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AUTOMATIC PREDICTIVE CONTROL FOR TERRAIN-FOLLOWING FLIGHT

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Abstract

Problems discussed in this article are focused on automatic, predictive flight control laws for low - altitude, terrain – following flights. The solution proposed below is based on simple idea of sliding horizon algorithm used for the reference signal anticipation. Longitudinal motion of the aircraft is considered to study the automatically controlled 'Nap of the Earth' (NoE) flight, which is performed by the UAV (Unmanned Aerial Vehicle) or by the manned aircraft operating in 'UAV mode' (e.g. for some emergency reasons). Control law is synthesised by extending typical altitude controller algorithm with the additional control loop, designed to follow after predicted flight trajectory angle. This angle is computed by on-line analysis of terrain profile ahead of the aircraft. The necessary data describing this profile is assumed to be obtained by an appropriate opto – electronic or radar – type device, the aircraft is equipped with, or by estimation techniques based on satellite navigation integrated with digitised map of terrain stored in autopilot's memory. The final solution is tested by computer simulations, where the model of small UAV (the mass about 20 - 30 kg) is used as an example. Obtained results prove the efficiency of proposed solution and its potential to be used in terrain awareness and obstacle avoidance systems.

INTRODUCTION

Problems discussed here are focused on automatic flight control, especially for flight missions accomplished at low altitude, when the flight trajectory is required to follow a profile of terrain ('*Nap of the Earth'- NoE* flight). Such missions are usually treated as military ones, mainly because of the essential importance of this kind of operations for some important types of air force tasks [2], [3], [6], [8], [13]. Indeed, most of known avionic solutions developed within this area of avionics are of military character, e.g. LANTIRN system (Low Altitude Navigation and Targeting Infra-Red for Night, combat - ready in 1986 [13]) and/or other flight control systems, designed for manoeuvring missiles (e.g.: Cruise, Tomahawk and others). In general, principles of operation developed for such systems are based on two main elements:

- on-board avionic, measuring equipment, being capable to detect in advance terrain obstacles and to synthesise on-line, repetitively, some representative characteristics of terrain profile ahead of the aircraft
- predictive algorithms designed for synthesising motion control signals, used as the autopilot's control laws, capable to assure safe motion of the aircraft in the nearest future.

The term *'prediction'* is used here to point out that synthesis of control signals at the current moment of time τ is accomplished on the basis of data characterising the shape of terrain profile ahead of the aircraft at the moment τ. Such data has to be persistently refreshed and available at every current moment of time. This makes the control system capable to execute on-line repetitive planning aircraft's desired motion for the nearest future and, finally, to avoid terrain obstacles appearing ahead, even if the flight altitude is low and the terrain – rough.

The important question appears: how to get in advance the data of terrain profile, which is necessary to execute the effective prediction. One possible solution is real - time scanning of terrain profile, when the scanned area (called the *'horizon of prediction'*) covers a certain distance L ahead of the aircraft (Fig.1). This distance has to be long enough for reliable terrain obstacle avoidance. When the data of terrain profile within the horizon of prediction is known, the more or less complex control laws can be used to assure safe aircraft motion. This solution is typical for military tasks – it does not depend on external sources of measuring signals, thus the aircraft and its' avionic equipment is fully autonomous. The process of scanning is realised by an appropriate measuring sub-system capable to „see'the terrain ahead of the aircraft. It is important to notice that results of such scanning are limited due to 'shadowed areas', which may occur (Fig.1) for obvious geometry. For example: one of the main sub-systems of aforementioned LANTIRN system is Terrain Following Radar (TFR) especially designed for such tasks.

Dimensions and sizes of units like this make them impossible to be installed in small airplanes: the mass of the AN/AAQ-13 pod containing TFR radar and other necessary sub-systems (standard equipment of F-16C/D Block 50/52 fighter) exceeds 200 kg [13].

