IOP Conf. Series: Materials Science and Engineering **327** (2018) 022092 doi:10.1088/1757-899X/327/2/022092

Control of fixed-wing UAV at levelling phase using artificial intelligence

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Abstract. The increase in the share of fly-by-wire and software controlled UAV is explained by the need to release the human-operator and the desire to reduce the degree of influence of the human factor errors that account for 26% of aircraft accidents. An important reason for the introduction of new control algorithms is also the high level of UAV failures due loss of communication channels and possible hacking. This accounts for 17% of the total number of accidents. The comparison with manned flights shows that the frequency of accidents of unmanned flights is 27,000 times higher. This means that the UAV has 1611 failures per million flight hours and only 0.06 failures at the same time for the manned flight. In view of that, this paper studies the flight autonomy of fixed-wing UAV at the levelling phase. Landing parameters of the UAV are described. They will be used to setup a control scheme for an autopilot based on fuzzy logic algorithm .

1. Introduction

From the point of view of mechatronics and robotics, the issues of automatic control of flight states and the planning of its mission are tasks of scientific research. Historically, the autonomy of the flight was achieved in space and military missions. The German V-4 was the first "autonomous" aircraft. The concept of flight autonomy over the years has changed. Today autonomy can be partial i.e. the aircraft is controlled remotely and full: where it is controlled by its autopilot without intervention of a human-operator. This type is called unmanned aerial vehicles.

UAVs are special air robots. They were mainly used in military tasks. The success of their implementation has attracted the attention of aircraft designers since orders of the civil market are more massive and profitable. Today, UAVs are used in patrolling space, protecting the environment, inspecting high-rise buildings and structures, football stadiums, as a fire-monitoring device, as well as in cinematography [14]. The development of technology and principles for the creation of UAV began in 1849 [1,2,3], when with the help of balloons the Austrian troops delivered bombs to besieged Venice. New discoveries in the field of telecommunications and radio equipment have significantly increased the degree of autonomy and improved controllability of the UAV. While in 1898, Tesla developed a miniature radio-controlled vessel, in 1910 Charles Kettering used this technology to propose, build and test various models of UAVs [4,5]. In 1933, the UK developed the first reusable UAV. As a result of continuous optimization, it is possible to conditionally describe the development of UAV by stating five historical moments [6].

- From 1849 to the beginning of the 20^{th} century: they were conducted during experimentation on the creation of UAV, formation of theoretical foundations of aerodynamics, theory of flight control and the calculation of aerodynamic, flying and design ratios of UAVs.

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- Beginning of the 20th century to 1945: UAVs were developed to perform military tasks only.
- The duration between 1945-1960 is the period of expansion of UAV classification by designation.
- From 1960 to 2000: in this period, the expansion of the UAV classification occured, civil applications for the UAV were developed .
- Present time: artificial intelligence control algorithm is integrated, unamanned flight regulations are created, integration of UAV in day-to-day operations such as to deliver healthcare services, commercial products, to perform building scanning, perimeters monitoring, assist cinematographic scenes etc.

2. Path planning methods for UAV

Path planning is the identification of geometric coordinates of the movement, depending on search criteria related to the target position [8]. To do this, it is necessary to understand successfully the odometric process and comparing information about the environment based on the position of the UAV. Odometry consists of two parts: software and hardware. Among computational algorithms, the most common methods are the direct explicit, global heuristic, search and pseudo-spectral, as well as algorithms based on a direct correlation and genetic algorithm. The definition of a geometric trajectory based on basic hardware is defined usually using encoders, inertial sensors, a machine vision and optical systems and navigation and location systems GLONASS or GPS. As a result, the main requirements for trajectory planning and flight control systems are the following: artificial Intelligence and adaptability of the control system, optimal control for stabilization and speed; possibility of planning and generating a trajectory for various flight tasks without reprogramming; trajectory planning should be resistant to communication channel loss with the human-operator.

