Research Article
Open Access
CrossMark

Automatic take-off control system

Abstract

The purpose of the work is to present a solution that will significantly contribute to the technological development of the European defense sector. The proposed solution raises the issue of controlling autonomous vehicles. This paper presents the concept of an algorithm that allows for automatic take-off of unmanned aircraft. Arguments are presented which justify the need for developing and applying such a system. The socioeconomic and environmental aspects of the project are also discussed. The automatic take-off algorithm complements existing aircraft flight control systems. The considered solution takes into account take-off as a maneuver made of three phases. The control on a runway is possible due to data fusion from the INS and GNSS systems. Data fusion may be supported by using the runway image processing system. The concept of an automatic take-off algorithm is presented along with the most appropriate testing methods, including software-in-the-loop and hardware-in-the-loop simulations.

Keywords: automatic take-off control system, unmanned aerial vehicles, defense technology, data fusion, image processing

Volume 7 Issue 2 - 2023

Mariusz Dojka, Kamila Jakubik, Tomasz Rogalski, Łukasz Wałek
Rzeszow University of Technology, Poland

Correspondence: Tomasz Rogalski, Avionics and Control System Department, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Poland, Email orak@prz.edu.pl

Received: May 05, 2023 | **Published:** June 15, 2023

Abbreviations: CF, complementary filtering; EGNOS, European geostationary navigation overlay service; GNSS, global navigation satellite system; INS, inertial navigation system; KF, kalman filtering; HIL, hardware in the loop (simulation); RIPS, runway image processing system, SBAS, satellite-based augmentation system; SIL, software in the loop (simulation); UAV, unmanned aerial vehicle.

Introduction

The modern world is a world of innovative technologies. Their influence on contemporary civilization is without a doubt. Nowadays, dynamic changes affect defense strategies and military tactics, organization, and equipment. These changes lead to increased requirements for advanced combat systems. Such systems should be able to use existing potential efficiently, give opportunities for further development, and provide a solution to upcoming challenges.

Aviation became a fundamental part of military power after World War I. Air forces are not only used for combat, but also provide transport, evacuation, and rescue services, or carry out covert missions against terrorism. These tasks are performed for both the army as well as for civil purposes. The development of unmanned aerial vehicles (UAVs) could potentially revolutionize the way that air forces will be used in the future. Although the performance of previous operations with the use of autonomous aircraft showed great promise, its full capabilities are largely unknown. However, it is clear these technologies will enable air forces to use their power more efficiently, and that means lower operational costs and lower risk for the human pilot. For these reasons, we are convinced of the relevance of autonomous aircrafts in Europe's defense and security.

The development of UAVs raises the possibility of conducting military operations in a more efficient and less risky fashion compared to human–controlled flights. Today's aircraft are highly automated machines. Diverse stabilization and control systems take over more and more tasks, previously performed purely by pilots. These systems are being implemented especially in control areas, in which the human perception and correct decision-making are found to be insufficient. Avionic solutions are already taking over many pilot duties, such as managing a stable flight on the desired path or performing a smooth touchdown. However, even UAVs require the active presence of the flight operator, who schedules the approach and performs take-off and taxiing. The indispensable factor in achieving complete flight automation is to complement control systems in these flight areas, which are still fully human–dependent. The most important of them is the take-off phase.

Overview of the system and its principles

The algorithms that provide automatic take-off maneuvers will be developed within this project. They will complement other flight control systems. In the development of the algorithms, the following design principles were adopted:

The automatic take-off system begins its operation when the aircraft is pre-configured for flight and positioned on the active runway.

The aircraft brakes are released.

The system does not provide control of the flaps.

The system provides an aircraft control unit up to 50 feet after lift-off.

The aircraft is equipped with a measuring system that provides information about the wheels of the forces exerted on the landing gear.

The aircraft is equipped with INS (Inertial Navigation System) and GNSS (Global Navigation Satellite Systems)/EGNOS (European Geostationary Navigation Overlay Service).

The aircraft is equipped with an on-board camera that records the view of the runway (as an optional feature).

