A Nonlinear Guidance and Active Fault Tolerant Control System for a Fixed Wing Unmanned Aerial Vehicle

G. Bertoni, N. Bertozzi, P. Castaldi* and S. Simani

Abstract — By using an interactive architecture of independently designed guidance and active fault tolerant control systems, this work proposes the development of a novel Guidance and Active Fault Tolerant Control Scheme for a fixed wing Unmanned Aerial Vehicle. As to the guidance segment, an approach, of the Feedback Linearization type, has been exploited for developing, directly on the dynamic model of the fixed wing Unmanned Aerial Vehicle, the guidance system. With reference to the control segment, this paper proposes a novel Active Fault Tolerant Control Scheme based on Adaptive Filters designed by means of the NonLinear Geometric Approach. The aim of these adaptive filters is to provide a fault estimate, which is used in a further control loop, thus avoiding a logic-based switching controller. The simulation results show good tracking capabilities, asymptotic fault accommodation and a stability analysis with respect to perturbed initial condition. Finally a comparison with the performance obtained by using the fault estimate obtained by another method is given.

I. INTRODUCTION

A conventional feedback control design for a complex system may result in an unsatisfactory performance, or even instability, in the event of malfunctions in actuators, sensors or other system components. To overcome these points, new approaches to control system design have been developed in order to tolerate component malfunctions, while maintaining desirable stability, and performance properties. This is particularly important for safety-critical systems, such as aircraft and spacecraft applications. In general, fault tolerant control methods are classified into two types, i.e., Passive Fault Tolerant Control Scheme (PFTCS), and Active Fault Tolerant Control Scheme (AFTCS) [1, 2]. In a PFTCS, controllers are fixed and are designed to be robust against a class of presumed faults. This approach does not need a fault estimate (or detection) or controller reconfiguration, but only limited fault-tolerant capabilities [2, 3]. In contrast to a PFTCS, an AFTCS reacts to the system component faults actively by reconfiguring control actions. An AFTCS relies heavily on real-time Fault Detection and Diagnosis (FDD) schemes to provide the most up-to-date information about the true status of the system. Usually, this information can be used from logic-based switching controller or a feedback of the fault estimate. The approach proposed in this paper relies on the latter strategy. Over the last three decades, the growing demand for safety has led to the development of many FDD techniques, see, e.g., the survey works [1, 4, 5]. Regarding the AFTCS design, it was argued that good FDD is needed [2, 3]. Moreover, it was claimed that, for the system to react properly to a fault, timely and accurate detection and location of the fault itself is needed. Fault Detection and Isolation (FDI) is the area where research studies have mostly been explored. On the other hand, FDD schemes are a challenging topic because they provide also the fault estimate. FDI and FDD schemes usually exploit dynamic observers or filters. Plant-model mismatches can cause false alarms or, even worse, missed faults. Robustness issues in FDI and FDD are therefore very important [4, 6, 7].

The present paper is focused on the development of a novel GAFTCS, which integrates a reliable and robust FDD scheme with the design of a controller reconfiguration system, together with a nonlinear guidance system based on a method of the FL type. Concerning the FDD procedure, this paper proposes a nonlinear scheme, developed by Castaldi, et al., in [8], which provides the fault detection, isolation and size estimation. The FDD nonlinear method is based on the NonLinear Geometric Approach (NLGA) developed by De Persis and Isidori in [9]. By means of the NLGA strategy, disturbance decoupled Adaptive Filters (NLGA-AF) providing fault estimation are developed. It is worth observing that the disturbances are often the other faults to be decoupled. The procedure given in [9] is concerned only with fault detection and isolation, controller reconfiguration is not given, as done in this paper. In particular, controller reconfiguration exploits a second control loop, depending on the on-line estimate of the fault signal. One of the main advantages of this strategy is that a structure of logic-based switching controllers is not required. The novelty of the proposed AFTCS lies hence in the feedback of the estimated fault signal, which is obtained by the adaptive filters designed via the NLGA. The Guidance System (GS), based on the FL type method, represents an application of a method borrowed from robotics, which turns out to be interesting as it directly applies to the dynamic model of the UAV. In fact, usually, the guidance system is designed by means of an aircraft description as a point mass. The complete GAFTCS for the fixed wing UAV has been implemented in the Matlab®/Simulink® environments and tested in a turn flight conditions in presence of wind shear. The stability of the overall scheme is tested by simulations.

