AUTONOMOUS TAKEOFF AND LANDING SYSTEM DESIGNED FOR UNMANNED AERIAL VEHICLES: COMPUTER SIMULATIONS

Abstract

The paper presents results of research taken in Rzeszów University of Technology, theoretical discussion and simulation research of selected take off and landing techniques are presented. The paper presents current status of research under autonomous UAV control system based on embedded computers with real-time operating system, artificial intelligence methods and classical feedback control methods. Described in the paper laboratory equipment is used for performing simulation tests in the stage of designing and testing UAV control algorithms.

Introduction

We can observe a significant development of application of Unmanned Aerial Vehicles (UAV) in last years in many fields of human lives. In general they are used to perform many military tasks such as battlefield observation and recognition for instance. Depending on construction and size they can carry firearms and explosives. UAV’s are becoming equipment for police, army and other services. Depended on the application, the construction requirement for Unmanned Aerial Vehicles are less or more complex. UAV’s becomes common equipment so it is necessary to know in many cases operators are people who don't have enough piloting skill. UAV’s efficient and safety pilotage requires many hours of theoretical and practical course, which may be difficult to achieve by people which are not connected with aviation. Therefore it becomes necessary to use for UAV autonomous and intelligent control systems. Many phases of UAV’s flight have been completely automated so far. Currently researchers focus the most dangerous phases of flight like take-off and landing. When the operator selects the 'start mission' option the flight control system starts executing it from take-off to final approach, flare and touch-down. All mission phases are maintained automatically.

Takeoff trajectory

Automatic control of UAV during takeoff and landing is an important from both practical and theoretical side. Usually UAV’s takeoff and landing tasks are performed in non-airport areas which are not equipped with an aircraft trajectory guiding systems. The autonomous takeoff geometry of the UAV is very similar to the takeoff geometry of the general aviation aircraft controlled manually by an operator. The most common technique of start is a normal start technique, other methods are used in specific situations that require additional restrictions, for example short runway. As far as possible takeoff should be performed against the wind along the straight line trough the middle of the runway. It consists of such steps as the run, ablation, first phase of running and soaring. The conventional takeoff phase limit is
dependent on achieve AGL 15m altitude and safety rate of climb dependent on the type of aircraft and its construction. After preparing to takeoff and passing all validation tests of actuators, control system begins takeoff run phase. The direction of run in the first phase is maintained by controlling the steering angle of the front wheel until the aircraft reaches steering speed on the ground and start to respond on aerodynamic rudders. Then the control of course is performed by the rudder. In the case of side wind appearance, its impact can be compensated by an appropriate aileron deflection into the wind suppressed adequately to the increasing speed. After reaching the right rotation speed ailerons pass in the neutral position, that does not allows to increase roll angle. When the object reaches the right lift-off speed, pitch angle start increasing gradual. The increasing of pitch angle should be customized to the airspeed of the UAV. After reaching lift-off speed (Ul) by the UAV it is necessary to set angle of pitch to guarantee a positive flight path angle and move the aircraft with safety velocity of climb. The UAV continues the flight with a constant course until obtain a value of altitude, on which it can perform maneuver safely and change the course (fig. 1).

![Fig. 1. Takeoff trajectory](image)

where: h - height above the ground, \( \theta_2 \) - desired pitch angle, \( \theta_1, \theta_2, \theta_3 \) - values of desired pitch angle, \( h_b \) – safely height, \( h_o \) - operation height, \( U \) - airspeed, \( U_l \) - lift-off airspeed