An aircraft will be controlled by two autopilot channels: longitudinal and lateral, with appropriate control surfaces: ailerons, elevator, rudder, and engine thrust. Additionally, the contact force of the system counts the landing gear. The algorithms will be implemented in a real avionic system and tested in the loop using general aviation aircraft. The developed control rules will imitate human pilot behavior. Figure 1 shows a general diagram of the control system.

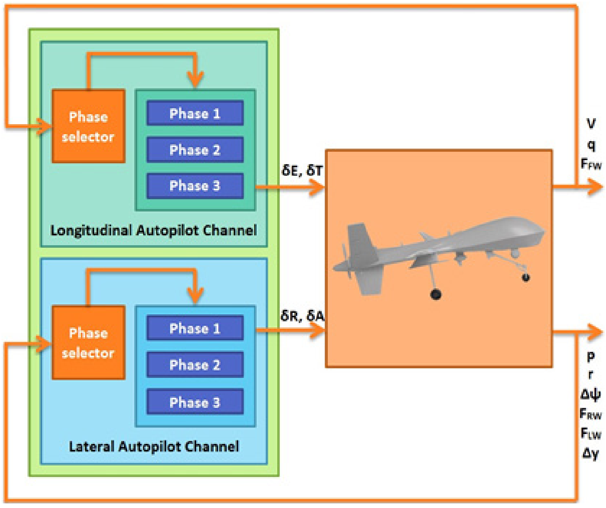

Figure 1 A general diagram of the control system [own study].

The internal routing signals are divided into two sections:

i. **Inputs:** heading ψ, flight track, indicated airspeed V, angular speeds in aircraft's 3-axes p, q, r, deviation from runway centerline Δy, pitch angle ϑ, contact forces (front–wheel pressure force FFW, right–wheel pressure force FRW, and left–wheel pressure force FLW) and wind forces

ii. **Outputs:** throttle setting δT, aileron displacement δA, elevator displacement δE, rudder displacement δR, and front–wheel turn δFW.

The take-off operation is marked by a large variability of flight parameters, as well as a large variability of the control surfaces efficiency η as shown in equation (1):

$$\begin{cases} t = 0 \rightarrow v = 0, \eta = 0 \\ t > 0 \rightarrow v > 0, \eta \gg 0 \end{cases} \quad (1)$$

At the stop (indicated air speed $v = 0$), the efficiency of the control surfaces is equal to zero. During the start roll, the change of aircraft speed causes a fluent change of the effectiveness of the control surfaces. While the speed increases, the efficiency increases to the value when a stable lift-off is possible. For that reason, the take-off of an aircraft can be divided into several phases. Due to efficiency changes, in each phase, separate control rules have to be applied.

Take-off control phases

The considered solution takes into account take-off as a maneuver made of three phases: start roll, take-off roll, and lift-off roll & transition (Figure 2).

Figure 2 Take-off control phases [own study].

Start roll

The start roll is the first phase of the take-off. In this phase, the front wheel is responsible for maintaining control of the aircraft on the runway. The take-off algorithm does not allow for the possibility of wheels skidding. The maintenance of front wheel traction is carried out with the elevator, which provides a consistent front wheel pressure force. The pressure is measured using a metering system installed in the aircraft.

While speed increases, the efficiency of the rudder rises. The rudder's task is to maintain the aircraft in the runway centerline at acceleration. During the start roll, a constant value of thrust (t) is held. Control in the first phase is also maintained with the use of ailerons, which compensate for the gusts of wind by holding an equal value of pressure forces on the left and right wheels of the main landing gear.

