Control System for Aircraft Take-off and Landing Based on Modified PID controllers

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Abstract. This article describes some of tasks carried out as a part of an international project ERA (Enhanced RPAS Automation, RPAS – Remotely Piloted Aircraft Systems). The works were focused on a control system for an optionally piloted aircraft MP-02 Czajka, especially on adapting the control system for piloting the aircraft in take-off and landing phases. The entry point was the control system built on using PID controllers in the aircraft. The quality of the control system was insufficient; especially for steering in critical flight states such as take-off and landing. The aim was to improve and fine-tune it to the object, which would allow to shorten time constants of the system, reduce overshoots and errors. It was decided to leave a general structure of a control algorithm based on PID controllers, however, it was extended with additional elements, among others blocks of additional damping, "fit forward" blocks and others. The article describes control laws and their modification as well as effects on steering in longitudinal motion, primarily an angle of pitch of the aircraft, as well as lateral movement, by controlling an angle of roll and a course of the aircraft.

1 Introduction

Nowadays, Unmanned Aerial Systems (UAS) are commonly used and their development is a dynamically growing area of knowledge [1-3]. Typically, such a system consists of an Unmanned Aerial Vehicle (UAV) and a Ground Control Station (GCS). The UAV mission is to follow a predefined 4D trajectory, while the GCS communicates with it and allows to plan and supervise such a mission. UAV behaviour is controlled by an autonomous autopilot device, but usually a GCS operator may also turn the autopilot off and manually pilot the supervised UAV.

An optionally piloted aircraft is a manned airplane, which has been adapted to become an UAV, during the whole flight, or some parts of the mission. Thus, a human pilot on-board may manually control the aircraft, e.g. during critical stages of the mission or in case of emergency. Such a system has been chosen for research described in this paper. The possibility of instant switching between automatic and manual control simplifies development of the control program for the autopilot, as well as makes possible to perform multiple tests of the partially developed system during flight. On the other hand, presence of people on-board imposes strict security rules on the behaviour of the automatic control system, as well as limits feasible linear and angular accelerations and velocities to the values comfort for the crew.

Rapid development of the UAS gives a possibility to conduct complex missions. Nowadays, UAS are gradually becoming the controlled airspace members. Thus, the necessity for development of the advanced autopilot control systems is obvious. The research described in this paper has been performed as a part of an international project ERA (Enhanced RPAS Automation, RPAS – Remotely Piloted Aircraft Systems) [4]. The paper focuses on automatic take-off and landing of the airplane.

Take-off and landing phases are most critical parts of the flight. Each mistake during these stages may lead to immediate crash of the airplane. Thus, numerous UAVs, especially smaller ones, simplify these stages and use take-off catapults and landing parachutes. Of course, such an approach is not possible in our case. Instead, the control system should perform automatic take-off and landing. To achieve this, numerous changes in the control system structure were necessary, as described in the paper.

The paper is organised as follows. Firstly, the general structure of the system, as well as a software structure of flight control computer are presented. In the following sections some of the extensions to the classical PID controllers, like feedforward filter and additional damping block are described. Finally, the structure of the altitude controller and experimental results are presented.

2 Structure of the system

The experimental UAS consists of an optionally piloted aircraft and the GCS installed on a car. The essential part is the modified "MP-02 Czajka" [5], an ultra-light plane shown in Fig. 1.

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Fig. 1. MP-02 Czajka ultra-light plane.

The plane has been adapted to perform unmanned flights [6, 7]. Its ailerons, flaps, elevator, rudder and engine can be controlled by the autopilot using digital servos. The autopilot computer (Fig. 2) gathers data from an Attitude Heading Reference System (AHRS), and GPS, as well as control the servos using Controlled Area Network (CAN) running CAN Aerospace [8, 9] protocol.

Fig. 2. Autopilot computer.

The autopilot computer is based on the ADS512101 board (Freescale MPC5121e processor, VxWorks 6.8 operating system). Its firmware has been developed during described research. The control parts of the software have been prepared in MATLAB/Simulink environment and integrated with the autopilot software [10].

