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AIRCRAFT FLIGHT CONTROL SYSTEM FOR AEROBATIC FLIGHT

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Abstract

The paper reviews and in some way concludes author's previous works touching problems of automatic flight control during aerobatic maneuvers. The nature of the maneuvers and the range of changes in flight parameters during their execution limit the possibility of using classic autopilot systems, as well as the possibility of obtaining accurate information about the exact both 3-D position and spatial orientation of the aircraft. The article presents an alternative approach to the design of automatic aircraft control systems that can be applied in the discussed cases, to guide the aircraft along an assumed flight trajectory. Selected aerobatic maneuvers are discussed from the perspective of the flight mechanics and pilot in correlation with the structure of control algorithms and the method of verifying their operation in simulation tests. The exact process of control systems synthesis, together with dedicated aircraft flight parameters and spatial attitude measurement, algorithms are discussed in works [12 25 26 27].

Keywords: autopilot, aerobatic flight, real time flight simulation

1. General Introduction)

Nowadays, the use of automatic flight control for civil and military aircraft is a standard solution. It has been applied for many years in aircraft to stabilize flight parameters such as spatial orientation, heading, altitude, speed, flight trajectory, and others. There is currently an increasingly popular concept of using automatic control systems in certain more unusual flight maneuvers including aerobatic flight [8, 17 18 36]. This solution could also be used in Unmanned Aerial Vehicles (UAV). The idea of execution of aerobatic maneuvers [9, 20, 36, 37] has already been presented in other works [12, 21, 27]. This article illustrates and in some way summarizes a specific approach to the problem of automatic execution of the desired unusual maneuvers (e.g. aerobatics maneuvers). Spin and Immelmann maneuvers have been selected as a samples to present the efficiency of the applied algorithms and the precision of flight control.

For the sake of clarity - the paper does not seek to provide any direct or exact, universal solution, in terms of any formal formula for how to control the aircraft to maintain the desired maneuver precisely. It presents an approach to the process of preparing control algorithms imitating the pilot's actions in some manner and being able to accomplish the aerobatic maneuver featured keeping proper pattern of maneuver.

The paper refers to the results of authors' previous research, which enables an automatic flight control system to perform selected elements of an aerobatic flight [16, 22, 23, 25, 26, 27, 28] and present algorithms in details.

2. Automatic Flight Control

Automatic flight control is being made by a wide set of autopilot systems. Basically, their role is not to replace human operators, they rather both assist and support pilots in controlling the aircraft. One of the functions an autopilot systems offer is controlling the flight pattern of the aircraft without necessity of any permanent corrections conducted by a human operator. This allows pilots to focus on the broader aspects of operations such as monitoring aircraft attitude, trajectory and weather and aircraft systems as well.

Basic heading and altitude autopilots protecting the pilot against too much effort during long hours of flying have been used from the very beginnings of the aviation and were a remarkable milestone in reducing the pilot's workload. Autopilots have evolved since that time (Figure 1) and nowadays, apart from horizontal and vertical guidance, autopilots are capable of performing flight from the take-off through the cruise phase to the final stop after landing at airports. It means that they are also capable of performing simple maneuvers such as climbing, descending and turning [4, 5].

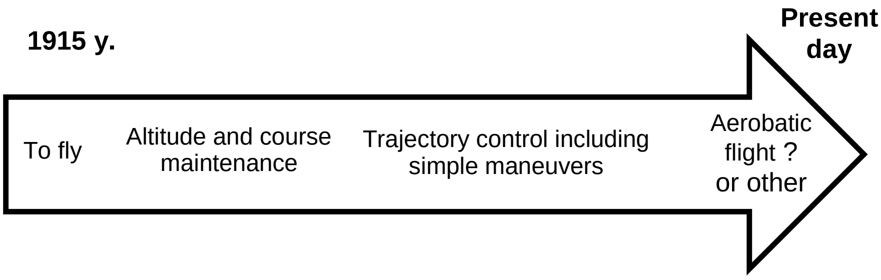


Figure 1 – The evolution of autopilots.

These solutions are currently being transferred to a relatively new branch of aviation - unmanned aircraft. Flight control systems can remain supported by a pilot/remote operator; however, in the case of fully autonomous aircraft, the entire flight from the initial take-off phase to the final stop after landing has to be executed automatically. Thus, in these cases, also complex maneuvers, if required, have to be successfully accomplished by an automatics. For instance, some military missions require the flight to travel along complex trajectories so, an execution of some elements of aerobatic flight is a solution to fulfil that requirement (e.g. maneuverable flying target imitators).

3. The control plant and the control goal

The control plant analyzed later in this paper is a plane in the conventional configuration. Its spatial orientation control is executed only by means of deflection of its control surfaces (elevator, ailerons and rudder) which generate aerodynamics forces and moments, respectively, along and around the axis of the aircraft body coordinate system $X_BY_BZ_B$. It is located in the aircraft's center of gravity with axes directed, respectively, forwards – the X_B axis, to the right wing – the Y_B axis, and downwards – the Z_B axis (Figure 2). Thrust is dependent on the particular maneuver being carried out.

In order to determine aircraft spatial orientation relative to the Earth's surface the Euler angles describing mutual orientation of an aircraft body coordinate system and the $OX_EY_EZ_E$ system are used. Its origin is located in the aircraft's center of gravity, but its axes X_E and Y_E are parallel to the Earth's surface.

There are also extra used pure integral in time of raw angular rates around $X_BY_BZ_B$ - P, Q, R to define aircraft rotation around the body coordinate system in some maneuverer's phases.

Once assumptions referring to the aircraft's geometric and mass symmetry in relation to the X_BZ_B plane, together with the theory of small disturbances, are applied [7, 18, 19, 34] it is possible to mutually separate aircraft dynamics into so-called 'longitudinal' and 'lateral' modes of motion. Despite the fact that this simplification could produce massive inaccuracies in the aircraft motion description, it may be reasonable and is profitable for synthesis of the first approximation of control algorithms - with full awareness of errors it introduces and all weaknesses of such simplifications, of course.

The work does't focus on aircraft dynamic models. That is why, research uses models implemented into flight simulator (X-Plane environment) treated as "black box" type models. Their dynamic characteristics and numerical parameters requested to tune the control algorithms were identified and found in dedicated experiments [22, 23, 25, 27]. Such approach is similar to works with real aircraft whose dynamics parameters get achieved in dedicated real flight campaigns.

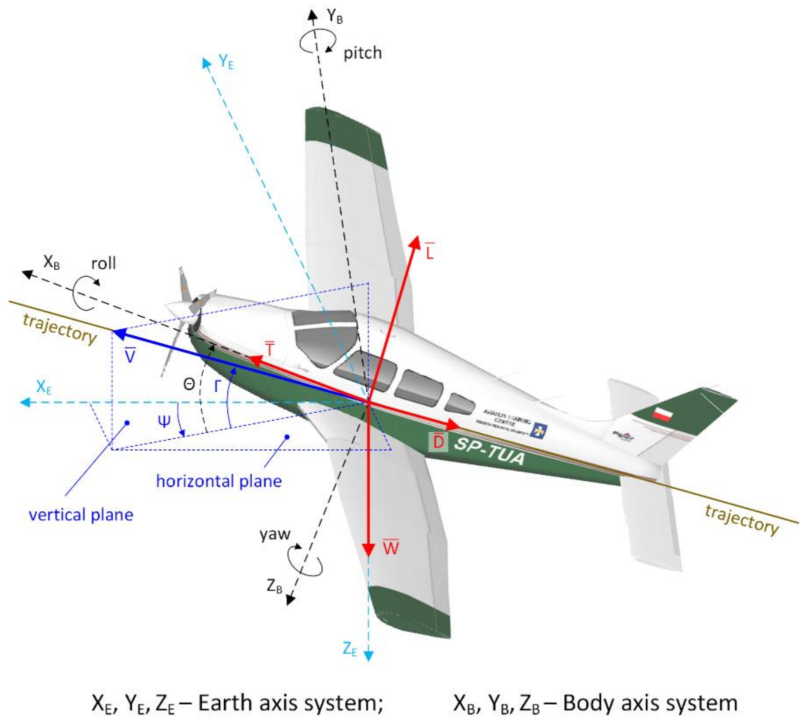


Figure 2 - Aircraft in classical configuration, Body and Earth coordinate axis systems and angles of spatial orientation.