The first phase of take-off is described by the following control rules (2)(3)(4)(5):

I. elevator control

$$\delta_E(t) = K_E(F_{FWC} - F_{FWM}) \quad (2)$$

where: KE – signal gain,

$FFWC$ – constant front–wheel pressure force (value estimated from engineering knowledge)

$FFWM$ – measured front–wheel pressure force (from pressure sensor)

II. aileron control

$$\delta_A(t) = K_A(F) \quad (3)$$

$$F = F_{RW} - F_{LW} = 0 \quad (4)$$

where: KA – signal gain

FRW – right wheel pressure force

FLW – left wheel pressure force

III. rudder control

$$\delta_R(t) = [-K_R \cdot \Delta x]_{-\delta_{min}}^{+\delta_{max}} \quad (5)$$

where: KR – signal gain

Δy – lateral deviation from the runway centerline

$\pm\delta max$ – limits imposed on the rudder incline

Take-off roll

A clear transition from the first phase ending to the second phase beginning is nearly impossible. The transition between these phases is commonly called a fuzzy transition. The first and second phases are described by the same control rules (as above). The ailerons are still compensating for wind influence, while the rudder holds the aircraft on the runway centerline.

In the first phase, the pressure force on the front wheel is consistent, whereas, in the second phase, the front wheel is steadily relieved of weight by the control system. This progresses until the aircraft reaches the rotation speed VR and the front wheel is raised off the runway surface. Detection of zero pressure force on the front wheel means that the aircraft then goes forward into the third take-off phase.

Lift-off and transition

In the third and last phase of the take-off, elevator efficacy is high enough to enable changes in the pitch angle. The proper value of the pitch angle is adjusted and maintained by the flight control system. Pitch angle θ rises in time and the controller adjusts its value in a keep-up manner. In this way, any aircraft movement oscillations do not occur and the control error is minimized over time. Pressure forces

DOI: 10.15406/aaoaj.2023.07.00175

on the main landing gear are monitored and held equally, as in the equation (4):

In this phase, keeping to the runway centerline is performed by rudder displacement. The control system makes use of the PID controller, which control rule equation (6) is as follows:

$$\delta_R(t) = K_R \Delta y + K_D \frac{d}{dt}\Delta y + K_I \int_{min}^{max} \Delta y dt \quad (6)$$

where: KR – proportional gain

KD – derivative gain

KI – integral gain

Δy – lateral deviation from runway centerline

The system provides aircraft flight control up to 50 ft after lifting the entire landing gear.[1–3]

Holding on runway centerline

The aircraft control in the lateral autopilot channel is responsible for holding the aircraft on the runway centerline. This is a difficult task due to disturbances such as gusts of wind or an uneven runway surface. The control system to eliminate the lateral deviation Δy in the shortest possible time without excessive overshoot. Controlling this based on the measurement of the magnetic heading alone is insufficient. The blowing wind may carry the plane parallel to the centerline, as shown in Figure 3.

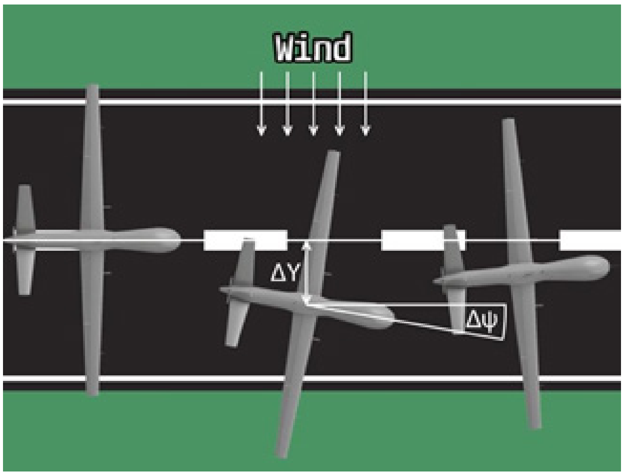

Figure 3 The influence of wind on the lateral deviation [own study].

The signal that can be best used to compensate for lateral deviation is the geostationary signal. Among all the current navigation systems, EGNOS is distinguished by the best parameters in this respect.

