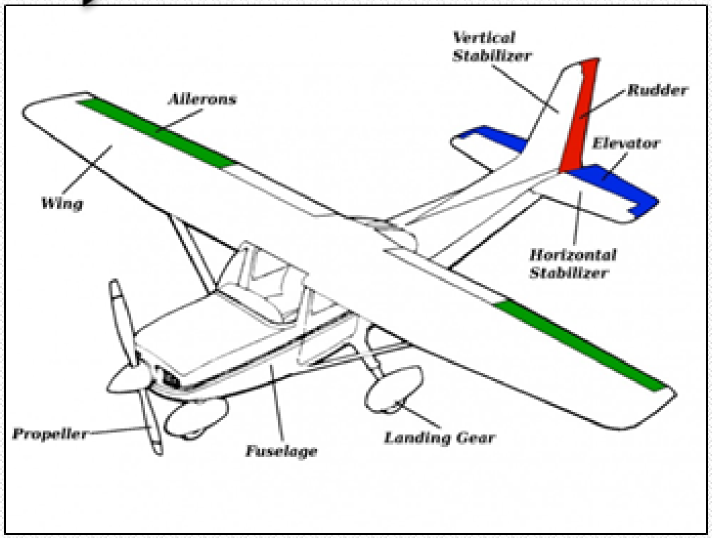
- Engines used in drones are usually run using petrol or electric batteries.
- Engine types commonly encountered are turbofans, two-stroke piston engines, turboprop, push and pull and electric with propeller.
- Larger copter drones such as RMAX or Autocopter are energised through petrol or diesel engines.
- Drones with electric batteries run only for short time. Their endurance is small, but they are highly useful in quick scouting and in obtaining close-up shots of crops.

- Based on the **Altitude** and **Endurance** together

  - Medium-altitude long endurance (MALE) UAVs
  - High-altitude long endurance (HALE) UAVs

UAV Classifications





Fixed-wing UAVs

- Wings are permanently attached to the airframe.
- Most civil aircraft and fighters are fixed-wing aircraft.
- Its propulsion system generates a forward airspeed,
- Lift force balance the vehicle's weight.
- Cannot take off and land vertically.
- Fixed-wing aircraft has a much simpler structure.
- Carry a heavier payload over a longer distance.
- Require of a runway or launcher for takeoff and landing.

Rotary Wing UAVs

Single Rotor UAV

- Lift & propulsive force from rotary wing
- Can vertically take-off and landing (VTOL), & Hover
- Can fly in any direction
- No runway or launcher is required for takeoff and landing.
- Limited by forward speed.
- Its complex structure incurs a high maintenance cost.

Multirotor/Multicopter

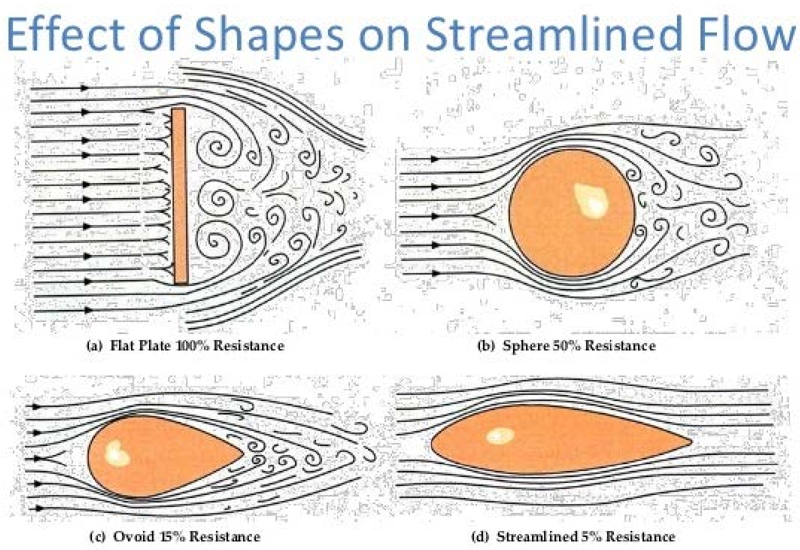
- It has three or more propellers.
- The most popular multicopter is the quadcopter.
- Can vertically take-off and landing (VTOL), & Hover.
- Can fly in any direction
- No runway or launcher is required for takeoff and landing
- The rapid lift adjustment is realized by the control of propeller angular speeds.
- The anti-torque moments can be canceled out by each other.
- Simple structure, easy-to use and low maintenance cost

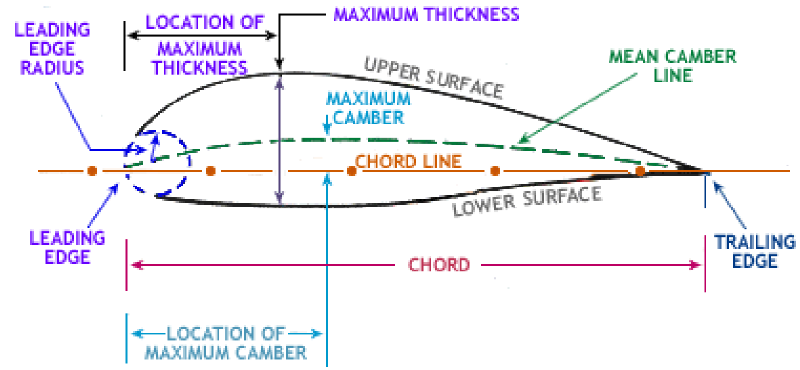
Comparison between Rotary Wings, Fixed Wings and Flapping Wings

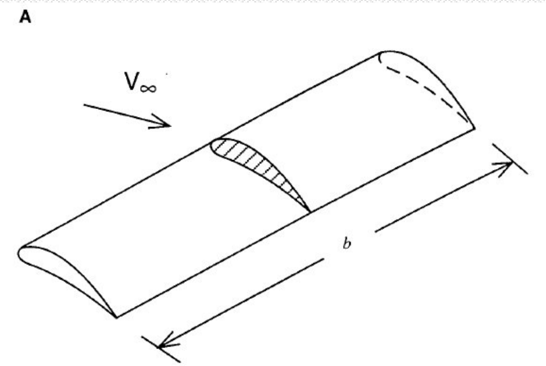
Comparison Between Rotary Wings, Fixed Wings, and Flapping Wings

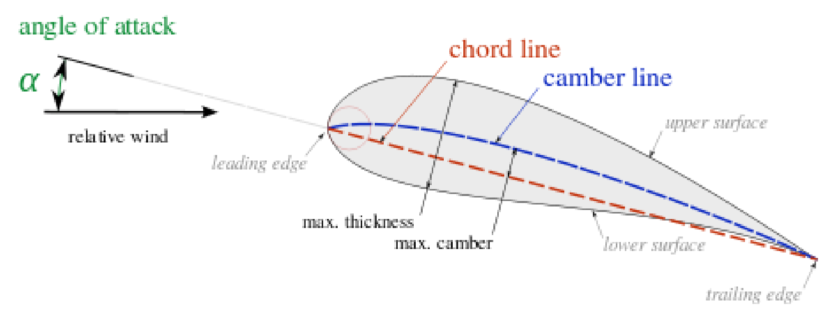
	Rotary Wing	Fixed Wing	Flapping Wing
Maneuver	High	Low	Medium
Cost	Medium	Low	High
Construction and repairing	Medium	Low	High
Civilian application	High	Low	High
Military application	Medium	Medium	Medium
Energy consumption	High	Low	Medium
Flight safety	Medium	High	Low
Range	Medium	High	Low

