Gain-Scheduled Control Using Fuzzy Logic and Its Application to Flight Control

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I. Introduction

GAIN-SCHEDULED control is one of the useful control techniques for linear parameter-varying (LPV) and nonlinear systems.[1,2] A typical design procedure for a gain-scheduled controller is as follows: For selected operating points or equilibrium points, multiple linear time-invariant (LTI) models for the original plant are constructed (step 1), and a linear controller is designed for each LTI model so as to stabilize the closed loop and to satisfy the control specifications (step 2). A disadvantage of gain-scheduled control is that it is not easy to design a controller that guarantees the global stability of the closed-loop system over the entire operating range from the theoretical points of view. Although some basic analyses[2,3] have been presented, numerical simulations are generally used to verify the global stability. Another disadvantage is that the interpolation increases in complexity as the number of scheduling parameters increases.

As an improvement, this Note presents a gain-scheduled control technique, called fuzzy gain-scheduled (FGS) control, in which fuzzy logic is used to construct a model representing an LPV or a nonlinear plant and to perform a control law.[4,5] Linear matrix inequalities (LMIs)[6] are then used to design an FGS controller that guarantees the global stability of the closed-loop system over the entire operating range of the fuzzy model. A number of LMI formulations have been presented so far. For example, Iwasaki and Skelton[7] and Gahinet and Apkarian[8] discussed H_∞ control problems in terms of LMIs. Moreover, gain-scheduled H_∞ control has been discussed by other authors in Refs. 9–11. The contribution of this Note is that it presents a new LMI formulation for the FGS controller that is based on a full-order observer-based controller. Compared to gain-scheduled H_∞ control,[9–11] an advantage is that parameters of the controller to be obtained are only two gains, that is, control and filter gains, which are easily parameterized by the LMIs solutions.

II. FGS Control

A. Fuzzy Model

Let us select r operating points of an LPV or a nonlinear plant and construct an LTI model for each operating point. Let η_j ($j = 1, \ldots, g$) be premise variables that recognize the operating points and N_{ji} ($i = 1, \ldots, r$) be fuzzy sets of η_j. For the ith operating point, the plant is modeled by the following fuzzy rules:

If $\eta_1 = N_{1i}$ and $\cdots$ and $\eta_g = N_{gi}$, then the plant is represented by

$$\begin{bmatrix} \dot{\boldsymbol{x}}(t) \\ \boldsymbol{y}(t) \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} \boldsymbol{x}(t) \\ \boldsymbol{u}(t) \end{bmatrix} + \begin{bmatrix} G_i & 0 \\ 0 & I_p \end{bmatrix} \begin{bmatrix} \boldsymbol{w}(t) \\ \boldsymbol{v}(t) \end{bmatrix} \qquad (i = 1, \ldots, r)$$

$$\boldsymbol{x}(t) \in \Re^n, \qquad \boldsymbol{u}(t) \in \Re^m, \qquad \boldsymbol{w}(t) \in \Re^s$$

$$\boldsymbol{y}(t), \qquad \boldsymbol{v}(t) \in \Re^p \tag{1}$$

where $\boldsymbol{u}(t)$, $\boldsymbol{y}(t)$, and $\boldsymbol{x}(t)$ are input, output, and state vectors, respectively. The pair of (A_i, B_i, C_i) is assumed to be stabilizable and detectable, and $\boldsymbol{w}(t)$ and $\boldsymbol{v}(t)$ are disturbance and noise vectors, whose covariance matrices are $W > 0$ and $Z > 0$. N_{ji} is characterized by the membership function μ_{ji}.

To evaluate the suitability of a given set of η_j ($j = 1, \ldots, g$), the following variable is introduced:

$$h_i \triangleq \mu_{1i}(\eta_1) \wedge \cdots \wedge \mu_{gi}(\eta_g), \qquad (i = 1, \ldots, r) \tag{2}$$

where $\wedge$ is the minimum operator in fuzzy logic. That is, the larger h_i is, the more suitable is the ith operating point LTI model for the LPV plant. Moreover, define α_i as

$$\alpha_i \triangleq \frac{h_i}{\sum_{i=1}^{r} h_i}, \qquad (i = 1, \ldots, r) \tag{3}$$

where

$$\alpha_i \geq 0, \qquad \sum_{i=1}^{r} \alpha_i = 1$$

Then, a model that corresponds to the entire operating range is given by

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \boldsymbol{y} \end{bmatrix} = \sum_{i=1}^{r} \alpha_i \left\{ \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{u} \end{bmatrix} + \begin{bmatrix} G_i & 0 \\ 0 & I_p \end{bmatrix} \begin{bmatrix} \boldsymbol{w} \\ \boldsymbol{v} \end{bmatrix} \right\} \tag{4}$$

It is called a fuzzy model[4,5] and is also one of the polytopic systems.[6]

B. FGS Controller

This section presents the FGS controller, which is basically derived from a full-order observer-based controller. An advantage of this formulation is that the only controller parameters that have to be obtained are the control and filter gains.