Finally, the control algorithms implemented into an "aerobatic autopilot" are a composition of the linear aircraft flight control theory [18, 19, 34] with nonlinear components and control techniques [1, 33] as well as components based on expert's knowledge (Figure 3). As experts are recognized pilots who are trained and experienced with aerobatic flight of aircraft (e.g. according to Part –FCL Flight Crew Licensing aviation regulations) or UAV operators at minimum instructor level, skilled with aerobatic flight.

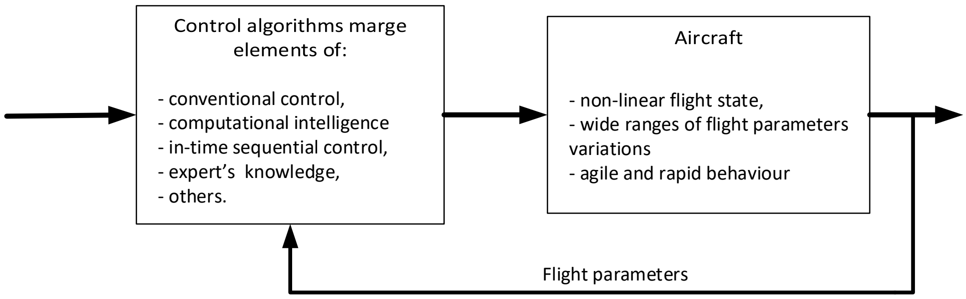


Figure 3 - The general concept of the control system capable of aerobatic flight.

4. Automatic aerobatic flight

Flight control systems remain the subject of many research and scientific activity focusing on highly specialized and untypical functionalities such as protecting the aircraft against hazardous or dangerous flight states, recovery maneuvers [15, 38] as well as intentional execution of non-conventional maneuvers – including flying along a so called "non trivial" trajectory, which is composed not only of straight legs but is defined in 3-D space. The last two of these functionalities just include components of an aerobatic flight. They require unconventional solutions pushing for an efficiency of control (recognized as a capability of the system to accomplish the desired aerobatic maneuver successfully), rather than very high precision of aircraft position control along the trajectory. Greater attention is be paid to the effectiveness as opposed to a very high precision of the maneuver. This idea is reflected in the structure of the control algorithms, which lead the system more towards the imitation of pilot control input and control strategy, unlike most analytical approaches. The paper presents a more recent approach to aircraft automatic control algorithms capable of maintaining flight trajectory and spatial attitude throughout different aerobatic maneuvers, characterized by different levels of sophistication of the control from flight with highly controlled flight trajectories (loop) to flights the trajectory is not directly controlled and results from aircraft characteristics (spin) (**Błąd! Nie można odnaleźć źródła odwołania.**), at a level of accuracy recognized by the expert as good enough [35, 41].

Control laws implemented into the flight control system strongly use expert knowledge. They are capable of aerobatic maneuvers characterized by different level of trajectory control, based on the following assumptions [22, 23, 25, 26]:

- The aerobatic maneuver in general is composed of three phases. The first is an initial preparatory stage characterized by maintaining recent steady flight conditions. The second is the essential aerobatic maneuver. The third is returning stabilization of new steady flight.
- Pilots do not always have full, precise information about aircraft flight parameters. Instead, they perform approximate assessment only.
- Patterns of pilot controls, indirectly impacting the flight trajectory, depend to a large extent on pilot experience and skills learned by training for the correct reactions.
- These rules, when taken into consideration allowed the design of an aerobatic autopilot model.

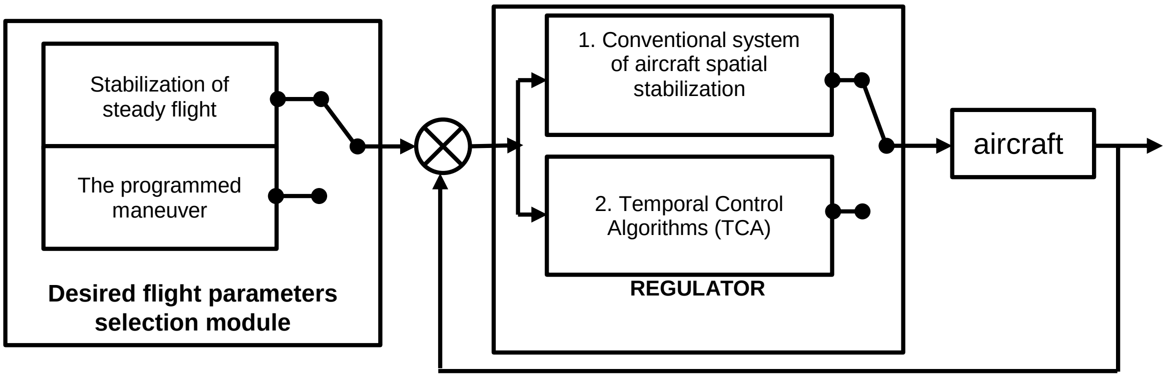


Figure 4 - The control algorithm scheme implemented for the aerobatic autopilot [20].

In general, the developed autopilot is based on performing a programmed maneuver at any time during the flight. This principle of operation is shown in Figure 4**Błąd! Nie można odnaleźć źródła odwołania.**, by switching a regulator from spatial stabilization to Temporal Control Algorithms (TCA). As presented, the control system can be programmed to perform one or more maneuvers. The aerobatic flight trajectory control can be executed in either closed or open loop, depending not only on the figure being made, but also on the phase of this figure.

The paper presents capability of the approach to the aircraft control developed by authors with the usage three selected maneuvers: spin, Immelmann turn and loop. They represents both different levels of trajectory and spatial attitude complexity and control actions.

4.1 The Spin Maneuver

The spin is a flight state originated by a lateral disturbance to the stalled aircraft. In the spin flight, at least one wing is stalled. The wing on the inside of the turn is stalled while the outside wing still produces lift and flies, causing that the aircraft autorotates towards the stalled wing. Both wings fly at very different and very high angles of attack and the aircraft rotates around all axis of the body coordinate system (Figure 2), with total rotation magnitude Ω calculated from (1), simultaneously rapidly losing altitude along the trajectory oriented to the plane of the horizon at path angle γ (Figure 5).

$$\Omega = \sqrt{(P^2 + Q^2 + R^2)} \tag{1}$$

Where: P, Q, R denote angular rates around respectively $X_B Y_B Z_B$ axes of the body coordinate system

(Figure 5).