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with different perturbed initial conditions and fault size. Furthermore, comparison with the performance of an AFTC scheme exploiting a different FDD (see [12]) is given.

The paper is organised as follows. Section II provides the description of the fixed wing aircraft model used for the simulations. Section III describes the design of a Guidance System (GS) based on the FL type method. Section IV summaries both the design of the FDD scheme based on the NLGA strategy, and the structure of the novel AFTCS strategy. Section V describes the design of the NLGA-AF for the estimation of the aircraft faults. Section VI shows the results achieved in simulation. Section VII ends the paper highlighting the main achievements and the open problems of the work.

II. FIXED WING UAV DYNAMIC MODEL

The following nomenclature will be used throughout the paper: \( x, y, z \) East, North, Up; \( V \) airspeed; \( \gamma \) flight path angle; \( \chi \) heading angle; \( W \) airplane weight; \( T \) thrust; \( n \) load factor; \( \mu \) bank angle; \( V_a \) wind speed; \( \rho, S \) air density, reference area; \( k, C_{D_w} \) induced and parasite drag coefficient, \( g \) gravitational acceleration.

The dynamic model of the fixed wing UAV is often used for control system design purposes. It consists of the following equations taken from [11]:

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\dot{V} \\
\dot{\gamma} \\
\dot{\chi}
\end{bmatrix} =
\begin{bmatrix}
V \cos \chi \cos \gamma \\
V \sin \chi \cos \gamma \\
V \sin \gamma \\
g((T + f_T) - D) / W - \sin \gamma \\
(g / V)((n + f_n) \cos \mu - \cos \gamma) \\
(g(n + f_n) \sin \mu) / V \cos \gamma
\end{bmatrix}
\] (1)

with the drag expression given by:

\[
D = 0.5\rho(V - V_a)^2 SC_{D_0} + 2k(n + f_n)^2 n^2 W^2 / \left[\rho(V - V_a)^2 S\right] (2)
\]

It is worth observing that the control inputs are \( T, n \) and \( \mu \), while \( g \) denotes the gravity acceleration constant. The terms \( f_T \) and \( f_n \) are the faults signals on \( T \) and \( n \), respectively. These signals are the faults usually considered for this model [10, 11]. In this paper, in order to model the actuator faults or, for example, battle damage, step functions are considered for \( f_T(t) \) or \( f_n(t) \), according also with [8] and [9]. Moreover, due to lack of space, the simulation results will regard only the case of the fault \( f_n \), as described in [11]. The parameters values are [10, 11]: \( \rho = 1.2251 \text{ km} / \text{m}^3; W = 14.515 \text{ kg}; S = 37.16 \text{ m}^2; T_{\text{max}} = 113.868.8 \text{ N}; C_{r_{\text{max}}} = 2.0; n_{\text{max}} = 7; k = 0.1; C_{D_w} = 0.2 \).

III. FEEDBACK LINEARIZATION BASED GS

As previously mentioned, the GS is designed by the FL type methodology directly applied to the dynamic model of the UAV. The linearization obtained allows to generate from the desired trajectory the three input signal \( T, n, \) and \( \mu \). Therefore, the guidance system is based on model (1) with no theoretical system approximation. It is worth noting, apart the main results related to the AFTC scheme, that the FL type tool is a method usually exploited in robotics, but quite unusual for aerospace applications. It is assumed that the reader is familiar with the concept of FL. However, it application to the aircraft model will be described in more detail. Due to several constraints of the FL type method, and to the system input strong nonlinear characteristics, the original system (1) needs to be augmented by three new states, corresponding to the original system inputs, i.e.,

\[
\pi(\bar{\eta}) = \begin{bmatrix} T \ n \ \mu \end{bmatrix}^T = \begin{bmatrix} \xi \ \zeta \ \nu \end{bmatrix}^T,
\]

where \( \xi, \zeta \) and \( \nu \) represent the new inputs of the augmented system, and they will be designed with respect to the desired Cartesian trajectory. Given a desired Cartesian trajectory motion, it is well known that the corresponding state trajectory is required:

\[
\begin{bmatrix}
x_d(t) \\
y_d(t) \\
z_d(t) \\
V_d(t) \\
\gamma_d(t) \\
\chi_d(t)
\end{bmatrix} =
\begin{bmatrix}
x_a(t) \\
y_a(t) \\
z_a(t) \\
V_a(t) \\
\gamma_a(t) \\
\chi_a(t)
\end{bmatrix}
\] (3)