**Landing trajectories**

Landing is the most difficult stage of flight and requires the high precision control of the aircraft trajectory. The manual piloting of the UAVs under the approach, flare and touchdown maneuvers requires intensive training and qualifications achieved during specialized courses which are expensive. Moreover, a light unmanned aircrafts and landing fields are not equipped with the special landing augmentation devices such as instrument landing system (ILS), onboard radar, etc. UAV designers are conducting research on autonomous landing systems ensuring such handling properties that will not require exceptional manual skills and specialized aviation training from the UAV operators. In last years, the autonomous flight control system for an attitude stabilization and maneuver tracking of the aircraft was designed at the Rzeszów University of Technology. The system is able to realize the defined mission from take-off to landing on the advisable landing field. This paper presents a proposal of control law synthesis and properties of this system that allow to lead unmanned aircraft up the landing trajectory from approach to stop on runway using two methods described in the refer-
ences. There are two methods of shaping aircraft landing trajectory on the vertical plane: there are classical trajectory (fig. 2) and simplified trajectory of constant flight track angle (fig. 3.). In both cases the aircraft control during landing takes place on the same way, they are different only in flare phase. The phase of approaching take place with constant flight speed, constant flight track ($\gamma_a=2.5^\circ$), thus a constant vertical speed. After reaching the decision altitude ($h_0$) it comes to change of selected flight conditions and it begins the flare maneuver, which is the transition phase before the change on the new steady state. During the landing there is a constant aircraft course correlation in such way that the longitudinal axis of the object was parallel to the conventional runway. The cross wind effect is reduced by the use of fit roll angle of driftS in the approach phase. After touchdown the engine power is minimized and the direction is maintained by the rudders and wheels.

In the case of classical UAV flight trajectory during the automatic control of the flare maneuver it is applied the principle of proportionality vertical speed of aircraft against the ground ($W$) to the conventional altitude ($H$) above the landing trajectory asymptote.

$$W = - k_H \cdot H \cdot \frac{d^2h}{dt^2}; \quad (1)$$

The altitude of starting flare maneuver ($h_0$), proportionality factor ($k_H$) and alignment plane altitude above the asymptote ($H$) we can determine from the assumed conditions of overload, which can interact on the aircraft during the flare maneuver $\frac{h}{dt} < A_{Z_{\text{max}}}$ and aircraft vertical speed limit in the touchdown moment $W < W_r$.

$$k_H = iZ_{\text{max}} \cdot \frac{w_a}{H} \cdot \frac{\Delta Z_{\text{max}}}{\Delta Z_{\text{max}}}; \quad (2)$$

$$H_t = - \frac{\Delta A}{\Delta A_{Z_{\text{max}}}} \cdot A_{Z_{\text{max}}}; \quad (3)$$

The altitude of touchdown plane above trajectory asymptote ($H_t$) according to the equations (1.1), which allows to set required vertical speed ($W_z$) as the function of measured real altitude above the runway ($h$) over the altitude of flare maneuver start.

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The algorithm of automatic landing control based on the principle described by the relation (1.4) requires constant measure of flight altitude above the landing plane. The errors occurred in measurement of real flight altitude and vertical speed will be case of considerable disruption of the control flare trajectory. Consequently, there is proposal for a different landing trajectory for UAV, presented on the fig. 3.

Fig. 3. Landing profile with the constant angle of flight track in touchdown phase, where: h - height above the ground, $h_0$ - decision height, $W_a$ - actual vertical speed, $U_0$ - actual airspeed, $\gamma_a$ - flight path angle during approach phase, $\gamma_f$ - flight path angle during flare phase, $W_t$ - vertical speed during touchdown


Landing approach phase is similar to the classical trajectory described above. Knowing the aerodynamic derivative $C_{Za}=dC_z/da$ it is possible to calculate the require change of the angle of pitch, which should be in flare phase. This change give consideration to the change of angle of attack. This value can be also determined on the basis of measurements carried out during the flight tests.

$$\Delta \alpha = \alpha_{APP} \left[ \left( \frac{V_{APP}}{V} \right)^2 - 1 \right], \quad (6)$$

$$\alpha_{APP} = \frac{2mg}{\rho_0 V_{APP}^2 S C_{Za}}, \quad (7)$$

where: $\alpha_{APP}$ - angle of attack for the approaches speed measured from zero position of aerodynamic lift calculated on the basis of $C_{Za}=dC_z/da$, $m$ - aircraft mass, $g$ - gravity force, $\rho_0$ - air density under normal conditions, $S$ - bearing surface, $V_{APP}$ - instrumental speed before starting maneuver of change of flight track angle, $V$ - true air speed.

In the section of the landing path after flare maneuver the pitch angle should be maintained by the dependence:

$$\delta_\gamma = \alpha_{APP} + (\gamma_a - \gamma_f) + A\alpha; \quad (8)$$

where: $\alpha_{APP}$ - average pitch angle in the last phase of approaching witch gamma track angle of flight path.

