PID제어와 튜닝준비

An **[Unmanned aerial vehicle]** (UAV) is a Unmanned Aerial Vehicle. UAVs include both autonomous (means they can do it alone) [drones] and [remotely piloted vehicles] (RPVs). A UAV is capable of controlled, sustained level flight and is powered by a jet, reciprocating, or electric engine.

PID 제어기초

PID 제어란?

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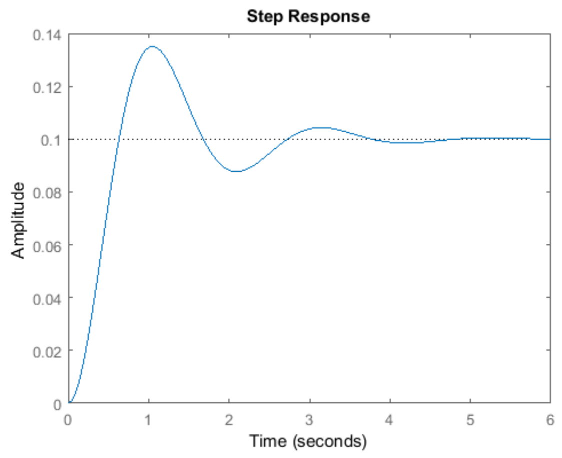
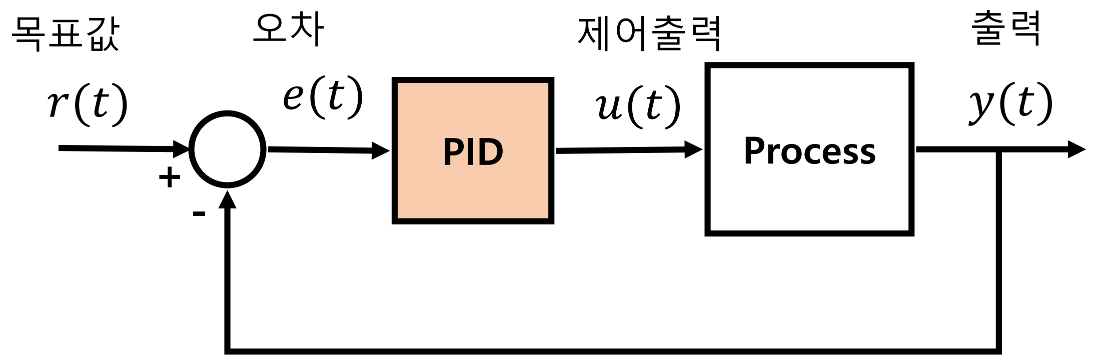
PID: Proportional, Integral, Derivative Control

- **비례·적분·미분제어**
  - 오차에 비례, 미분, 적분을 적용하여 원하는 목표를 달성하게 하는 제어기
- **제어목표**:
  - 프로세스의 출력이 원하는 시간 이내에 안정적으로 목표값에 도달하도록 함.

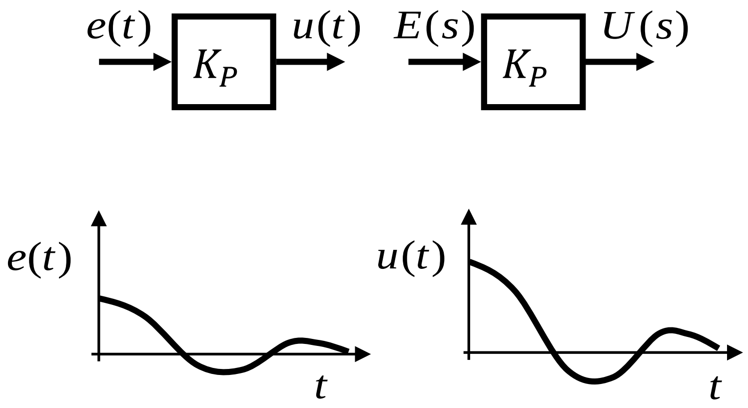




PID의 요소

■ 비례 제어(P: Proportional Control)

- 기본식
  - $u(t) = K_P e(t)$
  - K_P: 비례 게인(proportional gain)

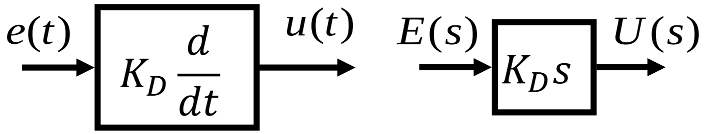


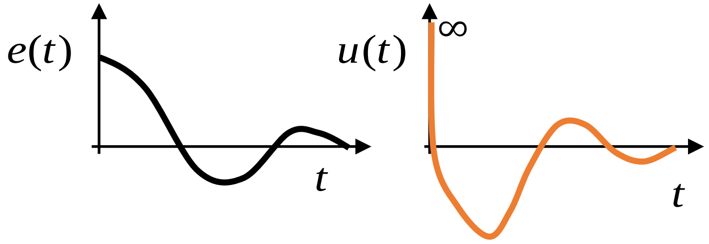
- 오차에 비례하는 출력을 내는 가장 직관적 제어기

PID의 요소

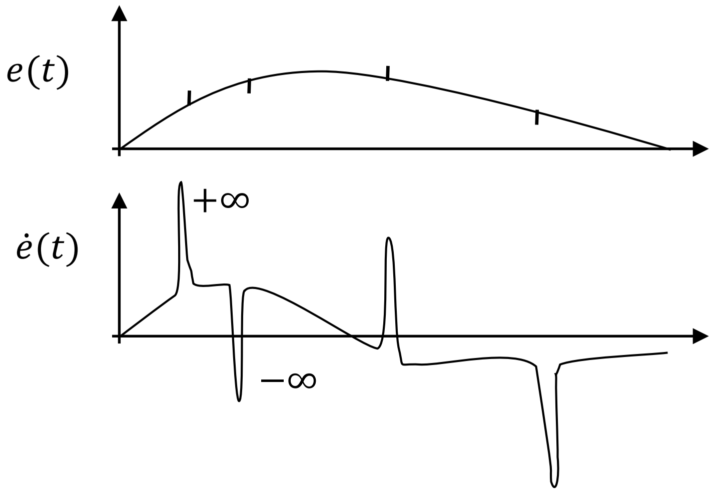
■ 미분 제어 (D: Derivative Control)

- 기본식
  - $u(t) = K_D \dfrac{de(t)}{dt}$
  - K_D : 미분게인





- 오차의 변화율에 비례하는 출력을 내는 제어기로서 댐핑을 증가시킴.
- 미분연산에 의하여 잡음에 민감하여 미분 게인을 너무 키우면 출력에 진동 발생



PID의 요소

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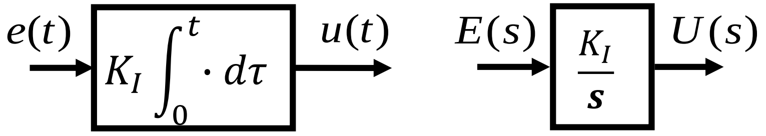
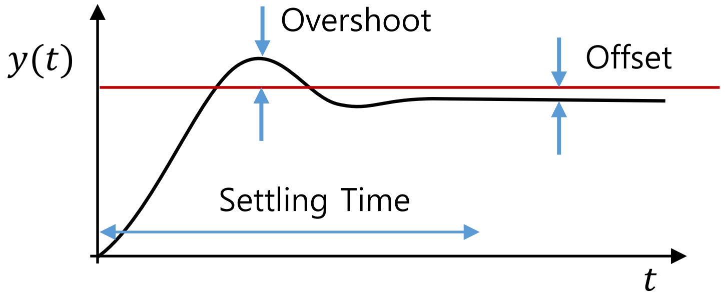
■ 적분 제어 (I: Integral Control)

- 기본식
  - $u(t) = K_I \int_0^t e(\tau)d\tau$
  - K_I : 적분게인



- 오차의 누적값에 비례하는 값을 출력 ➔ 정상상태 오차(Offset) 감소 효과.
- 적분 게인이 너무 크면
  - 분모에 적분기를 포함하는경우 시스템이 불안해질 수 있음.
  - Overshoot가 커짐
  - 정착시간이 길어짐



적분기의 Offset 감소효과
정상상태에 약간의 오차라도 남으면 적분 제어에 의하여 그 오차의 누적값이 계속 증가되므로 언젠가는 오차가 없어짐.