In this case, the FL type does not exploit difficult mathematical tools, when feasible trajectories are considered. As shown in the following, this situation corresponds to the nonzero condition velocity \( V \neq 0 \) during the path, which is compatible with the working condition of the original motion system (1). It will be assumed that an arbitrary trajectory remains feasible, as long as it does not come to a stop. In the following, the exact dynamic linearization procedure will be developed with reference to system (1). It will be shown also that it is necessary to define an augmented system in order to obtain an overall linear system.

The differentiation of the output vector with respect to time yields to:

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\dot{V} \\
\dot{\gamma} \\
\dot{\chi}
\end{bmatrix} =
\begin{bmatrix}
x_a(t) \\
y_a(t) \\
z_a(t) \\
V_a(t) \\
\gamma_a(t) \\
\chi_a(t)
\end{bmatrix}
\]

\[
\begin{bmatrix}
-2V^2 \chi \sin \gamma \cos \gamma - 2V^2 \gamma \sin \gamma - V^2 (\chi^2 + \gamma^2) \cos \chi \cos \gamma \\
V^2 \sin \gamma \cos \gamma - V^2 \chi \cos \gamma - V^2 \sin \gamma \cos \gamma \\
2V^2 \sin \gamma - 2V^2 \chi \sin \gamma - 2V^2 \gamma \sin \gamma - V^2 (\chi^2 + \gamma^2) \sin \gamma \sin \gamma \\
V^2 \sin \gamma \cos \gamma + V^2 \chi \cos \gamma + V^2 \sin \gamma \cos \gamma \\
2V^2 \gamma \cos \gamma - V^2 \chi \sin \gamma + V^2 \gamma \sin \gamma + V^2 \gamma \sin \gamma
\end{bmatrix}
\] (4)
where the terms $\tilde{V}$, $\tilde{\gamma}$, and $\tilde{\chi}$ are functions of the new inputs $\xi$, $\zeta$, and $\nu$, as well as the terms depending only on the augmented system states. At this point it is possible to define the third time derivative of the system outputs by means of a linear relationship of the augmented system inputs $\xi$, $\zeta$, and $\nu$, via the explicit use of the decoupling matrix $A(q)$:

$$
\begin{bmatrix}
\dot{\mathbf{x}} \\
\ddot{\mathbf{x}} \\
\mathbf{y}
\end{bmatrix} = F(q) + A(q) 
\begin{bmatrix}
\xi \\
\zeta \\
\nu
\end{bmatrix}
$$

(5)

Where $F(q)$ is composed of terms not depending on $\xi$, $\zeta$, and $\nu$, and $A(q)$ is non-singular if $V \neq 0$ and $n \neq 0$. Under these conditions, it is possible to write

$$
\begin{bmatrix}
\xi \\
\zeta \\
\nu
\end{bmatrix} = -A^{-1}(q)F(q) + A^{-1}(q) 
\begin{bmatrix}
\dot{\mathbf{x}} \\
\ddot{\mathbf{x}} \\
\mathbf{y}
\end{bmatrix}
$$

(7)

To obtain the resulting dynamic compensator, in an implicit form, Equation (7) is added with three decoupled integration of each generated input in order to determine $T$, $n$, and $\mu$ as inputs of the original rigid body model.

In other words, the expressions (7) and $\pi(\overline{q}) = [T \; n \; \mu]^T = [\xi \; \zeta \; \nu]^T$ are the inverse system of (1), so that the chain of (7) and

$$
\pi(\overline{q}) = [T \; n \; \mu]^T = [\xi \; \zeta \; \nu]^T
$$

represents a system with input $[\overline{x}_d(t) \; \overline{y}_d(t) \; \overline{z}_d(t)]$ (i.e. the third derivative of the desired trajectory) and the actual trajectory itself as output. Therefore the augmented system is fully linearized, as it results from the chain of three integrators for each element of the output vector. The dynamic compensator, as already noticed, has a potential singularity at $V = 0$ and $n = 0$ i.e., when the UAV is not moving and falling. This condition must be taken into account when designing control laws on the equivalent linear model. However, when aircrafts are considered, both conditions cannot obviously occur at the same time (the motion system has also a singularity for the zero velocity condition). However, there is another functional condition that has to be fulfilled in order to guarantee the correct behaviour of the guidance system. The dynamic compensator and the aircraft must be initialised perfectly at the same condition. In fact, even a small difference can lead to a complete wrong generation of the inputs by the dynamic compensator. To avoid this strict condition, as it will be shown in the paper, an external position feedback has been developed. It is well known how the guidance system generates its outputs. The NGC architecture is described in Figure 1.

