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In this communication we consider the problem of the design of an airborne system whose function is to solve the problem of allocation of transportation aircraft actuators during manoeuvres. The case of a roll manoeuvre, which may be quite demanding for the wings structure, is more particularly considered. The aim of this supervision function, similar to the load alleviation function, is to control the bending and flexion moments of the wings while performing a manoeuvre which can turn to be extreme. The wings actuators considered are the ailerons, the spoilers and the flaps, but the other aerodynamic actuators, elevators and rudders, must be considered to take into account the existing coupling effects between the three body axis . Their limitations, such as position, speed and response time are considered explicitly in this study.

First the contributions of each actuator to the aerodynamic forces and moments and to the bending and the flexion moments, M_B and M_F, are considered within an initial additive framework. Different models, parameterized by their current angular deflection, are proposed to compute these contributions. In general these models present an affine form with respect to the corresponding deflection, so that we get expressions such as: $M_{ik} = M_{ik}^0 + \mu_{ik}\,\delta_k$ where M_{ik} is the i^{th} considered moment ($\in$ {roll, pitch, yaw, bending, flexion}), δ_k is the deflection of the k^{th} actuator ($k \in K=$ {aileron, flap, right spoilers 1 to n_s, left spoilers 1 to n_s, elevator, rudder }) and μ_{ik} is the effectiveness of actuator k to produce moment i. M_{ik}^0 as well as μ_{ik} depend of various flight parameters such as speed, angle of attack, bank angle, etc. Here the different aerodynamic surfaces composing the elevator as well as the rudder are not discriminated.

Then, given the nominal dynamics of the desired manoeuvre, the non-linear inverse control theory is used to determine the necessary roll, pitch and yaw moments: L_d, M_d and N_d. It is easy to check that the rotational dynamics of the aircraft, taken as a rigid body:

$$\dot{q} = \frac{1}{I_{xx}}((I_{xx} - I_{zz})\,r\,p - I_{xz}(p^2 - r^2) + M)$$

$$\begin{pmatrix} \dot{p} \\ \dot{r} \end{pmatrix} = \begin{bmatrix} I_{xx} & -I_{xz} \\ -I_{xz} & I_{zz} \end{bmatrix}^{-1} \begin{pmatrix} (I_{yy} - I_{zz})\,q\,r + I_{xz}\,q\,p + L \\ (I_{xx} - I_{zz})\,p\,q - I_{xz}\,q\,r + N \end{pmatrix}$$

are invertible with respect to the roll, pitch and yaw moments. Here I_{xx}, I_{yy}, I_{zz} and I_{xz} are inertia moments of the whole aircraft.

Then, it is necessary to formulate a decision problem, which must be solved at each instant in a discretized time scale, to determine the respective deflections of the different actuators so that the desired moments are produced by the aerodynamic actuators while bending and flexion moments remain at acceptable levels. The discretization of time must be chosen so that its period is not only smaller than the time constants related with the flying qualities of the aircraft but also smaller then the actuators response times.

Here different objectives can be adopted:

- use spoilers as less as possible. In general, aileron deflection is controlled by three servo actuators and present a smaller response time than spoilers which are in general controlled by a unique servo actuator. In that case the problem to be solved is to check that using only ailerons, elevator and rudder, all the objectives can be reached and all constraints are satisfied. If this is not possible this approach must be left to consider the additional actuators.

- minimize the mean deflection of the actuators given by the index:

$$\sqrt{\sum_{k\in K} S_k \delta_k{}^2} \,/ \sum_{k\in K} S_k$$

where the reference aerodynamic surfaces of the different actuators, S_k , are taken as weights. In this case the decision problem turns out to be a classical linear-quadratic optimization problem.

- minimize the drag resulting from the whole set of actuators. In this case the decision problem is more directly related with the energy performance of the aircraft during the flight. The corresponding index is in this case:

$$\sum_{k\in K} S_k \; C_{xk} \; \delta_k$$

where C_{xk} is the drag coefficient associated with the k^{th} actuator.