PID 게인의 역할

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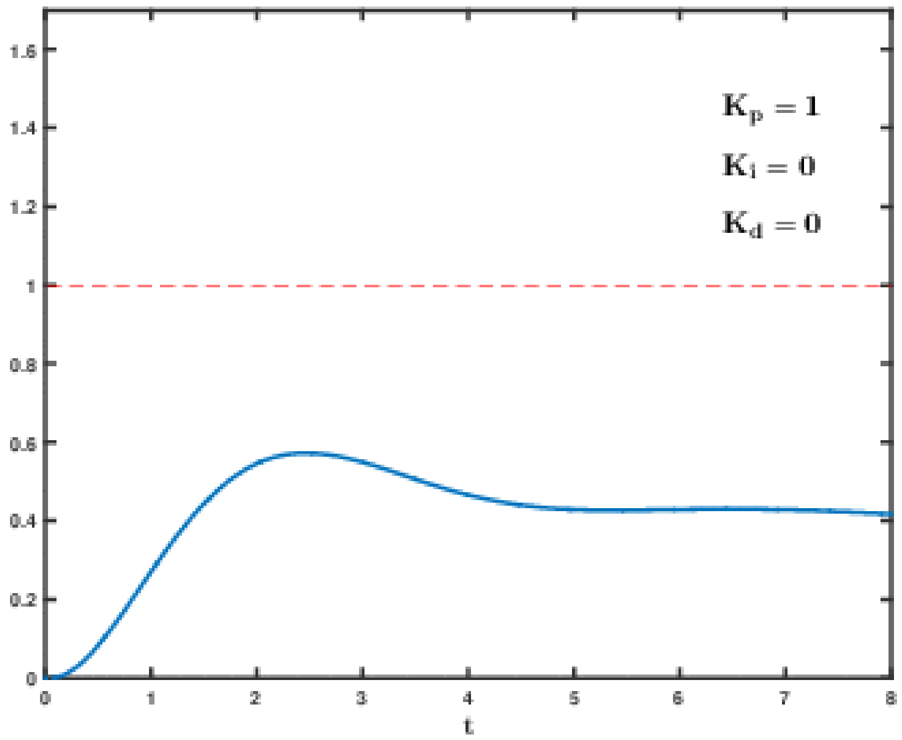
각 **게인의 역할**

- 각PID 제어 항에 대한 가중
- P - 기본제어
- I - 정상상태 오차 저감
- D - 과도기 진동 저감, 댐핑 증가.



https://commons.wikimedia.org/wiki/File:PID_Compensation_Animated.gif

PID의 요소

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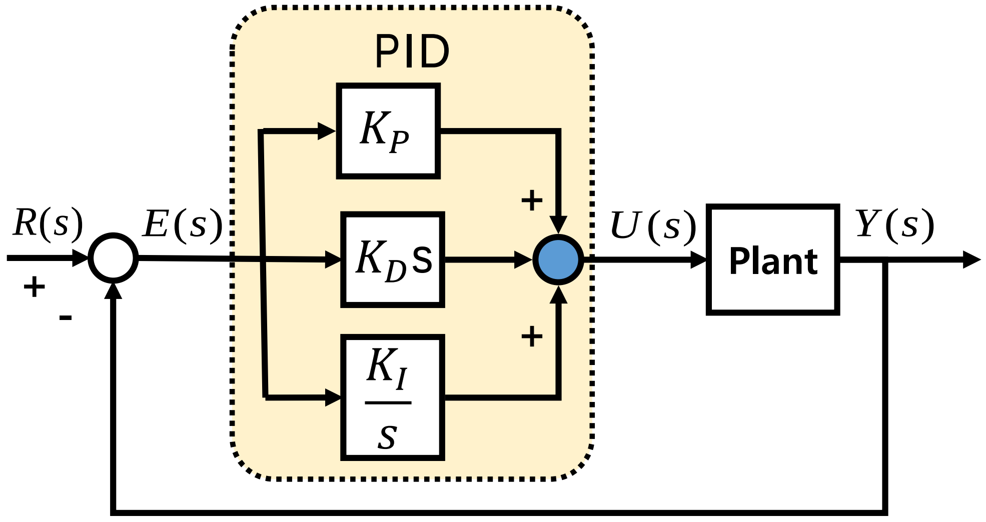
■ 비례 미분 적분 제어 (PID Control)

- 기본식

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \qquad (1)$$

$$\frac{U(s)}{E(S)} = K_P + \frac{K_I}{s} + K_D s$$



- 비례, 미분, 적분 제어기를 모두 조합하여 각각의 장점을 취한 제어기
- 시행착오에 의하여 비례, 미분, 적분게인을 설정하는 것이 일반적

Digital PID Control

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■ 디지털 비례 미분 적분 제어

- 샘플링 시간을 dt 라고 하고, 적분근사화과 오일러의 근사식을 (1)식에 적용

$$u(k) = \underbrace{K_P e(k)}_{\text{P-term}} + \underbrace{K_I \sum_{j=0}^{k} e(j)dt}_{\text{I-term}} + \underbrace{K_D \frac{e(k)-e(k-1)}{dt}}_{\text{D-term}} \qquad (2)$$

여기서, k는 샘플링 인덱스.

적분 근사화 $(dt \ll 1)$

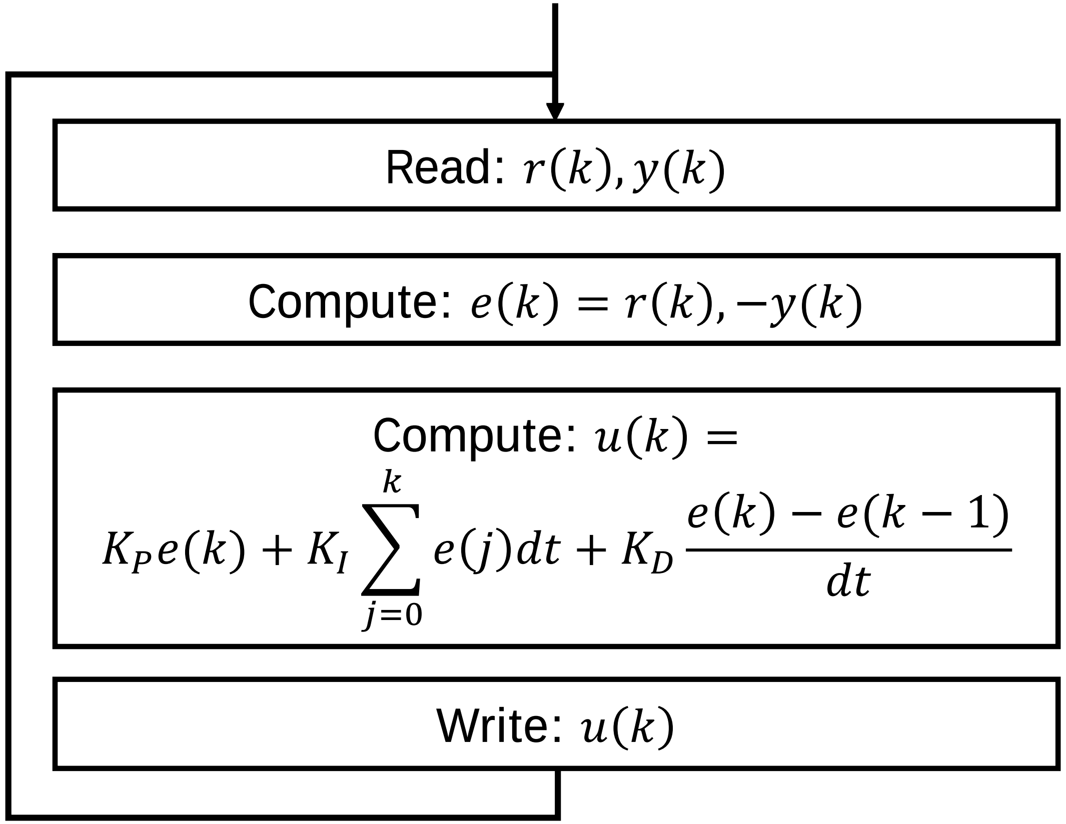
$$\int_0^t e(\tau)d\tau \cong \sum_{j=0}^{k} e(j)dt$$

오일러 근사화 $(dt \ll 1)$

$$\dot{x}(k) \cong \frac{x(k) - x(k-1)}{dt}$$

Digital PID Control

- 일반적 Digital PID의 순서도



PID 제어 알고리즘 개선

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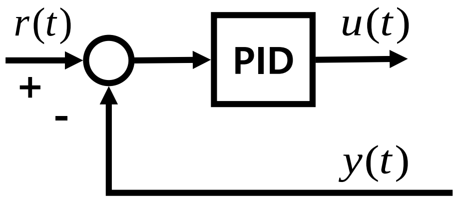
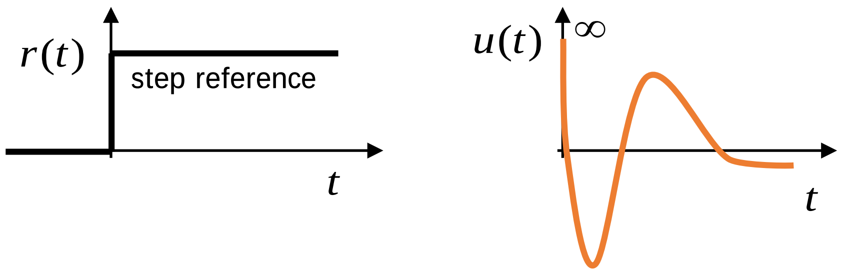
Standard PID 문제점

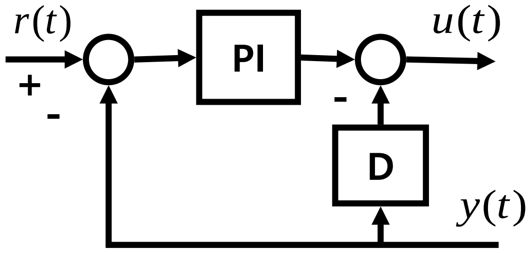
- $e(t) = r(t) - y(t)$ 이기 때문에 $r(t)$가 계단 입력인 경우 오차를 미분하면 출력 $u(t)$가 ∞
- 큰 오버슈트(overshoor) 발생





속도 feedback PID

- 미분제어기에서는 $e(t)$ 대신 $-y(t)$ 사용
- 계산식
  - $u(k) = K_P e(k) + K_I \sum_{j=0}^{k} e(j)dt - K_D \frac{y(k)-y(k-1)}{dt}$