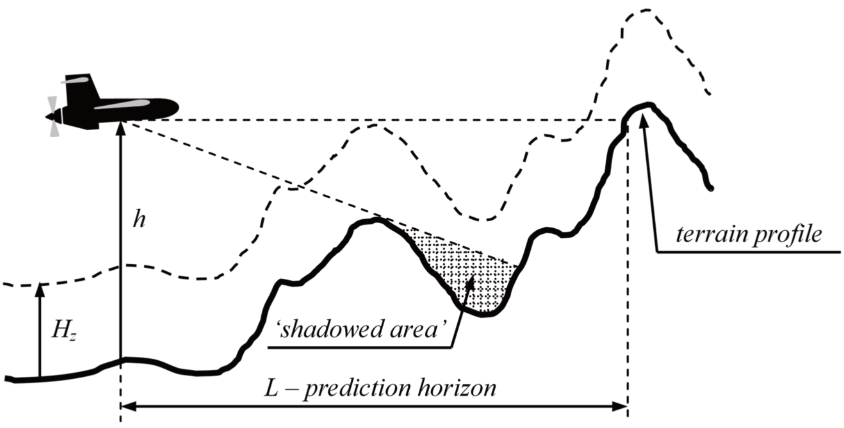

Fig. 1. Terrain-following flight at low altitude (with „shadowed area")

When civil applications are considered, requirements and tasks are not so extreme. In particular the requirement to maintain autonomous character of the system can be mitigated and terrain scanning process can be replaced by the terrain profile estimation techniques based on satellite navigation and digitised map stored in autopilot's memory. The final result has to be the same: at every current moment of time the control system has to know' the shape of terrain and terrain obstacles ahead of the aircraft to assure safe control of flight trajectory. Discussion presented further is focused mainly on searching for an automatic, predictive control law for longitudinal motion of the aircraft, to make it capable to accomplish the following task:

- the aircraft has to keep the safe clearence altitude, greater and close as possible, to the desired clearance altitude H_Z above the surface of terrain (Fig.1)

▪a cost, weight and dimensions of the measuring and control systems have to be low and small enough to make resulting units capable to be used as the on-board equipment for small unmanned aircraft (e.g. with the mass under 100 kg), designed for performing civil/commercial tasks.

Excluding the expensive and complex equipment (e.g. sophisticated, TFR like radar) and limiting the discussion only to simple and not expensive technical means, certainly may result in deterioration of control quality, however may also open the way for new possible applications, mainly in civil areas.

1. THE INSPIRATION

The important inspiration for the discussion presented here, came from the episode that happened in *Air Force Officers Training Centre* in Dęblin (Poland) more than eighty years ago. Possibly it has never been reported in scientific literature, because Janusz Meissner - those times the chief instructor of pilotage in the Centre, described this story in the novel belonging to belles-lettres kind of literature [10]. Fortunately, he had been engaged deeply in what had happened then thus, his description, written years later, is very precise and authoritative.

At late twenties of last century Meissner was teaching to fly the young aviation enthusiast - Stanisław Latwis, who learned quickly the art of controlling the aircraft in basic manoeuvres, but completely failed in landing. Meissner guessed at once that the reason was the way that Latwis was looking at the runway during the approach and flare phases of landing before touchdown. He was simply fixing his line of sight (*LoS*) at fixed point on the airfield, so when the aircraft flew over this point he always found himself confused and bewildered, too high above the ground with the speed too low. This caused that he was in no position to estimate precisely enough the true height above the ground during the approach and flare, so finally got an obvious result. However Meissner persuaded him to move the line of sight forward, to keep it ahead of the airplane and look at 'the whole airfield'in every moment, however they both tried to overcome the problem repeating landing manoeuvres for many times, results only went worse. The case seemed to be hopeless-Latwis was unable to stop fixing his line of sight at fixed point on the ground when approached the airfield.

The change appeared suddenly. After some days of break in flight exercises due to instructor's absence, Latwis landed correctly, and during short series of tests improved the technique enough to be able to accomplish this manoeuvre almost perfectly. Being investigated about his success and unexpected change, he presented his *'invention'*– the exercise which helped him learning how to move the line of sight forward, keeping it ahead of the moving vehicle.

He placed more than a hundred of big stones along a straight line, one about three steps after another. Then he started his exercises walking along this line and trying to *'move his eyes'* from one stone to the next one, to have a line of sight focused about *'twenty stones before him'*. When succeeded, he did the same running, then riding a bicycle (Fig.2) and finally, driving a motor cycle. After a few days of training he had this lesson learned and was sure that he could look at the airfield correctly. And he was right, shortly after that, he passed all practical exams and became his career as a pilot.