Generally, there is no universal approach to planning the flight trajectory. The limitations that occur are caused by the shortcomings of the planning algorithms. Therefore, nowadays the focus is on the developing of a planning algorithm suitable for local and global trajectory planning [14].

2.1. Levelling path characteristics

The control speed of the UAV during the landing phase is mainly determined by the fact that the runway should touch with slight deviations from the specified landing point. The landing point on the runway should lie within 150-500 m from the location of the timing generated by the Instrumental Landing System ILS [10,11]. The lateral deviation from the heading line should not exceed ± 8.2 m, the pitch angle should be less than 8°, yaw angle - less than 3°. The vertical speed should not exceed [0.2; 0.6] m/ s. In the process of reducing the glide path, the UAV has a rather high planning speed, which, according to existing standards, must exceed the stalling speed at least 1.3 times. Since the stability and controllability of the UAV in the landing phase is largely due to the speed of planning, this leads to a significant overestimate of the speed, which in turn is the cause of large vertical descent speeds along the glide path, reaching 3-4 m/s. Naturally, the contact of the UAV with the ground at such vertical speed is unacceptable. The necessary reduction in vertical speed can be achieved by reducing the angle of inclination of the UAV’s trajectory. The stage of flight, during which the UAV, moving along a curvilinear trajectory, going from descent along a glide path to a trajectory with a small angle of inclination to the earth’s surface, is called alignment.

With automatic control, the stages of holding and parachuting are practically absent. There are two ways to implement the alignment path; on a robust control scheme, when the trajectory is formed relative to the runway by means of special ground facilities (similar to the glide path), and by a flexible corrected program, when the trajectory is formed by onboard.

3. Autonomous identification of levelling path

In the first method, the on-board means should measure the deviation of the real flight path from the ground-based means specified by the robust control algorithm. The creation of such ground and airborne facilities is a difficult task. At the same time, when the UAV deviates from the alignment path under the influence of external disturbances, it is practically impossible to eliminate its consequences since the time of the transient process of stabilizing the UAV on a given trajectory is commensurate with the alignment time. Therefore, in modern UAV landing systems, a second method of realizing the alignment path is more often used.

In the presence of information about the current position of the UAV relative to a certain point on the runway (flight altitude and range to a given point), automatic control of the landing of the UAV can be carried out. The principle of such control is as follows. If there is a deviation from the initial alignment path during the flight, the UAV further descends along a new alignment path. Thus, the task of automatic alignment control involves selecting the method of forming the optimal trajectory of the UAV, which, in the absence of external disturbances and the calculated initial conditions, ensures that the UAV is brought to a given touchdown point of the runway.

In the process of levelling, the UAV moves along a curvilinear trajectory that mates the glide path and the straight line, parallel or having a small inclination to the earth's surface. The curvature of the trajectory occurs due to the action of the centripetal force arising when the angle of attack increases. The alignment of the UAV can be described either by an arc of a circle or by an exponential. The parameters of the alignment path, i.e. the height of the beginning of the alignment, the length of the alignment and the radius of the curvature of the trajectory depend on the UAV speed, the accepted values of the normal overload and the angle of the glide path.

In the automatic approach control mode, when the height of the alignment starts, the autopilot calculates the increment of roll angle $\Delta\psi$ over true height signals H_r of normal overload U_{no} of airspeed V_a. This signal goes to the autopilot and is processed by the elevator servo drive until the signal with the vertical gyroscope does not compensate it. Changing the pitch angle will cause a change in height, overload and speed, which will result in a decrease in the pitch increment. Then the servomotor will return the elevator to the balancing position. Any deviation of the UAV from the specified vertical drop speed is recalculated into a corresponding increment of the set pitch angle and processed by the elevator.

The exponential trajectory can be described in the following form:

$$T\frac{dH}{dt} + H = 0; \qquad (1)$$

here, $T -$ the process time.

The solution for equation (1) is computed below:

$$H(t) = H_v e^{-t/T}; \qquad (2)$$

here, $H_v -$ the height altitude; $t -$ the actual time.