PID 제어 알고리즘 개선

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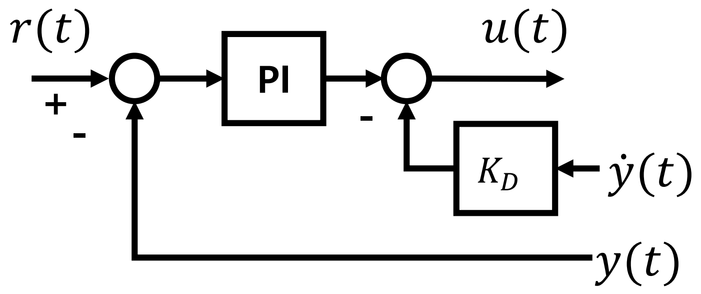
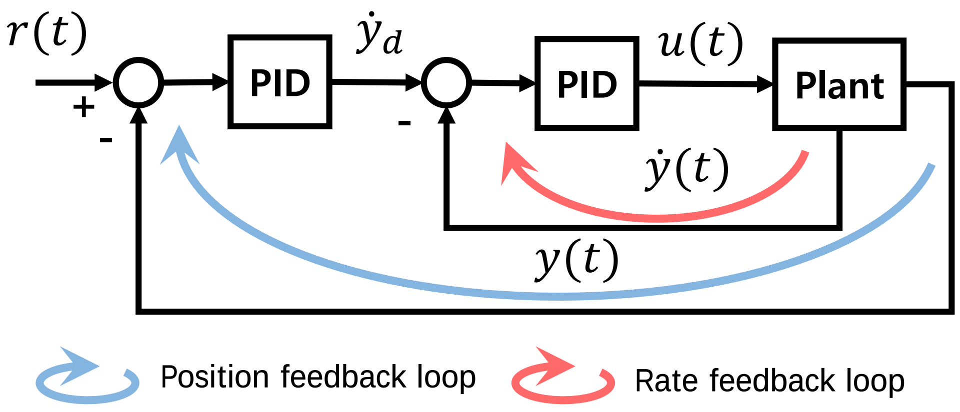
속도센서 feedback PID

- 속도 센서가 있는 경우



Dual loop PID

- 속도 센서 피드백의 속도 loop를 추가
- rate 와 position loop PID가 존재
  - rate loop는 position에 비하여 2배 이상 빨라야 좋은 성능 보장



PID 제어 알고리즘 개선

LPF가 적용된 D제어기

- 급격하게 변화하는 오차를 미분함으로써 발생되는 문제를 완화
- 1차 LPF의 전달함수

$$LPF(s) = \frac{Y(s)}{X(s)} = \frac{1}{Ts+1}$$

- 미분방정식

$$T\dot{y}(t) + y(t) = x(t)$$

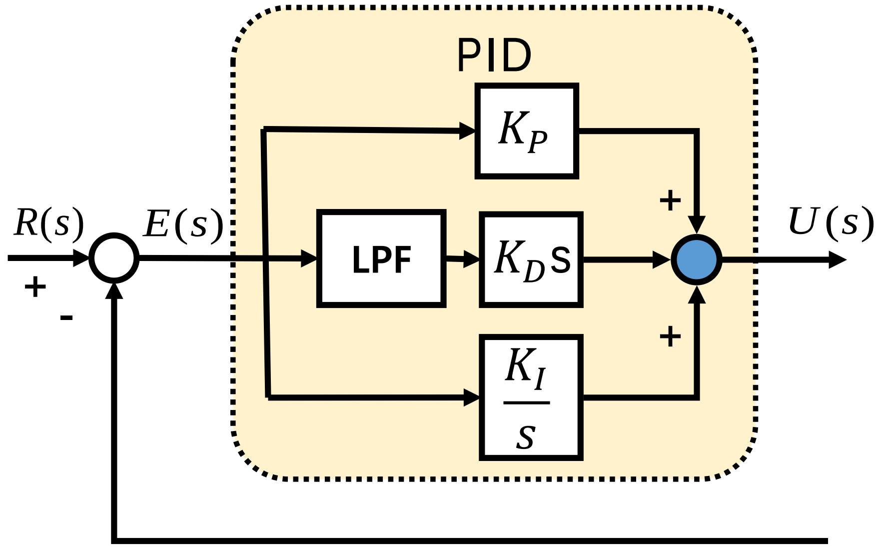
- 디지털 구현
  - 샘플시간이 dt일 때 오일러 근사식 적용

$$T\frac{y(k) - y(k-1)}{dt} + y(k) = x(k)$$

- 정리하면

$$y(k) = \alpha y(k-1) + (1-\alpha)x(k)$$

여기서, $\alpha = \frac{T}{T+dt}$ 이고



LPF에서 컷오프 주파수 f

$$f = \frac{1}{2\pi T}$$

PID 제어 알고리즘 개선

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- 미분기와 LPF를 포함한 전달함수

$$LPF(s) = \frac{Y(s)}{X(s)} = \frac{s}{Ts+1}$$

- 미분방정식

$$T\dot{y}(t) + y(t) = \dot{x}(t)$$

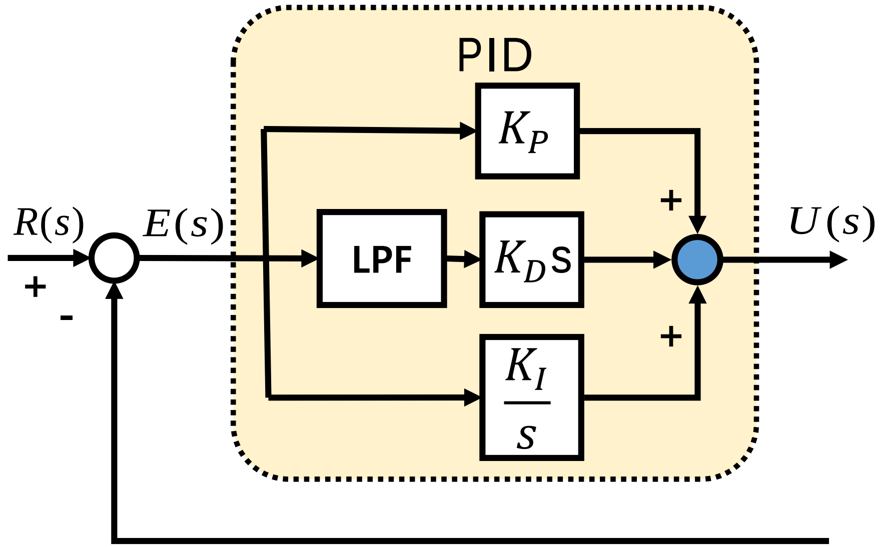
- 디지털구현
  - 샘플시간이 dt일 때 오일러 근사식 적용

$$T\frac{y(k)-y(k-1)}{dt} + y(k) = \frac{x(k)-x(k-1)}{dt}$$

- 정리하면

$$z(k) = \frac{x(k)-x(k-1)}{dt}$$

$$y(k) = y(k-1) + \frac{dt}{T+dt}(z(k)-y(k-1))$$



LPF에서 컷오프 주파수 f

$$f = \frac{1}{2\pi T}$$

PID 제어 알고리즘 개선

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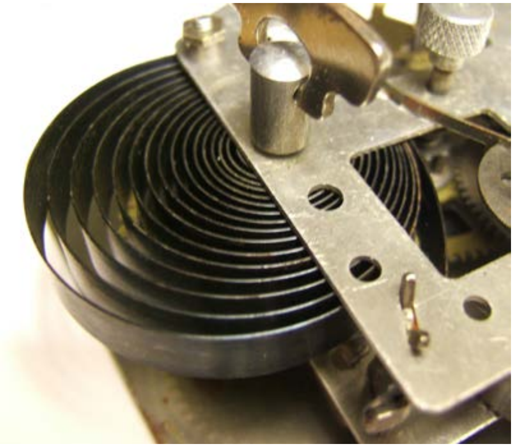
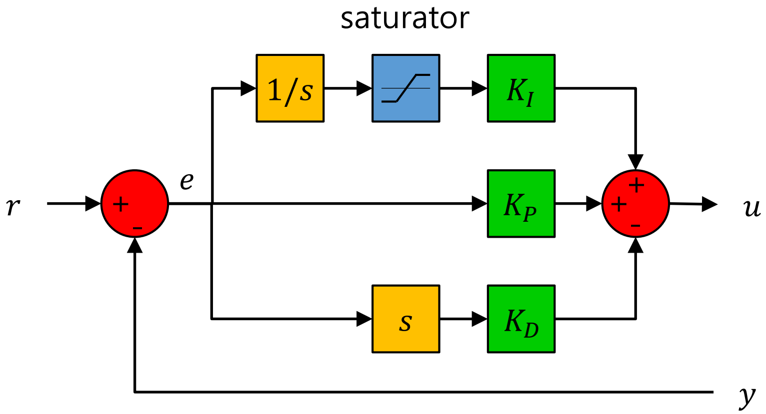
I 제어기의 문제점

- windup 현상
  - 작동기가 제어 한계나 외력에 의하여 제어 출력의 변화가 반영이 되지 않을 때 나타남.
  - 적분 값이 매우 큰 값으로 누적되어 원인이 제거되어도
    - 매우 큰 출력이 한꺼번에 반영됨
    - 그 값이 오랫동안 제어 성능을 저하시킴
- 대책
  - Anti-windup 알고리즘 적용
  - 적분값을 상한/하한으로 포화(saturate)시킴



Wikimedia Commons: Alarm clock mainspring.JPG



P, I - Control

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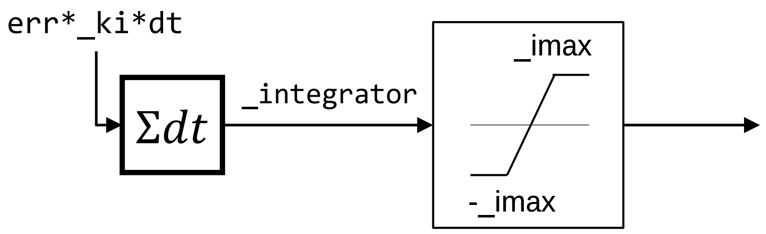
- get_p: 비례제어

```
int32_t get_p(int32_t error) {
    return (float)error * _kp;
}
```

- get_i: 적분제어




```
int32_t get_i(int32_t error, float dt)
{
    if((_ki != 0) && (dt != 0)){
        _integrator += ((float)error * _ki) * dt;
        if (_integrator < -_imax) {
            _integrator = -_imax;
        } else if (_integrator > _imax) {
            _integrator = _imax;
        }
        return _integrator;
    }
    return 0;
}
```