It is not easy to make clear all aspects of this experiment and results. Some of crucial questions belong rather to psychology, e.g. questions of the nature of Latwis's disability and possibility to overcome it by training. It is obvious that the way that aircraft's pilot is looking at the runway in landing manoeuvre is crucial and doing it properly allows him/her to assess precisely the current state of the aircraft - height above the ground, velocity, pitch angle, angle of attack, rate of descent, etc. On the other hand, when the airfield is visible from the air (*VFR* conditions), the pilot controlling the aircraft to complete the approach & flare-out manoeuvre knows a desired motion of the plane in advance. Thus, an interesting questions appear, e.g.: what is the role of this kind of prediction in human–controlled flights?, is there a possibility to use this idea in automatic control system ?, etc. However the case described above is not easy to be applied directly in order to improve known technical solutions, it is interesting as the inspiration for engineering tasks and is treated this way in further discussion.

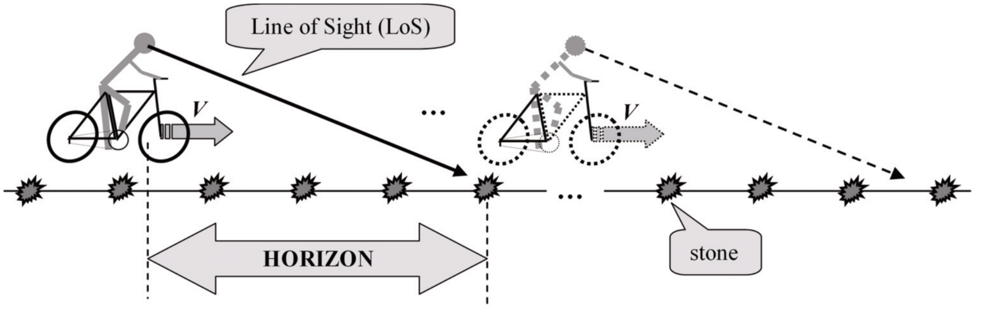

Fig.2. Latwis´s idea (the exercise)-„bicycle'phase

2. PREDICTIVE CONTROL–THE CLASSICAL APPROACH

In control theory it is convenient to discuss the idea of making use of anticipated behaviour of controlled object in discrete time domain. Time instants are denoted then by natural numbers: 0, 1,...,k, k+1, ... and it is assumed that all increments of time from one sample to the next one are equal i.e.: $t_{k+1} - t_k = \Delta t = const$ for every k.

The most typical ideas of control algorithms of this type are based on two general assumptions.

Assumption 1: The mathematical model (1) of controlled object is known a priori, with y, u denoting output and control signals respectively (in general, vector-signals of appropriate dimensions) and G-some causal operator. It is assumed that this model can be used for predicting by computation a future behaviour of controlled object when future sequence of control signal samples is known:

$$y_{k+1} = G(y_k, y_{k-1}, \ldots, u_k, u_{k-1}, \ldots) \tag{1}$$

where $y_i = y(t_i), u_i = u_i(t_i)$ for ever i.

Assumption 2: At every current moment of time the reference trajectory $y^{(ref)}$, representing the desired value of output signal, is known over a finite set of future time instants, called time horizon of prediction.

This means that at every moment k values: $y_{k+1}^{(ref)}, y_{k+1}^{(ref)}, \ldots, .y_{k+N}^{(ref)}$ are known where N is the time horizon of prediction.

Then, the control signal to be applied to the controlled object is computed by optimisation of typical quadratic quality index:

$$I(k)=\sum_{j=k}^{k+N-1}\left[y_{(j|k)}-y_j^{(ref)}\right]^T\mathbf{Q}\left[y_{(j|k)}-y_j^{(ref)}\right]+u_{(j|k)}^T\mathbf{R}u_{(j|k)} \tag{2}$$

where $\mathbf{Q},\mathbf{R}$ are symmetric, positive-definite weighting matrices of appropriate dimensions, $u_{(k|k)},u_{(k|k+1)},\dots,u_{(k|k+N-1)}$ is the sequence of control signal candidate's future samples, while $y_{(k|k)},y_{(k|k+1)},\dots,y_{(k|k+N-1)}$ is the sequence of predicted output signal samples computed by (1).