Considering that the UAV has zero speed at the first beginning, the distance to the landing spot is still large. The asymptote of the trajectory exponent must be below the runway at a certain distance designated as H_{asym}. Hence, equations (1) and (2) can be rewritten as follows:

$$T\frac{dH}{dt} + H = -H_{asym};$$
$$H(t) = C * e^{\frac{-t}{T}} - H_{asym}; \qquad (3)$$

here, $C -$ integration constant.

Assuming that $t -$ equal to zero and $H = H_v$, then one can write the following equation:

$$H(t) = (H_v + H_{asym}) * e^{-t/T} - H_{asym}; \qquad (4)$$

By differentiating equation (4), the vertical speed of the UAV can be computed:

$$V_v(t) = -\frac{(H_v + H_{asym})}{T} * e^{-t/T}; \qquad (5)$$

As the levelling trajectory must be a smooth continuation of the glide path, then speed at $t = 0$ must be equal to the speed needed for gliding. This speed can be computed by substituting $t = 0$ in equation (5):

$$V_{gp} = -\frac{(H_v + H_{asym})}{T}; \quad (6)$$

here, V_{gp} — the speed of the UAV at the glide path.

During the landing phase, the altitude is equal to zero. Replacing this value in equation (4), one can write:

$$0 = (H_v + H_{asym}) * e^{-T_L/T} - H_{asym}; \quad (7)$$

here, T_L — the landing time and it can be obtained resolving equation (7):

$$T_L = T * \ln\left(\frac{(H_v + H_{asym})}{H_{asym}}\right. \quad (8)$$

The landing speed can be calculated as well:

$$V_L = \frac{(H_v + H_{asym})}{T} e^{-T_L/T} = -\frac{H_{asym}}{T}; \quad (9)$$

Using equations (6) and (9), one obtains the following values: $T = 3{,}125\ [s]$; $H_{asym} = 0.625\ [m]$; and $T_L = 10.058\ [s]$.

3.1. Kinematic analysis

In this section, the kinematic diagram of the UAV elevator is described. At a later stage, control loops are analysed and controller's transfer functions are identified. The kinematic scheme is used to solve the inverse problem of kinematics; which consists in finding the stroke of the hydraulic booster. For this, it is necessary to analyse the geometry of the kinematic scheme (7) and to find the lengths of the thrust and to determine the forces on the hydraulic cylinders (HC).

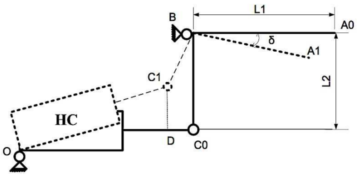


Figure 2. A kinematic scheme of the elevator

Using the similarity theory of triangles A_0BC_0, OBC_0, BC_0C_1 and C_1C_0D, and taking into consideration that the rudder chord is equal to 22% of the wing chord, one can find the stroke of the cylinder rod. The automation of the levelling process requires identification of the electrohydraulic mechatronic components and parameters such as the determination of the force factors on the swing mechanism; calculation and selection of hydraulic cylinder; selection of hydraulic equipment and determination of pressure losses; selection and control of the power source and calculation of the injection pipeline for strength. The aforementioned mechanical components are controlled in order to achieve the desired results; however, in this paper; the study will be limited to the theoretical analysis of the UAV as a physical macro element.

3.2. Trajectory Control loops

To achieve the autonomous gliding, the following control loops should be described: linear speed loop, which includes the engines thrust circuit and vertical speed loop.

The principle of constructing an automatic control system for a speed loop is based on subordinate regulation. The output value of the circuit is the thrust of motor F_T. The motor is described by an aperiodic first order transfer function. Hence, it is necessary to design a controller so that the process remains aperiodic [9].