3 Software structure of flight control computer

Each mission carried out by the UAS consists of flight phases which follow each other: take-off, flight from waypoint to waypoint and landing. Take-off and landing are the most difficult stages of flight and require the high precision control of the aircraft trajectory. Moreover, unfortunately light unmanned aircrafts and landing fields are not equipped with the special landing augmentation devices. UAV designers are conducting research on autonomous landing systems, ensuring such operational features that will not require exceptional manual skills and specialised aviation training from the UAV operators. In recent years, the autonomous flight control system for an attitude stabilisation and manoeuvre tracking of the aircraft has been designed at Rzeszow University of Technology. The system is able to perform the defined mission from take-off to landing on the advisable landing field. During these flight phases, the unmanned control system performs many tasks, such as maintaining a desired flight parameter, failure diagnosing or data transition. Software of the onboard control system is modular and composed of cascaded elements responsible for controlling flight parameters according to specific control laws (Fig. 3).

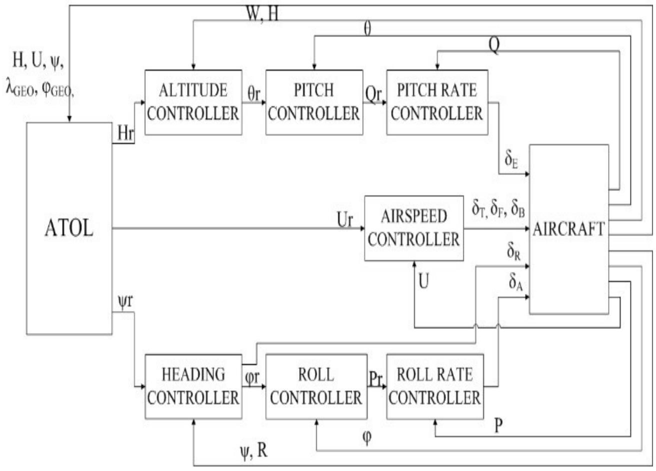

Fig. 3. Software structure of the flight control computer, where H – altitude above the ground; λ_{GEO}, φ_{GEO} – longitude, latitude; W_r, W– required and actual vertical speed, θ_r , θ – required and actual pitch angle, Q_r, Q – required and actual pitch rate, U_r, U – required and actual airspeed, ψ_r, ψ – required and actual heading, φ_r, φ – required and actual roll angle, P_r, P – required and actual roll rate, δ_E, δ_F, δ_B, δ_T, δ_R, δ_A – control signals of elevator, flaps, brakes, thrust, rudder and aileron [14, 15].

Both, take-off and landing phases executed, according to trajectory models generated by ATOL module, require high quality stabilisation of selected flight parameters during all stages. The flight control system consists of such parts as: a pitch rate controller, pitch angle controller, altitude controller, true airspeed controller, roll rate controller, roll angle controller, heading controller, and ATOL (Automatic Take-Off and Landing) module. These modules use the control laws based on the classic cascaded PID and PI controllers with saturations and modifications. The ATOL module is responsible for generating commands for low level control modules, used to control aircraft on the take-off and landing trajectory [12, 14].

This system performed well at the control of attitude angles, control of altitude and heading on the flight in a wide range of cruising speeds. However, when attempting to configure the aircraft for take-off or landing, the operating of the control system was too slow at a relatively low flight speed, especially after deployment of the flaps.

To limit changes in the structure of the autopilot, an attempt to modify the PID controller coefficients was made to ensure correct control efficiency [11, 13].

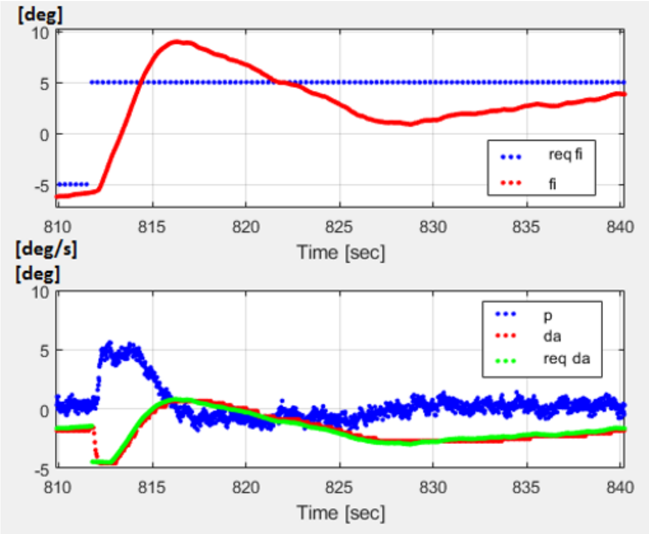

Fig. 4. Roll angle (phi) control.