Basic Aerodynamics

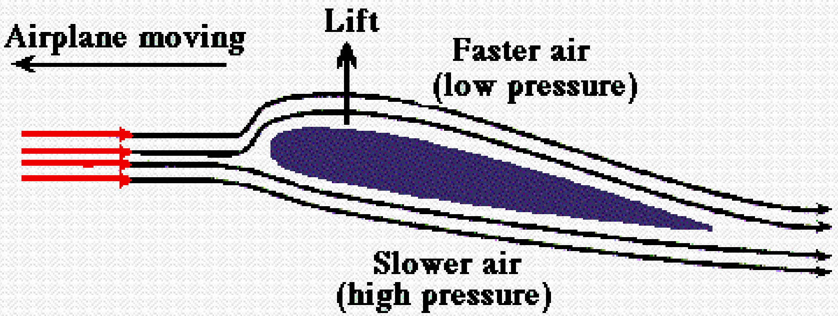


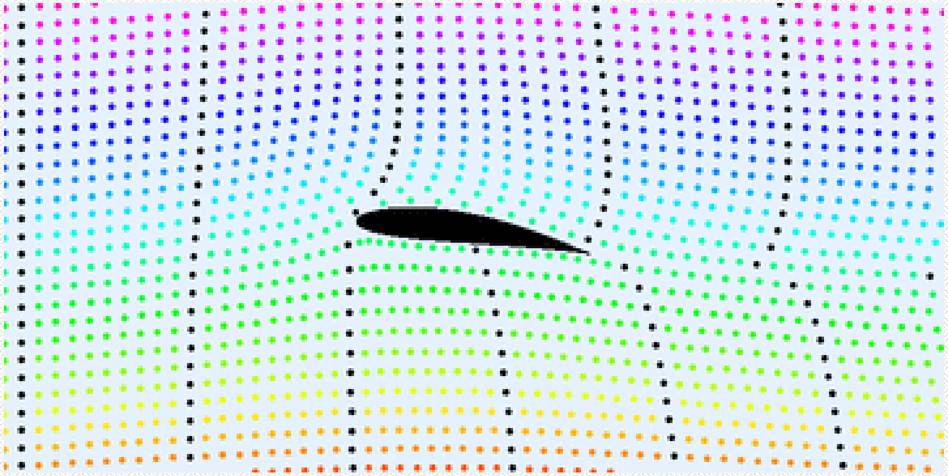




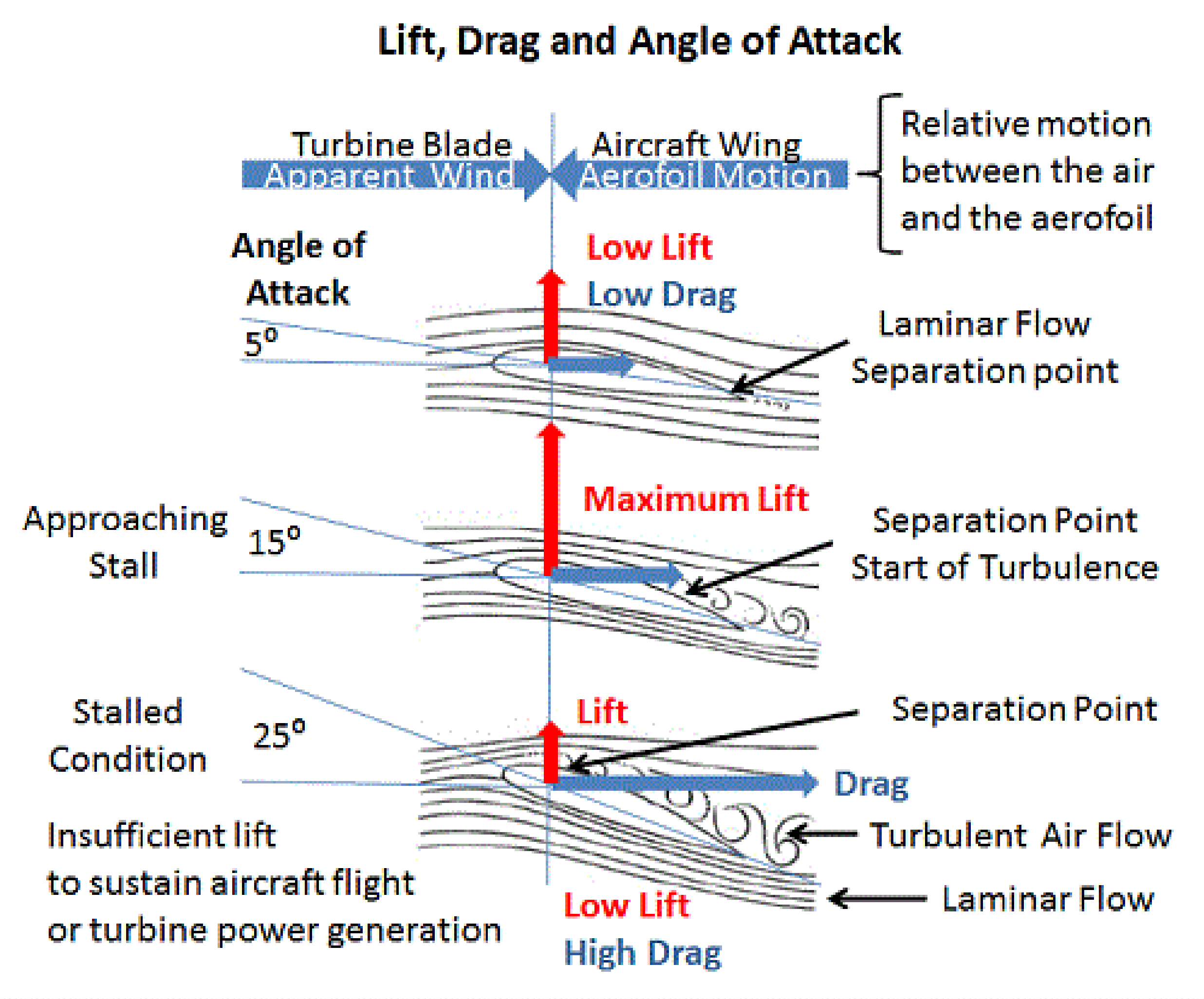


Basic Aerodynamics





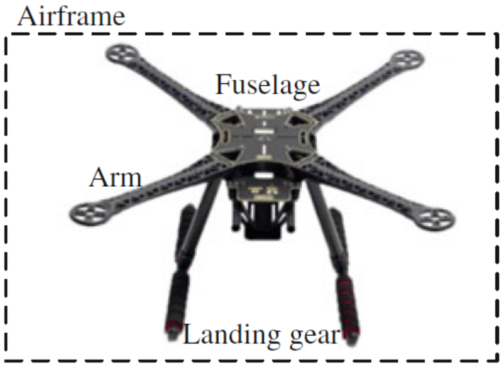
Basic Aerodynamics (Contd...)



History of Multicopters

- The history of the development of multicopter technology can be divided into five periods:
  - Dormancy period (before 1990),
  - Growing period (1990–2005),
  - Development period (2005–2010),
  - Activity period (2010–2013), and
  - Booming period (2013 →).

Multicopter Design

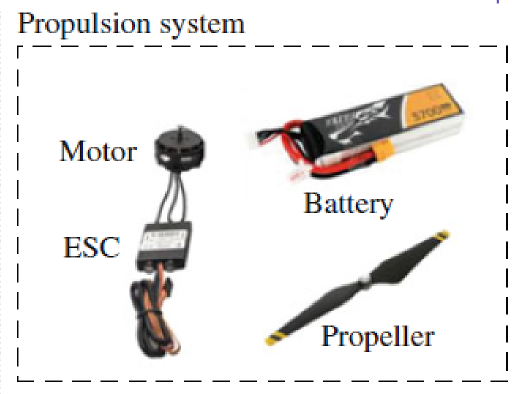


- Simple airframe only includes a fuselage and a landing gear.
- Fuselage acts as the platform to carry all the equipment of a multicopter.
- The safety, durability, usability, and the performance of a multicopter are often highly dependent on the configuration of its fuselage.
- For a well-designed multicopter, all factors including the scale, shape, material, strength, and weight should be carefully taken into consideration.
- The weight of the fuselage is mainly determined by its size and material.
- Under the same thrust a smaller fuselage weight means a larger remaining payload capacity.

Propulsion System of Multicopter

- A propulsion system includes propellers, motors, ESCs, and often a battery.