In principle, the entire spin maneuver is composed of main phases as follows: pre-spin phase, leading in fact to static stall, spin and post-spin flight recovery (Figure 5). However, in both pre-spin and spin phases flight trajectory is not the main goal of the applied control. In fact it results mainly from aircraft characteristics and not from a control pattern. The post-spin phase trajectory is an indirect effect of applied control recovering the aircraft from the spin and is controllable to a limited extent.

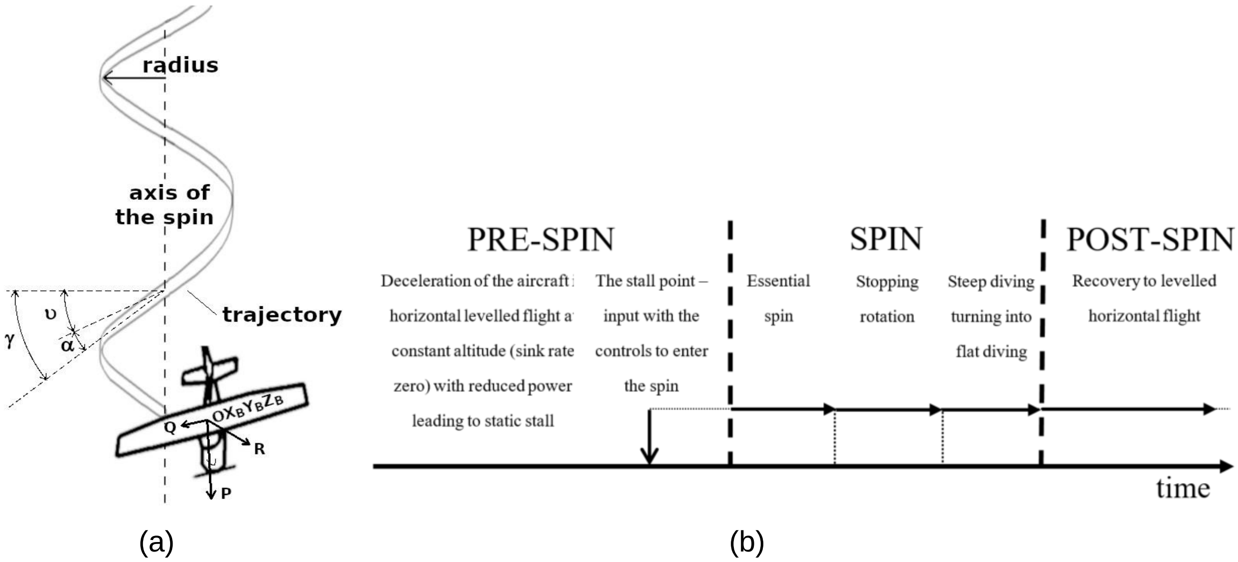
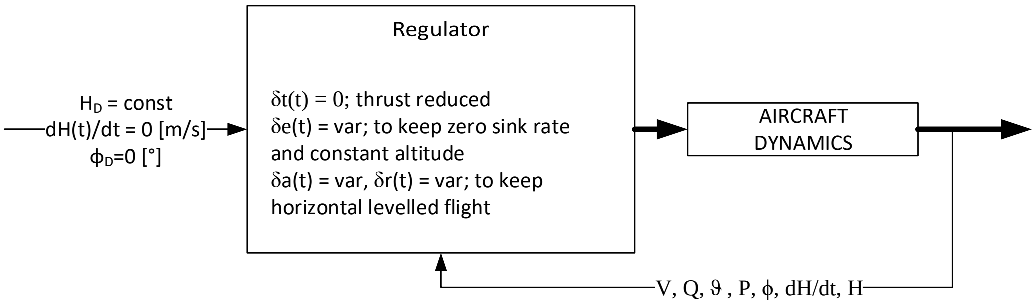
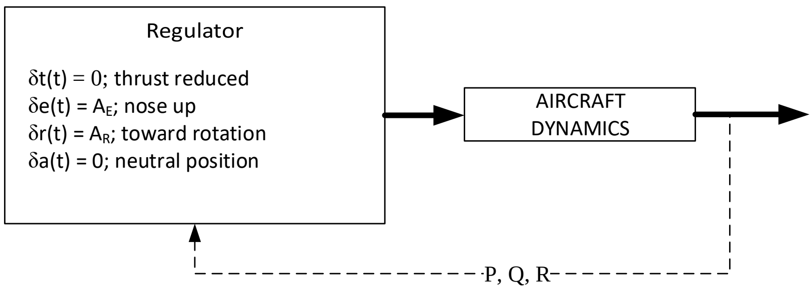


Figure 5 – The spin pattern (a) and time history of the basics spin phases (b).

Thus, the entire spin can be divided into the following sequences from the control point of view (Table 1).

Table 1. The control sequences for spin. The control signals are: δe, δa, δr, δt – elevator, ailerons, rudder and thrust respectively. Outputs are flight parameters: P, Q, R - angular rates, H – altitude, ϑ - pitch angle, ϕ –roll angle, V - speed.

<table>
<tr><td>1.</td><td>The aircraft decelerates at constant altitude H_D until stall speed is reached. During this phase the system reduces thrust to minimum, maintaining zero sink rate and wings levelled.
</td></tr>
<tr><td>2.</td><td>The system (by TCA) starts the essential spin by full elevator - A_E and rudder – A_R deflections. It doesn’t use feedback data to produce the control signals. The trajectory is not controlled at all, it results only from aircraft characteristics.
</td></tr>
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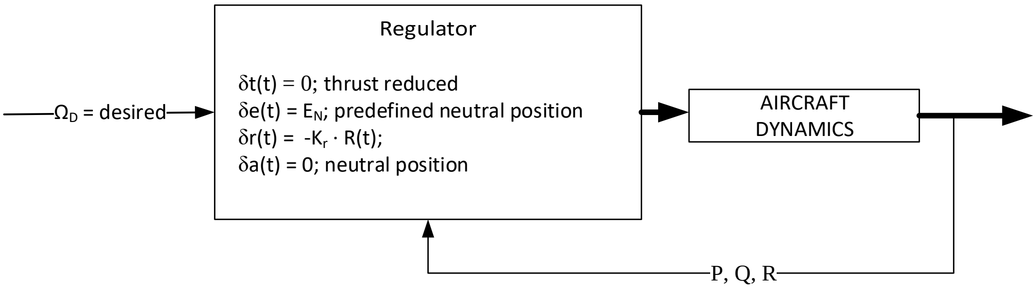
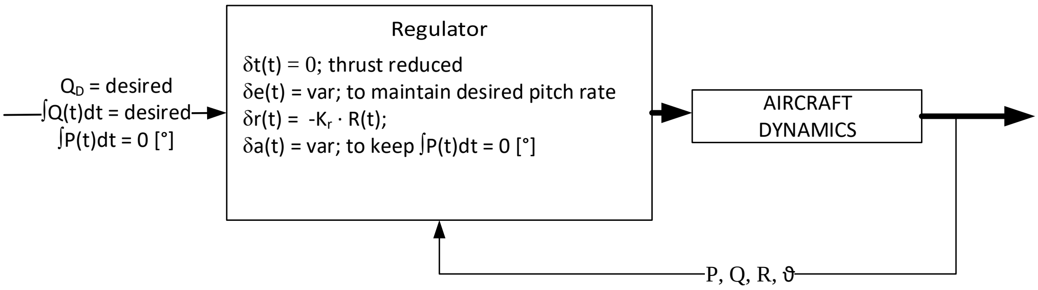
3.	The system (by TCA) arrests total rotation Ω until its magnitude is smaller than predefined, desired Ω_D value [20]. During this phase, the elevator is set to a predefined neutral position E_N. The trajectory remains uncontrolled and is not a subject of any action of the control system. It remains the output from aircraft characteristics. 
4.	Recovery from diving (steep at the beginning and flat afterward) to levelled horizontal flight. The system (by TCA) stabilizes predefined, desired, constant pitch rate. An integral of roll rate P is used, by aileron channel, instead of bank angle to protect the aircraft against rolling around OX_B axis. The trajectory should be a piece of the arc at the vertical plane of the aircraft motion. In the ideal case, it is a quarter of the circle, and is an outcome of the aircraft dynamics and desired pitch rate. The control goes back to the conventional algorithms if predefined, desired magnitude of integral of Q rate reached. 