When comparing the process time of the circuit with the process time of operation of the engine, the overall time constant is less than two; hence the transfer function of the regulator can be computed as follows:

$$W_T(p) = \frac{\frac{K}{p}}{\frac{K_M}{T_M p + 1}} = \frac{K}{p} * \frac{T_M p + 1}{K_M} = \frac{T_M p + 1}{\frac{K_M}{K} * p}; \quad (10)$$

here, $W_T(p)$ – the transfer function of the regulator; p – the Laplace operator; K – transfer factor; T_M – the process time of operation of the engine; K_M – the transfer factor of the engine.

Similarly, as the process speed of the linear speed it bigger than the process time of the thrust loop, then the latter can be neglected. Linear speed controller transfer function $W_{pVx}(p)$ can be computed as follows:

$$W_{pVx}(p) = \frac{K\left(\frac{m}{2K_{Vx}V_x} * p + 1\right)}{\frac{1}{2K_{Vx}V_x} * K_T * p}; \quad (11)$$

here, m – the mass; K_{Vx} – the transfer factor of the linear speed loop; V_x – the linear speed value; K_T – the transfer factor of thrust loop.

In line with the thrust loop, the vertical speed loop acts similarly as an aperiodic first order transfer function. The controller for vertical speed is described in the following equation:

$$W_{pVy}(p) = \frac{K\left(\frac{m}{2K_{Vy}V_y} * p + 1\right)}{\frac{1}{2K_{Vy}V_y} * K_T * p}; \quad (12)$$

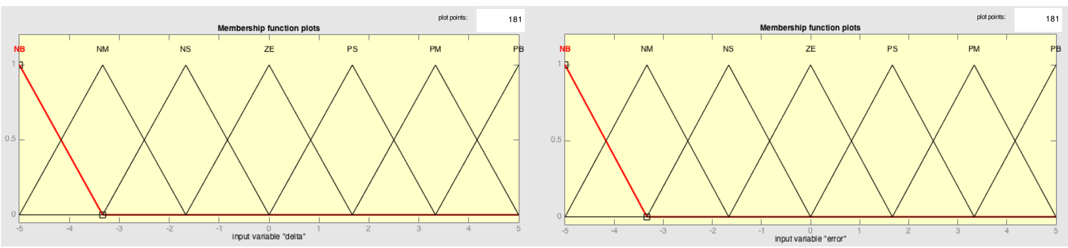
here, $W_{pVy}(p)$ – the vertical speed controller transfer function; V_y – the vertical speed value; K_{Vy} – the transfer factor of the linear speed loop.

3.3. Fuzzy Logic Controller

Synthesis of a fuzzy regulator to control the parameters of the flight is based on the results obtained for PI controllers [12]. It is known that for controlling physical systems one of the most important optimality criteria is the speed of the reaction against changes in the surrounding environment. The reaction time reflects changes either in the reference input signal or in the parameters of the system itself. Therefore, with regard to fuzzy logic, the time for processing the feedback and its derivation are taken into account as two inputs of the fuzzy controller. The fuzzy controller acts as an integrator, in which the resulting incremental output (Δuφk) is added to the previous value (uφk-1) to obtain the final output (uφk). To model the set of inputs and outputs, let us use the triangular membership function since it is easy to intercept corners from the membership function. The triangular membership function can be represented by the following expression:

$$\mu(s) = \max\left[\min\left(\frac{s - s_1}{s_2 - s_1}, \frac{s_3 - s}{s_3 - s_2}\right), 0\right]; \quad (13)$$

here, s – a clear value of one of the sets; s_1 – the point of the left edge of the corresponding set; s_2 – the peak of the corresponding set; s_3 – the point of the right edge of the corresponding set.
The membership functions for the input and output signals are illustrated in figure 3.



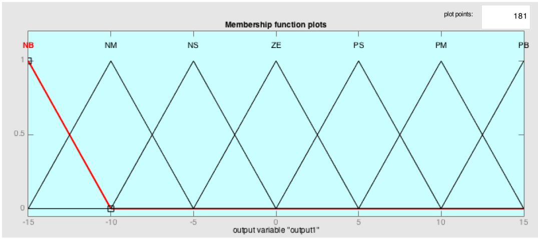


Figure 3. Membership functions for the two input signal and the output control signal

The fuzzy surface representing the correlation between the input and output is illustrated in figure 4. The flatness of the surface and the unidirectional aspects of the quiver endorse the successful assigning of the fuzzy rules.

