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FLIGHT RECOVERY SYSTEM

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Abstract: Primary task of an automatic recovery system is to solve a situation when a pilot loses orientation. This space disorientation happens when there is a variance of angle position between what pilot thinks and real physical angle position of the airplane. This situation occurs firstly in case when the pilot cannot see the horizon (by low or zero visibility, during a night flight over monotonous terrain without distinct segmentation, when wrongly reading/failure of position indicators, with disturbance of the pilot and losing concentration under high pressure e.g.).

Keywords: automatic control, disorientation, θ-Φ diagram.

1 INTRODUCTION

Main reason of disorientation is the fact that human sensors of angular velocity (inner ear – semicircular channels) are insensitive to angular speeds under 2°/s. If the pilot does not have visual information this insensitiveness is integrating and becoming a drift. This drift leads to lose bearings. Automatic recovery system can stabilize the plane without involving the pilot and bring it to slightly climbing flight. Then the system hands over the control back to the pilot.

This whole procedure has a few limit factors. Above all it is a marginal angle of attack and sideslip angle (separation of the streamline from the profile – aerodynamic limitation), maximum pitch and roll rate (mechanical limitations of the plane), maximum folds in particular directions (physiological pilot protection) and a control limit (maximum helm deviation and maximum velocity of position change). On this account was a model predictive control (MPC) method chosen.

Superior decision level for MPC is a θ- Φ diagram. Diagram defines the procedure of controlling the plane in various plane positions. In dependence on its position angles it determines next control/motion of the plane.

2 FLIGHT MODEL

Flight motion characteristic is described by moment and force equations with six degrees of freedom. Full deduction of these equations is not in range of this paper and it is described in ref. 1 and 2. These equations are strongly nonlinear due to influence of aerodynamic coefficients and describing these equations is very complicated. For control purposes it is preferred to use particular working point (airspeed, altitude, mass of aircraft, angle of attack ...) then linearize the model and store the result in state-space form.

State-space model

We have separated the model to longitudinal and lateral motion. State-space model used for control is derived from motion of training aircraft L-39. Original separated longitudinal and lateral motions are fused together and supplemented with equation of altitude and vertical speed. Altitude equation is derived from vertical speed ($\dot{h}$) which is directly depending on air speed (V), angle of attack (α) and pitch angle (θ):

$$\dot{h} = V \sin\gamma + u_z = V \sin(\theta - \alpha) + u_z \tag{1}$$

If we suppose small fly path angle γ, we can write goniometric dependence[1] $\sin(\gamma) \approx \gamma$

$$\dot{h} = V \cdot \gamma + u_z = V(\theta - \alpha) + u_z \tag{2}$$

where u_z is wind disturbance. If we integrate last equation, we get altitude equation with initial condition H_0. States matrix is supplemented of altitude equation and output matrix is supplemented of vertical speed equation.

3 MODEL PREDICTIVE CONTROL

This is a type of control which uses optimal state-feedback and predictive strategy for optimal design sequence of control action with reference to future states and outputs of system. Discrete model is described as follows:

$$\begin{aligned} x(k+1) &= M \cdot x(k) + N \cdot u(k) \\ y(k) &= C \cdot x(k) + D \cdot u(k) \end{aligned} \tag{3}$$

We search for control sequence $u(k)$ on the prediction horizon with length T_p which minimizes following criterion:

$$J = \sum_{t=0}^{T-1} \left\{ q(t)[y(t) - w(t)]^2 + r(t)u(t)^2 \right\} \tag{4}$$