Figure 4 shows an example of the course of signals in the roll channel. For settled coefficients, controller speed is good enough for take-off or approach phases, however quite too high oscillations appeared (3-4 degrees). It was not possible to tune better this classical PID. To ensure an improvement in the quality of operation, the control system has been extended with additional blocks.

4 Feedforward filter

The first modification was to ensure the speed of reaching the setpoint value by entering the feedforward filter (Fig. 5).

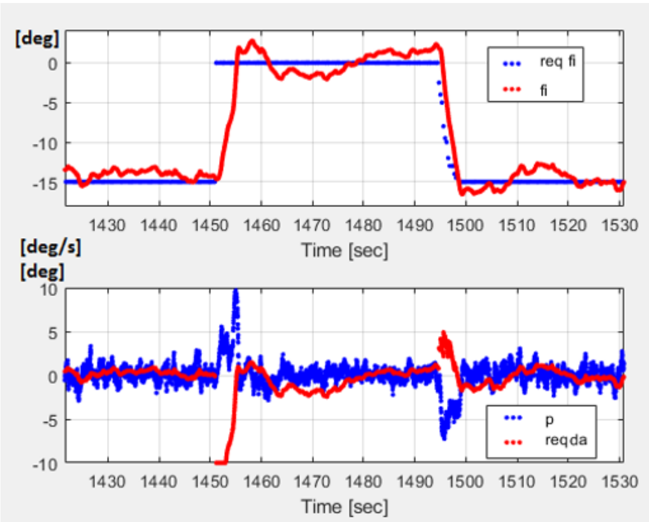

Fig. 5. "Fit forward" filter activity.

This block filters the setpoint in the high-pass filter and if it changes, it rapidly increases the value of the control signal, and over time this value disappears. This filter contains two coefficients, the first one is the gain *Kf*, the second is the time constant *Tf* of the filter. The operation of the filter is similar to that of the pilot. Which means that when the set point of the flight parameter in the initial phase is changed, it performs motion of the tiller to set the plane in a rotating motion, and then withdraws the force after obtaining the appropriate angle or angular velocity (Fig. 6).

The operation of the feedforward filter in the roll channel is visible in figure 5. In the case of a step change in the setpoint value (from -15 deg. to 0 deg. at 1452nd sec), the signal for the servomechanism reaches the limitation. In the second case, with a continuous change of the setpoint of roll angle signal (1495 sec), a multiple jump of the signal value for the servo is visible, which is the effect of the high-pass filter (and differential frequency of the setpoint signal – 4 Hz and autopilot circuit calculations – 50 Hz).

During the conducted tests, it was observed that the "fit forward" block works as expected. With unchanged coefficients of the classic PID controller, it allows faster approach to the parameter (pitch or roll angle) to its setpoint without generating overshoot and oscillations [13].

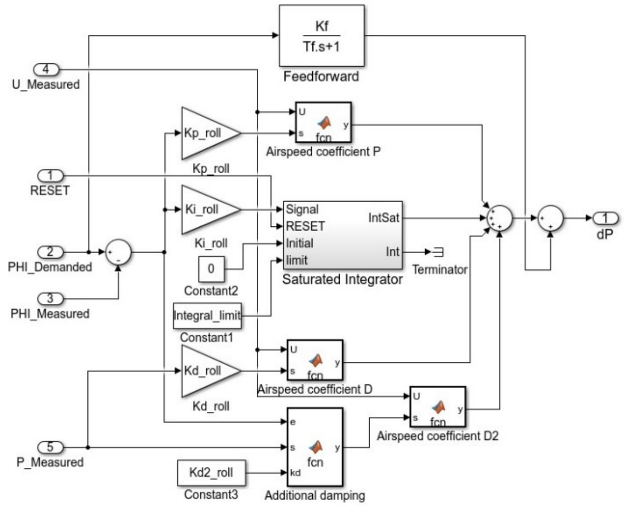

Fig. 6. Simulink block diagram of modified roll angle controller, U_Measured – measured airspeed, PHI_Demanded – required roll angle, PHI_Measured – measured roll angle, P_Measured – measured roll rate, dP – required roll rate sent to roll rate controller, Kp_roll, Ki_roll, Kd_roll, Kd2_roll, Kf, Tf, Integral_limit – control law coefficients.