![Figure 1: Guidance system equivalent dynamic system.](image)

It is worth noting that the global guidance and control system have to be made robust with respect to external disturbances and non-perfect initialisation of the flight parameters. Obviously, thanks to the FL type method, the control loop gains can be computed by means of linear methodologies.

IV. FDD DESIGN: NLGA ADAPTIVE FILTERS

In this section the symbol $f$ denotes both the fault $f_n$ and $f_T$. The design of NLGA-AF used to obtain an FDD scheme relies directly on the UAV model (1) and exploits the following procedure. The proposed FDD scheme can be applied only if the fault detectability condition, described in [9], holds and the following constraints are satisfied: the fault is a step function of the time, hence the parameter $\dot{f}$ is a constant to be estimated; it is possible to determine a coordinate change in the state and output space, such that in the new coordinates there exists a proper scalar component of the state vector, denoted with $\overline{x}_{1s}$, such that there exist a corresponding scalar component of the output vector $\overline{y}_{1s} = \overline{x}_{1s}$, and the following relation holds (see details in [8]):

$$
\dot{\overline{y}}_{1s}(t) = M_1(t) \cdot f + M_2(t)
$$

(8)

where $M_1(t) \neq 0, \forall t \geq 0$. Moreover $M_1(t)$ and $M_2(t)$ can be computed for each time instant, since they are functions just of input and output measurements. It is important to note that, by means of the NLGA structural decomposition
[8, 9], the subsystem (8) is affected by the fault to be estimated, and decoupled from the other faults. In this way it is possible to determine, in the new coordinates, a subsystem affect by \( f_n \) and decoupled from \( f_F \), and vice versa. On the basis of (8) it is possible to design an adaptive filter estimating, e.g., \( f_n \) and decoupled from \( f_F \) (as described in the following) and vice versa. In this way, both the fault estimate and its isolation can be achieved.

**Problem 1** The design of an adaptive filter is required, with reference to the system model (8), in order to perform an estimation \( \hat{f}(t) \), which asymptotically converges to the magnitude of the actual fault \( f \).

The proposed NLGA-AF that solves Problem 1 is based on a least squares algorithm with forgetting factor based described by the following adaptation law [8]:

\[
\begin{align*}
\dot{P} &= \beta P - \frac{1}{N^2} P^2 \bar{M}_1^2, \\
\dot{f} &= P \epsilon M_1, \\
P(0) &= P_0 > 0, \\
\hat{f}(0) &= 0
\end{align*}
\]  

(9)

where the following equations represent the output estimation and the corresponding normalized estimation error, respectively:

\[
\begin{align*}
\bar{y}_{ls} &= M_1 \hat{f} + M_2 + \lambda \bar{y}_{ls} \\
\epsilon &= \frac{1}{N^2} (\bar{y}_{ls} - \bar{y}_{ls})
\end{align*}
\]  

(10)

Note that all the involved variables of the adaptive filter in (18) are scalar. In particular, \( \lambda > 0 \) is a parameter related to the bandwidth of the filter, \( \beta \geq 0 \) is the forgetting factor and \( N^2 = 1 + \bar{M}_1^2 \) is the normalisation factor of the least squares algorithm. Moreover, the proposed adaptive filter exploits the signals \( M_1 \), \( M_2 \), and \( \bar{y}_{ls} \), which are obtained by means of the low-pass filtering of the signals \( M_1 \), \( M_2 \), \( \bar{y}_{ls} \) shown in (19):

\[
\begin{align*}
\dot{M}_1 &= -\lambda M_1 + M_1, \\
\dot{M}_2 &= -\lambda M_2 + M_2, \\
\dot{\bar{y}}_{ls} &= -\lambda \bar{y}_{ls} + \bar{y}_{ls}, \\
M_1(0) &= 0, \\
M_2(0) &= 0, \\
\bar{y}_{ls}(0) &= 0
\end{align*}
\]  