Where $q(t)$ and $r(t)$ are weights of regulation deviation and control action, $w(t)$ is referential signal. Horizon of prediction is a time after which we find optimal control sequence. We specify the prediction of outputs as system response on the prediction horizon T_p:

$$\begin{bmatrix} y(k) \\ y(k+1) \\ y(k+1) \\ \vdots \\ y(k+T_p-1) \end{bmatrix} = \begin{bmatrix} C \\ CM \\ CM^2 \\ \vdots \\ CM^{T_p-1} \end{bmatrix} \cdot x(k) + \begin{bmatrix} D & & & & \\ CN & D & & & \\ CMN & CN & D & & \\ \vdots & & & \ddots & \\ CM^{T_p-2}N & & & CN & D \end{bmatrix} \begin{bmatrix} u(k) \\ u(k+1) \\ u(k+2) \\ \vdots \\ u(k+T_p-1) \end{bmatrix} \tag{5}$$

We can write this equation in matrix form:

$$y_k = V \cdot x(k) + S \cdot u_k = \tilde{y}_k + S \cdot u_k \tag{6}$$

Where $\tilde{y}_k$ is system response to initial condition $x(k)$ and $S.u_k$ is system response to control sequence on horizon of prediction T_p. We establish this equation to the scalar criterion:

$$J(u_k \mid x(k), w_k) = (\tilde{y}_k + S \cdot u_k - w_k)^T Q(\tilde{y}_k + S \cdot u_k - w_k) + u_k^T R u_k \tag{7}$$

Matrix Q defines weight of regulation deviation and matrix R defines weight of control values. Vector w_k is reference sequence on prediction horizon. We can weigh only amplitude of inputs with this criterion formulation. If we want to weigh input change $\Delta u(k) = u(k) - u(k-1)$ we must modify previous criterion to the following form:

$$J(u_k \mid x(k), w_k) = (\tilde{y}_k + S \cdot u_k - w_k)^T Q(\tilde{y}_k + S \cdot u_k - w_k) + \Delta u_k^T \cdot R \cdot \Delta u_k \tag{8}$$

where:

$$\Delta u_k = D_i u_k - \tilde{u}_k$$

$$D_i = \begin{bmatrix} 1 & 0 & & & \\ -1 & 1 & 0 & & \\ 0 & -1 & 1 & 0 & \\ & 0 & & \ddots & 0 \\ & & 0 & -1 & 1 \end{bmatrix} \quad \tilde{u}_k = \begin{bmatrix} u(k-1) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{9}$$

We obtain following form if we substitute previous equation to the equation (8):

$$\begin{aligned} J(u_k \mid x(k), w_k) &= \tilde{y}_k^T Q \tilde{y}_k + \tilde{y}_k^T Q S u_k - \tilde{y}_k^T Q w + \\ &+ u_k^T S^T Q \tilde{y}_k + u_k^T S^T Q S u_k - u_k^T S^T Q w - w^T Q \tilde{y}_k \\ &- w^T Q S u_k + w^T Q w + (D_i u_k)^T R (D_i u_k) - \tilde{u}_k R D_i u_k + \\ &+ (D_i u_k)^T R \tilde{u}_k + \tilde{u}_k^T R \tilde{u}_k = u_k^T (S^T Q S + D_i^T R D_i) u_k + \\ & u_k^T \left[(SQ)^T (\tilde{y}_k - w) - D_i^T R \tilde{u}_k \right] + \\ &+ \left[(\tilde{y}_k - w)^T Q S - \tilde{u}_k R D_i^T \right] u_k^T + c \end{aligned} \tag{10}$$

Constant c describes all variables which don't depend upon vector u_k and haven't influence on optimization criterion. It is used quadratic programming for criterion solving and minimization function has following form:

[1] This form true only for angle lower than 5°

$$\min_x J(x) = \min_x \frac{1}{2} x^T H x + f^T x \tag{11}$$

Where matrix ***H*** and vector ***f*** are equal:

$$\begin{aligned} H &= S^T Q S + D_i^T R D_i \\ f^T &= (SQ)^T (\tilde{y}_k - w) - D_i^T R \tilde{u}_k \end{aligned} \tag{12}$$

As next we define inequality for change of input constraint as:

$$\begin{aligned} du_{\min} &\le \frac{u_k - u_{k-1}}{T_s} \le du_{\max} \\ u_k &\le du_{\max} \cdot T_s + u_{k-1} \\ -u_k &\le -du_{\min} \cdot T_s - u_{k-1} \end{aligned} \tag{15}$$