D - Control

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get_d: 미분 제어

- 다음 식을 구현

$$z(k) = \frac{x(k)-x(k-1)}{dt}$$

$$y(k) = y(k-1) + \frac{dt}{T+dt}(z(k) - y(k-1))$$

_d :	$z(k)$
input :	$x(k)$
_last_input:	$x(k-1)$
_deriv:	$y(k)$
_last_deriv:	$y(k-1)$

```
int32_t get_d(int32_t input, float dt){
    if ((_kd != 0) && (dt != 0)) {
         float _d = (input - _last_input) / dt;
        // discrete low pass filter
         _deriv = _last_deriv +
         (dt/(_filter + dt))*(_d-_last_deriv);
        // update state
        _last_input        = input;
        _last_deriv = _deriv;

        // add in derivative component
        return _kd * _deriv;
    }
    return 0;
}
```

PID 적용

조종의 {E}, {B}좌표계

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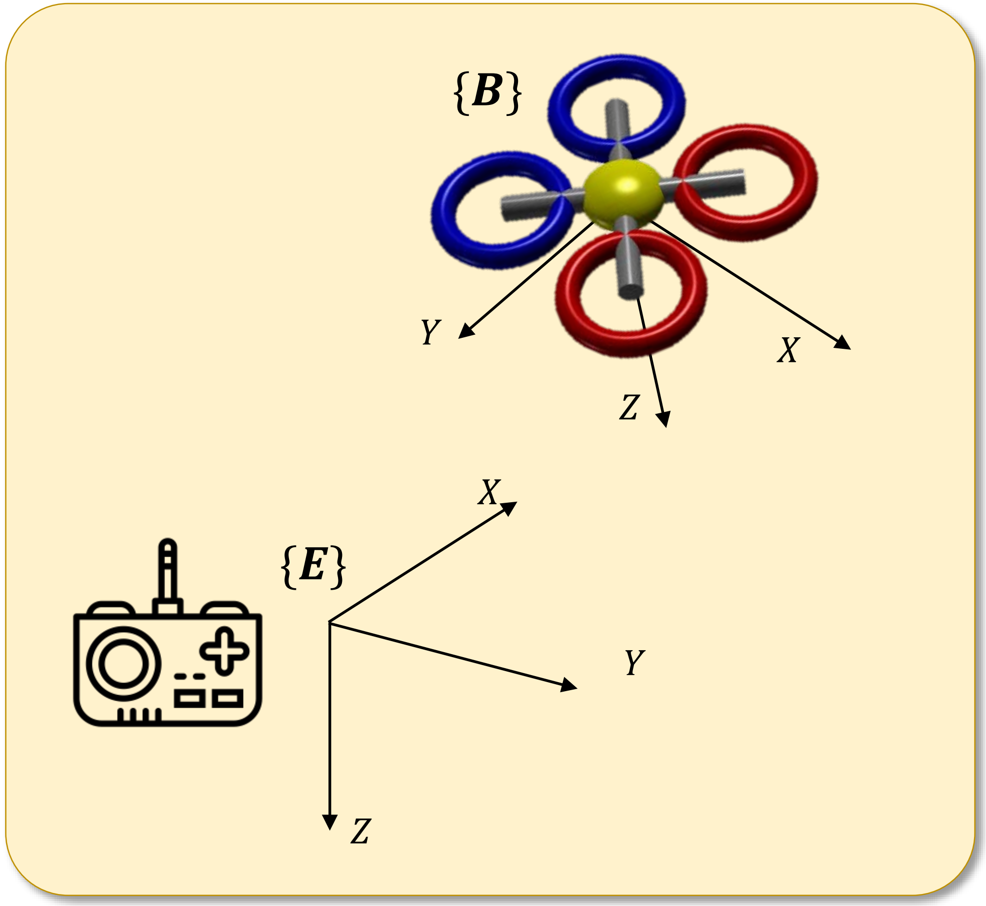
- 고도 제어
  - throttle을 올리면 {E} 좌표의 -Z축으로
- 자세제어
  - {E} 좌표를 기준으로 각도 판단



이중 루프 PID - Roll

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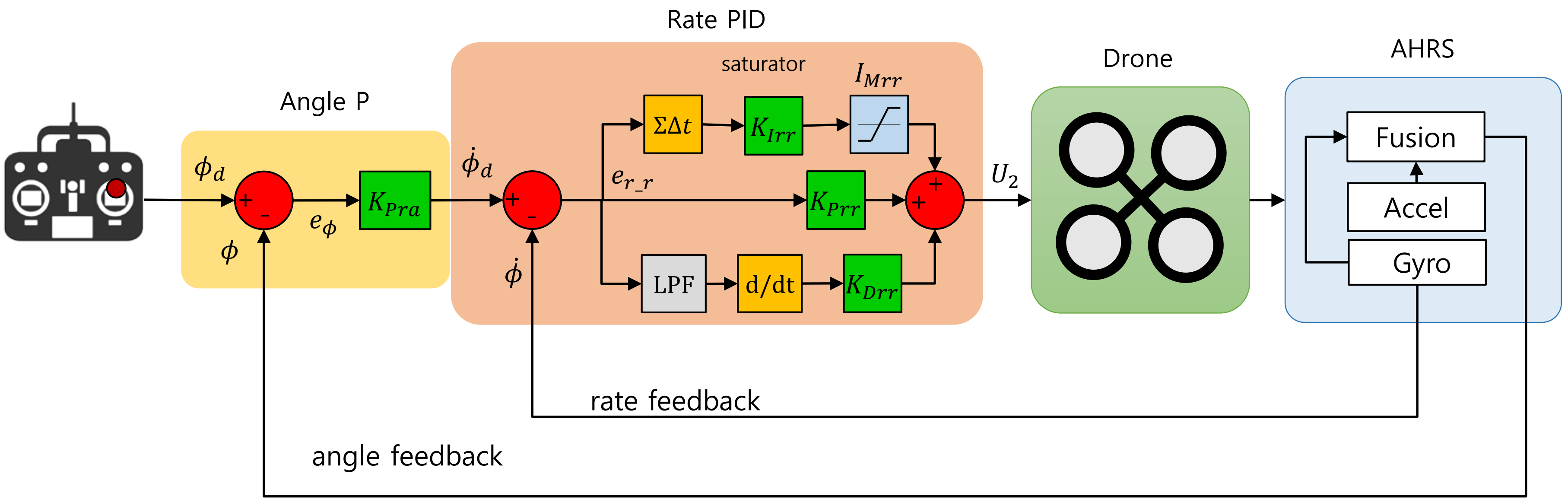
■ Roll 각도 제어



이중 루프 PID - Pitch

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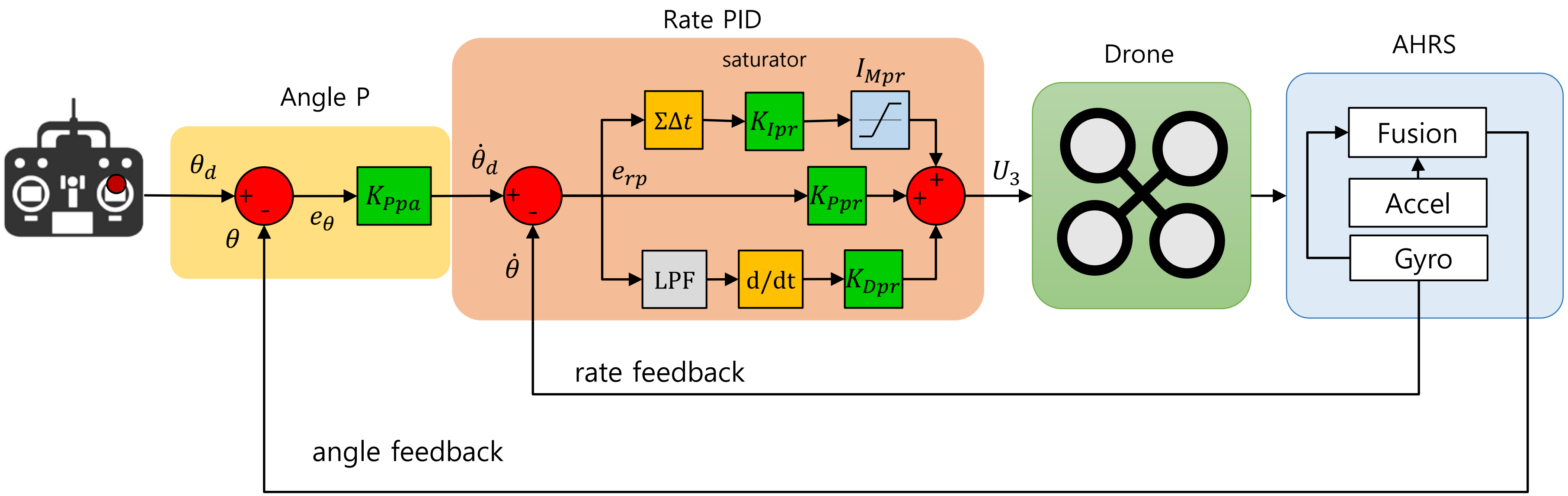
Pitch 각도 제어