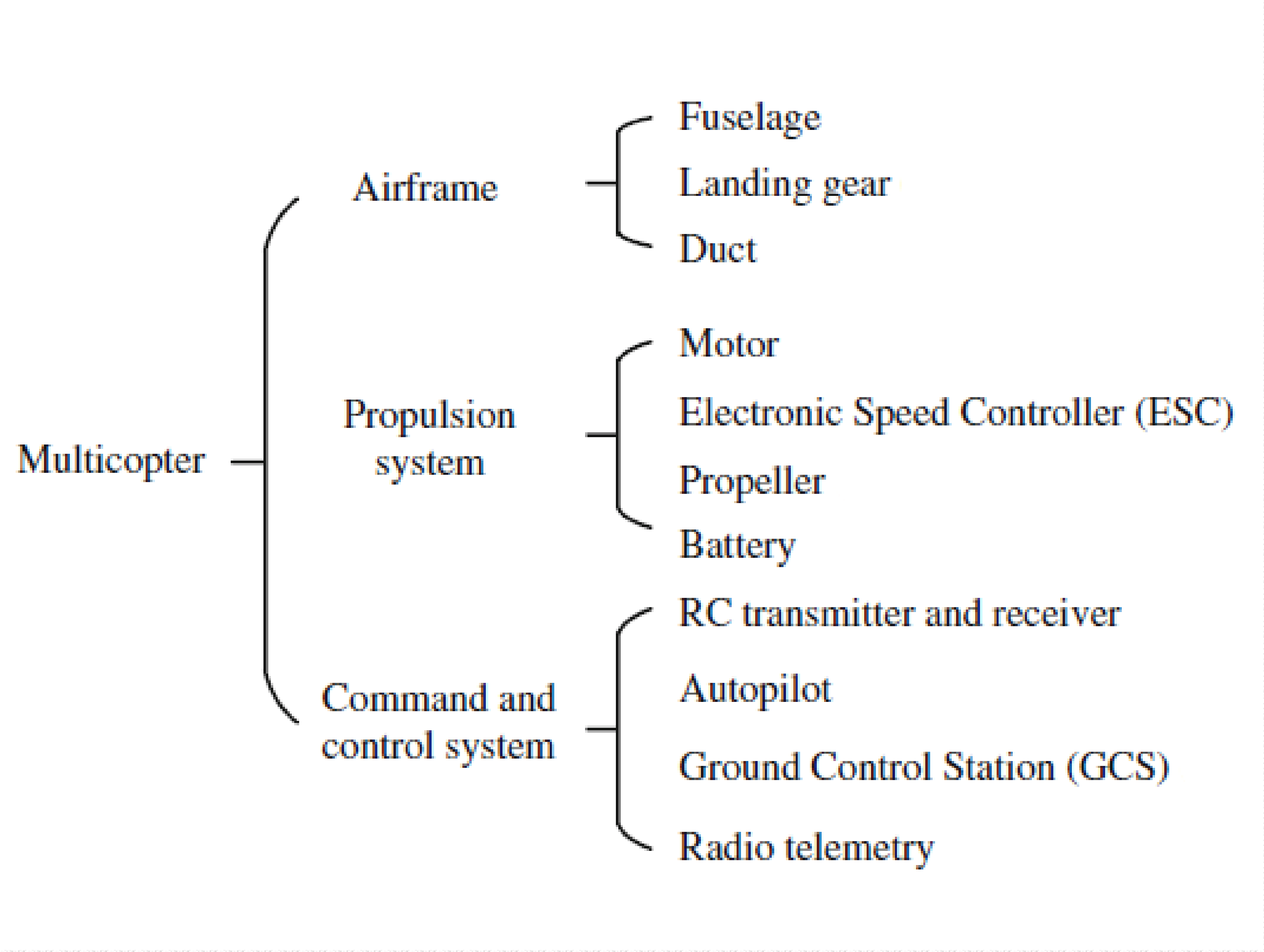
- It is the most important part of the multicopter, which determines the main performances such as the hovering time, the payload ability, and the flying speed and distance.



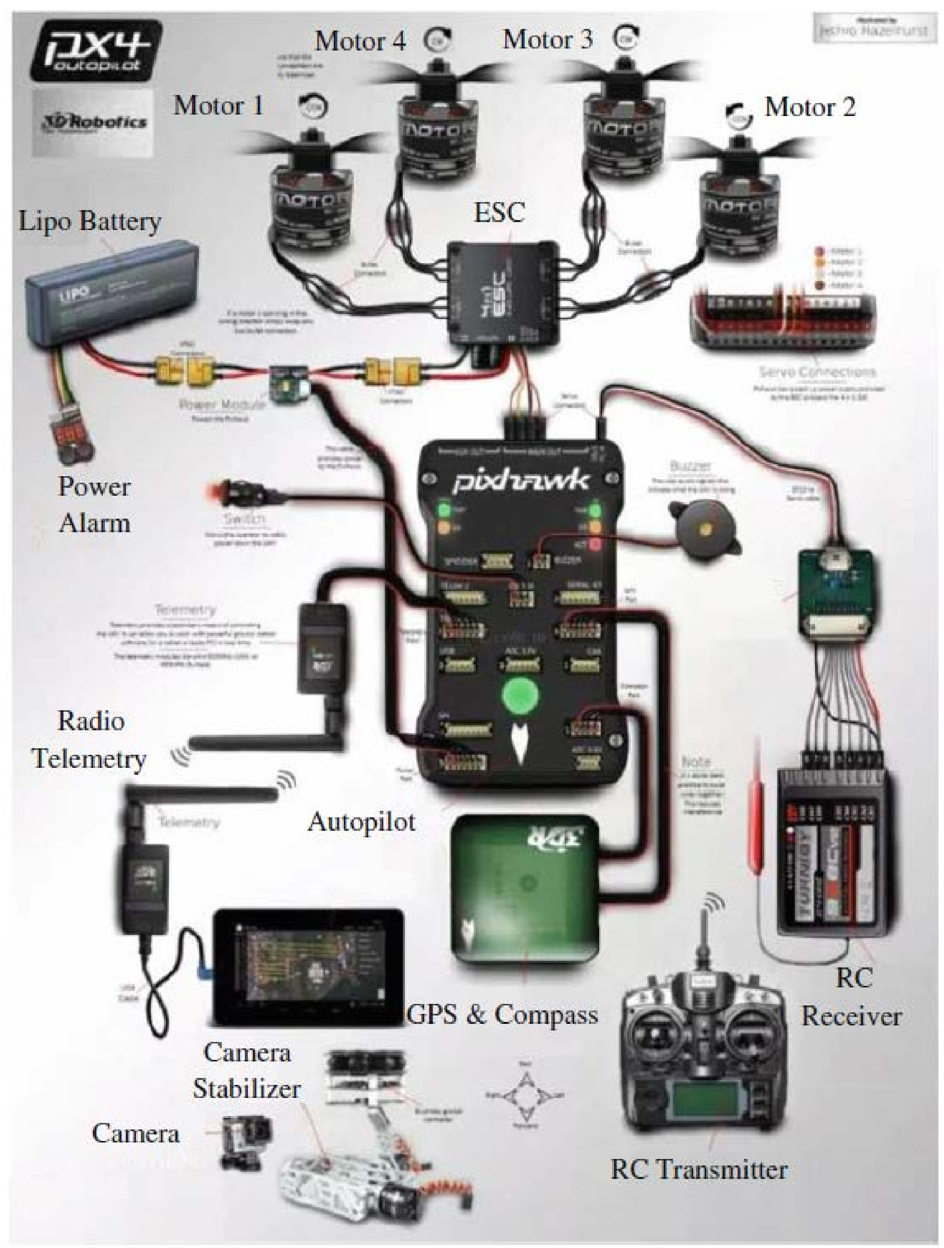
- Components of the propulsion system have to be compatible with each other, otherwise they cannot work properly or even fails in some extreme cases.

- For example, in some conditions, an aggressive maneuver may make the current exceed the safety threshold of the ESC, then make the motors stop working in the air, which is very dangerous.