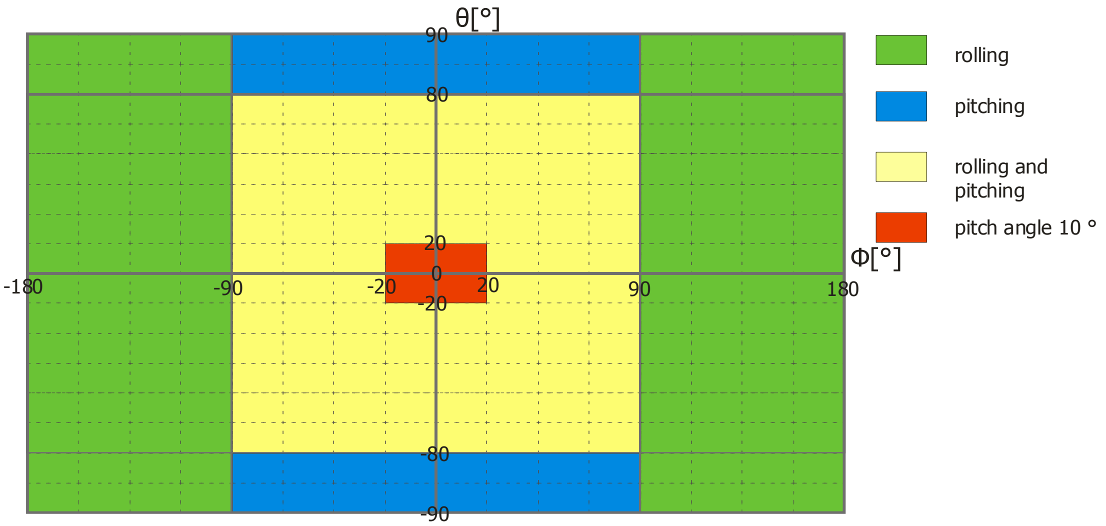

Figure 1 Φ-θ diagram

Constraints of inputs/outputs

In light of limitations it is suitable to solve MPC regulation problematic by quadratic programming in terms of limiting particular parameters of regulation. We can solve constraint equation as: ***A.x <= b***, where ***x*** is optimal input vector on prediction horizon T_p. When determining maximal and minimal output values, we proceed as follows:

$$\begin{aligned} Y_{\min} &\le y(k) \le Y_{\max} \\ Y_{\min} &\le V \cdot x(k) + S \cdot u_k \le Y_{\max} \end{aligned} \tag{13}$$

We obtain finally inequality for output constraint only by simple translation:

$$\begin{aligned} S \cdot u_k &\le Y_{\max} - V \cdot x(k) \\ S \cdot u_k &\le -Y_{\min} + V \cdot x(k) \end{aligned} \tag{14}$$

We can formulate input constraint:

$$\begin{aligned} u_{\min} &\le u_k \le u_{\max} \\ u_k &\le u_{\max} \\ -u_k &\le u_{\min} \end{aligned} \tag{15}$$

We can write whole inequality for constraint of optimal predictive control in matrix form:

$$A \cdot x \le b$$

$$\begin{bmatrix} -S \\ S \\ eye(n \cdot T_s) \\ -eye(n \cdot T_s) \\ eye(n \cdot T_s) \\ -eye(n \cdot T_s) \end{bmatrix} u_k \le \begin{bmatrix} Y_{\max} - V \cdot x(k) \\ -Y_{\min} + V \cdot x(k) \\ u_{\max} \\ u_{\min} \\ du_{\max} \cdot T_s + u_{k-1} \\ -du_{\min} \cdot T_s - u_{k-1} \end{bmatrix} \tag{0.1}$$

Where ***n*** is order of the system and T_s is sample period. We can count matrix ***A,*** from previous equation, at the beginning of control, during control process it remains the same.