Functional (2) can be treated as a function of $u_{(k|k)},u_{(k|k+1)},\dots,u_{(k|k+L-1)}$, because, according to Assumption 1, $y_j^{(ref)}$ samples appearing in this relationship are known and appropriate samples of $y_{(j|k)}$ can be computed using the model (1).

Indeed:

$$y_{(k+i|k)}=G\left(y_{(k+i-1|k)},\dots,y_{(k+1|k)},y_k,\dots,u_{(k+i-1|k)},\dots,u_{(k+1|k)},\ u_k,u_{k-1},\dots\right) \tag{3}$$

for $i=1,\ 2,\dots\ ,k+N-1,\ \dots$. Finally the control algorithm can be presented as follows [3]:

Step 1: Get (measure) the y_k sample of output signal

Step 2: Compute the control sequence: $u_{(k|k)},u_{(k|k+1)},\dots,u_{(k|k+N-1)}$ by optimising the quality index (2)

Step 3: Apply $u_{(k|k)}$ as uk to control the object for one time step;

Step 4: Time update: $k:=k+1$

Step 5: Return to Step 1 and repeat the cycle

The main difference between ideas discussed in this paragraph and presented in Fig.1, as well as discussed in paragraph two, is the domain of horizon of prediction. Classical approaches of predictive control are focused on time domain, like the algorithm presented above. However, when the NoE flight is considered, the natural domain for defining the horizon of prediction has a different, spatial nature (Fig.1). More details of this difference are treated in the next paragraph.

3. PREDICTIVE ALGORITHM FOR DESIRED AIRCRAFT MOTION

A key problem for the synthesis of automatic control law for NoE flight is how to get and organise data characterising the terrain profile ahead of the aircraft. The autopilot „has to know'in advance the vertical profile of terrain, to synthesise control signals for the future, to keep the motion safe and avoid obstacles manoeuvring effectively to reject the risk of crash to the ground [7]. Technical means mentioned in introduction are too heavy, expensive and energy consuming to be used in small unmanned aircraft. The military character of such systems also excludes the possibility to use them to accomplish simple commercial tasks. In Fig.3 the algorithm of obtaining the simple predictive estimate for terrain profile assessment is illustrated [5], [9]. It works following ideas presented in paragraph two. It is assumed that considered aircraft is equipped with the range finder (no matter what type: laser [11], another optoelectronic or microwave), which is installed in fixed position on-board, in plane of symmetry of the aircraft in such a way that the angle between the aircraft's x-body axis and the measurement x_d axis (Line of Sight-LoS) of range finder, is constant and equal ξ. This range finder is assumed to be capable to measure a distance D between the aircraft and the ground along the LoS axis x_d.

The angle γ , defined in Fig.3 is treated as a desired flight trajectory angle. Assuming that the angle ξ - θ, where θ represents pitch angle, is small, the value of γ can be approximated by simple formula:

$$\gamma \approx \frac{H_z}{D} + \theta - \xi \tag{4}$$

This variable will be treated as the predictive estimate of the terrain profile ahead of the moving aircraft.

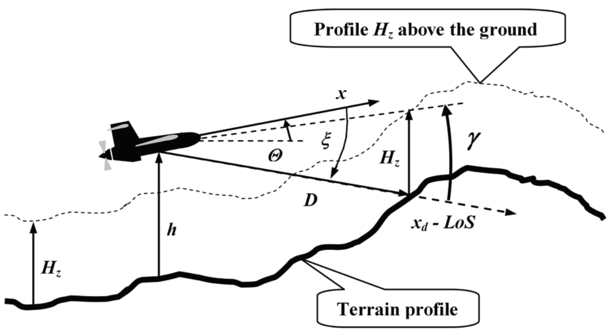

Fig. 3. Estimation of the desired flight trajectory angle [9]

It is assumed that the range finder measures the distance D on-line and two types of result of every measurement may occur.

- The result is 'indefinite' when the measuring axis xd does not 'touch the ground' (is directed 'to the sky'), so the distance D, defined above, does not exist
- The result is also 'indefinite' when the value of D exists but is greater than certain maximum value D_{max}–maximum distance that can be measured by the range finder (in simulations presented further it is assumed that D_{max}=600m - typical value of this parameter for not expensive laser range finders [11])
- in other cases the result of measurement is equal to the measured distance D.

