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Robust off-line control allocation

Fabio A. de Almeida

IAE, Instituto de Aeronáutica e Espaço, 12228-904 São José dos Campos, Brazil

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ABSTRACT

This work presents a novel scheme for robust constrained control of multivariate over-actuated systems. It combines two well-known control techniques for systems with limitations: control allocation and reference governor. With allocation of control, the number of manipulated variables is reduced to only three aerodynamic moments around the aircraft body axes, simplifying considerably the subsequent control synthesis. To improve the robustness of the operation that converts virtual into real control inputs, the robust set of attainable moments is defined, which accounts for several uncertainties in the vehicle control effectiveness. This set is then treated as the main system constraint in a new form of reference governor. The virtual input is calculated based on feedback of estimated states and feedforward of the steady-state aerodynamic moment, but the reference is governed in order to guarantee constraint satisfaction. A sequence of off-line polyhedral projections eliminates the need of on-line optimization for the computation of control actions. The complete control method is then illustrated with two design cases. Simulations are conducted with two fighter aircraft models, in the presence of uncertainties on control and stability derivatives, as well as large variations in flight conditions. Results demonstrate satisfactory performance while tracking demands of large amplitude, with proper and admissible distribution of control effort.

1. Introduction

The advent of new aircraft configurations, focused on the fulfillment of highly strict handling qualities and performance requirements, is driving the design of new forms to control an aerial vehicle [25]. The basic relationship between three aerodynamic surfaces that generates three moments around the body axes may no longer exist in future aircraft design. Instead of this, multiple surfaces will be responsible of the task to create angular accelerations and velocities along one or more directions. Moreover, tolerance against faults, operational and airworthiness constraints may impose limitations at several levels of the control system. Safe separation and collision avoidance [11,24], envelope protection [26] and control physical limitations are already some of the challenges present on current flight control system design.

Fortunately, there are several control techniques already available to handle input and output constraints on multivariate systems. In the last years, three methods have been extensively studied, with several contributions: Model Predictive Control (MPC) [23], Reference Governor (RG) [17] and Control Allocation (CA) [16]. MPC is probably the most elaborated method among those three, since accounts for both input and output limitations in current and future control actions. This results in a constrained optimization problem that needs to be solved every sampling time. Off-line solutions, i.e. algorithms that do not require on-line optimization, are already available [2,7]. Nevertheless, the complexity of a MPC design increases significantly with the number of control effectors, demanding high computational effort to manipulate polyhedral sets [21].

Reference Governors can be seen as nonlinear schemes to enforce the satisfaction of closed-loop system constraints through manipulation of the reference commands. They are generally simpler to conceive than model predictive controllers, but also demands programming algorithms to solve the resulting constrained optimization. The preferable choice for over-actuated systems, i.e. more control effectors than reference inputs, has been Control Allocation, because is able to distribute efficiently virtual inputs (moments), demanded from the controller, among several control inputs. If constraints are also present, the problem of allocation of control may demand constrained optimization [14].

Thus, MPC, RG and CA offer the possibility to control over-actuated constrained systems, but with a higher level of complexity than unconstrained solutions. The on-line computational burden is one of the main drawbacks. Moreover, control allocation lacks of robustness against uncertainties in the input effectiveness. Present robust schemes are still based on expensive robust least-squares methods [12,6].

E-mail address: almeidafaa@iae.cta.br.

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Therefore, this work proposes a novel form of reference governor, followed by a new robust control allocation formulation, exploring the benefits of both methods and tackling the disadvantages of each technique. The large number of control effectors, which can compromise the synthesis of the constrained control, is reduced to only three, due to the control allocation. The physical control displacement limits are then projected onto a robust attainable moment set. This set is the main constraint of a new form of off-line reference governor that drives the reference inputs to maintain closed-loop feasibility, stability and performance, despite the presence of system uncertainties. During the operation of the controller, the virtual inputs are mapped to real control actions through a simple generalized inverse followed by a null space transformation [22]. The entire sequence of control computation is then executed without any type of constrained optimization algorithm. The proposed method is then simulated using two different aircraft numerical models, where the benefits are demonstrated: ADMIRE and F/A-18 HARV.

This paper is structured as follows. Section 2 establishes the constrained control problem and initial assumptions. Section 3 presents the concept of the Robust Attainable Moment Set and quasi-linear forms to convert virtual into real inputs. Section 4 introduces the off-line reference governor based on the virtual input constraints. Finally, section 5 shows two design examples of the complete controller using two highly-maneuverable aircraft models.