The stalled aircraft is put into a spin by full elevator and rudder deflections in a typical case (Table 1, sequence 2). It is important that during the initial and essential spin, the regulator does not use input data about aircraft spatial orientation, even if fed with it (Table 1, sequence 3). Thus, it can be stated that during this phase, the control takes place in an open loop and without direct trajectory control. The pattern of the fight trajectory results mainly from the aircraft's characteristics.
In the end of the next step (sequence 4, Table 1), the control is turned back from TCA to conventional spatial stabilization.

4.2 The Immelmann and Loop Maneuvers

This section focuses on both loop and Immelmann maneuvers. Features of them implies the loop maneuver can be used as a tool for the Immelmann execution (Figure 6). That feature has been applied in control strategy realized by the developed system.

The Immelmann turn (also known as a roll-off-the-top, or simply an Immelmann) is an aerobatic maneuver that results in levelled flight in the opposite direction at higher altitude. Basic principles of its implementation are expressed in three steps:

1. Levelled flight.
2. Half loop (pitch angle 180 degrees upwards).
3. Half roll (roll angle 180 degrees to recover aircraft to horizontal flight).

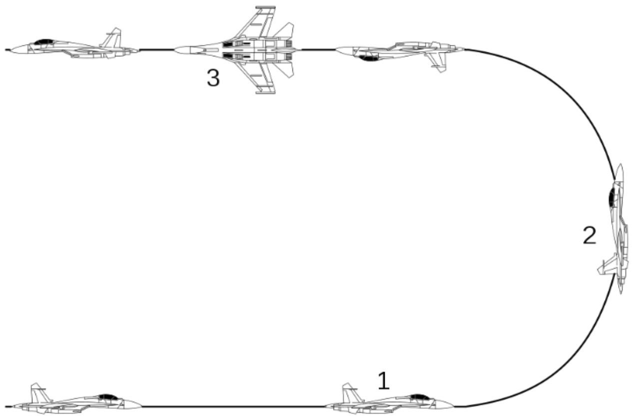
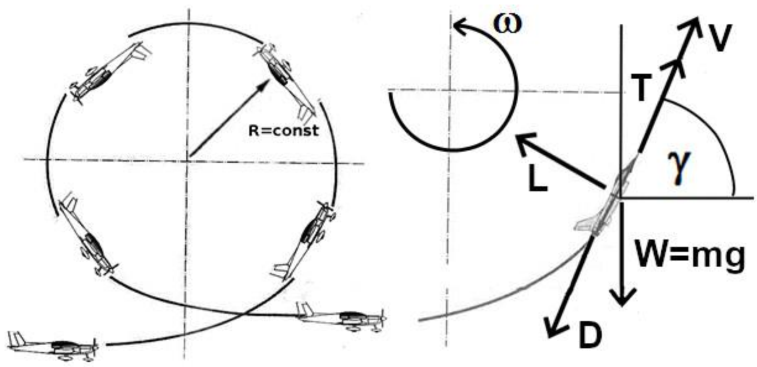


Figure 6 - The Immelmann turn pattern [22].

To execute it, the pilot accelerates the aircraft to an airspeed potentially sufficient to perform the loop maneuver. At this point, he pulls the stick, starting the loop. Ailerons must be used to keep the half-loop regular in the vertical plane. When the aircraft passes over the point at which the loop was commenced, it should be in an upside-down configuration and a half loop will have been accomplished. At the top of the loop, the pilot executes a half-roll to regain normal upright aircraft orientation. Finally, the aircraft is at a higher altitude on a the heading opposite to the initial direction of travel.

The half loop is the first important pattern during the Immelmann turn. It is like the first phase of the classical loop maneuver but terminates when the aircraft is in an upside-down configuration. This maneuver is one of the so-called symmetric maneuvers, i.e. those in which the aircraft movement takes place within the plane of mass and geometric symmetry. Additionally, the plane of motion is orientated vertically, and the motion trajectory is supposed to be circular. The simplified non-linear dynamic equations of aircraft motion assume that both the balance of longitudinal moments is kept and the thrust force vector T, orientation and sense are also compatible with the speed vector V (Figure 7) [20].



(a) (b)

Figure 7 - Aircraft trajectory (a), and the main forces affecting aircraft motion (b).

$$\frac{W}{g}\frac{dV}{dt} = T - D - \mathrm{W}\sin\gamma; \quad V\frac{W}{g}\frac{d\gamma}{dt} = L - W\cos\gamma \tag{3}$$

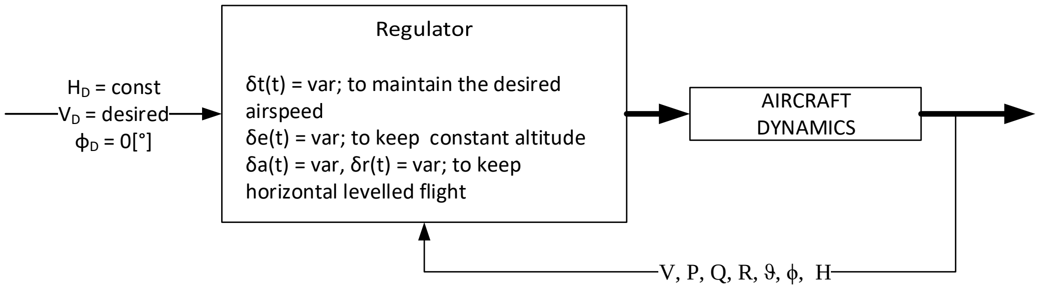
$$\omega(t) \approx \frac{d\gamma(t)}{dt} \approx \frac{d\vartheta(t)}{dt} \approx Q(t) \tag{4}$$

where: W – weight, g – gravity, V – speed, L – lift, D – drag, T – thrust, γ – flight path angle, Q – pitch rate, ϑ – pitch angle recognized as a rotation around the OY axis, ω – angular rate of the aircraft around the loop centre.

The second phase is a fast half-roll (ideally 180 degrees). The assumption is that the rotation of the aircraft is fast enough so that lateral and vertical deviations of its X-axis during the roll are negligible from the point of view of the entire pattern of maneuver. Due to the dominant position of the roll, the mode of motion of pure roll approximation could be applied for preparing control algorithms [22].

The whole Immelmann turn can be divided into phases, which made possible the control sequences to be elaborated (Table 2).

Table 2. The control sequences for Immelmann Turn. The control signals are: δe, δa, δr, δt – elevator, ailerons, rudder and thrust respectively. Outputs are flight parameters: P, Q, R - angular rates, H – altitude, ϑ - pitch angle, ϕ –roll angle, V- speed.