The European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional satellite-based augmentation system (SBAS). Its main goal is to enhance the accuracy of global navigation satellite systems (GNSSs) like GPS and Galileo. The system was designed to fulfill the demand for a reliable navigation service dedicated to air and land traffic users throughout Europe. Positioning in EGNOS is performed with the use of measurement signals being sent over by strictly located reference stations on the ground. To minimize any positioning errors, the system transfers data to a computing center where differential corrections are applied. The calculations performed are broadcast by geostationary satellites over a certain area. This creates an overlay on the top of the original GNSS measurement.[4]

Thanks to the functioning of EGNOS, the basic navigation parameters of the GPS and GLONASS systems are as follows:

i. accuracy, i.e., the ability to determine the position of the measured object within the allowable system error with a probability of 95%,
ii. reliability, determining the level of confidence in the measurement provided by the system,
iii. continuity, i.e., the ability to work uninterrupted throughout its flight over the user's horizon,
iv. availability, defined as the likelihood of navigational services being provided at any time.[5]

Typical GNSS systems operate at a 10 Hz frequency, which means that with aircraft speed equal to $v \approx 100$ kph and during time $\Delta t \approx 0{,}1s$, the lateral deviation will be equal to $\Delta y \approx \pm 2{,}5$ m. The dispersion of measurements may be too large to control the aircraft without excessive oscillations and overshoot. For this reason, the inertial navigation system (INS) will also be used. The INS determines the orientation and position of an object in relation to a known initial state and position with the use of measurements obtained from a set of accelerometers and gyroscopes. The system enables to track the position in real time. INS usually provides high accuracy within a short period of time. The position is obtained by double integration of the acceleration values. It means that any measurement error will be integrated as well, causing a rising bias of the velocity and a continuous drift of the estimated position. However, inertial navigation allows for continuous positioning even in cases when the requested satellite is not available.[6,7] Determinately, the system's operation combines complementary data from EGNOS and INS for accurate aircraft positioning. This integrated system will be able to provide superior performance compared to each of the systems working separately. The main strengths and weaknesses of INS, EGNOS, and INS+EGNOS are summarized in Table 1.

Table 1 The main strengths and weaknesses of INS and EGNOS[2]

INS	EGNOS
High position accuracy over the short term	High position accuracy over the long term
Accurate altitude information	Noisy altitude information
High measurement output rate	Low measurement output rate
Autonomous	Non-Autonomous
No signal outage	Possibility of signal loss
Affected by gravity	Not sensitive to gravity
Accuracy decreasing with time	Accuracy independent of time
INS + EGNOS	
High position accuracy	
Precise attitude determination	
High data rate	
Navigational output in case of GPS signal outages	
Cycle slip detection and correction	
Gravity vector determination	

In order to increase the accuracy of the aircraft positioning, there are several methods used to combine data from different sensors. In the literature, Kalman filtering (KF) is the method widely used in data fusion. However, in this project, the use of a complementary filter (CF) algorithm is proposed. CF is an effective and versatile procedure to combine noisy sensor outputs. The advantages of complementary filtering are: simplicity of the algorithm, easy to perform, good quality

DOI: 10.15406/aaoaj.2023.07.00175

computations in real-time, and no need for initial conditions. The CF used in an integrated navigation system can achieve precision close to Kalman filtering.[6]

Complementary filtering delivers a single output created by combining two or more signal sources that represent the same measured parameter. The signals vary in owned noise properties. Regarding this project, the EGNOS signal contains high–frequency noise and the INS signal contains low–frequency noise. The data fusion of these signals is based on the use of low- and high-pass filters with accurately defined dynamics as expressed in equation (7).

$$H = H_{LP} + H_{HP} = \frac{1}{Ts+1} + \frac{Ts}{Ts+1} = 1 \quad (7)$$

where T means the time constant of the inertial element determining the dynamics of the filter.[8,9]

Figure 4 shows a diagram of complementary filtering for data sourced from EGNOS and INS. Using this approach, advantages such as low computation load, good stability, and steady state accuracy are achieved, making this integrated navigation system suitable for unmanned aircraft control systems.[6,10] The runway image processing system (RIPS) is an additional element of the system to determine the lateral deviation, complementing the signals from GNSS and INS. It operates based on the picture recorded by the onboard camera. The use of RIPS is an option that allows an even more accurate determination of the lateral deviation Δy. The camera signal can be added to the navigation systems. The RIPS system calculates the coordinates of runway sidelines. This operation is accomplished by applying a linear Hough transform. The lines coinciding with the edges of the runway in the image are convergent, and their intersection point is on the runway centerline. The distance between the designated intersection point and the vertical line, passing through the center of the image, determines the level of deviation of the longitudinal axis of the aircraft from the runway centerline. The number of pixels between the point and the centerline specifies this level of deviation and is calculated in relation to half of the horizontal resolution of the image, which is expressed as a percentage value. Figure 5 shows the image from the onboard camera, processed by the system.