Thus the final assessment of terrain profile ahead of the aircraft is constructed as follows:

if (*D* is *„indefinite”*) **then**

if *γ*last≥0 **then**

*γ:=p * γlast*

else

γ:= γlast

end if

else

$\gamma := (H_Z/D) + \theta - \xi$

end if

where γ_{last} denotes the previous result of *γ* computation, and $p \in (0,1)$ is a constant parameter introduced to avoid too aggressive pull up manoeuvres.

It is important to notice that proposed algorithm is very simple-it does not require scanning the terrain profile ahead of the aircraft. Only the distance *D* has to be measured for the current moment of time. It is the preliminary solution. It does not contain protection guaranteeing that the aircraft is capable to ‘realize’ the trajectory characterised by the angle *γ* computed by the algorithm, because in this phase of work the analysis is focused rather on the checking if the idea works good, than on technical details of realisation. These details will be defined precisely during the next, more technical phases of project.

4. CONTROL LAW AND RESULTS OF SIMULATION EXPERIMENT

The signal *γ*, representing a desired flight trajectory angle is used in typical control law for altitude stabilisation (5), where δ_{II} denotes elevator’s deflection, *h* –real height of flight over the ground surface, H_Z –desired height over the ground, *θ*-pitch angle, *q*–angular rate of pitching and parameters *k* with different indices-constant gain factors.

The control law is also illustrated in Fig.4 to give clear insight into controller’s structure and extension consisted in additional feedback loop for flight trajectory angle.

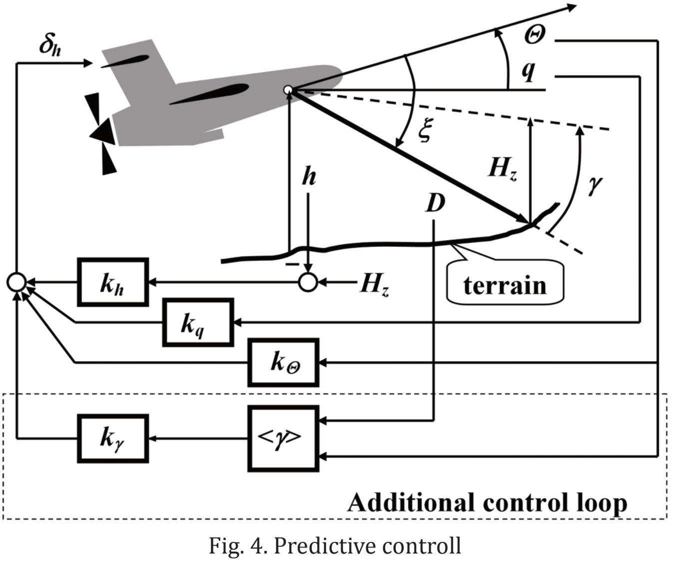

Fig. 4. Predictive controll

$$\delta_H = k_h(H_z - h) - k_\theta\theta - k_q q - \underbrace{k_\gamma\gamma^*}_{\substack{additional \\ control\ loop}} \tag{5}$$

Proposed control law (5) was verified by simulation with linearised mathematical model of longitudinal motion of small UAV (the mass about 20-30 kg) [4], [5]. In [4] the result of clasical altitude controller synthesis are presented (gain factors k_h, $k_{\theta,}$ k_q are discussed). The model of aircraft's motion takes the form:

$$\dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{b}\delta_H \tag{6}$$

where state variables h, θ, q are included in state vector z as well as components u, w of linear velocity in body axis (for more details, see Appendix, where equations of motion are presented n details).