이중 루프 PID - Yaw

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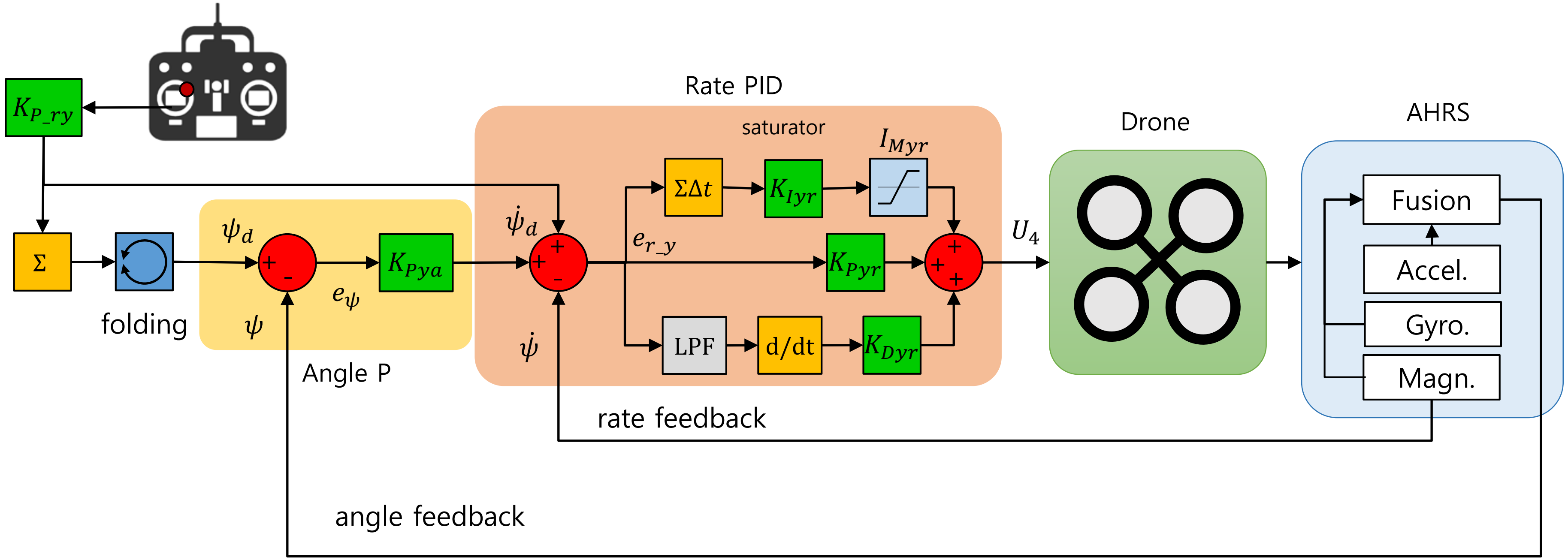
■ Yaw 제어



삼중 루프 PID - Alt

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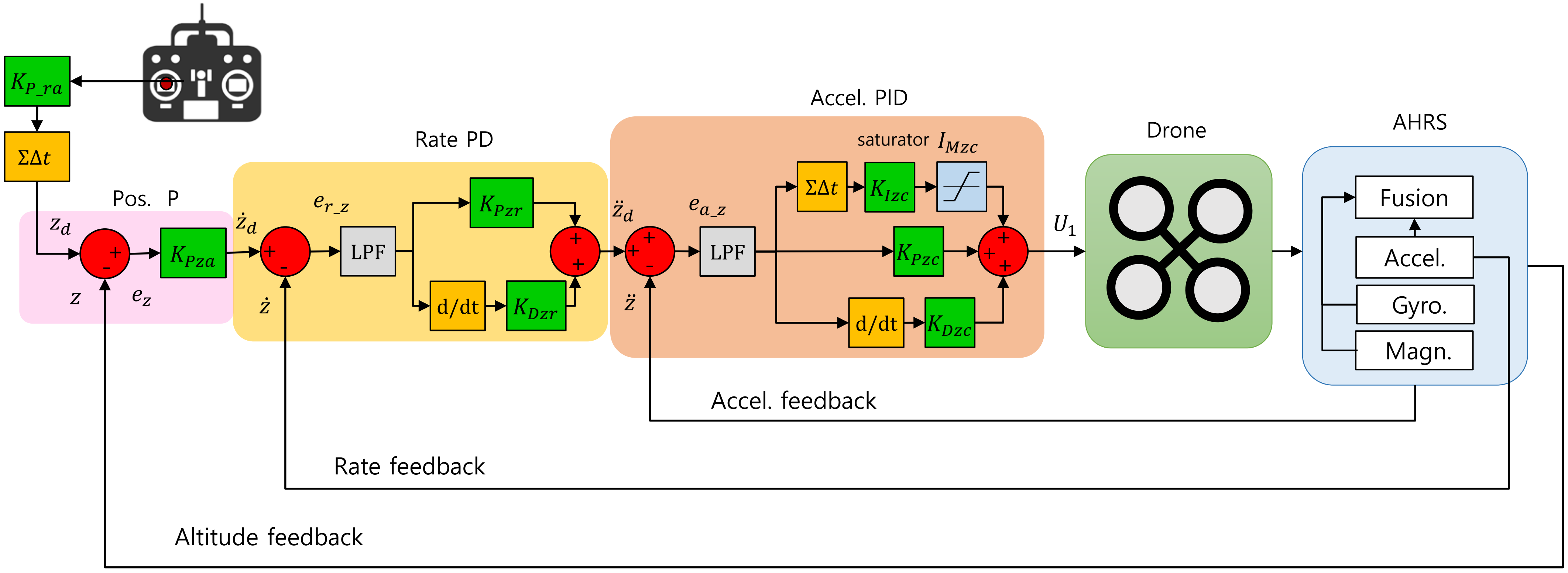
■ 고도 제어



주요 파라미터

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Roll, Pitch, Yaw, Alt PID Parameter

		Angle/Position loop				Rate loop				Acceleration loop				
		P	I	D	Imax	P	I	D	Imax	P	I	D	Imax	
Roll	r	K_{Pra}				K_{Prr}	K_{Irr}	K_{Drr}	I_{Mrr}					
Pitch	p	K_{Ppa}				K_{Ppr}	K_{Ipr}	K_{Dpr}	I_{Mpr}					
Yaw	y	K_{Pya}				K_{Pyr}	K_{Iyr}	K_{Dyr}	I_{Myr}					
Alt	z	K_{Pza}				K_{Pzr}		K_{Dzr}		K_{Pzc}	K_{Izc}	K_{Dzc}	I_{Mzc}	

AC_PID 클래스선언

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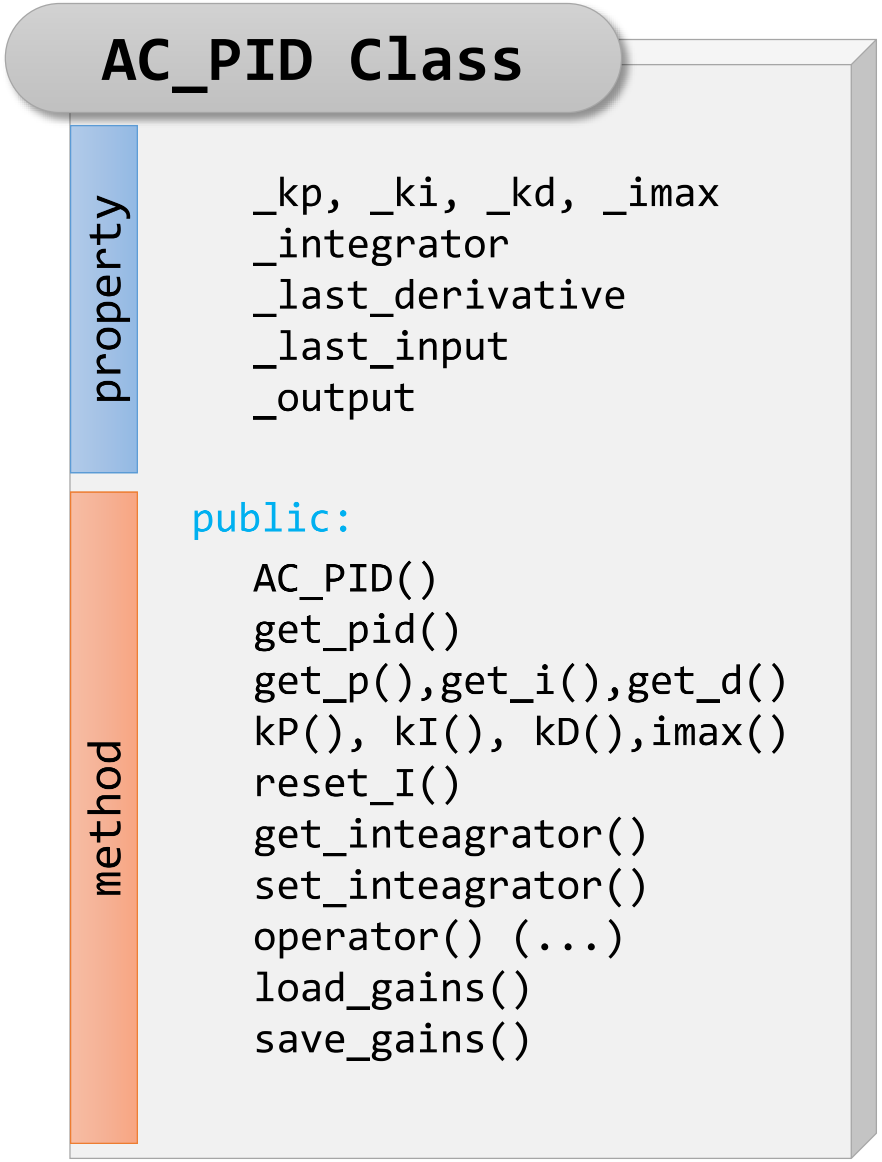
AC_PID Class:

- Property
  - _kp, _ki, _kd: 각 항의 게인
  - _imax : 적분기 saturation
  - _integrator: I항 적분값
  - _last_input : 전 스텝의 오차
- Method
  - AC_PID(): 생성자
  - get_pid(): PID 계산값
  - get_p(), get_i(), get_d(): P,I,D 각 항
  - kP(),kI(),kD(),imax(): 읽기/쓰기
    - function overload
  - operator() (...):
    - Operator Overload로 게인을 한꺼번에 바꿀 수 있음.