2. Problem formulation

This work separates the problem of control of over-actuated systems into two steps. The control design step assumes a approximate discrete-time state-space model defined by

$$\begin{aligned} x_{k+1} &= A_d x_k + B_d \upsilon_k + B_w w_k \\ w_{k+1} &= w_k \\ y_k &= E x_k \\ z_k &= H y_k \end{aligned} \tag{1}$$

where $x_k \in \mathbb{R}^n$ is the state vector, $\upsilon_k \in \mathbb{R}^3$ is the input vector of aerodynamic moment coefficients around the three body axes, $y_k \in \mathbb{R}^p$ is the output vector of observed variables, $w_k \in \mathbb{R}^3$ is the constant vector of disturbances and $z_k \in \mathbb{R}^3$ is the output vector of controlled variables. The disturbance vector is included to account for mismatches between the plant and the nominal model as well as constant external disturbances acting on the plant.

Assumption 1. The pair (A_d, E) is assumed to be detectable with E full row rank. The following condition is equivalent:

$$rank \begin{bmatrix} A_d - I & B_d \\ E & 0 \end{bmatrix} = n + p \tag{2}$$

Assumption 2. It is assumed that the state and disturbance vectors are estimated by a nominally asymptotically stable observer. The observer proposed by Maeder, Borrelli and Morari [20] is chosen for of this work, because also provides offset-free tracking of piece-wise step inputs.

Assumption 3. The disturbance is bounded and lies in a compact convex polyhedron containing the origin in its interior.

The objective of the control system is to asymptotically eliminate the tracking error given a piecewise constant reference command r_c, which is

$$z_k \xrightarrow[k \to \infty]{} r_c \tag{3}$$

in the presence of a disturbance w_k and given constraints on the state $x_k \in \mathbf{X}$, where $\mathbf{X}$ is a closed, bounded and convex set expressed by linear inequalities.

The constraints on virtual inputs drive the discussion of the second step of the control synthesis. It is assumed that the control inputs are constrained on the following closed, bounded and convex set

$$\Omega = \left\{ u \in \mathbb{R}^m | u_{min} \le u \le u_{max} \right\} \tag{4}$$

where $0 \in \Omega$. The image of Ω under the linear transformation B is the nominal Attainable Moment Set (AMS) [8,9] and represents the constraints on the virtual inputs of the system given by Eq. (1). While the set Ω is well-defined in terms of physical limitations, the moment set depends on the control effectiveness matrix B. Thus, plant-model mismatches can reduce the accuracy on the representation of the limitations on the virtual inputs. This may affect the stability and performance of the closed-loop system.

Therefore, the second step of the proposed control system in this work is to compute a control input u from a virtual input υ, where an uncertainty ΔB is included in the continuous-time control effectiveness matrix B. This problem of robust control allocation can be stated as

$$\begin{aligned} &\min_u \max J = \|(B + \Delta B)u - \upsilon\| \\ &\text{subject to: } u \in \Omega, \|\Delta B\|_\infty \le \rho \end{aligned} \tag{5}$$

In the next section, it will be presented a geometrical solution of the problem stated by Eq. (5). The controller synthesis is shown in the subsequent section.

3. Robust control allocation

Following the seminal work of Durham [8], the problem of control allocation can be seen as a constrained control problem, where a virtual input, assumed to be inside an attainable moment set, is demanded from the controller. Then, the control is computed using a transformation, linear or not, which maps virtual into real system inputs. During the control synthesis, the path to be followed is the opposite: first, the attainable moment set is computed based on the control displacement limitations and effectiveness, followed by the choice of virtual–real input mapping.

This section introduces the concept of Robust Attainable Moment Set, to cope with limitations caused by linear representations of the control effectiveness. After this discussion, a quasi-linear control mapping is presenting. The complete sequence of on-line calculations to perform the allocation of control herein presented is done without any type of optimization.

3.1. Robust attainable moment set

The attainable moment set of an aerial vehicle is the achievable set of aerodynamic moments generated through control surface deflections. It is a convenient way to express the capability of the system to create angular velocities around its three axes. The availability of numerical tools to compute and visualize such polyhedral sets makes this representation suitable for application in multivariate systems.

In linear control allocation, the nominal attainable set Φ is simply a image of the admissible controls under the linear transformation B

$$\Phi = \left\{ Bu \in \mathbb{R}^n | u \in \Omega \right\} \tag{6}$$

The numerical computation of Φ is easily done by multiplying each vertex of Ω by B and then computing the convex hull