This last approach has been selected in this study. It results in the formulation of a small linear programming problem such as:

$$\min_{\delta_k} \; \sum_{k\in K} S_k \; C_{xk} \; \delta_k$$

under the constraints:

$$\sum_{k\in K} M_{Lk} \; \delta_k = L_d - \sum_{k\in K} M^0_{Lk}$$

$$\sum_{k\in K} M_{Mk} \; \delta_k = M_d - \sum_{k\in K} M^0_{Mk}$$

$$\sum_{k\in K} M_{Nk} \; \delta_k = N_d - \sum_{k\in K} M^0_{Nk}$$

and

$$\sum_{k\in K} M_{Bk} \; \delta_k \le M_{B\max} - \sum_{k\in K} M^0_{Bk}$$

$$\sum_{k\in K} M_{Fk} \; \delta_k \le M_{F\max} - \sum_{k\in K} M^0_{Fk}$$

with

$$\max\{\delta_{k\min}, \delta_k(t) - \dot{\delta}_{\max} \;\Delta t\} \le \delta_k \le \min\{\delta_{k\max}, \delta_k(t) + \dot{\delta}_{\max} \;\Delta t\} \qquad k \in K$$

Here Δt is the discretization period, $\dot{\delta}_{k\max}$ is the maximum deflection rate of actuator k and $\delta_k(t)$ is the current deflection of actuator k. This problem is useful not only to define, through its direct solution, minimum drag actuator deflections, but also to evaluate beforehand the feasibility of an intended manoeuvre. In that case, it is useful to observe that during the manoeuvre, only the constraints related with the desired roll, pitch and yaw moments, present changes. So, if the intended manoeuvre is characterized by the evolution of these three moments, it is possible to check that the feasible solution set of the linear programming problem remains non empty.

Two solution approaches can be adopted:

- one solution is a direct solution approach in with the linear programming problem is solved on line. In that case, an important difficulty when solving the above linear program is to guarantee that the time needed to get the solution is bounded by a value very small with respect to the discretization period adopted.

- Another solution makes use of a predictor, computed off line, to generate on line control signals towards the actuators according to the selected manoeuvre. In general this predictor can take the form of a feedforward neural network which has been trained to provide the solution of the linear problem for given flight conditions and desired levels of roll, pitch and yaw moments. Anyway, here also, it is also interesting to solve each instance of the linear programming problem as quick as possible to minimize the training time.

From one period to the next the linear programming problem changes slightly but the solution of the new linear programming problem can be quite different from the last one. However, it looks profitable to try to use the last solution as a starting point for the current problem. The solution of the linear programming problem being in the border of its feasible set, a scheme is developed to adopt, as starting point for the simplex procedure, the closer summit point of the new feasible set. Considering the observation about the moment levels during manoeuvre, this is a direct task. A dual linear approach can be also introduced to evaluate the distance to the solution during the iterations of the simplex. The number of these iterations is limited so that the maximum solution time is acceptable. Obviously, other solution approaches are available for the solution of this problem, however , the simplex method appears to be the more predictable in this particular case.
Then, the design of a feed-forward neural network to generate on line solutions to the allocation problem is discussed.

The case study which will be displayed in this paper, is relative to a wide body aircraft performing the manoeuvre characterized by the output equations:

$$\begin{cases} \ddot{\phi} + 2\varsigma\,\omega\,\dot{\phi} + \omega^2\,\phi = \omega^2\phi_c \\ q = 0 \\ \tau_r\,\dot{r} + r = (g/V)\sin\phi\,\cos\theta \end{cases}$$

where ζ, ω and τ_r are positive constants, g is the "gravity constant", V is the inertial speed, ϕ is the current bank angle, ϕ_c is the final bank angle and θ is the pitch angle. These equations correspond to a roll manoeuvre towards a stabilized turn with constant pitch angle. Numerical application for different values of the manoeuvre parameters allows to identify the trade-offs between manoeuvre characteristics and wings loads.
Another case study which is considered in the paper is the situation in which a wing actuators remains stuck at neutral position, the above approach is then useful to reallocate the control efforts such as either the flexion and bending constraints are satisfied or, if this is not possible, their violation is minimized.
Finally, the effective realization of such a function is discussed. One of the main consideration at this stage is relative to the availability of accurate and on time data.

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