C++ 참고

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Function Overload

- 이름이 동일하고 매개변수가 다른 두 함수가 공존
- 예와 같이 다음 모두가 가능하다.
  - kP() : _kp 값을 반환
  - kP(v): v 값으로 _kp 변경
- 단, 매개변수의 개수 또는 타입이 달라야 함.

```
class AC_PID {
public:
...
    float kP() {
      return _kp; }
    void  kP(const float v) {
      _kp=v;}
...
};
...
AC_PID pid;
    pid.kP(1.5);
    Serial.println(pid.kP());
...
```

C++ 참고

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Operator Overload

- 연산자를 Class에 적용하여 기존 연산 기호를 대치
- 예)
  - Complex operator + (Complex &obj2) {}
    - obj1 + obj2 가 가능하도록 + 오버로드
  - void operator ()(int r, int i){...}
    - object(a,b) 인 경우 실행

```cpp
#include<iostream>
using namespace std;
class Complex {
private:
    int real, imag;
public:
    Complex(int r=0, int i=0):real(r),imag(i){}
    Complex operator + (Complex &obj) {
        Complex res;
        res.real = real + obj.real;
        res.imag = imag + obj.imag;
        return res;
    }
    void operator ()(int r, int i){ real=r;imag=i;}
    void print() {cout<<real<<" + i"<<imag<<endl;}
};
int main() {
    Complex c1(10, 5), c2(2, 4);
    Complex c3 = c1 + c2;  // + operator
    c3.print();
    c1(-5,7); //  () operator overloading
    c3 = c1 + c2;
    c3.print();
}
```

AC_PID Class 코드

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

■ 헤더

AC_PID.h [1/2]

```
class AC_PID {
public:
    AC_PID( const float &initial_p = 0.0, // constructor
           const float &initial_i = 0.0,
          const float &initial_d = 0.0,
             const int16_t &initial_imax = 0.0):
        _kp (initial_p), _ki (initial_i),
          _kd (initial_d),_imax(abs(initial_imax)){}
    int32_t get_pid(int32_t error, float dt);
    int32_t get_pi(int32_t error, float dt);
    int32_t get_p(int32_t error);
    int32_t get_i(int32_t error, float dt);
    int32_t get_d(int32_t error, float dt);
    void reset_I();
    void    load_gains();
    void    save_gains();
     // Overload the function call operator
    void operator() (const float p, const float i,
                     const float d, const int16_t imaxval) {
      _kp = p; _ki = i; _kd = d; _imax = abs(imaxval);
    }
```

AC_PID Class 코드

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

■ 헤더

AC_PID.h [2/2]

```
    float   kP() const   { return _kp; }
    void  kP(const float v)   { _kp=v; }
    float   kI() const   { return _ki; }
    void  kI(const float v)   { _ki=v; }
    float   kD() const   { return _kd; }
    void  kD(const float v)   { _kd=v; }
    int16_t imax() const { return _imax; }
    void imax(const int16_t v) { _imax=abs(v); }
    float   get_integrator() const    { return _integrator; }
    void set_integrator(float i)   { _integrator = i; }
private:
    float       _kp, _ki, _kd, _imax;
    float       _integrator; // integrator value
    int32_t  _last_input; // last input for derivative
    float       _last_derivative; // last derivative for low-pass filter
    float       _output;
    static const float _filter =15.9155e-3;
     // 1/(2*PI*f_cut) LPF for derivative
};
```

AC_PID Class 코드

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

- C++

AC_PID.cpp [1/3]

```
#include "AC_PID.h"
int32_t AC_PID::get_p(int32_t error) {
    return (float)error * _kp;
}
int32_t AC_PID::get_i(int32_t error, float dt) {
    if((_ki != 0) && (dt != 0)){
        _integrator += ((float)error * _ki) * dt;
        if (_integrator < -_imax) {
            _integrator = -_imax;
        } else if (_integrator > _imax) {
            _integrator = _imax;
        }
        return _integrator;
    }
    return 0;
}
```

AC_PID Class 코드

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

- C++

AC_PID.cpp [2/3]

```cpp
int32_t AC_PID::get_d(int32_t input, float dt){
    if ((_kd != 0) && (dt != 0)) {
        float _derivative = (input - _last_input) / dt;
        _derivative = _last_derivative +
                (dt / ( _filter + dt)) * (_derivative - _last_derivative);
        _last_input        = input;
        _last_derivative    = _derivative;
        return _kd * _derivative;
    }
    return 0;
}
int32_t AC_PID::get_pi(int32_t error, float dt){
    return get_p(error) + get_i(error, dt);
}
int32_t AC_PID::get_pid(int32_t error, float dt) {
    return get_p(error) + get_i(error, dt) + get_d(error, dt);
}
```

AC_PID Class 코드

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- C++

AC_PID.cpp [3/3]

```
void AC_PID::reset_I() {
    _integrator = 0;
    _last_input = 0;
    _last_derivative = 0;
}
void AC_PID::load_gains() {
//  to be finished
}
void AC_PID::save_gains() {
//  to be finished
}
```

아두이노 코드

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ino

PIDClassTest.ino [1/2]

```
#include "AC_PID.h"
// default PID values
#define TEST_P 0.5
#define TEST_I 0.5
#define TEST_D 0.2
#define TEST_IMAX 20
AC_PID ratePID(TEST_P, TEST_I, TEST_D, TEST_IMAX);
int count=0;
float dt=0.01;
uint32_t prevTime=micros();
void setup() {
    Serial.begin(115200);
    angPID(0.7,0.8,0.5,10);
}
void loop() {
  makeDt(10000);
  float t= 0.01*count;
  int error_r=100*sin(t);
  int32_t pTerm_r=ratePID.get_p(error_r);
```

AC_PID Class 코드

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

- ino

PIDClassTest.ino [2/2]

```
  int32_t iTerm_r=ratePID.get_i(error_r,dt);
  int32_t dTerm_r=ratePID.get_d(error_r,dt);
  int32_t control_r= pTerm_r+ iTerm_r+ dTerm_r;
  Serial.print(error_r);Serial.print(",");
  Serial.print(pTerm_r);Serial.print(",");
  Serial.print(iTerm_r);Serial.print(",");
  Serial.print(dTerm_r);
  Serial.print("\n");
  count++;
}
void makeDt(uint32_t p){
  uint32_t newTime;
  do {newTime = micros();}while (newTime - prevTime<p);
  prevTime = newTime;
}
```

각항의 비교

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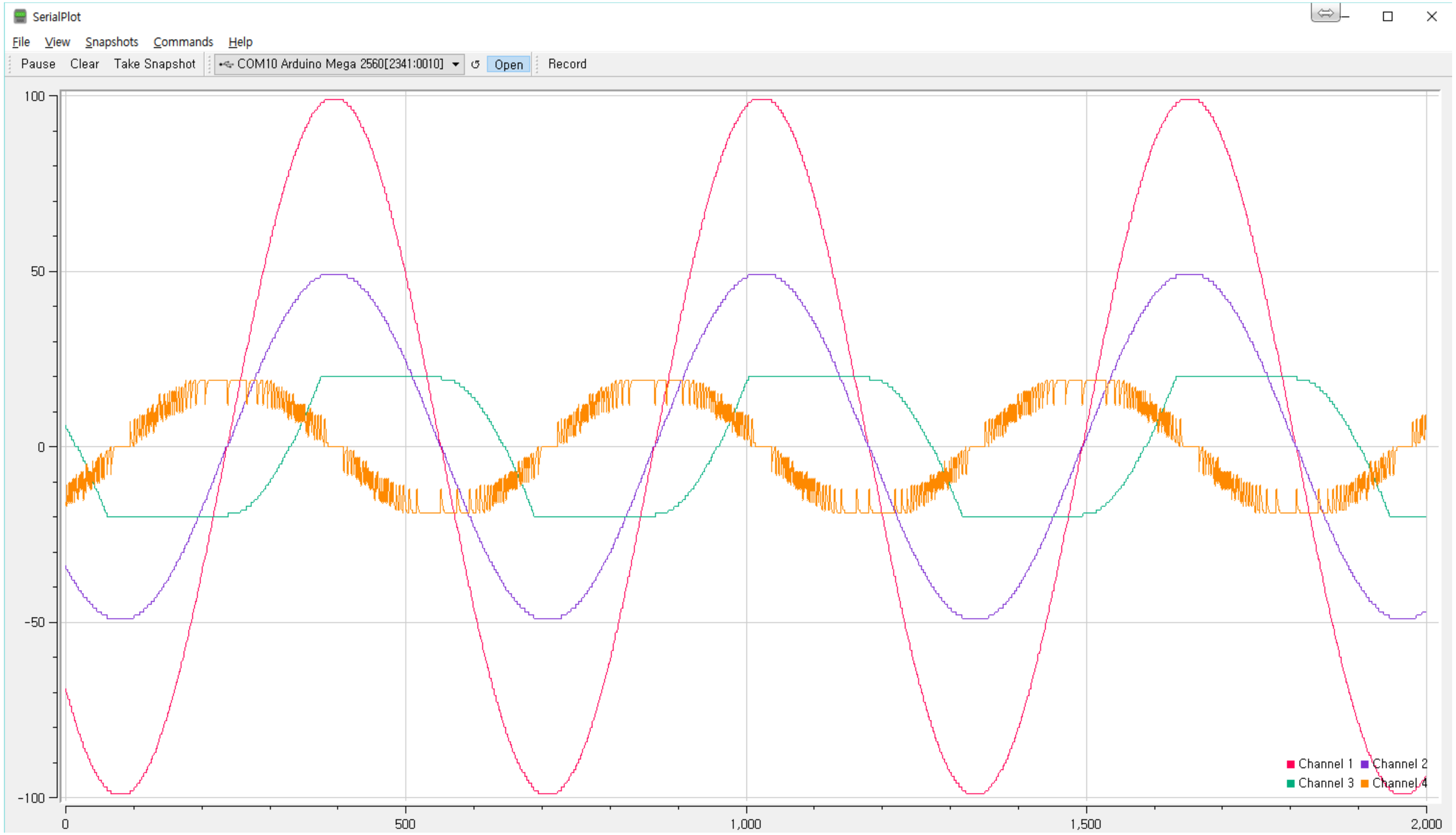