On the contrary it has to be counted limitating factor ***b*** in every control step. Hereby is then proposed MPC regulator for linear model of aircraft motion with limited control magnitude and output values.

4 RECOVERY CONTROL

Until now we have not mentioned recovery control. In the concrete by which way/logic is recovery control leaded to stabilize the airplane. Such system logic can be preferably described by Φ-θ diagram. Location of the airplane is in every moment given by two values Φ (roll) and θ (pitch). Value of third position angle, heading, is not important for us in light of recovery control. Every such pair is represented by a point in Φ-θ diagram which is divided in sectors. In every sector is defined which part of control acts are turned on, i. e. which acts are to be provided.

Following function realizes Φ-θ diagram by examining the output predicted on the prediction horizon $\boldsymbol{T_p}$. This is used to determine when the roll and pitch reaches requested angle.. For particular step is set the control from next sector. Here it is used control where we optimize value of actuating intervention when knowing requested reference in advance. This is set by Φ-θ diagram logic so that for green sector (only rolling) is pitch constant and reqest for roll is zero. For yellow sector (synchronous rolling and pitching) is reference for roll and pitch zero. And finally in red sector (slight climb) is roll reference zero and pitch reference 10°.

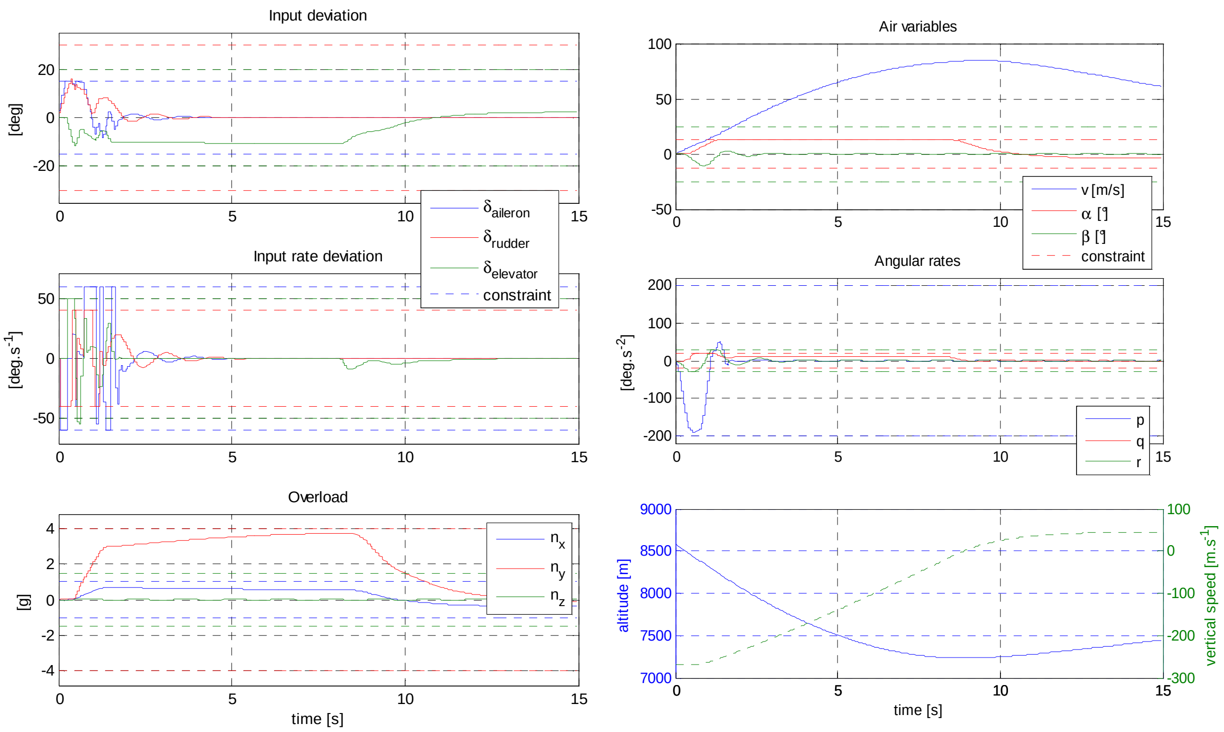

Figure 2 flight magnitudes during recovery

Basic consideration is that the goal of recovery system is slightly climbing flight with zero roll. As next it is necessary to ensure primary rolling (roll change) at great Φ angles followed by simultaneous rolling and pitching (pitch change). Reversely when recovering the plane with big initial pitch it it necessary to ensure pitching first. Then with lower value of pitch can be provided simultaneous rolling and pitching. This is show on figure 1.

