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A two-stage approach for managing actuators redundancy and its application to fault tolerant flight control

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Abstract In safety-critical systems such as transportation aircraft, redundancy of actuators is introduced to improve fault tolerance. How to make the best use of remaining actuators to allow the system to continue achieving a desired operation in the presence of some actuators failures is the main subject of this paper. Considering that many dynamical systems, including flight dynamics of a transportation aircraft, can be expressed as an input affine nonlinear system, a new state representation is adopted here where the output dynamics are related with virtual inputs associated with the intended operation. This representation, as well as the distribution matrix associated with the effectiveness of the remaining operational actuators, allows us to define different levels of fault tolerant governability with respect to actuators' failures. Then, a two-stage control approach is developed, leading first to the inversion of the output dynamics to get nominal values for the virtual inputs and then to the solution of a linear quadratic (LQ) problem to compute the solicitation of each operational actuator. The proposed approach is applied to the control of a transportation aircraft which performs a stabilized roll maneuver while a partial failure appears. Two fault scenarios are considered and the resulting performance of the proposed approach is displayed and discussed.

1. Introduction

To meet the stringent reliability and safety requirements for critical systems such as modern aircraft,[1] spacecraft,[2] hazardous material processing,[3] marine vehicles[4] and over-redundant actuator systems are often introduced. Many of these controlled systems are known to be complex nonlinear systems. Nowadays, direct nonlinear control law design techniques such as sliding mode control,[5] nonlinear inverse control,[6] backstepping control[7] as well as combinations of these techniques[8,9] are available

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to provide improved control performances. However, since these control design techniques do not consider explicitly actuators' failure scenarios, they should be completed to allow the management of these hazardous situations. Then, the control of these nonlinear systems while managing actuator redundancy when facing control channels' failures remains a challenge.

Two main active fault tolerant control strategies have been developed to manage these failure scenarios depending on the availability of a fault detection and identification (FDI) device[10]: adaptive control and two-stage approaches (control allocation). Adaptive control methods estimate online the effectiveness of actuators and redistribute effects accordingly, while control allocation techniques separate the control law synthesis task from the actuator distribution task which is dependent on the FDI diagnostic. It appears that the adaptive control strategy provides acceptable results only in the case of limited degradation of actuators' effectiveness[11] comparable with a parameter change scenario. When using a control allocation scheme, a large variety of failure cases can be handled successfully depending on the FDI performance and the controllability resulting from the remaining operational actuators.

Over the past two decades, different control allocation methods have been developed. The explicit ganging method[12] can be used when it is obvious as to how to combine redundant actuators. The direct allocation method[13,14] attempts to match the desired control efforts in both magnitude and direction. Daisy chaining[15] assumes a hierarchy of actuators and distributes the desired control efforts according to some priority. Besides these direct methods, optimization based control allocation methods making use of linear programming,[16] quadratic programming,[17] even nonlinear programming[18] have been proposed. The optimization based approaches try to use the healthy actuators to the most possible degree as well as guarantee the integrity of the system and performance when some actuator failure occurs and has been detected and identified successfully. Numerical approaches such as active set, interior point and neural networks can be used to effectively solve the resulting optimization problems[19–21] and implement them in an online control context. These approaches have been applied in reconfigurable control allocation such as flight control, control of marine vehicles and robots.[19–22]

This paper considers the case of a complex nonlinear system, provided with redundant actuators which are subject to some partial actuator failure while performing a standard maneuver. Here it is supposed that an FDI scheme produces a timely exact diagnostic for the different actuators and control channels. Then a general two-stage approach to deal with this situation is proposed. This approach makes use of an output based state representation which is associated with virtual inputs, which is output state representation with associated virtual inputs (OSVI), and the distribution of these virtual inputs among the operational actuators. This new representation allows us to introduce some new concepts with respect to fault tolerant governability and is in accordance with the adopted two-stage approach. At the first stage, according to the desired maneuver, virtual inputs are computed through the use of a nonlinear control technique, while at the second stage a control allocation problem, considering the remaining operational actuators, is solved.

2. Output state representation with associated virtual inputs

Many dynamical systems admit a state space representation termed input affine:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \sum_{j=1}^{m} g_j(\boldsymbol{x})u_j \tag{1}$$

where $\boldsymbol{x} \in \mathbf{R}^n$ is the state vector representing the system dynamics, u_j $(j = 1, 2, \ldots, m)$ the control input, $\boldsymbol{f}(\boldsymbol{x})$ and $g_j(\boldsymbol{x})$ $(j = 1, 2, \ldots, m)$ the smooth vector fields of $\boldsymbol{x}$.

When considering an output trajectory tracking problem for this nonlinear system, a characteristic output vector must be chosen and the corresponding output based state representation can be adopted to compute the corresponding control signal according to a nonlinear control technique.[23] Let

$$\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}), \quad \boldsymbol{y} \in \mathbf{R}^p \tag{2}$$

be the chosen independent outputs, where $\boldsymbol{h}(\boldsymbol{x})$ is a smooth vector field of $\boldsymbol{x}$. It is supposed that $p < n$ and $p < m$. The output based state vector is given by

$$\boldsymbol{X} = \left[y_1, \dot{y}_1, \ldots, y_1^{(r_1)}, \ldots, y_p, \dot{y}_p, \ldots, y_p^{(r_p)}, z_1, z_2, \ldots, z_q\right]^{\mathrm{T}} \tag{3}$$

$$\text{with } q + \sum_{j=1}^{p}(r_j + 1) = n \tag{4}$$

where r_j $(j = 1, 2, \ldots, p)$ is the relative degree of output y_j, and z_i $(i = 1, 2, \ldots, q)$ the inner dynamics. In the following text, it is supposed that the output variables are chosen so that there are no left internal dynamics and that the system is governable when adopting these outputs. Then the output based state representation can be written as

$$\dot{\boldsymbol{X}} = \boldsymbol{F}(\boldsymbol{X}) + \boldsymbol{G}(\boldsymbol{X})\boldsymbol{u} \tag{5}$$

where $\boldsymbol{u} \in \mathbf{R}^m$ is the control inputs' vector, $\boldsymbol{F}(\boldsymbol{X})$ a vector of dimension n, and $\boldsymbol{G}(\boldsymbol{X}) \in \mathbf{R}^{n\times m}$ a matrix with p non zero rows at positions $s_1, s_2, \ldots, s_p$ given by

$$\begin{cases} s_1 = \sum_{k=1}^{1}(r_k + 1) \\ s_2 = \sum_{k=1}^{2}(r_k + 1) \\ \vdots \\ s_p = \sum_{k=1}^{p}(r_k + 1) \end{cases} \tag{6}$$

and with zero rows for any other positions.

Then, the OSVI is written as

$$\dot{\boldsymbol{X}} = \boldsymbol{F}(\boldsymbol{X}) + \boldsymbol{H}\boldsymbol{v} \tag{7}$$

where $\boldsymbol{H} \in \mathbf{R}^{n\times p}$, whose (s_k, k)th elements are 1 and other elements are 0 which can be expressed as

$$\begin{cases} H_{s_k k} = 1 & (k = 1, 2, \ldots, p) \\ H_{ij} = 0 & \text{Otherwise} \end{cases}$$

$\boldsymbol{v}$ is a vector with element $v_i = \sum_{j=1}^{m} G_{s_i j}(\boldsymbol{X})u_j$ $(i = 1, 2, \ldots, p)$, with $G_{s_i j}(\boldsymbol{X})$ the (s_i, j) th element of matrix $\boldsymbol{G}(\boldsymbol{X})$, or