Combination of Systems in Multicopters

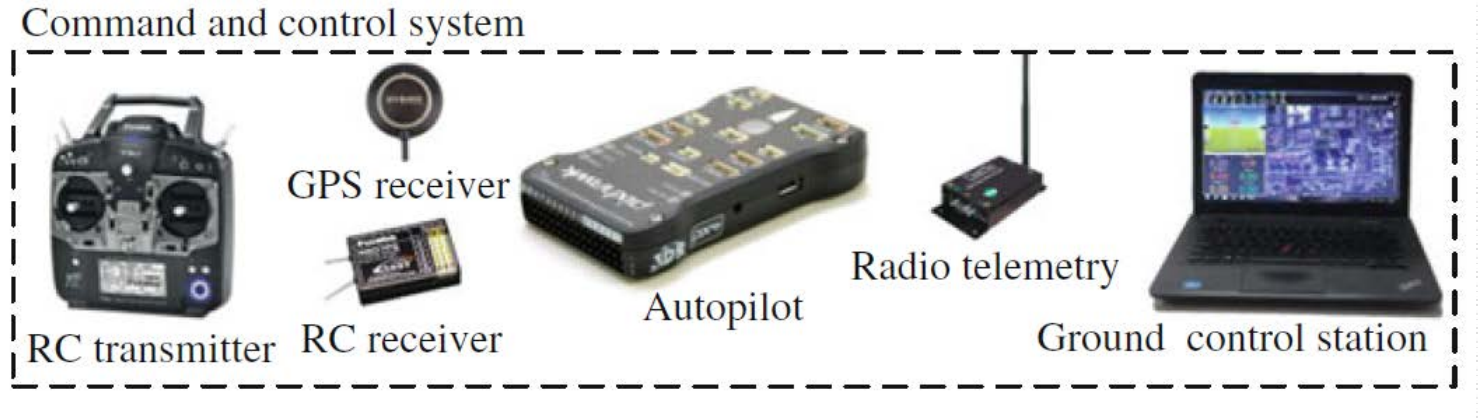


Connection of a Multicopter System

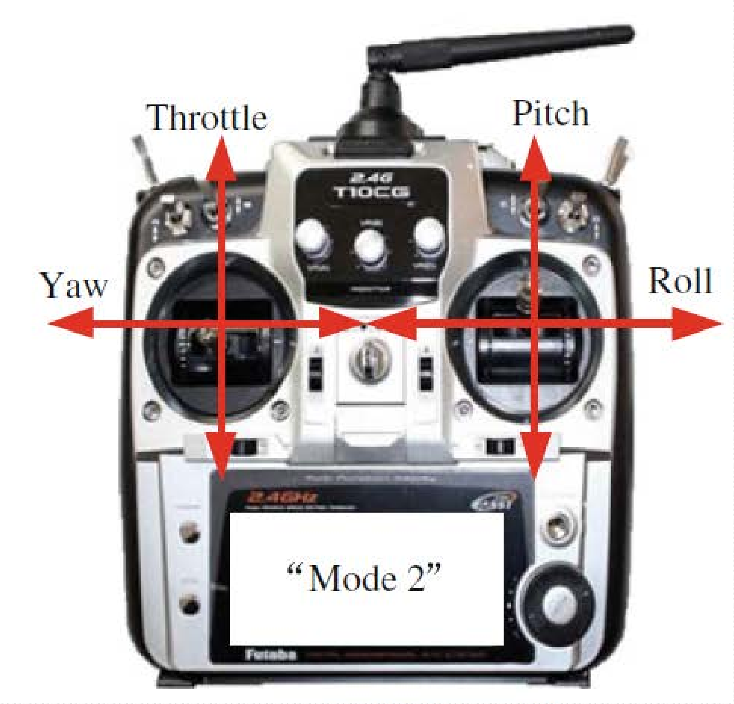


Command and Control Systems

- The *RC transmitter* is used to transmit commands from remote pilots to the corresponding receiver.
- Then, the *receiver* passes the commands to the autopilot after decoding them.
- Finally, the multicopter flies according to the commands.
- Some flight parameters can be set on the transmitter, such as the throttle direction, stick sensitivity, neutral position of RC servo motors, function definitions of channels, record and remind setting of flight time, and lever function setting.
- Advanced functions include battery voltage and current, flight data of multicopters.



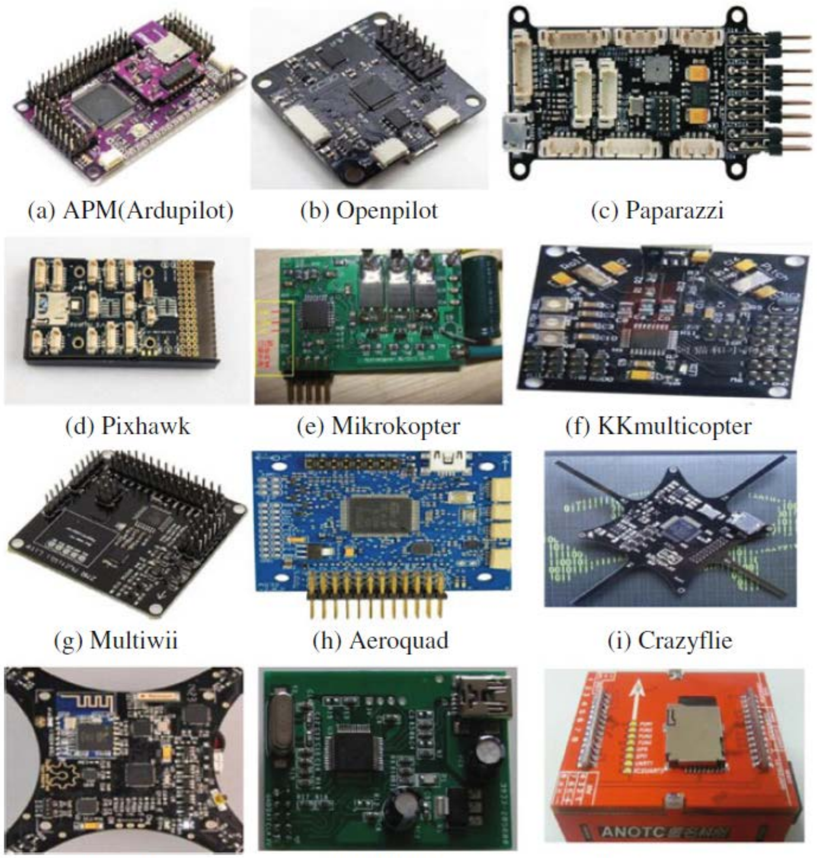
Different Control Modes of an RC Transmitter



Throttle : control the upward-and-downward movement
Pitch : control the forward-and-backward movement
Yaw : control the yaw movement
Roll : control the leftward-and-rightward movement

Autopilot

- A multicopter *autopilot* is a flight control system used to control the attitude, position, and trajectory of a multicopter.
- It can be semi-automatically (needs commands from remote pilot) or fully automatically.
- Autopilots have a control framework which is often based on Proportional-Integral-Derivative (PID) controllers, leaving parameters to be tuned for different multicopters.



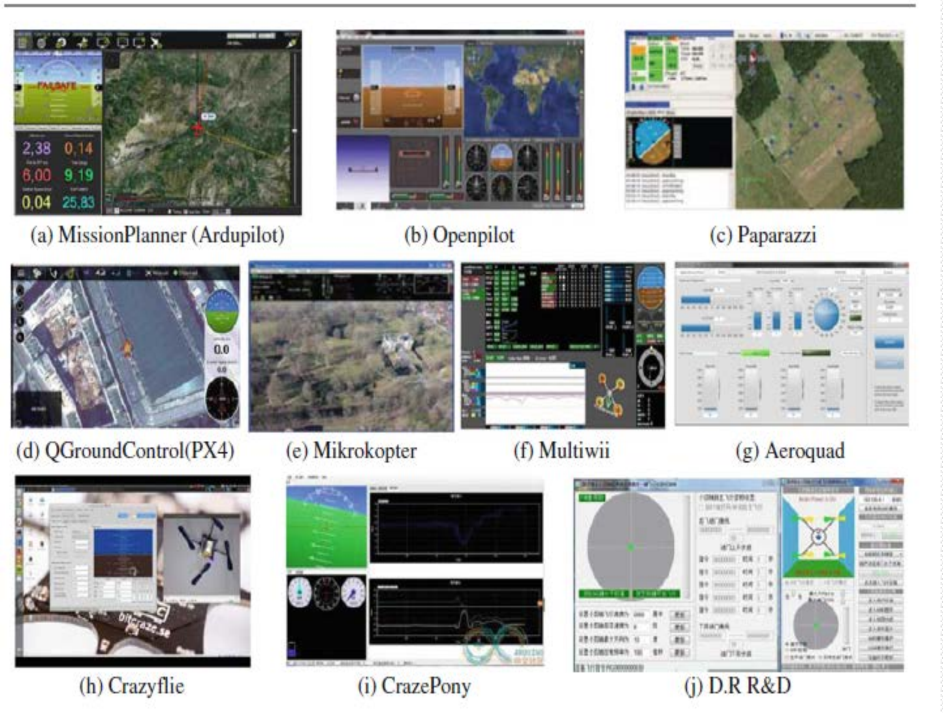
(a) APM(Ardupilot) (b) Openpilot (c) Paparazzi
(d) Pixhawk (e) Mikrokopter (f) KKmulticopter
(g) Multiwii (h) Aeroquad (i) Crazyflie
(j) CrazePony (k) DR.R&D (l) Anonymous

The parameters of open source autopilot flight control boards

Description	Size (mm)	Weight (g)	rocessor	Process frequency (MHz)	Gyroscope	Accelerometer	Magnetometer	Barometer
Arducopter	66 × 40.5	23	ATmega2560	16	MPU-6000	MPU-6000	HMC5843	MS5611
Openpilot	36 × 36	8.5	STM32F103CB	72	ISZ/IDC-500	ADX330	HMC5843	BMP085
Paparazzi(Lisa/M)	51 × 25	10.8	STM32F105RCT6	60	MPU-6000	MPU-6000	HMC5843	MS5611
Pixhawk	40 × 30.2	8	LPC2148	60	ISZ/IDC-500	SCA3100-D04	HMC5843	BMP085
Mikrokopter	44.6 × 50	35	ATmega644	20	ADXRS610	LIS344ALH	KMZ51	MPX4115A
Kkmulticopter	49 × 49	11.7	ATmega168	20	ENC-03	–	–	–
Multiwii	N/A[a]	N/A[a]	Arduino[b]	8–20	ISZ/IDC-650	LIS3L02AL	HMC5883L	BMP085
Aeroquad	N/A[a]	N/A[a]	Arduino[b]	8–20	ITG3200	ADXL345	HMC5883L	BMP085
Crazyflie 2.0	90 × 90	19	STM32F405	168	MPU-9250	MPU-9250	MPU-9250	LPS25H
CrazePony-II(4)	38.9 × 39.55	20	STM32f103T8U6	72	MPU6050	MPU6050	HMC5883L	MS5611
Dr.R&D(2015)IV	33 × 33	300 (the whole)	STM32F103	72	MPU6050	MPU6050	HMC5883L	Ultrasound HC-SR04
Anonymous(V2)	75 × 45	40	STM32F407	168	MPU6050	MPU6050	AK8975	MS5611

Ground Control Station

- An important part of a GCS is the software.
- Remote pilots can interact with the software using the mouse, keyboard, button, and joystick. So, way points can be planned by remote pilots for multicopters in advance.
- Furthermore, remote pilots can monitor the flight status in real time and set new missions to intervene flight.
- Besides, the software can record and playback flight for analysis.