5 Additional damping block

The second modification extended the classic PID controller with an additional damping element (Fig. 7). The operation of this system depends on the signs of angular velocity and control error. The control signal is modified if the error sign *e* (defined as the set value minus the current value) is opposite to the angular speed sign (angular velocity causes the error to increase) (Listing 1). This modification is equal to the product of angular velocity *s (P_Measured)* and the gain *kd (Kd2_roll)* factor of this block (Additional damping). It is worth recalling that a differentiating element of the PID controller in the aircraft instead of differentiating the error, is most often used for the angular velocity appropriate for the channel. The angular velocity is relatively easy to measure, and its value is close to the differentiated error value. Its advantage is that it has no discontinuities, but it should be remembered that the sign of the angular velocity value is opposite to the sign of the differentiated error, which implies the opposite sign of the coefficient for the differentiator block.

Some parts of roll controller have been modified by adding to proportional, derivative and damping signals additional gains depended of airspeed (Airspeed coefficient

P, Airspeed coefficient D, Airspeed coefficient D2) of the aircraft (Fig. 6). If the airspeed *U (U_Measured)* of aircraft is higher than the approach airspeed value, signals of controller will be increased proportionally to the measurement airspeed. This solution allows to adjust the control signal to different work points by adjusting the effectiveness of the control surfaces [15].

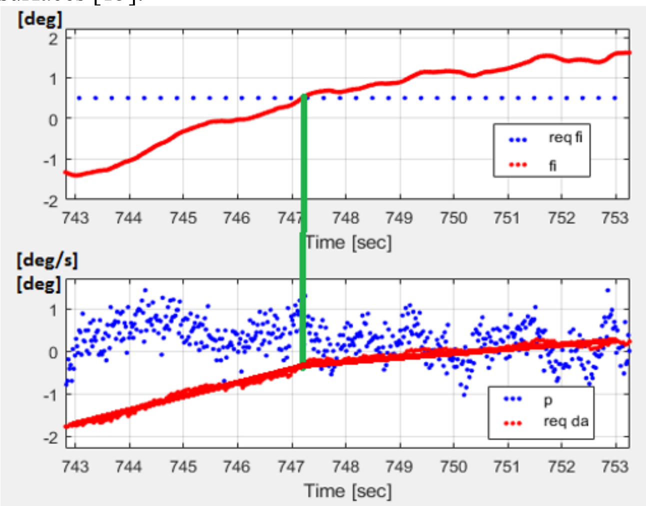

Fig. 7. Additional dumping block activity.

Figure 7 shows the operation of the additional damping block in the roll channel. For consistent error and angular velocity (up to 747.2 sec) the block does not work. If the angle setpoint is less than the current one at the positive angular speed, the slope changing of the signal for servo is visible. In addition to improving the operation of the PID controller, this modification will also increase the elimination of control disturbances caused by the movements of the atmosphere around the aircraft. The corrected action of the modification was confirmed in the conducted flight tests.

Listing 1.

```
function y = fcn(e, s, kd)
%#codegen

sign = single(0);
wsp = single(0);
mnoznik = 1;
etemp = single(e);

if(etemp * s * mnoznik) == 0
    sign = single(0);
elseif(etemp * s * mnoznik) > 0
    sign = single(1);
else
    sign = single(-1);
end

if(sign < 0)
    wsp = single(1);
else
    wsp = single(0);
end

if abs(etemp) < 1
    etemp = single(1);
end

y = kd * s * wsp * abs(etemp);
```

6 Altitude controller

The flight altitude control system is built from cascaded intermediate value controllers. The altitude regulator develops a signal for the vertical speed (w) regulator, and this one for the pitch angle regulator described in previous points. The structure of flight altitude controller is shown in figure 8.