<table>
<tr><td>1.</td><td>The aircraft maintains the desired speed in leveled, horizontal flight – any classical control laws could be used.

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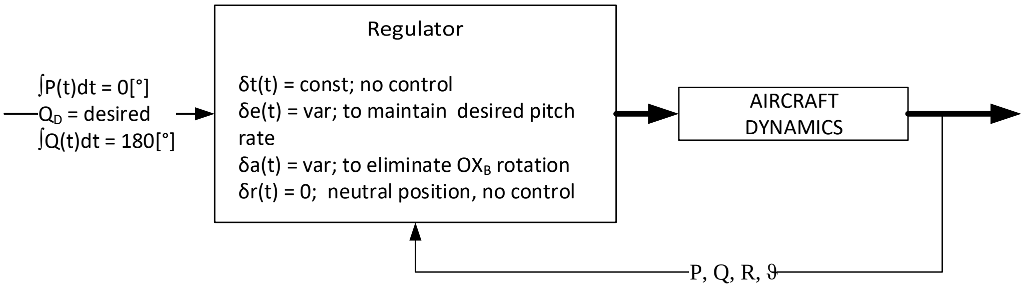
<tr><td>2.</td><td>Half loop performed (by TCA) at desired value of Q_D pitch rate until 180 degrees of integral of Q is reached. Also, there is no rotation around aircraft OX_B axis by ailerons control – integral of P used as a feedback in this channel.

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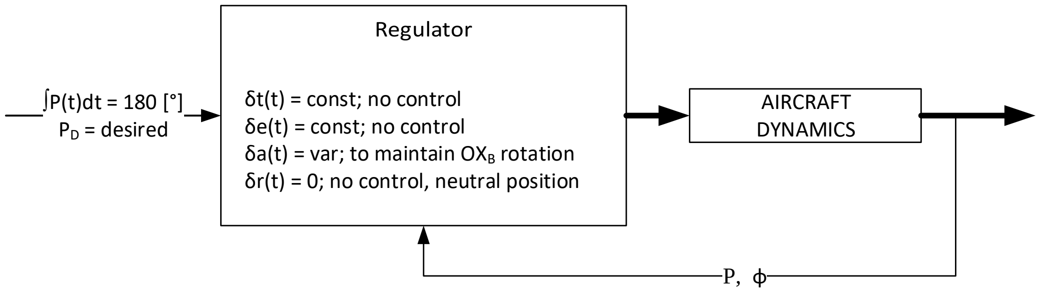
<tr><td>3.</td><td>Half roll performed (by TCA) at desired value of P_D roll rate until theoretically straight horizontal flight is reached - integral of P is equal 180 degrees.

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Straight horizontal flight means that the last sequence of TCA has set a zero constant value of bank angle to hold after reaching it during rolling, with approximately constant roll angular rate. With the wing levelled and constant altitude, the aircraft is intercepted by a conventional autopilot maintaining further spatial stabilization.

Thus, Immelmann is an example of a maneuver wherein all of the control sequences including TCA are based on closed loop control laws. Moreover, it can be stated that the Immelmann turn is a maneuver whose trajectory is one of the direct objectives of automatic control.

5. Simulation Tests and Results

Simulation of the operation of currently designed control systems was conducted by connecting the Matlab-Simulink environment with the X-Plane flight simulator [40] via the UDP protocol [11, 17]. A model of the control system designed and built in the Simulink environment sends control signals to the flight simulator. As feedback, it receives aircraft flight data required to ensure proper functioning

(Figure 9) [31, 32].

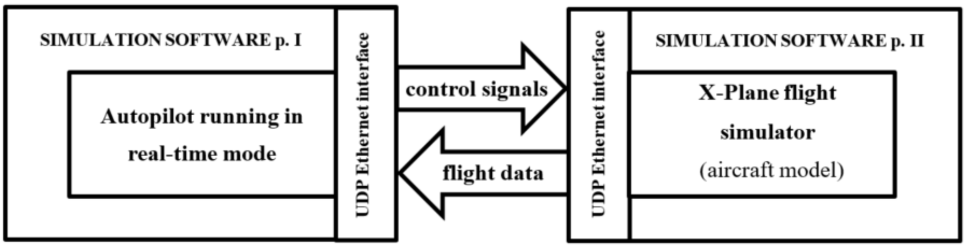
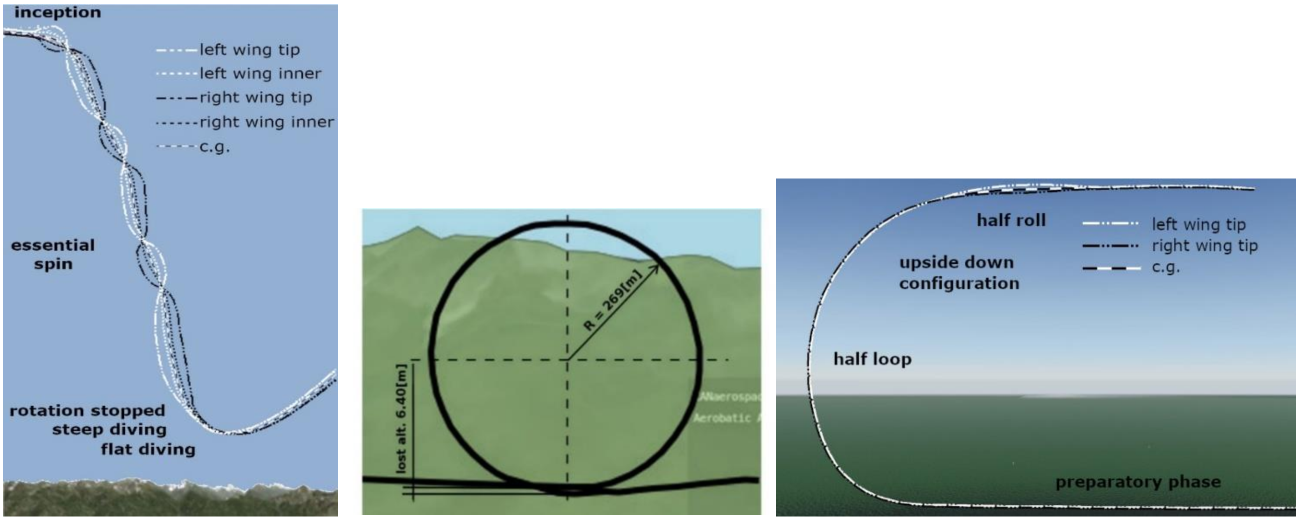


Figure 8 - Configurations of tests rig for SIL simulations.

This design of test rig allows conducting two group of experiments. The first are experiments conducted to identify aircraft models dynamics and parameters The second are tests of developed structures of autopilots and performing simulated flights[20, 21]. The simulation results utilized later in next sections have been achieved for some sample aircraft: Cesna-172 (spin), XtremeAir Sbach 300 (loop), SU-35S (Immelmann) whose dynamics models are implemented into the X-Plane flight simulator (Figure 9).



(a) (b) (c)

Figure 9 – Sample trajectories of discussed maneuvers achieved during simulations: (a) spin, (b) loop, (c) Immelmann analyzed later in this section.