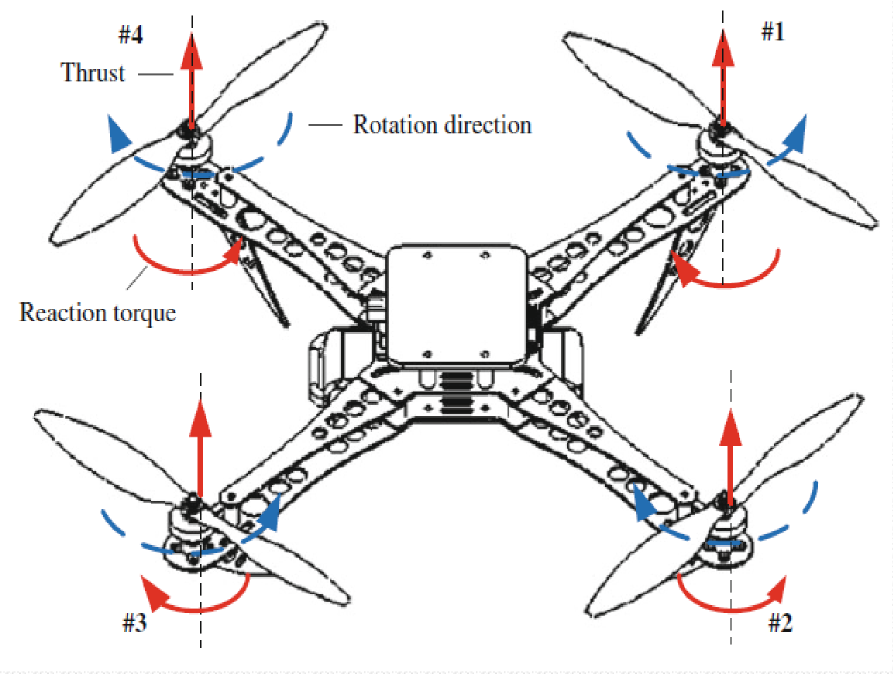


Quadcopter in Hovering Flight

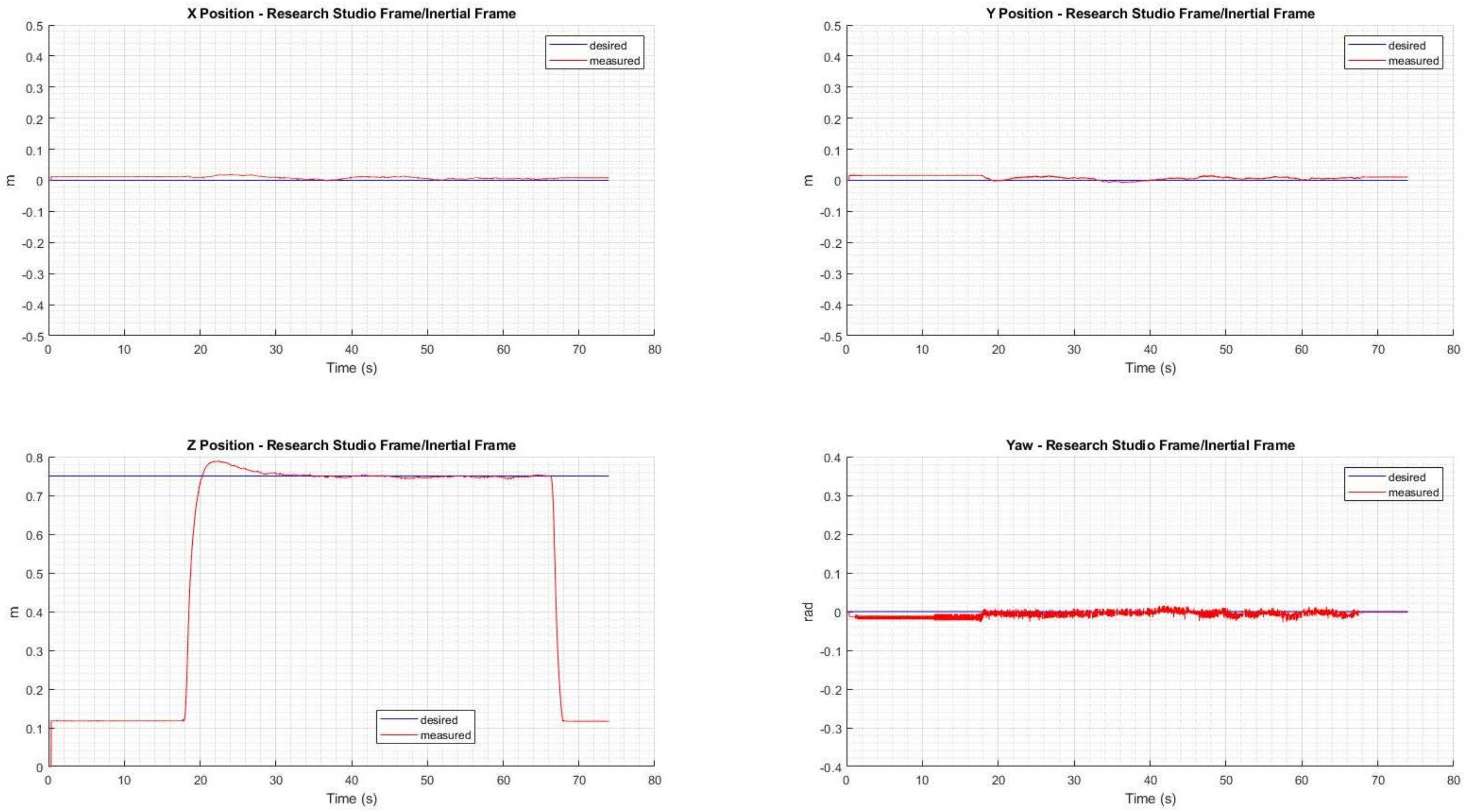
- At hover position: all propellers are spinning at the same angular speed with propellers **#1** and **#3** rotating counterclockwise and propellers **#2** and **#4** clockwise.

- The total thrust of four rotors compensates the weight of the quadcopter.

- The thrust of four propellers are the same and the sum of four propellers moment equal to zero.



Hover



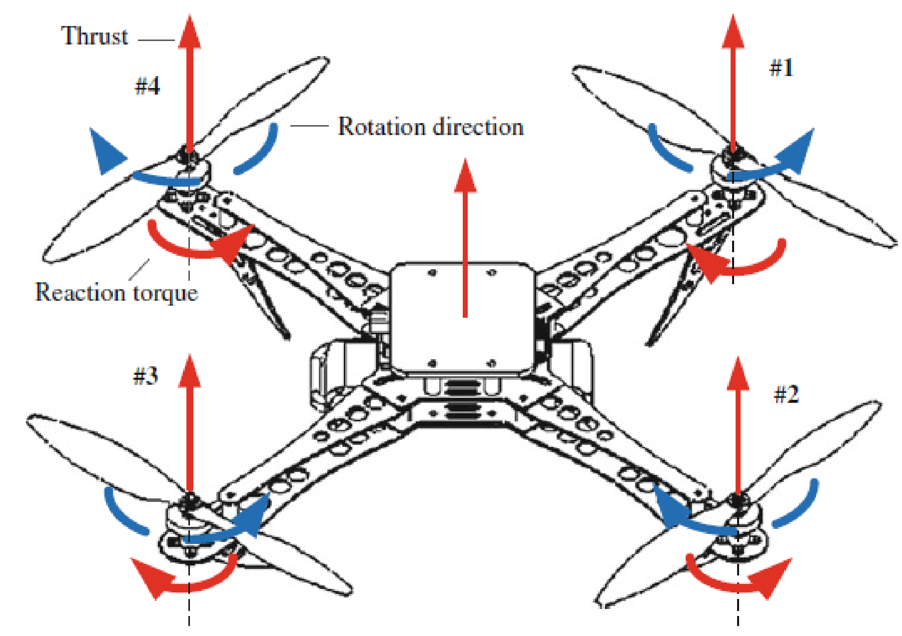
X Position - Research Studio Frame/Inertial Frame
Y Position - Research Studio Frame/Inertial Frame
Z Position - Research Studio Frame/Inertial Frame
Yaw - Research Studio Frame/Inertial Frame
desired
measured
m
rad
Time (s)

Upward Movement of a Quadcopter

- The angular speed of four propellers increased by the same amount.

- As a result, the total thrust increased, but the sum of four propellers moment still equal to zero.

- If the quadcopter is placed on a leveled ground, it will move up once the thrust is greater than the weight of the quadcopter.



