Adaptation of multi-channel PID controllers in flight simulation environment

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Abstract

The usefullness of flight simulation in professional pilot training is unquestionable. The quality of the trainig device is utterly important for the participants to achieve their goal of making the airline industry more safe. There are a set of governing rules of the development of these devices, specifying the technical parameters to be obtained. The Fly-by-wire systems implemented in some of the modern jet aircrafts are fitted with compex flight path stabilization algorithms (so called "flight law"-s). These algorithms are designed in top of PID controllers. The simulation of such an aircraft will have the same complexity involved making these controllers stable and oscillation free for all of the flight manouevre envelope of the aircraft with all the configurations possible. This whitepaper will present a solution for making these controllers sturdy but flexible enough.

Keywords: Flight Simulation, Proportional–Integral–Derivative (PID) controller

1 Key affecting parameters

The parameters that are affecting the controllability of an aircraft are listed below. These effect should be conunteracted by our controller in the whole envelope. The problem is bound to our need of having the aircraft in the normal flight envelope. The PID-s should be designed in such way, that they are never allowed to leave out of this regime. The stability coefficients that are affected by the mentioned parameters are very complex and, by including the external wind and turbulence effects on the controller, we have to take in accout various possibilities in our controller design.

1.1 The Dutch-Roll effect

The principal axes of rotation of an aircraft in flight are the following:
- Normal axis, or yaw axis — an axis drawn from top to bottom, and perpendicular to the other two axes. Parallel to the fuselage station.
- Transverse axis, lateral axis, or pitch axis — an axis running from the pilot's left to right in piloted aircraft, and parallel to the wings of a winged aircraft. Parallel to the buttock line.
- Longitudinal axis, or roll axis — an axis drawn through the body of the vehicle from tail to nose in the normal direction of flight, or the direction the pilot faces. Parallel to the waterline.

While the pitch axis is mostly free from interference with other axes, the normal and the longitudinal are interconnected aerodynamicaly by the so-called Dutch Roll mode of the aircraft. This effect is more accentuated in swept wing aircraft. The coupling between the two axes will give us a loosely coupled, cascaded controller by insering the output of one PID controller as an error signal to the other.

1.2 The effect of configuration of the aircraft

For keeping the aircraft stable in all of their operating envelope – going from low speed, high angle of attack takeoff phase to trannsonic speed low angle of attack cruise and low speed, high angle of attack approach and landing – the aircraft manufacturers are using high-lift devices, such as leading edge slats, trainling edge flaps to equalize the aircraft's aerodynamic performance through the operating envelope. Also, the gear system used on ground gives a huge aerodynamic impact on the manoeuvrability of the aircraft.

1.3. Center of gravity

The center of gravity (CG) of an aircraft is the point over which the aircraft would balance. The position of this point will give the inherent statical and thus dynamic stability of the aircraft related to the lateral (pitch) axis.

The air density is a key factor affecting the stability and performance of an aircraft. An aircraft flying high altitude with high speed and high weight are very close to the so called "coffin corner", where the options of the pilot to modify any parameter of an aircraft will be lost, because of the incipient structural failure because of high speed or loss of control because of low stall margin.

Although it is not the most affecting parameter, but the outside air temperature should be considered as well.

2 The Multi-Channel non-linear PID controller

2.1 The basic discrete time PID controller

The PID linear time equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}e(t)$$

Laplace form:

$$C(s) = K_p + \frac{K_i}{s} + K_d s$$

We discretize this equation with Euler-form, and an added Low-Pass filter for the derivative part for noise supression:

$$C(z) = K_p + \frac{K_i T_s z}{z-1} + \frac{K_d N(z-1)}{(1+NT_s)z-1}$$

The pseudo-code form of the implemented controller is:

```
public void Calculate(double Input, double Time)
{
    // Compute the error value
    Error = Setpoint - Input;
    Result;
    DerivatorFilter = 0.05;

    // Integrator calculation with windup protection
    _Integrator = _Integrator + (Error * Time);

    // Derivator calculation with discrete exponential filter
    _Derivator = (1.0 - DerivatorFilter) * _PreviousDerivator
+ DerivatorFilter * ((Input - _PreviousInput) / Time);
    _PreviousDerivator = _Derivator;
    _PreviousInput = Input;
```

```
    result = Proportional *Error + Integral * _Integrator +
Derivative * _Derivator;
}
```

This implementation is the straight forward form of a digital PID controller.

2.2 Integral windup

A large modification in the setpoint will make the reset (Integrator) part to accumulate a large amount of error and the controller will overshoot the setpoint. There are a few possibilities to mitigate this, the process is called anti-windup method. This addition can be addressed in multiple ways, like:

- Setting the integral part to a pre-defined value in case of large inputs
- Filtering the setpoint – thus avoiding abrupt changes in its value
- Disabling the integral function until the process variable enters in a small error region
- Bounding the integral value between pre-determined thresholds

2.3 Non-linear proportional term

For our controller to be usable in various circumstances and regimes, we made tests and measurements using various configurations, speed and mach regions and altitudes. The measurement was done with an implemented autopilot module, using the afformentioned PID algoritm with reset windup and setpoint filtering, tuned for middle altitudes (15000 feet) and medium speeds (220 knots). From the analysis of the data it turned out that the controller will have its performance peek at this point (where it was tuned using open loop *Ziegler-Nichols* PID tuning).

We found out from the tests that there is a linear correspondence between the airspeed (and configuration) and the magnitude of the P part of the controller. The altitude had the same effect, making the process more sensitive in more dense air. By using the airspeed (indicated airspeed – calculated from the dynamic pressure on the Pitot system) corrected for instrument, position, compressibility error and MACH effect – the so called True Air Speed: TAS – we have found out that there is no need to take the altitude in account.

From this measurement we collected enough data to be able to calculate the proportional term related to TAS. This gave us a logarythmic function of inverse of the true air speed, thus modifying our discrete PID to the following form:

$$C(z) = K_p \log(\frac{1}{V_{tas}}) + \frac{K_i T_s z}{z-1} + \frac{K_d N(z-1)}{(1+NT_s)z-1}$$

2.4 Implementation

By extending the aforementioned basic form with the selectable integral windup form and the slightly modified logarythmic P function, we designed a controller that can whitstand the whole speed, altitude and configuration regime of the simulated aircraft, withut using multiple controllers for specific cases. The tunig of the parameters, including the non-linear logatythmic term was done using the measurement data available from the tests.

2.5 Stability

If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable. Generallyn stabilization of response is required and the process must not oscillate for any combination of process conditions and setpoints.

In Laplace domain, the loop transfer fucntion

$$H(s) = \frac{K(s)G(s)}{1 + K(s)G(s)}$$

Where

$K(s)$ is the PID transfer function and
$G(s)$ is the simulator (plant) transfer function

If the H(s) diverges for some *s*, the the system will be unstable. It can be seen, that if $K(s)G(s) = -1$ the loop transfer function is divergent.

Because of the complexity in calculating the transfer functions, we decided to asses the stability of the system by a series of corner point measurements, then look for the remanent oscillations in the acceleration of the *Euler* angles of the aircraft.

The system behaved well even outside the usable regime of the simulator.

3 Results

By using the presented complex PID algorithm to control the aircraft in all possible circumstances, we succeded to create a very stable, high performance system with relatively easy tuning process. The hands-on tests and the retrieved data helped us to learn the dynamic and static characterystics of a big jet's flight model. The algorythm is used in the Fly-by-wire system of our simulator and in the Qualification and Test Guide software.

Acknowledgements

References

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