5.1 Simulation of Spin maneuver

Predefined algorithms were validated in the simulated research flights. The SIL simulations enabled simulating an overall spin maneuver (Figure 9) from inception to final recovery when control is returned from TCA to a classical aircraft control algorithm (Figure 4). Figure 10b provides a time history of control signals and angular rates (in the body axis system) during the inception phase, shortly before and just after the “stall point” is detected. The aircraft starts rotating, stimulated by elevator and rudder deflections. Figure 10c presents time histories of control signals and angular rates at the recovery phase of the spin when rotation is stopped, and the aircraft goes from steep to flat diving. At all times, the aircraft is guided by a control algorithm based on considerations and assumptions given earlier in this paper and presented in detail in [21]. The spin is the maneuver controlled by TCA, while the trajectory is not directly controlled, however TCA built on the basics of assumptions enumerated earlier in this paper and elaborated in details in [20, 21] works effectively.

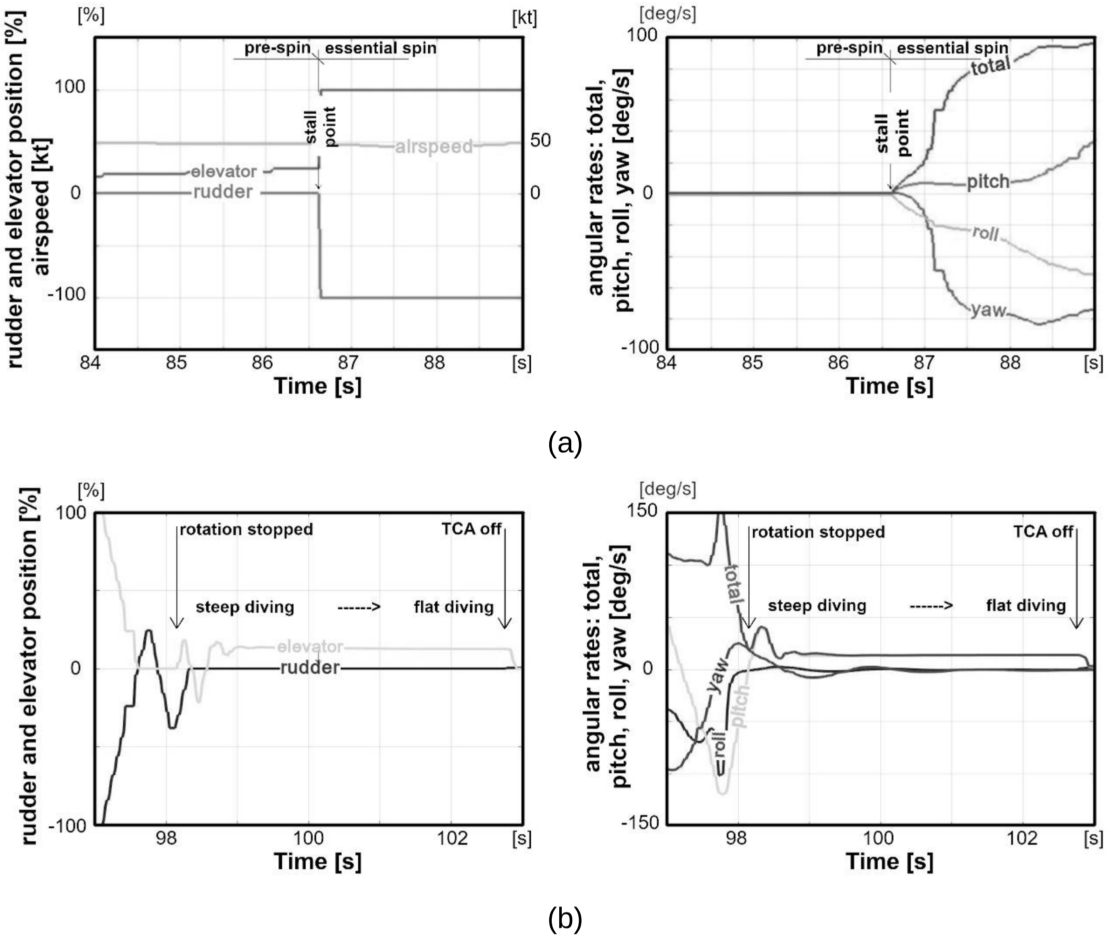


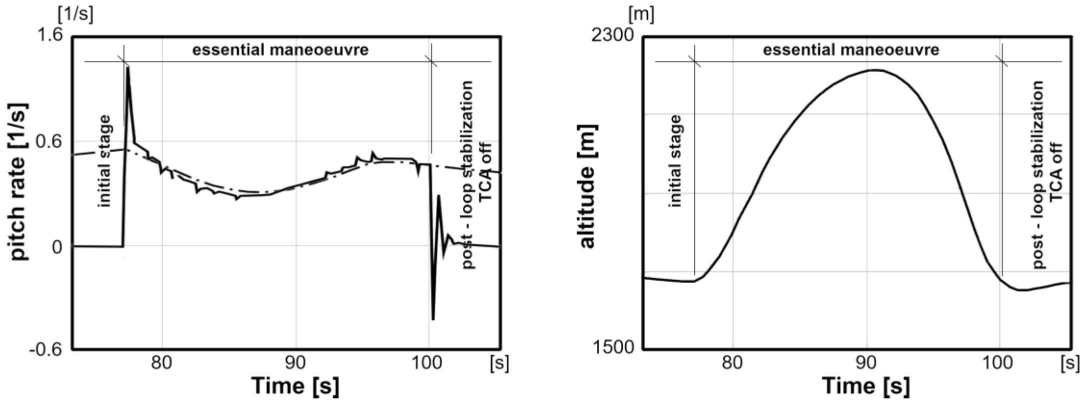
Figure 10 - Sample controls deflections and angular rates during spin inception (a), controls deflections and angular rates during the spin recovery phase (b) - Greg_R(s) = -1.5 to stop rotation, no control afterwards, Greg_Q(s) = 0.1, Greg_ϕ(s) = 0.5 + 0.1s. For picture clarity the following convention is applied: positive elevator deflection means nose up applied to the graphs.

On the basis of simulations, experts concluded that the TCA approach can manage the aircraft control sufficiently to accomplish the spin maneuver keeping an acceptable trajectory pattern.

5.2 Simulations of Loop and Immelmann maneuvers

The SIL simulations of these maneuvers were performed in the same way as previously. In fact, the Immelmann is composed of two different and independent sequences of control. The first is the half loop – and, as maneuver is used as a tool to start the Immelmann turn, prior to discussing this, brief results of simulations of the full loop are presented. Full consideration and more detailed results included in the work [20].

The control algorithm created with the approach presented in this paper and in [20] is sufficient to ensure a loop trajectory, qualified, by experts, as good enough. Sample quantitative measures of control quality are given in Figure 11and Table 3.



(a) (b)

Figure 11 - Flight parameters logged in a flight simulator for desired radius R=250[m] (XtremeAir Sbach 300 aircraft X-Plane model, Greg_ω(s) = 0.003 + 0.025/s, Greg_ϕ(s) = 0.02 + 0.0005/s). [28]; (a) desired pitch rate – dash-dot line and real pitch rate continuous line; (b)altitude changes in this manoeuvre.

Table 3. Sample assessment of control precision along the loop trajectory [16 25].

Desired radius [m]	Deviation of radius [m]	Lost altitude [m]
250	19	6.40

Once half-loop is followed by the half-roll the Immelmann is achieved (Table 2).
Finally, a simulation of autopilot performing the Immelmann was carried out. To present this process, (Figure 12), coupled time graphs of angles of aircraft space attitude - pitch and bank are shown.