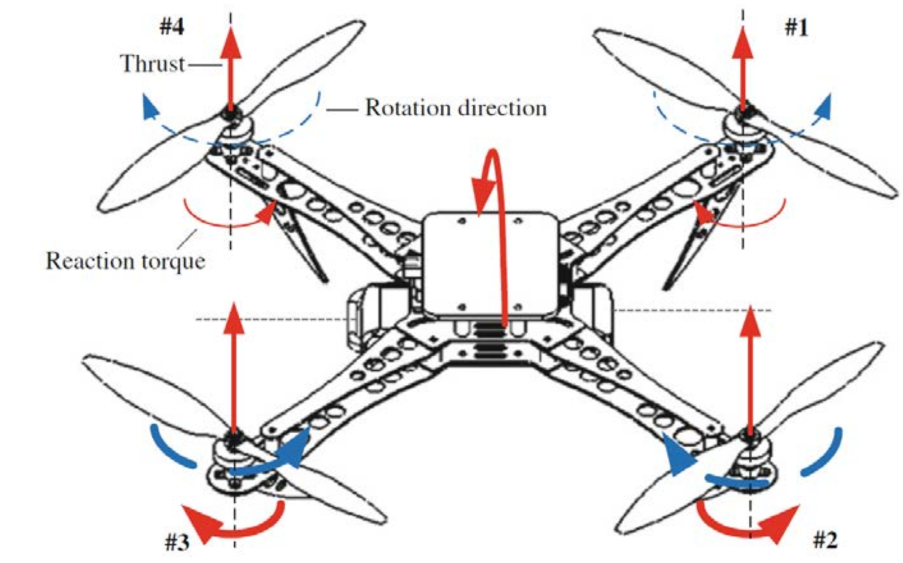
Forward Movement of a Quadcopter

- The angular speeds of propellers **#1**, **#4** are decreased by the same amount, while the angular speeds of propellers **#2**, **#3** are increased by the same amount. This will lead to a moment which makes the quadcopter pitch forward.

- The thrust has a forward component. However, at this moment, the vertical component of the thrust is decreased, which will not be equal to the weight of the quadcopter.

- Based on the previous change, the four propeller angular speeds should be further increased by the same amount to compensate for the weight.

- Similarly, the backward movement can be also achieved.



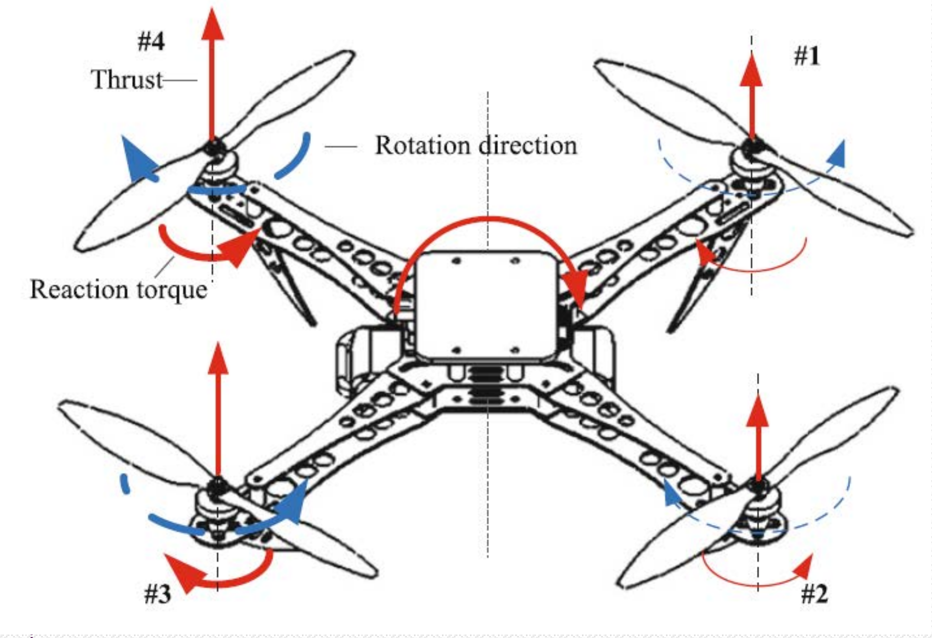
Rightward Movement of a Quadcopter

- The angular speeds of propellers **#1**, **#2** are decreased by the same amount, while the angular speeds of propellers **#3**, #4 are increased by the same amount. This will lead to a moment which makes the quadcopter roll to the right.

- The thrust has a right component. However, the vertical component of the thrust is decreased, which will not be equal to the weight of the quadcopter.

- Based on the previous change of the four propellers, the four propeller angular speeds should be further increased by the same amount to compensate for the weight.

- Similarly, the leftward movement can be also achieved.



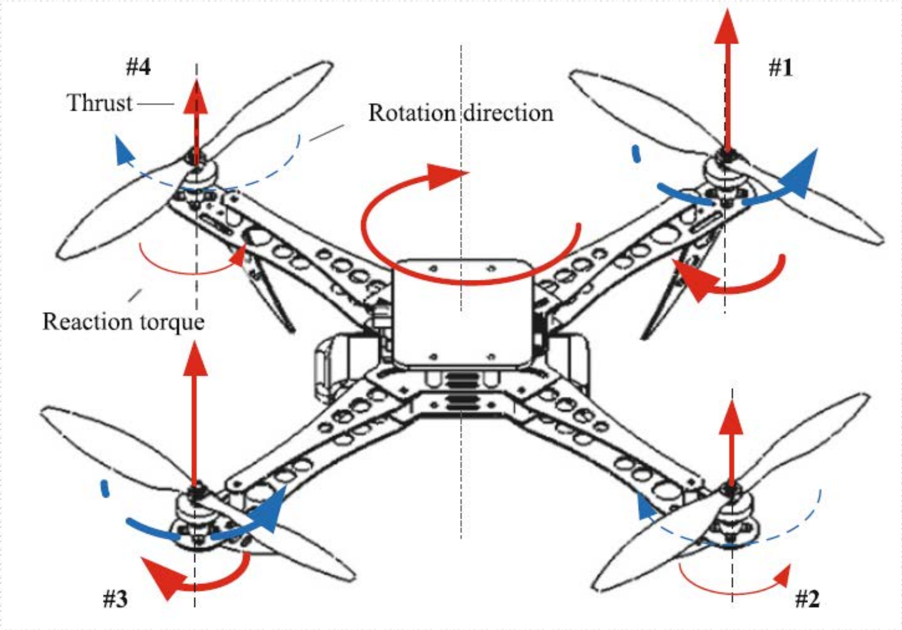
Clockwise Yaw Movement of a Quadcopter

- The angular speeds of propellers **#2**, **#4** are decreased by the same amount, while the angular speeds of propellers **#1**, **#3** are increased by the same amount.

- This will lead to zero moments both in the forward-and-backward and in the leftward-and-rightward directions.

- Newton's Third Law, every action has an equal and opposite torque reaction.

- The clockwise yaw moment is increased because the angular speeds of propellers **#1**, **#3** are increased in the counterclockwise direction. On the other hand, the counterclockwise yaw moment of the quadcopter is decreased because the angular speeds of propellers **#2**, **#4** are decreased in the clockwise direction.



- Finally, this results in a clockwise yaw moment of the quadcopter.

Quadcopter Controller : PID

- The basic principle of the PID control scheme is to act on the variable to be manipulated through a proper combination of three control actions:
  - proportional control action (where the control action is proportional to the actuating error signal, which is the difference between the input and the feedback signal),
  - integral control action (where the control action is proportional to the integral of the actuating error signal), and
  - derivative control action (where the control action is proportional to the derivative of the actuating error signal).