For the ith operating point, a controller for Eq. (1) is given by the following fuzzy rules:

If $\eta_1 = N_{1i}$ and $\cdots$ and $\eta_g = N_{gi}$, then a controller is given by

$$\dot{\hat{\boldsymbol{x}}} = A_i\hat{\boldsymbol{x}} + B_i\boldsymbol{u} + K_i(\boldsymbol{y} - \hat{\boldsymbol{y}}), \qquad \hat{\boldsymbol{y}} = C_i\hat{\boldsymbol{x}} + D_i\boldsymbol{u}$$
$$\boldsymbol{u} = -F_i\hat{\boldsymbol{x}}, \qquad (i = 1, \ldots, r) \tag{5}$$

where F_i and K_i ($i = 1, \ldots, r$) are $m \times n$ control gains and $n \times p$ filter gains, respectively. Similar to the deviation of the fuzzy model Eq. (4), using α_i defined in Eq. (3), a controller that corresponds to the entire operating range is given by

$$\begin{bmatrix} \dot{\hat{\boldsymbol{x}}} \\ \boldsymbol{u} \end{bmatrix} = \sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{l=1}^{r} \alpha_i\alpha_j\alpha_l \begin{bmatrix} A_i - B_iF_j - K_i(C_l - D_lF_j) & K_i \\ -F_j & 0 \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{x}} \\ \boldsymbol{y} \end{bmatrix} \tag{6}$$

Equation (6) is called the FGS controller. Defining an error vector as $\boldsymbol{e}(t) \triangleq \hat{\boldsymbol{x}}(t) - \boldsymbol{x}(t)$, the closed-loop system is given by

$$\dot{\boldsymbol{x}}_L = \sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{l=1}^{r} \alpha_i\alpha_j\alpha_l \left\{ A_{L_{ijl}}\boldsymbol{x}_L + G_{L_i}\boldsymbol{w}_L \right\} \tag{7}$$

where

$$\boldsymbol{x}_L(t) \triangleq \begin{bmatrix} \boldsymbol{x}(t) \\ \boldsymbol{e}(t) \end{bmatrix} \in \Re^{2n}, \qquad \boldsymbol{w}_L(t) \triangleq \begin{bmatrix} \boldsymbol{w}(t) \\ \boldsymbol{v}(t) \end{bmatrix} \in \Re^{s+p}$$
$$A_{L_{ijl}} \triangleq \begin{bmatrix} A_i - B_iF_j & -B_iF_j \\ 0 & A_i - K_iC_l \end{bmatrix}, \qquad G_{L_i} \triangleq \begin{bmatrix} G_i & 0 \\ -G_i & K_i \end{bmatrix} \tag{8}$$

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III. Controller Design Using LMI

The parameters in the FGS controller to be designed are the control and filter gains F_i and K_i $(i = 1, \dots, r)$, which guarantee the global stability of the closed-loop system Eq. (7) over the entire operating range. In this Note, the global stability is discussed in the frame of quadratic stability with a Lyapunov function. LMIs are then derived to guarantee the global stability and to obtain F_i and K_i. Many researchers have proposed LMI formulations for several purposes: H_∞ bound and pole-region constraint amongst others.[6,12] This section puts forth a new LMI formulation for F_i and K_i.

The closed-loop system Eq. (7) is quadratically stable only if there exists a positive definite function

$$V \triangleq \boldsymbol{x}_L^T \begin{bmatrix} X^{-1} & 0 \\ 0 & Y \end{bmatrix} \boldsymbol{x}_L \tag{9}$$

such that

$$\frac{\mathrm{d}V}{\mathrm{d}t} < -\sum_{i=1}^{r}\sum_{j=1}^{r}\sum_{l=1}^{r} \alpha_i\alpha_j\alpha_l \boldsymbol{x}_L^T \delta_{i,j,l} Q_{L_i} \boldsymbol{x}_L \tag{10}$$

where

$$Q_{L_i} \triangleq \begin{bmatrix} Q_i + F_i^T R_i F_i & 0 \\ 0 & Y\left(G_i W_i G_i^T + K_i Z_i K_i^T\right)Y \end{bmatrix}$$

$$Q_i = H_i^T H_i \ge 0, \qquad \mathrm{rank} H_i = q \tag{11}$$

$$X, Y, R_i, W_i, Z_i > 0, \qquad (i = 1, \dots, r)$$

$$\delta_{i,j,l} \triangleq \begin{cases} 1, & i = j = l \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

Because $Q_{L_i} \ge 0$, Eq. (10) is a sufficient condition that Eq. (7) is quadratically stable. In Eq. (11), $Q_i + F_i^T R_i F_i$ is a weighting matrix, which resembles a quadratic form of the optimal regulator, whereas $Y(G_i W_i G_i^T + K_i Z_i K_i^T)Y$ is a covariance matrix, which resembles a quadratic form of the Kalman filter. Defined by Eq. (12), $\delta_{i,j,l}$ means that the weights are imposed on r operating points. A parameterization of control and filter gains F_i and K_i $(i = 1, \dots, r)$ in Eq. (6) is given as follows.