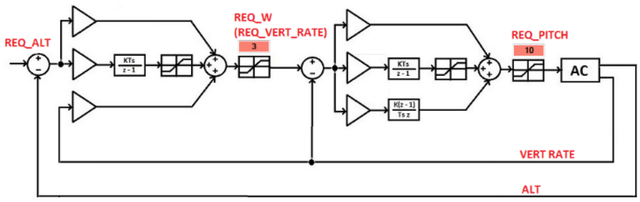

Fig. 8. Structure of cascaded altitude controller.

The classic flight altitude regulator should cooperate with the engine power/rpm regulator (during the upward flight it is necessary to increase engine power, during dropping down – to reduce power). For designed controller, reduction in required vertical speed is possible and allows to change the altitude without changing the engine power (in a limited vertical speed range, in this case from -3 to 3 [m/s]), at the expense of small speed changes.

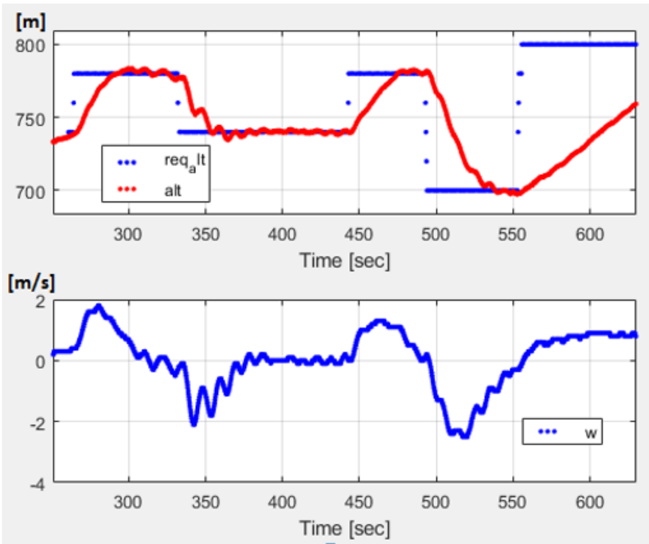

Fig. 9. Altitude regulation.

The operation of the altitude controller is presented in figures 9 and 10. The regulator was working properly maintaining the set altitude with an accuracy of up to +/- 2 [m] (with maximum overshoot under 5 [m]). In the post-flight analysis an erroneous differential coefficient value (opposite sign) was detected in the vertical speed controller. This resulted in vertical rate (w) oscillation effects shown in figure 9. The second inconvenience associated with the erroneous sign of the coefficient was the change in the value of normal acceleration (shown in figure 10, Δaz). For people on the board, it was uncomfortable and very tiring in the long run time.

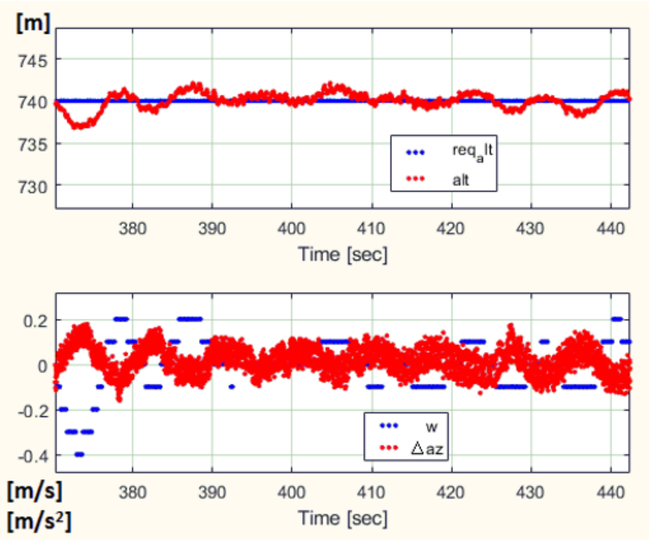

Fig. 10. Maintaining a constant altitude .

7 Summary

Controlling of the optionally piloted aircraft during take-off and landing phases is a demanding task. To achieve it some modifications to the classical PID controllers are necessary. Experimental results confirm control quality improvement.

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