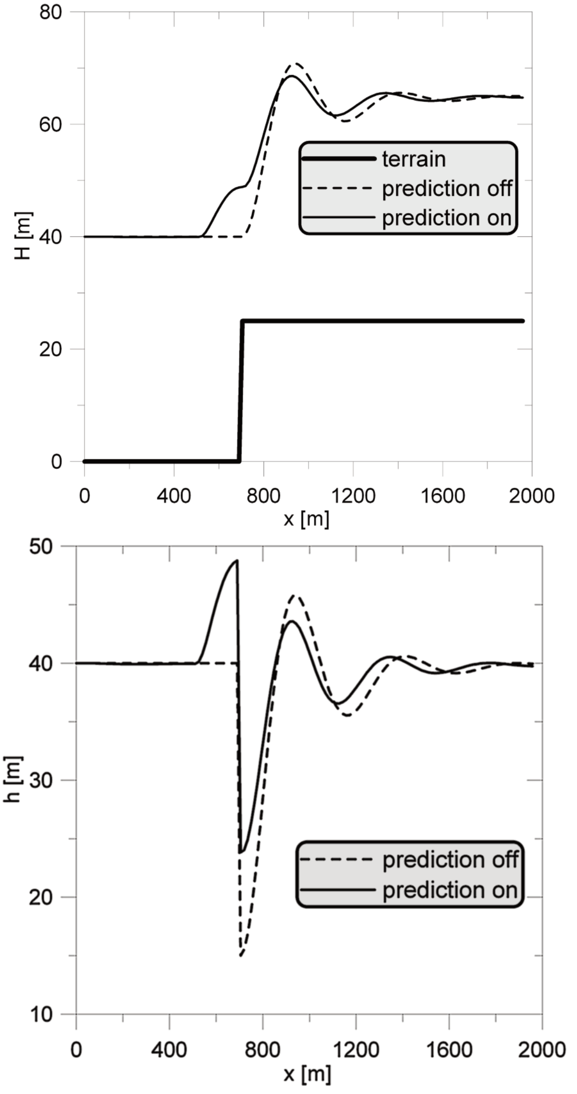

Fig. 5. Classical vs. predictive control responses of altitude control system [5]

Typical results of simulation are presented in Fig.5. It was assumed that in the initial moment the aircraft's motion is trimmed on straight horizontal trajectory, 40 m over the ground with linear velocity 50 m/s. The shape of terrain before the aircraft is the 25 m high step, like for flight over the sea towards 25 m high seashore (cliff). It was assumed that the constant angle between LoS of range finder and x body axis is ξ=10 directed „downwards".

Dotted line illustrates typical reaction of altitude controller (with k_γ=0), whereas solid line represents the reaction of predictive controller (with k_γ=100). It is easy to notice that activation of predictive algorithm results in important reduction (about 15 m)of maximum value of altitude error H_z-h, but also reduces overshooting.
Other results of the simulation experiment can be shortly summarised as follows:
- pitch angle is less than 10
- velocity reduction in this manoeuvre is less than 4 m/s, although throttle position is constant during the manoeuvre
- maximum deflection of elevator is less than 3.5.

One of the main advantages of predictive control is the smoother transient of the manoeuvre. The illustration of acceleration in vertical plane is presented in Fig.6–overload factor is seven times greater for non-predictive control.

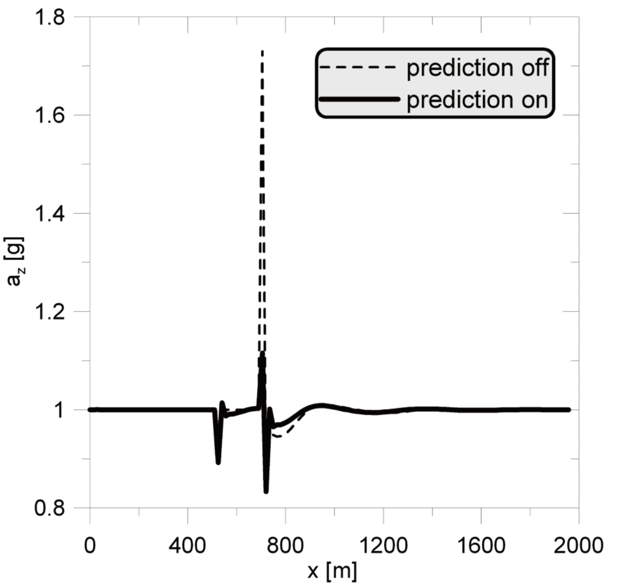

Fig. 6. Vertical acceleration [5]

CONCLUSIONS

Presented solution for longitudinal motion control in terrain – following flight is simplified to get less restrictive requirements for measuring. Finally four variables have to be measured (or estimated/observed): *h, D, θ, q*.