(11)

**Lemma 1** The considered adaptive filter is described by Eqs. (9)-(11). The asymptotic relation between the normalised output estimation error \( \epsilon(t) \) and the fault estimation error \( f - \hat{f}(t) \) has the form:

\[
\lim_{t \to \infty} \epsilon(t) = \lim_{t \to \infty} \frac{\bar{M}_1(t)}{N^2(t)} (f - \hat{f}(t))
\]  

(12)

The proof of Lemma 1 is reported in [8].

**Theorem 1** The adaptive filter described by Eqs. (9)-(11) represents a solution to Problem 1, so that \( \hat{f}(t) \) provides an asymptotically convergent estimation of the magnitude of the actual step fault \( f \).

The proof of Theorem 1 is reported in [8].

V. NLGA-AF ESTIMATION OF AIRCRAFT FAULTS

As described in the Sections 1 and 2, in order to assess the performance of the proposed FDD schemes, the UAV simulation model is used. Fortunately this model directly fulfils the NLGA requirements with reference to \( f_n \). On the other hand, with reference to \( f_F \), it is possible to obtain a synthesis model satisfying the NLGA assumptions by means of simple approximation of the simulation model. In this way, it can be shown that it is possible to achieve good estimates also for the fault \( f_F \). For the sake of clarity and due to lack of space, this paper focuses only on the case of the fault \( f_n \).

With reference to Section 4, the design of the NLGA-AF described by (9)-(11) for \( f_n \) is based on these dynamics:

\[
\begin{align*}
\dot{\bar{y}}_{ls} &= M_{1n} f_n + M_{2n} \\
M_{1n} &= \frac{g k_c \cos \mu}{V} \\
M_{2n} &= \left( \frac{g}{V} \right) \left( n \cos \mu - \cos \gamma \right)
\end{align*}
\]  

(13)

It is worth observing that \( M_{1n}(t) \approx 0 \), \( \forall t \geq 0 \), since the bank angle \( \mu \) has been kept far from the value of 90° during the set of simulations performed in this work.

Regarding the AFTCS, the logic scheme of the integrated adaptive fault tolerant approach is shown in Figure 2, where the following nomenclature and symbols have been used: \( u_r \), reference input (e.g. the reference trajectory); \( u \), actuated input; \( u_c \), controlled input; NGC, Navigation and Guidance.
Control system; \( u_{NGC} \), feedback signal from the NGC system; \( y \), controlled output (e.g., the aircraft trajectory); \( f \), actuator fault; \( \hat{f} \), estimated actuator fault.

Therefore, the logic scheme depicted in Figure 2 shows how the AFTCS strategy has been implemented by integrating the FDD module (i.e., the NLGA adaptive filters) with the existing NGC system. From the controlled input and output signals, the FDD module provides the correct estimation \( \hat{f} \) of the actual actuator fault \( f \), which is injected into the control loop, for compensating the effect of the actuator fault itself. After this correction, the current NGC module provides the exact tracking of the reference trajectory. Both the simulation results proposed in this work and the analytical results presented in future works have shown that the feedback of the estimated fault \( \hat{f} \) improves the identification of the fault signal \( f \) itself, by reducing also the estimation error and possible bias due to the model-system mismatch.

The formal proof of the stability of the overall AFTCS will be investigated in further works. However, simulation results highlight that the aircraft state variables remain confined to a bounded set, which assures standard flying quality, even in the presence of large fault sizes. Moreover, the assumed fault conditions do not modify the system structure, thus guaranteeing flexibility and global stability.