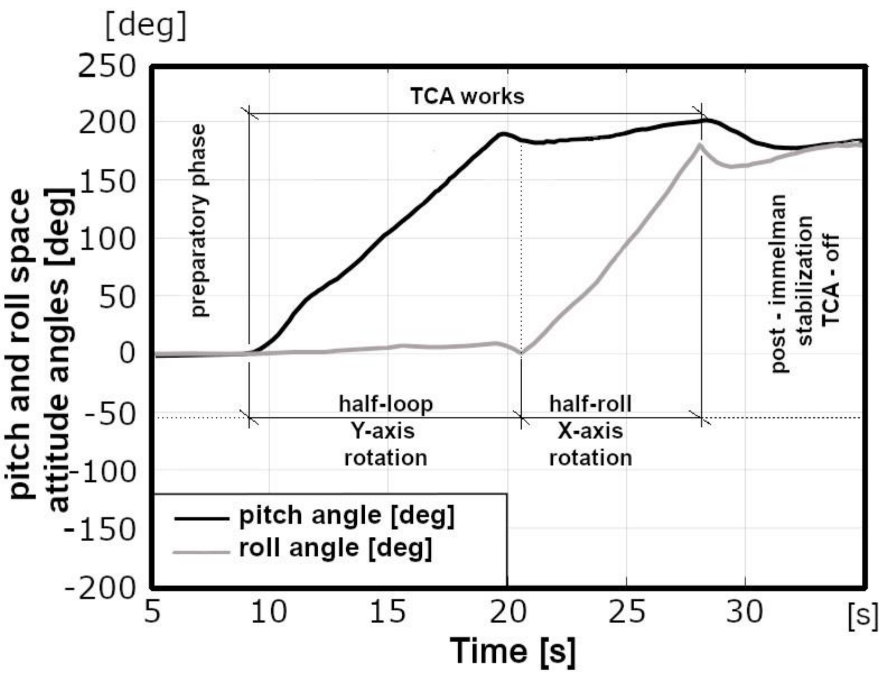


Figure 12 - Time histories of pitch and bank angles during simulated Immelmann manoeuvre (SU-35S aircraft X-Plane model Greg_Q(s) = 0.04 + 0.15/s, Greg_P(s) = 0.002 + 0.008/s) [22].

Experiments confirmed this approach to flight control algorithms based on TCA is capable of ensuring the control of the aircraft to fly it along a trajectory which is an approximation of some assumed Immelmann maneuver trajectory.

6. Conclusion

The article presents the approach to the process of synthesis of automatic control algorithms for small aircraft, capable of guiding the aircraft through various unconventional flight tasks. The flight along an assumed trajectory is one such partial task. The accuracy level of the control depends on specific features of the executed maneuver and particular control rules that the control system uses. Control algorithms applied to the control system, the structure of which is discussed in the paper, engage different components of flight control techniques, are often strongly based on expert knowledge, and finally are able to imitate real pilot control strategies. They are more focused on keeping characteristic features of the trajectory of the aircraft rather than achieving very high control precision. Examples given in this paper have been selected to be different enough to prove that an approach based on TCA working according to specific control laws and exploiting features of aircraft dynamics is efficient enough to execute certain aircraft aerobatic maneuvers.

The paper refers to two very different maneuvers characterized by different levels of controllability of the trajectory. In the spin maneuver, the trajectory is not directly controlled and results only from aircraft characteristics. The task of the flight control system is to execute the sequence of controls putting the aircraft into the spin and generate controls recovering the aircraft when the spin is completed. There is no “active” permanent control in the essential spin phase.

The second maneuver discussed – the Immelmann turn, requires some control continuously for a proper trajectory as well as the aircraft’s center of gravity needing to move inside the vertical plane along (in an ideal case) the trajectory which results from the applied controls. It is composed of two sequences of controls, executing a half loop in the first stage and a half roll in the next. The TCA presented in this paper, supported by some dedicated data fusion measurement algorithms [22, 25] and aircraft dynamic features, use loop algorithm to initialize the maneuver and control the airplane until upside down attitude reached (Figure 13). Afterwards, only by the usage of ailerons the aircraft is recovered to upside-right configuration.

Both cases use the TCA concept, which merges aircraft features, flight control theory, pilot knowledge-based controls, supported by dedicated aircraft attitude measurement algorithms [25] supplementing a classical approach [2, 14, 29] to accomplish the desired maneuver.

The results indicate that the presented approach, apart from specific use in highly maneuverable UAVs – e.g. imitators of flying target [12, 27], might be beneficial in the synthesis of aviation control systems. Although, both the spin and Immelmann maneuvers are not applicable for regular passenger or cargo flights, it is worth considering them to present a specific approach to the development of control algorithms. Some components or development rules might be used in the construction of an aircraft control system for recovering from stall or spin conditions [38] as well as in the case of maneuvers that might be an effect of aircraft systems failure or the influence of atmospheric turbulence [15] on normal aircraft flight.

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8. Copyright Statement

References

[1] Bates D., Hagström M., Nonlinear Analysis and Synthesis Techniques for Aircraft Control, ISBN 978-3-540-73718-6 Springer-Verlag Berlin Heidelberg, 2007.

[2] Biezad D., Integrated Navigation and Guidance Systems, AIAA Educational Series, 1999, ISBN1563472910.

[3] Blajer W., Graffstein J., Krawczyk M., Modeling of aircraft prescribed trajectory flight as an inverse simulation problem, Modeling Simulation and Control of Nonlinear Engineering Dynamical Systems: State of The Art, Perspectives and Applications, Springer, 2009, pp.153-162.

[4] Blajer W., Graffstein J., Krawczyk M., Inverse Simulation Study of Aircraft in Prescribed Trajectory Flight, International Review of Mechanical Engineering, No. 1, Praise Worthy Prize, 2008, pp.16-25, Naples.

[5] Blajer W., Graffstein J., Krawczyk M., Computational framework for the inverse simulation of Aircraft in predetermined trajectory flight, Multibody dynamics 2007, ECCOMAS Thematic Conference, Milano 2007.

[6] Blajer W., Kosma Z., Krawczyk M., Graffstein J., Prediction of the dynamic characteristics and control of aircraft in prescribed trajectory flight, Journal of theoretical and applied mechanics, No.1, Vol 39, s.79-103, 2001

[7] Bociek S., Gruszecki J., Układy sterowania automatycznego samolotem, Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów, 1999.

[8] Bulka, E., Nahon, M., Automatic Control for Aerobatic Maneuvering of Agile Fixed-Wing UAVs, Journal of Intelligent & Robotic Systems, 2019, Volume 93, Issue 1–2, pp. 85–100, https://doi.org/10.1007/s10846-018-0790-z.

[9] Burdun, I.Y., Parfentyev, O.M., Analysis of Aerobatic Flight Safety Using Autonomous Modeling and Simulation, (Paper 2000-01-2100), Proc. of the 2000 Advances in Aviation Safety Conference, April 11-13, Daytona Beach, FL, USA (P-355), SAE, 2000, pp. 75-92.

[10] Carretero, J. G.-H., Nieto, F. S., Cordon, R., Aircraft Trajectory Simulator Using a Three Degrees of Freedom Aircraft Point Mass Model, Poster at the International Conference on Application and Theory of Automation in Command and Control Systems, Naples, Italy, 2013.

[11] Chudý, P., Dittrich, P., Rzucidlo, P., HIL Simulation of a Light Aircraft Flight Control System, Digital Avionics System Conference, AIAA/IEEE Digital Avionics Systems Conference - Proceedings , art. no. 6382395 , pp. 6D11-6D113, Williamsburg, VA, US, 2012, p. 1-11.