The trajectory of landing consists of maintaining the constant angle of flight path before touchdown does not require high measurement precision of real altitude, its more important task is to change the angle of UAV at the specific altitude above the runway.
Flight control system design

Each mission carried out by UAV consists of flight phases which follow each other: takeoff, flight from waypoint to waypoint and landing. During these flight phases unmanned control system performs many tasks like maintaining a desired flight parameters or data transition. The onboard control system is modular and composed of elements responsible for receiving and processing of data according to specific control laws (fig. 4).

![Fig. 4. Block diagram of the onboard control system](Source: own elaboration)

The module called „Flight Parameters" is responsible for handling main CAN bus and receiving data from onboard measurement devices (AHRS, GPS, ADC). It periodically updates the data, such as angle values of the aircraft position (º, 9, y), corresponding angular speed (Q, P, R), geographical location and course (ºGEO, 9GEO, yMAG), speed in relation to ground (GS), vertical speed (W) and the actual altitude above the ground (H). Another set of information coming from the outside to the onboard control system is a mission plan sent from the ground station module named "Ground Station". This package contains the geographical position and height above the ground of waypoints programmed by the operator. In addition it includes the information about current autopilot mode, desired altitude and airspeed. The onboard control system sends information about a current status of mission and flight parameters to the ground station.

The system produces a six types of output control signals: elevator deflection (SE), ailerons deflection (SA), rudder deflection (SR), flaps position (SF), engine power (ST) and
brakes efficiency (S8). This values are sent to the actuator drivers. To the most important elements of the control system are modules which carry out the tasks of stabilization of specific flight parameters: roll angle – "Roll Stabilization", pitch angle - "Pitch Stabilization", course - "Heading Stabilization", vertical speed - "Vertical Speed Stabilization", air speed - "Horizontal Speed Stabilization", altitude - "Altitude Stabilization". These modules use a control laws based on the cascaded PID and PI controllers with saturation functions and modifications. The modules performing attitude stabilization take an actual values of angles and angular velocities from "Flight Parameters" module and desired values of these flight parameters from higher order modules and then produce a control signal for the actuators (fig. 5, fig. 6).

![Fig. 5. Block diagram of pitch control law](source)

where: Theta Req - desired pitch angle, Theta - actual pitch angle, Q Req - desired pitch angular velocity, Q - actual pitch angular velocity

*Source: own elaboration.*

![Fig. 6. Block diagram of roll control law](source)

where: Fi Req - desired roll angle, Fi - actual roll angle, P Req - desired roll angular velocity, P - actual roll angular velocity

*Source: own elaboration.*

"Heading Stabilization" module use the control laws based on two PID controllers with different coefficients. One of them maintains required value of course and generates control signal in the form of desired roll angle. Second PID controller reduces sideslip angle by generating control signal that is transmitted to the rudder actuator. When the altitude of UAV is low the first controller is disabled, and second controller stabilizing course of flight. The "Vertical Speed Stabilization" and "Altitude Stabilization" modules employs the typical PI controller. Desired values of vertical speed changes and atmospheric disturbances are relatively small and fast. The input signal of PI controller is a step function. So that principle of control ensure high quality of vertical speed and altitude stabilization (fig. 7).
Control system unit represented by the block called „Navigation" includes a set of navigation features. They are used to calculate the desired heading and desired altitude based on the information contained in mission plan, current geographical position, heading and altitude values. Main component of the control system is a module called "Mission Controller", which performs mission plan. Thanks to communication with ground station, it can make modifications of mission plan during its execution, but also abort the mission and relay on the manual control to operator. The controller generates desired value of flight parameters and activating signals \((H_{ACT}, W_{ACT}, 0_{ACT}, 9_{ACT}, y_{ACT})\) according to a specific algorithm, and then places them on the inputs of stabilization modules. Each stabilization module has a logical input on which it gets an activation signal. This signal can take one of two values TRUE or FALSE. If on the input of stabilization module will arrive TRUE value, the module will be activated. In the other case, stabilization module is not activated and its control signal is exchanged on the corresponding value set by the controller module. The controller performs many a logical tasks and decides about the conduct of the flight.