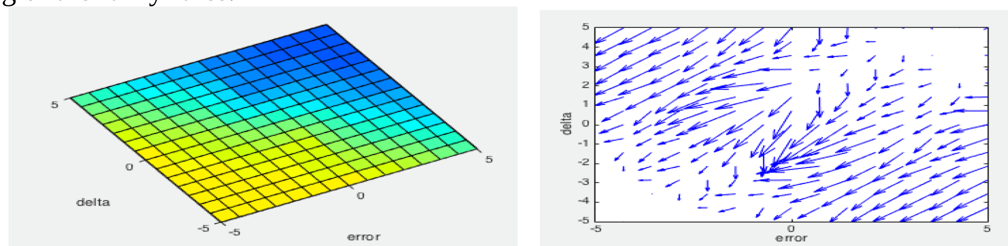


Figure 4. Fuzzy surface and quiver representation

4. Results and discussion

The simulation results are shown in fig.5

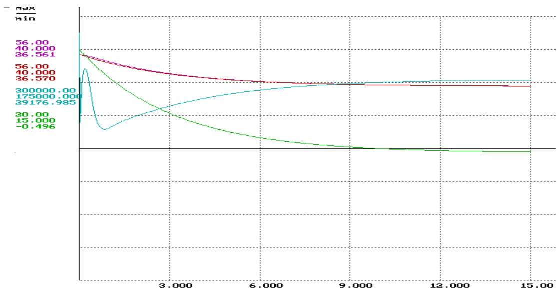


Figure 5. Simulation results for the linear speed loop

The figure above represents the following: the purple curve is the desired linear speed; the red curve is the achieved speed with the fuzzy controller. As it is clearly seen, the control task has been fulfilled. The maximum and minimum values of the linear speed were also respected and supported by the thrust value changes (blue curve). The thrust drops causing the linear speed to decrease and then increases to keep a lifting force necessary avoid perpendicular landing. The green curve represents the asymptotic altitude. During the previous analysis, the intended value is 0.625 m with negative signature as it is goes theoretically below the runway. By using the fuzzy controller, the value of the asymptotic altitude was reduced to 0.496 with minus signature. This reduction is optimal to the UAV landing as it reduced the running distance on the runway. In other words, the breaking and stopping process were reduced and that is what should be aimed for.

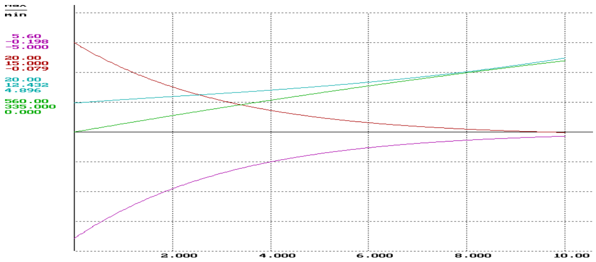


Figure 6. Simulation results of vertical speed loop

Similarly, for the vertical speed loop, one sees that the flight altitude (red curve) has tracked the asymptotic value taking into consideration the reduction of the vertical speed (purple curve) reaching a zero value when time is equal to 10.058 s, which proves the theoretical results found earlier.

5. Conclusion

In this paper, a fixed-wing unmanned aerial vehicle was analysed during the levelling stage. The aim was to achieve autonomous levelling and landing of the UAV taking into consideration a desired gliding path. The kinematic diagram of the fixed wing was studied; control loop for the linear and vertical speed of the UAV were identified; PI controllers transfer functions for the thrust, vertical and linear speed were found, based on which a fuzzy logic autopilot was designed and implemented. Simulation results were illustrated and analysed, which showed satisfactory speed, thrust and altitude tracking for the desired values.

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