2개의 PID

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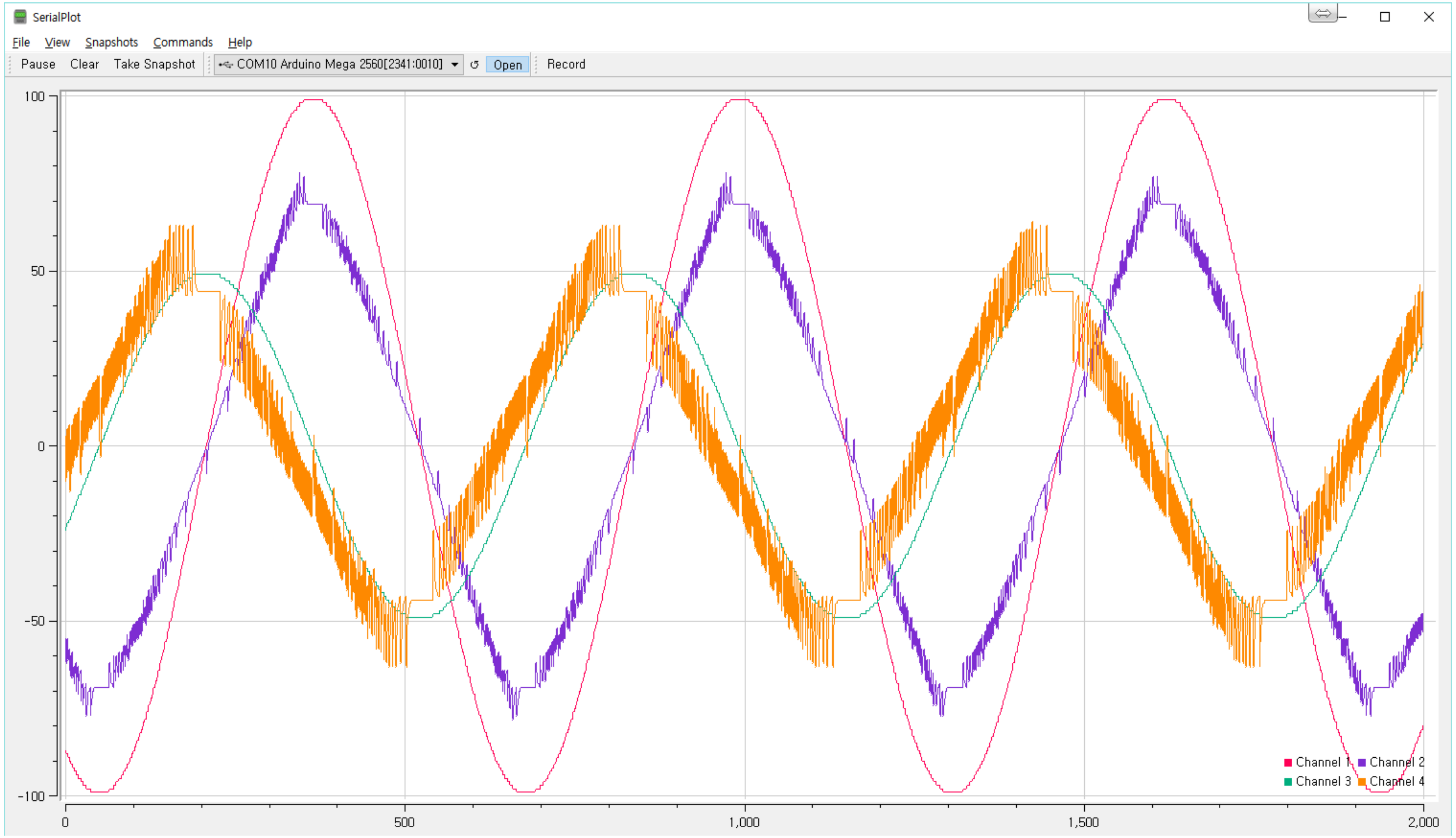

Parameters

EEPROM 사용

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내장 EEPROM library

- #include <EEPROM.h>
- **API**
  - length()
  - Single byte 읽고 쓰기
    - read(), write(), update()
  - 구조체로 읽고 쓰기
    - get(), put()
- **[] operators**
  - 배열처럼 사용

```
uint8_t read(int idx);
void write(int idx, uint8_t val);
void update(int idx, uint8_t val);
```

```
template<typename T> T &get(int idx, T &t);
template<typename T> const T &put(int idx,
                                   const T &t);
```

```
// read the byte from address 88
uint8_t data = EEPROM[88];
// write a byte to address 76
EEPROM[76] = 97;
// increase the value in address 2 by 1
EEPROM[2]++;
```

EEPROM 사용

Dept. of Mechanical System Design, Seoul National University of Science and Technology.

- 구조체 test

```
#include <EEPROM.h>
void setup() {
  Serial.begin(115200);
  struct Format {char str[25]; int i;  float f; } ;
  Format  a = {"This is EEPROM Test!", 32767, -0.09567}, b;
  EEPROM.put(0, a); // Write all
  EEPROM.get(0, b); // Read all
  Serial.println(b.str);  //Print:
  Serial.println(b.f, 5);
  Serial.println(b.i);
    int i_new = -784;     float f_new = 782.10132;
  // write each new value to EEPROM:
  EEPROM.put(offsetof(Format, i), i_new);
  EEPROM.put(offsetof(Format, f), f_new);
  // read each new value from EEPROM:
  EEPROM.get(offsetof(Format, f), a.f);
  EEPROM.get(offsetof(Format, i), a.i);
  Serial.println("===========");   // Print:
  Serial.println(a.i);
  Serial.println(a.f, 5);
}
```

```
This is EEPROM Test!
-0.09567
32767
============
-784
782.10131
```

EEPROM 사용

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이중 구조체 사용

- PID
- PARAM

```
#include <EEPROM.h>
void setup() {
  Serial.begin(115200);
  struct PID { float kP, kI, kD; uint16_t imax;};
  struct PARAM {
    PID angle, rate, acc;
   };
  PARAM  a = {{1.1,1.2,1.3,0},{2.1,2.2,2.3,1},{3.1,3.2,3.3,2}}, b;
  EEPROM.put(0, a); // Write all
  EEPROM.get(0, b); // Read all
  Serial.print("angle kP=");Serial.println(b.angle.kP);
  Serial.print("rate kI=");Serial.println(b.rate.kI);
  Serial.print("acc kD=");Serial.println(b.acc.kD);
}
void loop() {}
```

```
angle kP=1.10
rate kI=2.20
acc kD=3.30
```

PID gain에 적용

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PID 삼중 구조체

- PARAM
  - CONTROL
    - PID

```
#include <EEPROM.h>
struct PID { float kP, kI, kD; uint16_t imax;};
struct CONTROL { PID angle, rate, acc; };
struct PARAM { CONTROL roll, pitch, yaw, alt; };
void setup() {
  Serial.begin(115200);
  PARAM  initial_gains = {
   // kP,    kI,   kD,    imax        roll gains
   {{0.05, 0.01, 0.003, 100},  // angle
    {0.01, 0.02, 0.03, 100},   // rate
    {0.0, 0.0, 0.0, 0}},
   // pitch gains
   {{0.05, 0.01, 0.003, 100}, // angle
    {0.01, 0.02, 0.03, 100},  // rate
    {0.0, 0.0, 0.0, 0}},
```

PID gain에 적용

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```
    // yaw gains
    {{0.06, 0.01, 0.003, 100}, // angle
     {0.02, 0.04, 0.03, 100},  // rate
     {0.0, 0.0, 0.0, 0}},
    // alt gains
    {{0.07, 0.01, 0.003, 100}, // angle
     {0.03, 0.00, 0.03,   0},  // rate
     {0.2, 0.02, 0.03, 100}}   // acc
   };
   saveGains(initial_gains);
   PARAM gains=loadGains();
   Serial.print("kPra="); Serial.println(gains.roll.angle.kP);
   Serial.print("kIyr="); Serial.println(gains.yaw.rate.kI);
   Serial.print("kDar=");Serial.println(gains.alt.acc.kD);
   PARAM c;
   uint16_t offset=offsetof(PARAM, alt)+offsetof(CONTROL, acc)
                  +offsetof(PID, imax);
   EEPROM.get(offset, c.alt.acc.imax);
   Serial.println(c.alt.acc.imax);
 }
```

PID gain에 적용

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주요내용

- saveGains(a)
  - a를 eeprom에 저장
- c = loadGains()
  - 읽어서 c에 저장

```
void loop() {}
void saveGains(PARAM a){
    EEPROM.put(0, a); // Write all
}
PARAM loadGains(){
  PARAM b;
    EEPROM.get(0, b); // Read all
  return b;
}
```