**Simulations testbed**

Designing and testing the individual control system elements required application of special implemented research station (fig. 8). Very helpful tools were engineering packages Matlab/Simulink with xPC library and PC-flight simulator X-Plane developed by Laminar Research.

![Fig. 7. Block diagram of vertical speed control law, where: \(W_r\) - desired vertical speed, \(W\) - actual vertical speed, \(\text{Thetar}\) - desired pitch angle](image)

*Source: own elaboration.*

![Fig. 8. The block diagram presented research station design](image)

*Source: own elaboration.*
Individual modules and algorithms of UAV control system were modeled in Matlab/Simulink in the form of S-function using ANSI-C programming language. Thanks to the tools which are available in the xPC Target, control system is running as real-time operation system. Each system module is an individual real-time process performed in specific time intervals. The information transfer between processes is performed by using the global data structures. The structures which stored values of flight parameters are updated with a constant rate by the xPC Target library functions. They are responsible for communication with external PC - class computers, on which work the X-Plane simulator and the all ground station software. UAV flight control system works on the onboard PC104 - class computer equipped with CAN communication interface and the radio modem. Transfer between onboard computer and flight simulator is possible by using CAN Aerospace Protocol. However the communication between onboard computer and ground station is possible by using radio modems plugged to the RS232 ports. Originally, control system project was realized in Matlab/Simulink using Real-Time Windows Target library. Unfortunately, tools available in the library did not pass all the project requirements. For the most significant disadvantages of this approach are: no pre-function responsible for communication with CAN protocol, instability of operating some components available in the library, failure to provide the real-time system assumptions, delays in communication with the flight simulator. In the future studies the structure of the research station will be changed according to the new thesis. For the study, it was constructed a dynamic model of an aircraft for the X-Plane simulator, which in terms of aerodynamics and construction is similar to the light aircraft type "Czajka" MP-02 using as UAV (fig. 9).

![Fig. 9. The MP-02 “Czajka” model presented in X-Plane simulator](source: own elaboration)

The engineered research station allows designing, simulating and testing the onboard control systems, their individual algorithms and diagnostic procedures. After designing and implementing the selected system function, it is possible to check automatically propriety of operating by observing virtual model presented in simulator. One of elements of the research station is an embedded systems running under the control of real-time operating systems such RTAI Linux and VxWorks. These components can be installed on board of a real UAV and allow to carry a flight tests.

**Simulation test results**

The simulations were performed using a special test stand consisting of the flight simulator X-Plane and onboard computer with xPC control system. For the purpose of analysis, synthesis, and initial computer simulations, linear models of aircraft, engine and actuators have been used.
The research station will be used to conduct research on the development and increasing functionality of autonomous UAV control system. In the near future it is planned research for testing the selected methods and techniques of artificial intelligence algorithms cooperating with classical control algorithms. There are also started work on the control module based on neural-fuzzy expert systems, which is part of the onboard computer. In this paper, some aspects of actual condition of research into Intelligent Autonomous Control System for Unmanned Aerial Vehicles has been presented. Significant area of the research is the professional station for carrying simulation tests and designing control laws. These research are concentrated on such parts of flight as take-off and landing because these phases are the most difficult and require to apply reliable control system with high value of quality coefficient.

Final remarks
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AUTONOMICZNE SYSTEMY STARTU I ŁĄDOWANIA DLA STATKÓW BEZZAŁOGOWYCH: SYMULACJE KOMPUTEROWE

Streszczenie

W pracy przedstawiono wyniki badań przeprowadzonych w Politechnice Rzeszowskiej. Zaprezentowano ponadto teoretyczną dyskusję i badanie symulacji wybranych technik startów i lądowań. W pracy zaprezentowano bieżący status badań nad autonomicznym systemem kontroli statku bezzałogowego, który opiera się na wbudowanych komputerach z zainstalowanymi systemami czasu rzeczywistego, sztucznej inteligencji i klasycznymi metodami kontroli sprzężenia zwrotnego. Sprzęt laboratoryjny opisany w pracy był stosowany w testach symulacyjnych na etapie projektowania i testowania algorytmów kontroli statków bezzałogowych.