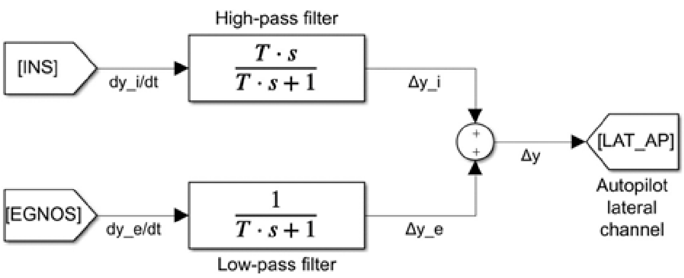

Figure 4 Diagram of complementary filtering [own study].

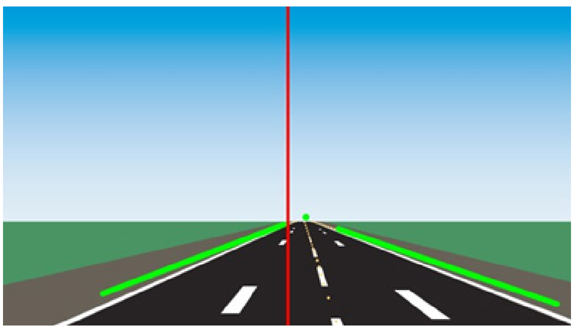

Figure 5 Runway image with marked lines [own study].

The lines that coincide with the edges of the runway and the intersection point of these lines are drawn in green. The vertical red line passes through the center of the onboard camera frame and coincides with the longitudinal axis of the aircraft. The determined value of the lateral deviation from the runway centerline is positive when the aircraft is on the left side of the runway, while values below zero mean the position of the plane is to the right.[11]

Testing the system

The first stage of testing is mainly based on checking the developed algorithms. These tests can be described as software-in-the-loop (SIL). The test stand consists of a computer with installed MATLAB & Simulink software, in which the behavior of the aircraft has been modeled. Through Ethernet communication, the control rules within the model are transmitted to the computer with the X-Plane flight simulator, where their accuracy is being analyzed. The second stage of the test includes hardware-in-the-loop (HIL) simulations. In HIL, designed control laws become implemented into the hardware system devoid of the power converter and feedback sensors, which are simulated. HIL simulations require hardware responding to the outputs from these control laws and simulated sensors. This research approach has been used in the automotive and aerospace industry for years due to its high efficacy in the development of complex systems. HIL can support testing of physical devices and provides plenty of advantages, such as:

i. Research cost reduction: HIL makes up a proper substitute for expensive tests on complex machinery, simulating work of particular subsystems.

ii. Failure–related risk reduction: A malfunction of the tested control system can lead to a catastrophic failure of the entire machinery, to destruction of equipment and also presents serious safety hazards. HIL can help to validate designed controllers before they meet the physical equipment.

iii. Testing fault models: HIL allows more robust fault testing, in which any fault can be induced within the software and further synchronized with widely changing conditions.[12]

At this stage, the MATLAB functions enable the automatic generation of a source code for the real autopilot using the developed system. Then, the tests can be carried out in the X-Plane flight simulator.

Figure 6 shows the signal that is carried through the HIL simulation. The autopilot and the aircraft model communicate over Ethernet. The enforced signals generated by the autopilot control the model. In the feedback loop, the information about the attitude returns to the autopilot and adjusts the module accordingly. After receiving satisfactory results, the programmed module can finally be tested on a real plane.[12]

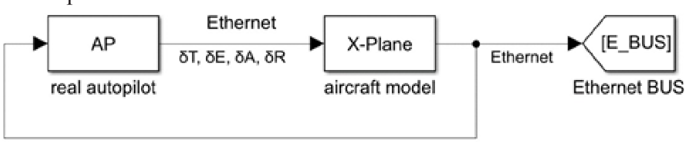

Figure 6 Hardware in–the–loop (HIL) [own study].