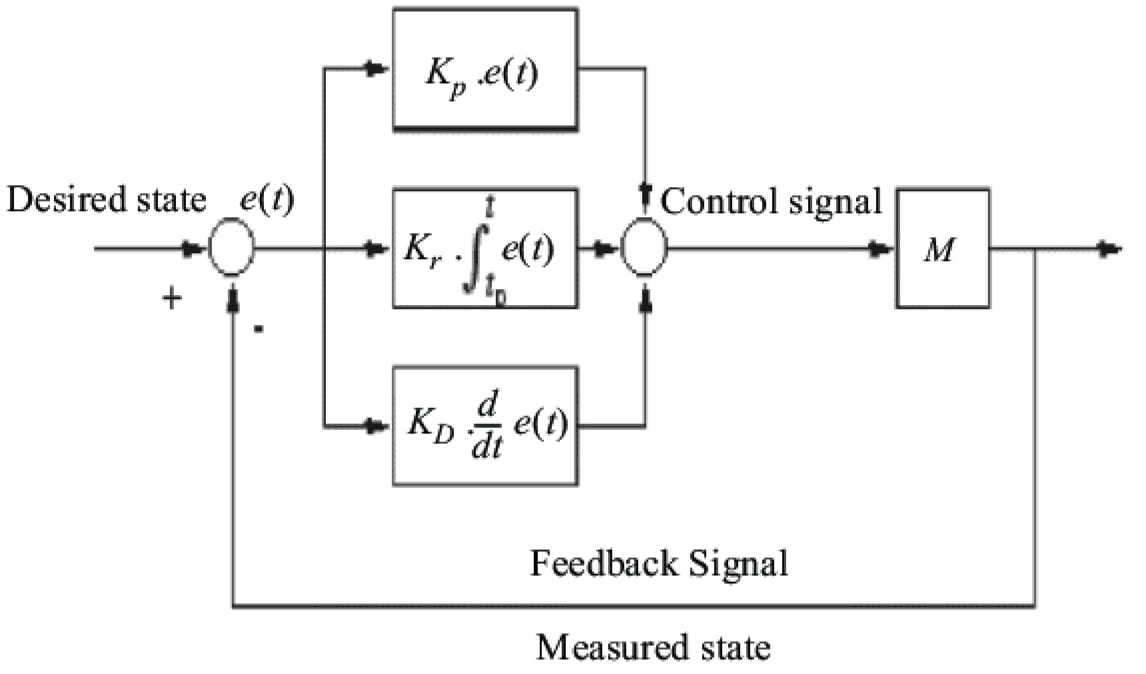
- Where many plants are controlled directly by a single digital computer the majority of the control loops may be handled by PID control schemes.

- The PID control action in analog controllers is given by

$$m(t) = K\left[e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d\frac{de(t)}{dt}\right]$$

PID Controller

- Where $e(t)$ is the input to the controller (the actuating error signal), $m(t)$ is the output of the controller (the manipulating signal), K is the proportional gain, T_i is the integral time (or reset time), and T_d is the derivative time (or rate time).

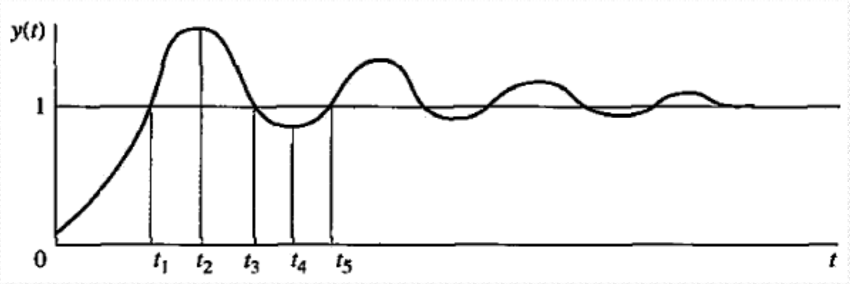


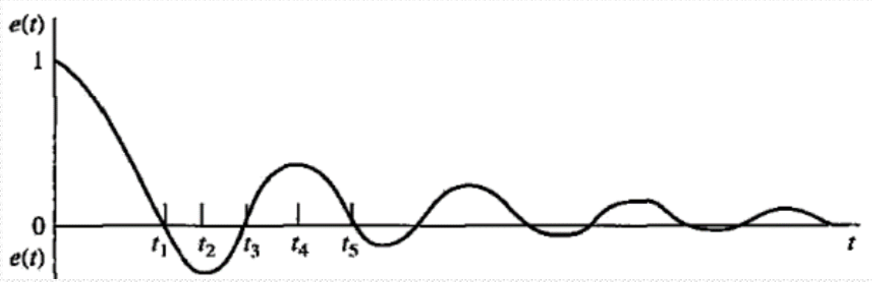
Design with the Proportional Controller

- Assume that the system contains a motor of some kind with its torque proportional to *e(t)*.

- $0 < t < t_1$: *e(t)* is positive. The motor torque is positive and rising rapidly. The large overshoot and subsequent oscillations in the output *y(t)* are due to the excessive amount of torque developed by the motor and the lack of damping during this time interval.

- $t_1<t<t_3$: The error signal *e(t)* is negative, and the corresponding motor torque is negative. This negative torque tends to slow down the output acceleration and eventually causes the direction of the output *y(t)* to reverse and undershoot.





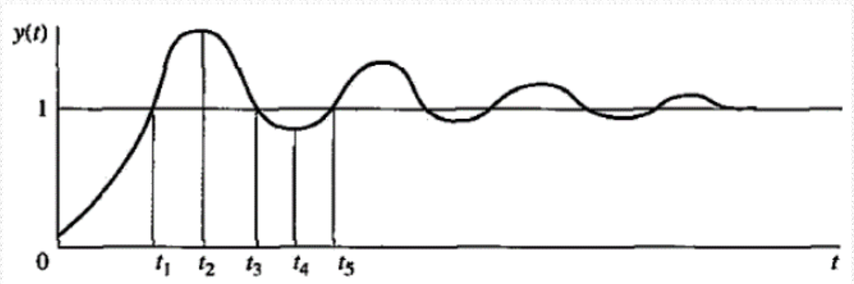
$t_3<t<t_5$: The motor torque is again positive, thus tending to reduce the undershoot in the response caused by the negative torque in the previous time interval.

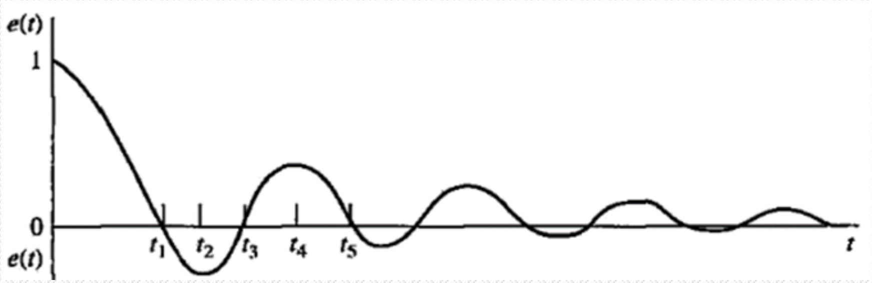
Design with the Proportional Controller

- From the above analysis of the system time response, we can say that the contributing factors to the high overshoot are as follows:

- The positive correcting torque in the interval $0 < t < t_1$ is too large.

- The retarding torque in the time interval $t_1 < t < t_2$ is inadequate.





Design with the PD Controller

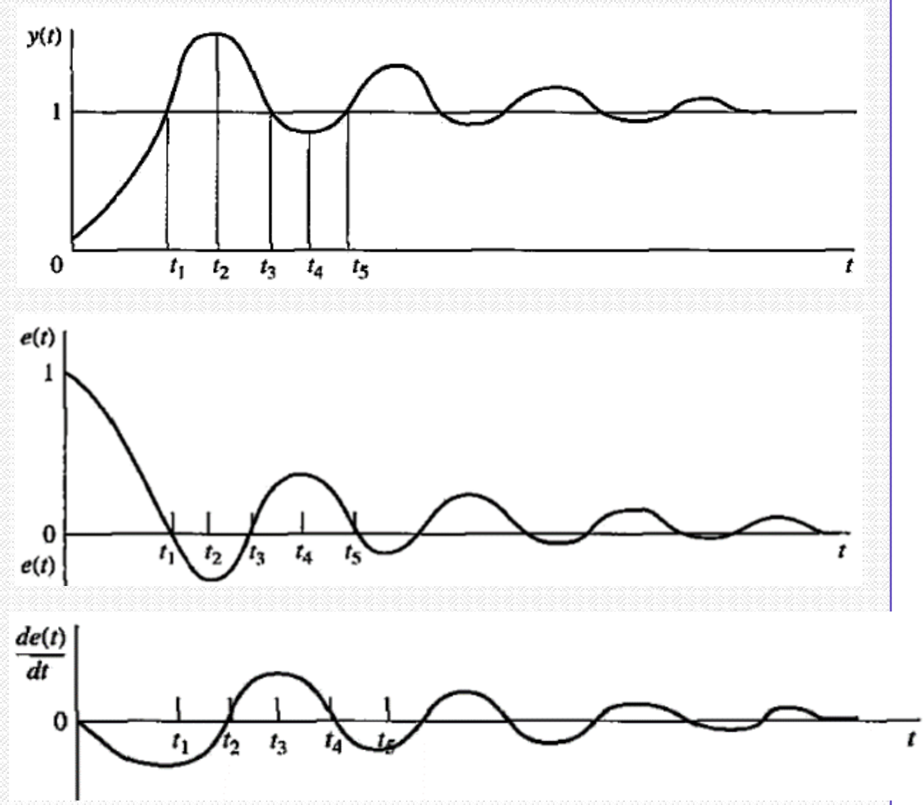
- To reduce the overshoot in the step response, without significantly increasing the rise time, a logical approach is:

- Decrease the positive torque during $0 < t < t_1$

- Increase the retarding torque during $t_1 < t < t_2$.