[12] Dołega B., Rogalski T., Control System for Medium-Sized Flying Target, Aviation. Vilnius: Technika, Vol. 13, No. 1 , p.11-16. DOI: 10.3846/1648-7788, Vilnius, 2009.

[13] Dołęga B, Rogalski T.,The New Conception of The Laboratory Testing of the FBW Control Systems for Small Aircraft, Aircraft Engineering and Aerospace Technology: An International Journal No 3, Emerland, 2004.

[14] Kopecki G., Rogalski T., Aircraft attitude calculation with the use of aerodynamic flight data as correction signals, Aerospace Science and Technology, 2014, Volume 32, Issue 1, Pages: 267-273, DOI: 10.1016/j.ast.2013.10.009.

[15] Krawczyk M., Graffstein J., Maryniak J., Mathematical Model of UAV in Numerical Simulation of the Recovery Manoeuvres During Perturbed Flight, Journal of Theoretical and Applied Mechanics, 2005, Vol 38, No 1, s.121-130, PTMTiS.

[16] Kuliberda M., Implementation of Control Algorithms for Chosen Aerobatic Fgures, diploma work supervised by T. Rogalski, Mechanical Faculty, Rzeszow University of Technology, Rzeszów, 2015.

[17] Levin J., Nahon M. Paranjape A., Aggressive Turn-Around Manoeuvres with an Agile Fixed-Wing UAV, IFAC-PapersOnLine, Volume 49, Issue 17, 2016, Pages 242-247. https://doi.org/10.1016/j.ifacol.2016.09.042

[18] Levin J., A. Paranjape A., Nahon M., Motion Planning for a Small Aerobatic Fixed-Wing Unmanned Aerial Vehicle, 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, 2018, pp. 8464-8470.

[19] Majka M., Rogalski T., Wykorzystanie oprogramowania Matlab do sterowania w czasie rzeczywistym modelem samolotu w symulatorze lotu, monografia ISBN 978-83-937270-0-1, Tomasz M. Majka Publisher, Tarnów, 2014.

[20] McLean D., Automatics Flight Control Systems, Prentice Hall International Ltd, Cambridge (UK), 1990.

[21] McRuer D., Ahkenas I., Graham D., Aircraft Dynamics and Automatic Control, ISBN 0-691-08083-6, Princeton University Press, Princeton (USA), 1973.

[22] Mieszkowicz-Rolka, A., Rolka, L., Flow Graph Approach for Studying Fuzzy Inference Systems. Procedia

Computer Science 35 (2014) 681–690, www.sciencedirect.com/science/article/pii/S1877050914011156

[23]Milkiewicz A., Praktyczna aerodynamika i mechanika lotu samolotu odrzutowego w tym wysokomanewrowego, Wydawnictwo Instytutu Technicznego Wojsk Lotniczych, Warszawa, 2009.

[24]Nowak D., Rogalski T., Możliwości wykorzystania bezzałogowych statków powietrznych w polskiej przestrzeni powietrznej, Czasopismo Logistyka, 2014, Nr 6/2014, str. 7949-7955, ISSN 1231-5478.

[25]Plewka S., Automatic Flight Control During the Performance of Selected Aerobatic Figures, diploma work supervised by T. Rogalski, Mechanical Faculty, Rzeszow University of Technology, Rzeszów, 2019.

[26]Prusik J., Automatic Control System Recovering an Aircraft From the Spin Using Fuzzy Logic Controller, diploma work supervised by T. Rogalski, Mechanical Faculty, Rzeszow University of Technology, Rzeszów, 2019.

[27]Rauw M., FDC 1.2 – A Simulink Toolbox for Flight Dynamics and Control Analysis, 2-nd edition, PDF format report, 2001, ISBN: 90-807177-1-1, http://www.dutchroll.com.

[28]Rogalski T., Unmanned aircraft automatic flight control algorithm in loop maneuver, Aircraft engineering and aerospace technology, 2018, ISBN/ISSN: 1748-8842, t.90, z.6, p.877-884.

[29]Rogalski T., Nowak D., Pruchniak M., Prusik J., Układ automatycznego wykonywania manewru korkociągu, Autobusy – technika, eksploatacja, systemy transportowe, 2017, ISSN: 1509-5878, p. 1245-1251.

[30]Rogalski T., The Control Algorithms for Maneuvering Flying Target, Scientific Aspects of Unmanned Mobile Vehicles, t.1, s. 177-184, Politechnika Świętokrzyska , Kielce, 2010.

[31]Rogalski T., Alternatywne sterowanie ruchem bocznym samolotu, Journal of Aeronautica Integra, 2008, pp. 99-103, Sieć Naukowa Aeronautica Integra, Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów.

[32]Rogers R., Applied Mathematics in Integrated Navigation Systems, Third Edition, AIAA Educational series, 2007, ISBN-13: 978-1563479274.

[33]Ruibin X., Gaohau C., Formation Flight Control of Multi-UAV System with Communication Constraints, J. Aerosp. Technol. Manag. vol.8 no.2 São José dos Campos Apr./June 2016, ISSN 1984-9648 On-line version ISSN 2175-9146, http://dx.doi.org/10.5028/jatm.v8i2.608.

[34]Rzucidlo P., Chudy P., Rydlo K., Simulation and Prototyping of FCS for Sport Aircraft, Aircraft Engineering and Aerospace Technology, 2013, Volume 85 issue 6, Emerald Group Publishing Limited.

[35]Rzucidło P., Unmanned Air Vehicle Research Simulator - Prototyping and Testing of Control and Navigation Systems, Mechatronic Systems and Materials IV, Solid State Phenomena, Vol. 198, Trans Tech Publications Inc., Zurich, 2013, pp. 266-274.

[36]Sajith Kumar K. K., Arya H., Joshi A., Longitudinal Control of Agile Fixed-Wing UAV Using Backstepping, 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-11, DOI: 10.1109/AERO.2019.8742162.

[37]Seborg D., Process Dynamics and Control - 4th edition, 2017, ISBN10: 1119285917 John Wiley & Sons, Inc.

[38]Stevens B., Lewis F., Aircraft Control and Simulation, Willey & Sons, 1995.

[39]Subakan Y.C., Agcaoglu O., Sankur B., An automatic maneuver assessment system for r/c aerobatic model helicopter competitions, Signal Processing and Communications Applications (SIU) 2011 IEEE 19th Conference on, 2011, pp. 650-653.

[40]Thompson S. Smith P., Air Combat Manoeuvres the Technique and History of Air Fighting for Flight Simulation, Ian Allan Publishing, 2008, ISBN 978-1903223949.

[41]Wiliams N., Aerobatics, Airlife, publishing Ltd, Great Britain, 2003, ISBN 0950454303.

[42]Cheng Z, Two-Stage Heuristic Algorithm for Aircraft Recovery Problem, Discrete Dynamics in Nature and Society, Volume 2017, Article ID 9575719, https://doi.org/10.1155/2017/9575719.

[43]Zhang S., Liao F., Chen Y, He K., Aircraft trajectory control with feedback linearization for general nonlinear system, 2017, arXiv:1712.10077. [Online]. Available: https://arxiv.org/abs/1712.10077

[44]http://www.x-plane.com/. Official webpage of X-Plane simulator environment (contents on 01.05.2018).

[45]http://yoyosims.pl/figury.html