Conclusions and perspectives

The methods and tactics of air force operations depend mainly on factors such as social and political conditions, operational and tactical situations, spatial and temporal conditions, or environmental conditions. These are fundamental factors that influence the principles,

DOI: 10.15406/aaoaj.2023.07.00175

possibilities, and methods of using aviation and shape its further technical development. For this reason, it is so important to adapt the newly emerging solutions to the contemporary world conditions. In the case of fully automated UAV technology, research provides a strategic future vision for autonomous UAV usage by highlighting its many advantages. The presented take-off control algorithm completes existing autopilot systems and creates a coherent control environment. An automatic take-off process will allow pilots to focus on other tasks while managing the flight. It is particularly relevant in adverse weather conditions or during military operations, in which the pilot has to run multiple onboard combat systems. For applications in unmanned aerial vehicles, automation reduces the duration of maneuver and adjusts it to the structural capabilities. This system solves the problem of 'one operator, one machine', which does not allow controlling multiple units at the same time.

Groups of UAVs could be used in airspace defense systems, supporting surface-to-air missile systems, which are unable to identify targets before interception. Autonomous aircraft might be applied in reconnaissance missions replacing fighter jets and helicopters and also significantly reducing the time-span of operations. Launching a group of autonomous aircrafts facilitates extending the operational area. The use of fully autonomous units brings about a number of additional benefits, including economic and ecological aspects. Financial benefits come from the possibility of carrying out unmanned missions, implying a lower demand for pilots and the ability to control many machines by one ground operator. The green aspects are related to the smaller dimensions of the aircraft (the lack of a pilot cabin), which leads to a reduction in the use of construction materials in production. Smaller and more aerodynamic designs result in lower fuel consumption during missions.[13]

Acknowledgments

None.

Conflicts of interest

The author has no conflicts of interest to declare.

References

1. Allerton D. Principles of Flight Simulation. 1st ed. Wiley; 2009.
2. McLean D. Automatic Flight Control Systems. Prentice Hall; 1990.
3. Nelson RC. Flight Stability and Automatic Control. 1st Ed. McGraw-Hill College; 1989.
4. What is EGNOS? 2020.
5. Krzykowska Piotrowska K, Dudek E, Siergiejczyk M, et al. Is Secure Communication in the R2I (Robot-to-Infrastructure) Model Possible? Identification of Threats. *Energies*. 2021;14(15):4702.
6. Baudoin Y, Habib MK. Using Robots in Hazardous Environments: Landmine Detection, De-Mining and Other Applications. 1st ed. Woodhead Publishing; 2010;269–275.
7. Berrabah SA, Sahli H, Baudoin Y. Visual-based simultaneous localization and mapping and global positioning system correction for geo-localization of a mobile robot. *Measurement Science and Technology*. 2011;22(12).
8. Dobre C, Xhafa F. Pervasive Computing: Next Generation Platforms for Intelligent Data Collection (Intelligent Data-Centric Systems: Sensor Collected Intelligence). 1st ed. Academic Press; 2016.
9. Zhao Y, Yan G, Qin Y, et al. Information Fusion Based on Complementary Filter for SINS/CNS/GPS Integrated Navigation System of Aerospace Plane. *Sensors*. 2020;20(24):7193.
10. Chen WK. The Electrical Engineering Handbook. 1st ed. Academic Press; 2004.
11. Nowak D. Controlling unmanned aerial vehicles. Doctoral thesis, Rzeszów Technical University; Rzeszów; 2020.
12. Ellis G. Control System Design Guide: Using Your Computer to Understand and Diagnose Feedback Controllers. 4th ed. Butterworth-Heinemann; 2012.
13. Christ RD, Wernli RL. The ROV Manual: A User Guide for Remotely Operated Vehicles. 2nd ed. Butterworth-Heinemann; 2013.