- Similarly, the negative corrective torque in $t_2 < t < t_3$ should be reduced, and the retarding torque during $t_3 < t < t_4$, which is now in the positive direction, should be increased to improve the undershoot of $y(t)$.

- The PD control gives precisely the compensation effect required.



Therefore, all these effects will result in smaller overshoots and undershoots in $y(t)$.

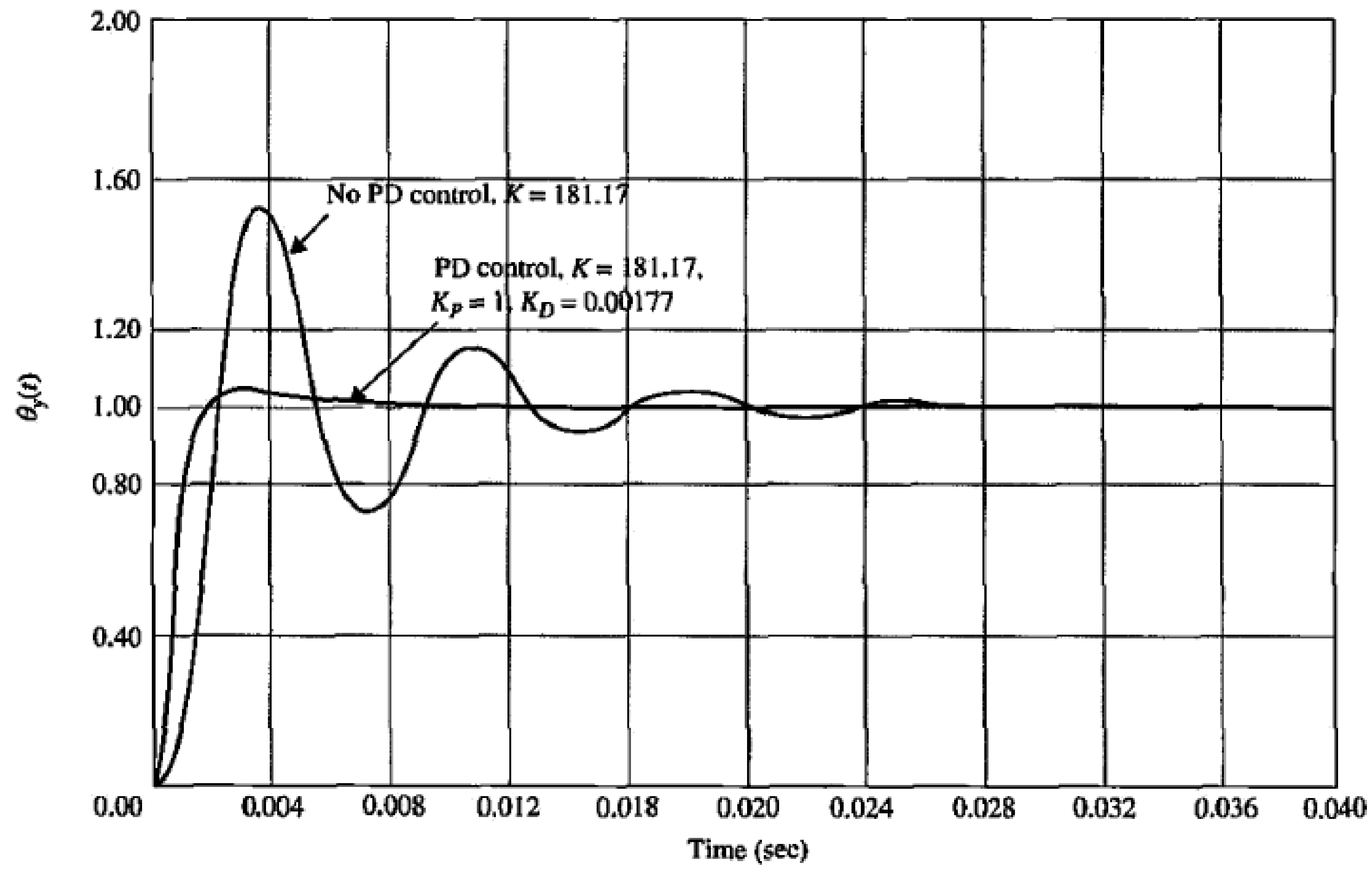
Design with the PD Controller

- Thus, the control signal applied to the process is

$$u(t) = K_P e(t) + K_D \frac{de(t)}{dt}$$

- Another way of looking at the derivative control is that since $de(t)/dt$ represents the slope of *e(t)*, the PD control is essentially an *anticipatory* control.
- That is, by knowing the slope, the controller can anticipate direction of the error and use it to better control the process.
- The derivative control measures the instantaneous slope of *e(t)*, predicts the large overshoot ahead of time, and makes a proper corrective effort before the excessive overshoot actually occurs.
- Intuitively, derivative control affects the steady-state error of a system only if the steady-state error varies with time.
- If the steady-state error of a system is constant with respect to time, the time derivative of this error is zero, and the derivative portion of the controller provides no input to the process.
- The PD control does not alter the system type that governs the steady-state error of a unity-feedback system.

PD Control



2.00
1.60
1.20
1.00
0.80
0.40
0.00
0.004
0.008
0.012
0.018
0.020
0.024
0.028
0.032
0.036
0.040
Time (sec)
$\theta_y(t)$
No PD control, $K = 181.17$
PD control, $K = 181.17$,
$K_P = 1$, $K_D = 0.00177$

PD: Drawbacks

- The control term is filtered to limit the increase in gain at high frequencies and smooth the differentiation process which amplifies any noise present in the error signal.

- Differentiation is always sensitive to noise.

- This is clearly seen from the transfer function $G(s) = s$ of a differentiator which goes to infinity for large s.

- Example: Consider the signal $y(t) = \sin t + n(t) = \sin t + a_n \sin \omega_n t$

- where the noise is sinusoidal noise with frequency ω_n . The derivative of the signal is

$$\frac{dy(t)}{dt} = \cos t + n(t) = \cos t + a_n \omega_n \cos \omega_n t$$

PD: Drawbacks

- **Signal to noise ratio:**
  - It is defined as the **ratio** of **signal** power to the **noise** power, often expressed in decibels.
  - A **ratio** higher than 1:1 (greater than 0 dB) indicates more **signal** than **noise**.

- The signal to noise ratio for the original signal is $1/a_n$ but the signal to noise ratio of the differentiated signal is $\frac{1}{w_n a_n}$. This ratio can be arbitrarily low if ω_n is large.

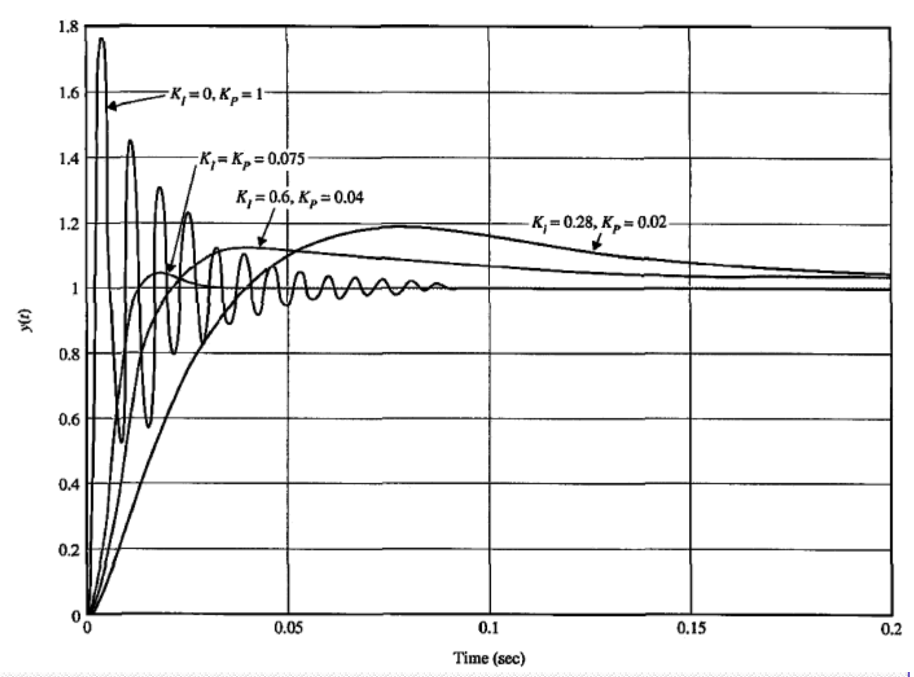
- In a practical controller with derivative action it is therefore necessary to limit the high frequency gain of the derivative term.

PI Controller

- PI control will improve the steady-state error.

- Thus, the steady-state error of the original system is improved by one order; that is, if the steady-state error to a given input is constant, the PI control reduces it to zero (provided that the compensated system remains stable).

- Because the PI controller is essentially a low-pass filter, the compensated system usually will have a slower rise time and longer settling time.



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Thank You!