The most difficult requirement is measurement of distance *D*, which has to be repeated quite frequently (0.3 s of repeating period was assumed), and there is no method to make this condition not so difficult. A need for precise estimate of pitch angle defines another difficult question (expensive gyro), but this task is expected to be easier because of the possibility to use observation techniques assisted by not expensive MEMS gyros.

Results of simulations are close to expected ones, despite of very simple control law. The main advantage of predictive control is a capability to react before the threat of collision with the obstacle is critical. Such capability is noticed and improved the control quality of typical altitude controller.

APPENDIX: MODEL OF LONGITUDINAL MOTION OF EXAMPLE AIRCRAFT

The small unmanned aircraft is used as an example for discussion presented in the article. Mass of the vehicle is about 20 – 30 kg and its features are expected to be close to commercial needs for terrain observation and surveillance. Simplified, mathematical model of longitudinal motion, representing trimmed horizontal flight is used (6). State space equations describing this motion are linearised in the vicinity of the point in state space which represents this trimmed horizontal flight taken as a reference. This motion is characterised by 50 m/s horizontal velocity at 0 m altitude (a.s.l.) [5]. State space vector **z** is composed of five state variables: $\mathbf{z}=[u, w, q, z, \theta]^T$ where all of them represent differences between true value of state variable and the value of the same variable corresponding with the reference motion.

Thus, subsequent variables denote the following deviations:

u - x - component (longitudinal) of velocity in body axis [m/s]

w - z - component (vertical) of velocity in body axis [m/s]

q -pitch rate [deg/s],

z -vertical coordinate of position in inertial reference system [m]

θ -pitch angle [deg]

δ_H -control signal δ_H representing deflections of the elevator [deg]

Matrices appearing in (6) are of the following form:

$$\mathbf{A}=\begin{bmatrix} -0{,}1317 & 0{,}0048 & 0{,}5027 & 0{,}0003 & -9{,}8092 \\ -0{,}5429 & -8{,}6079 & 38{,}2159 & 0{,}0008 & 0{,}1265 \\ -0{,}0379 & -2{,}4276 & -0{,}79 & 0 & 0 \\ 0{,}0134 & 0{,}9999 & 0 & 0 & -40{,}0 \\ 0 & 0 & 1{,}0 & 0 & 0 \end{bmatrix}, \quad \mathbf{b}=\begin{bmatrix} 0 \\ 0{,}5313 \\ -0{,}8897 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

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MASŁOWSKI PIOTR

AUTOMATYCZNE STEROWANIE PREDYKCYJNE DLA LOTU ZE ŚLEDZENIEM PROFILU TERENU

Streszczenie

Problemy omawiane w artykule skupiają się wokół praw automatycznego, predykcyjnego sterowania lotem na małej wysokości ze śledzeniem profilu terenu. Zaproponowane rozwiązanie wykorzystuje prosty algorytm z przesuwającym się horyzontem predykcji, umożliwiający antycypowanie sygnału zadanego. Model ruchu podłużnego samolotu został wykorzystany do badań automatycznie sterowanego lotu na małej wysokości, wykonywanego przez samolot bezzałogowy (UAV) lub przez samolot z załogą ale poruszający się jako bezzałogowy (na przykład z powodu wystąpienia sytuacji awaryjnej). Prawo sterowania zostało zaprojektowane jako rozszerzenie typowego regulatora wysokości lotu przez dodanie do niego dodatkowej pętli sprzężenia zwrotnego, zaprojektowanej tak, by zrealizować śledzenie przewidywanego kąta toru lotu. Kąt ten jest wyliczany poprzez analizę on line kształtu profilu terenu przed samolotem. Przyjmuje się, że niezbędne dane opisujące ten profil są uzyskiwane przez odpowiednie urządzenia pokładowe, optoelektroniczne lub radarowe, albo metodami estymacji bazującymi na nawigacji satelitarnej zintegrowanej z cyfrową mapą przechowywaną w pamięci autopilota. Ostateczne rozwiązanie zostało przetestowane podczas badań symulacyjnych, w których wykorzystano jako przykład model matematyczny małego samolotu bezzałogowego (UAV) o masie ok. 20-30 kg. Otrzymane rezultaty potwierdziły poprawne działanie proponowanego rozwiązania i możliwość wykorzystania go w układach antykolizyjnych i ostrzegających o bliskości ziemi.