```
kPra=0.05
kIyr=0.04
kDar=0.03
100
```

Gyro Calibration

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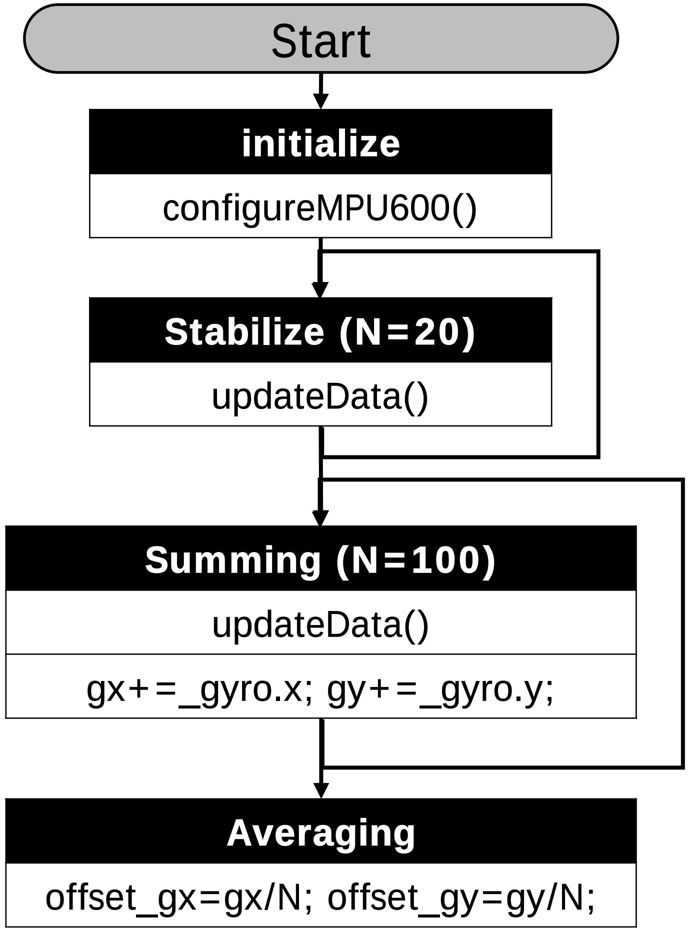
IMU gyro의 offset

- PID 의 rate control에 roll, pitch, yaw 각속도 값이 사용됨
  - Gyro의 측정값에 작은 offset 값이 있으면
  - 정지상태에서도 각속도 값이 존재

Calibration 방법

- 장치를 초기화
- 신호의 안정화
- 100회 측정 및 누적
- 평균 구하기



Gyro Calibration 코드

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MPU6000 Class

- calibrate()추가

MPU6k.cpp

```
void MPU6000::calibrate(){
  float gx=0,gy=0,gz=0;
  // Stabilize signal
  for (int i=0;i<20;i++){
    updateData();  delay(10);
  }
  // Measure and accumulate
  for (int i=0;i<100;i++){
    updateData();
    gx+=_gyro.x; gy+=_gyro.y; gz+=_gyro.z;
    delay(10);
  }
  // Averaging
  offset_gx=gx/100; offset_gy=gy/100;
  offset_gz=gz/100;
}
```

Gyro Calibration 코드

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MPU6k.cpp

- updateData()
  - offset 반영

MPU6k.cpp

```
bool MPU6000::updateData( ) {
    ...
  sei();   //enable interrupts
  count_scale = 1.0 / count;
  _gyro.x = _gyro_scale*_gyro_data_sign[0]*sum[_gyro_data_index[0]]*count_scale;
  _gyro.y = _gyro_scale*_gyro_data_sign[1]*sum[_gyro_data_index[1]]*count_scale;
  _gyro.z = _gyro_scale*_gyro_data_sign[2]*sum[_gyro_data_index[2]]*count_scale;
  ...
  _gyro.x -= offset_gx; _gyro.y -= offset_gy;  _gyro.z -= offset_gz;
  return true;
}
```

Gyro Calibration 결과

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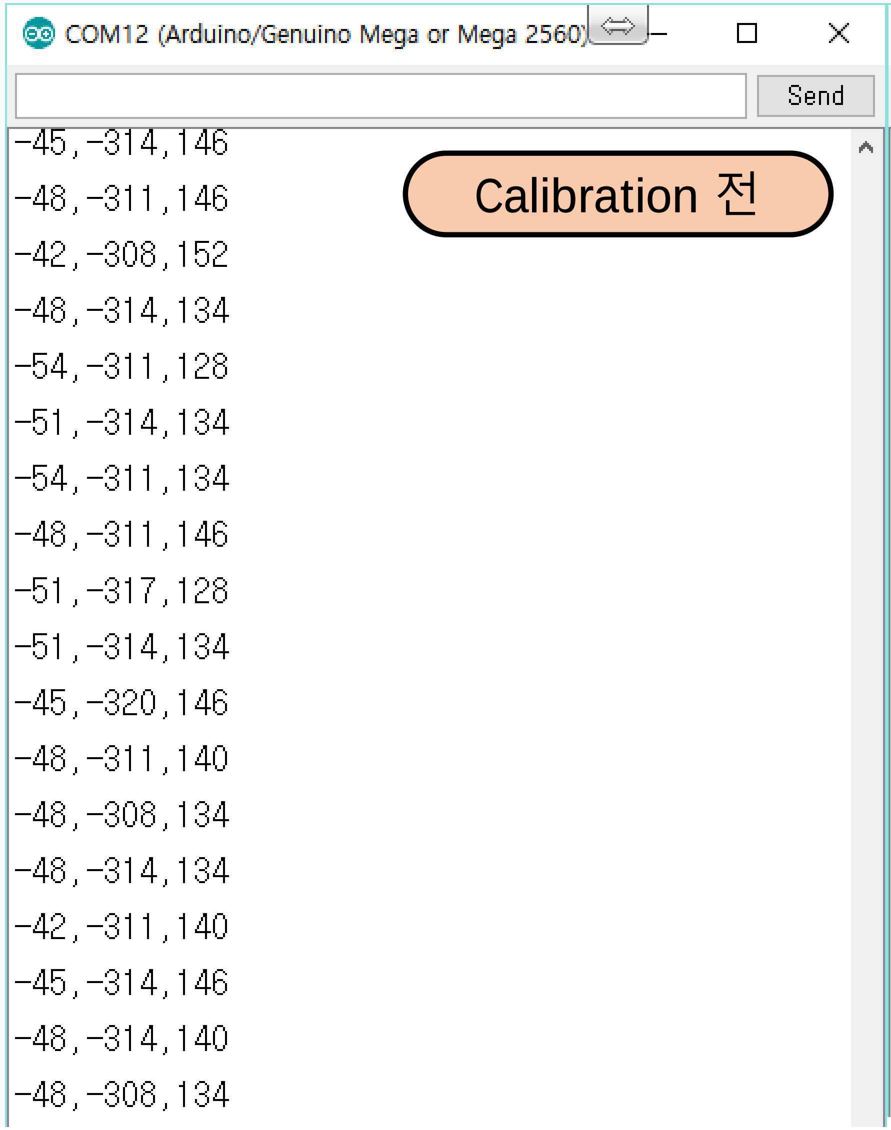
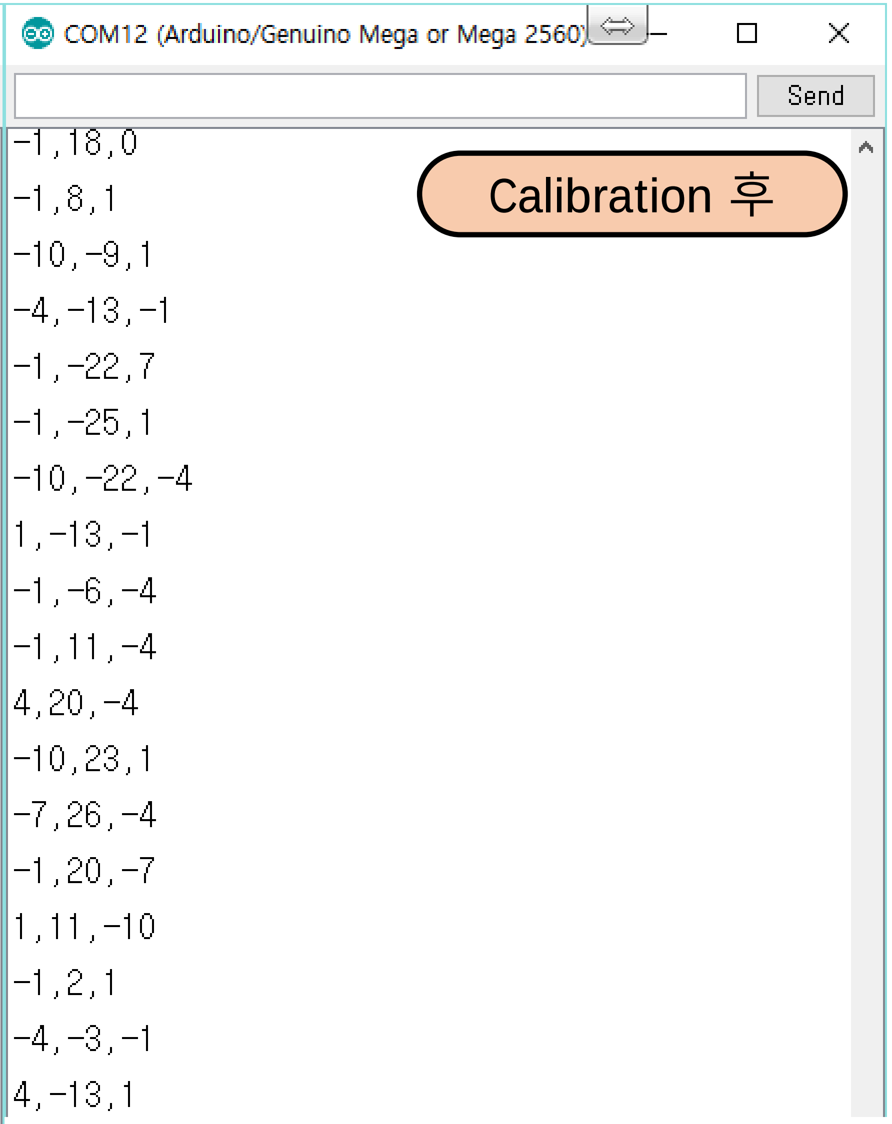
- offset 반영





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