**VI. SIMULATION RESULTS**

In this section simulations show the performance and the stability properties of the proposed GAFTCS. Moreover, a comparison with a method (see [12]) exploiting a different FDD module is also provided. A circular trajectory corresponding to a turn characterized by a radius of curvature of \( 1000 \text{ m} \), true air speed \( V \) of \( 52.36 \text{ m/s} \) and altitude \( H \) of \( 330 \text{ m} \) (so that \( 120 \text{ sec} \) corresponds to the so-called ‘turn time’), has been implemented. The following results refer to the simulation in case of actuator fault \( f_n \) with a size of \(+0.5\) and commencing at \( t = 60 \text{s} \). It is important to note that the estimate of \( f_n(t) \) is decoupled from \( f_n(t) \) thanks to NLGA. Figure 3 shows the tracking error of the overall GAFTCS with reference to the reference trajectory when the fault is recovered (dashed line) and without fault accommodation (continuous line). The tracking error is defined as the Euclidean distance between the locus of the points of the reference trajectory and the corresponding actual three-dimensional aircraft position. The simulations have been performed by considering noise signals modelled as white noises affecting the system state and inputs. Moreover a wind shear of \( 1 \text{ m/s} \) coming from South has been considered starting from \( t = 30 \text{s} \). It is worth observing that the fault is correctly estimated, the corresponding figure is not given due to lack of space. It can be observed that Figure 3 shows that the error introduced by the wind shear is reduced by the NGC and is not affected by the presence of the FDD module. Furthermore, as previously remarked, the error due to the fault is strongly reduced by means of the fault estimate feedback (denoted “with AFTCS”) with respect to the case without the fault estimate feedback (denoted as “without AFTCS”). Moreover the tracking errors on each space component due to sensor noise are in phase, and this leads to the constant error of about \( 0.5 \text{ m} \) shown in Figure 3. The GAFTCS stability properties are investigated by simulations performed with initial conditions in the attitude states \([V\gamma\chi]\) change randomly within a \( \pm25\% \) range between the equilibrium values. A fault \( f_n \) with a size of \(+0.3\) and commencing at \( t = 5 \text{s} \) affects the system during the transient given by stability analysis. Figure 4 shows that the system state variables return to the equilibrium values, proving the overall system stability, and even the fault occurrence does not affect the stability properties. As show in Figure 4 the mean tracking error induced by the variable system initialization goes to zero within less than half a ‘turn time’. The next analysis, reported in Figure 5, compares the performances of the proposed GAFTCS with another method of fault detection described in [12].

![Figure 2: Logic diagram of the integrated AFTCS strategy.](image)

![Figure 3: Tracking errors with and without AFTCS scheme](image)
with a size of $+0.3$ and commencing at $t = 20s$, has been considered in the simulation.

![Stability analysis](image1.png)

**Figure 4: stability analysis**

Due to the noise sensitivity of the method [12], the comparative performance analysis of Figure 5 considers white noise signals with a lower standard deviation with respect to the case of Figure 3. In more detail, the input noise signals have a standard deviation of about 5% of the equilibrium values. The state measures have a standard deviation of $10^{-1}$ for the Pitot signal and a standard deviation of $10^{-3}$ for the flight angles. It can be observed that these noise levels can be obtained in practice by using high cost sensors and filters based on a noise error model (obtained, for example, by mean of a laboratory calibration based on a test-rig). The fault estimates and tracking errors comparisons, reported in Figure 5, shows that the proposed GAFTSCS proves a good robustness with respect to signal noises. On the other hand, the Kaboré-Wang FDD module suffers greatly signals noises.

![Comparison analysis](image2.png)

**Figure 5: Comparison of proposed GAFTCS with method [12]: fault estimates and tracking errors**

VII. CONCLUSIONS

This paper described the development of a novel active fault tolerant control scheme, which integrates a robust fault diagnosis scheme with the design of a controller reconfiguration system. The methodology was based on a fault detection and diagnosis procedure relying on adaptive filters designed via the nonlinear geometric approach. The main point of the proposed fault tolerant scheme consisted of the use of the fault signal estimated by these adaptive filters and exploited in the closed loop scheme for improving the performances of the overall system. The fault tolerant strategy was tested by using a fixed wing UAV model. An approach relying on the feedback linearization method was exploited for developing a guidance system directly designed on the dynamic model of the fixed wing UAV. The simulations showed that the overall guidance and control system guidance provided fault rejection, high flexibility, good tracking accuracy, and global guidance performance. The important aspect of the suggested scheme is that the fault tolerant capabilities, or their improvement, also in the case of already implemented fault tolerant guidance systems, can be obtained by independent design of the guidance system and the fault detection and diagnosis module. Further investigations will regard the proof of the stability of the overall fault tolerant scheme, and its application to real case studies.

REFERENCES