It is obvious that there are two marginal sectors. Firstly it is rolling sector where absolute roll value is greater than 90° and secondly pitching sector where absolute pitch value is greater than 80°. For pitch between -80° and 80° and roll between -90° and 90° applies synchronous rolling and pitching to zero mode. Finally for absolute values of elevation smaller than 20° is the airplane stabilized to zero roll and pitch of 10° to keep the airplane slightly climbing.

5 SIMULATION

In this paragraph is introduced example of simulation of control system where initial value of pitch is 85°, roll is 120° and heading is set to 45°. The airplane is then in almost vertical flight rewounded on the back. This can simulate the final phase of spiral during which the pilot lost orientation and the airplane goes spontaneously to spiral heading towards the ground thanks to unstable spiral mode.

On the figure 2 is shown that maximal input magnitudes values were not overcome. Transition speeds of control surface deviation are in bounds set by us. Then it is to see that multiples, or more precisely mechanical-physiological limitations, are under limit values. Flight limit factors, such as angle of attack/yaw angle, are also in bounds.

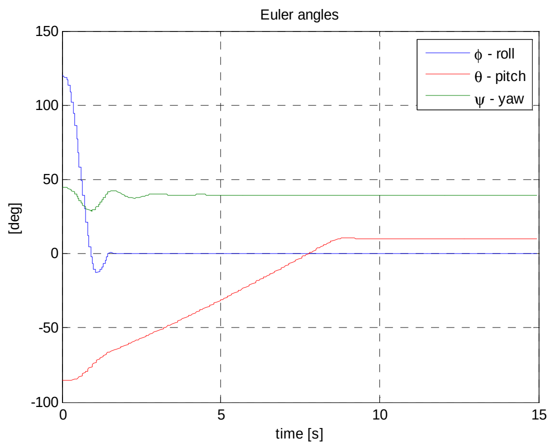

Figure 3 elevations during automatic recovery

From course of elevation it is obvious that change of roll is much faster than by pitch. This is caused partly by mass persistence in particular axes and partly by limited angle velocities. It is worth noticing that for change of pitch is firstly used maximal roll velocity which has to be then lowered due to limited angle of attack.

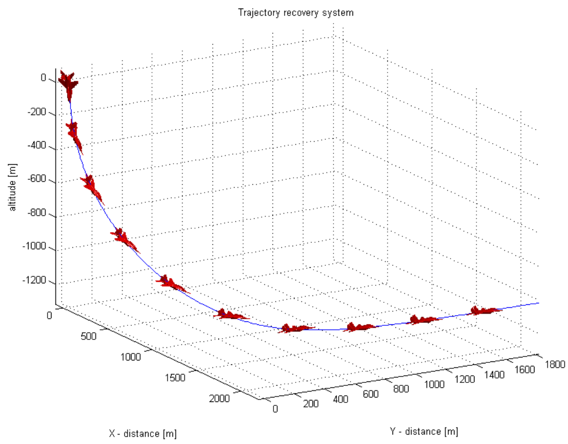

Figure 4 path of flight

6 CONCLUSION

In this paper we have presented how to design MPC strategy to control a linear aircraft model with a superior decision function. An advantage of MPC strategy is prediction ability of states and outputs and in dependence on prediction horizon we can optimize inputs for whole recovery maneuver. MPC for a nonlinear aircraft model will be a subject of future work.

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