Theorem 1. Equation (10) holds only if there exist $n \times n$ positive definite matrices X and Y, $m \times n$ matrices M_i, and $n \times p$ matrices N_i $(i = 1, \dots, r)$ that satisfy the following $r(r+1)$ LMIs:

$$\begin{bmatrix} A_i X + X A_i^T - B_i M_i - M_i^T B_i^T & X H_i^T & M_i^T \\ H_i X & -I_q & 0 \\ M_i & 0 & -R_i^{-1} \end{bmatrix} < 0 \qquad (i = 1, \dots, r) \tag{13}$$

$$(A_i + A_j)X + X(A_i + A_j)^T - (B_i M_j + B_j M_i) - (B_i M_j + B_j M_i)^T < 0 \qquad (i = 1, \dots, r, \quad j = i+1, \dots, r) \tag{14}$$

$$\begin{bmatrix} Y A_i + A_i^T Y - N_i C_i - C_i^T N_i^T & Y G_i & N_i \\ G_i^T Y & -W_i^{-1} & 0 \\ N_i^T & 0 & -Z_i^{-1} \end{bmatrix} < 0 \qquad (i = 1, \dots, r) \tag{15}$$

$$Y(A_i + A_l) + (A_i + A_l)^T Y - (N_i C_l + N_l C_i) - (N_i C_l + N_l C_i)^T < 0 \qquad (i = 1, \dots, r, \quad l = i+1, \dots, r) \tag{16}$$

Then F_i and K_i in Eq. (6) are given by

$$F_i = M_i X^{-1}, \qquad (i = 1, \dots, r) \tag{17}$$

$$K_i = Y^{-1} N_i, \qquad (i = 1, \dots, r) \tag{18}$$

□

Equations (13–16) can be derived by transforming Eq. (10) into matrix inequalities, introducing new variables M_i and N_i, and using the Schur complement.[6]

IV. Longitudinal Flight Control Problem

To illustrate the proposed FGS control, simulation studies were carried out for the longitudinal flight control of the Lockheed P2V-7 aircraft. In this example, the flight conditions, the altitude, and the flight velocity vary, that is, the plant was given as an LPV system.

A. Equation of Longitudinal Motion of LPV Aircraft

A state-space equation for the longitudinal motion of an aircraft is given by

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \gamma \end{bmatrix} = \begin{bmatrix} A & B \\ C & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \delta \end{bmatrix} \tag{19}$$

where

$$\boldsymbol{x} \triangleq [u \quad \alpha \quad \theta \quad q]^T \in \Re^4, \qquad \delta \in \Re^1$$

$$A = \begin{bmatrix} X_u & X_\alpha & -g & 0 \\ Z_u/U & Z_\alpha/U & 0 & 1 + Z_q/U \\ 0 & 0 & 0 & 1 \\ M_u + M_{\dot\alpha} Z_u/U & M_\alpha + M_{\dot\alpha} Z_\alpha/U & 0 & M_q + M_{\dot\alpha}(1 + Z_q/U) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ Z_\delta/U \\ 0 \\ M_\delta + M_{\dot\alpha} Z_\delta/U \end{bmatrix}, \qquad C = [0 \quad -1 \quad 1 \quad 0]$$

In the state vector $\boldsymbol{x}$, here u is the incremental velocity in the flight direction, α the angle of attack, θ the pitch angle, and q the angular velocity of the pitch angle. Also, γ is the angle of the flight path, and δ is the deflection angle of an elevator. In the matrices A and B, the $X_u, Z_\alpha, \dots$, are stability derivatives in the frame of the stability axis. In this numerical example, they were changeable with respect to the altitude H and the flight velocity U, whose ranges were given as $H_l \le H \le H_u$ and $U_l \le U \le U_u$, respectively. To cover the entire operating range, fuzzy rules were given at the following four operating points: $(H, U) = (H_l, U_l)$, (H_l, U_u), (H_u, U_l), (H_u, U_u), and an LTI model was constructed for each operating point. Membership functions, μ_H and μ_U, of H and U are given in Fig. 1. Then, h_i is given by

$$h_i = \mu_H(H) \wedge \mu_U(U), \qquad (i = 1, \dots, 4) \tag{20}$$

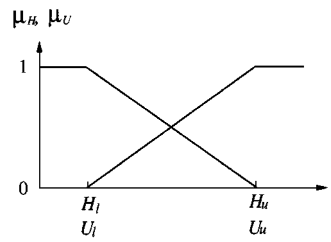

Fig. 1 Membership functions of *H* and *U*.

B. Numerical Simulation

Numerical data of the Lockheed P2V-7 aircraft were used in the simulation.[13] The ranges of H and U were given as $1000 \leq H \leq 7000$ m and $50 \leq U \leq 150$ m/s. Because the matrix C in Eq. (19) was constant, the LMIs given by Eq. (16) were not needed. The number of LMIs to be solved was then $4 \times (4+1)/2 + 4 = 20$. To find matrices $X > 0$, $Y > 0$, M_i, and N_i ($i = 1, \ldots, 4$) that satisfy the 20 LMIs, the LMI Control Toolbox in MATLAB[12] was used for the calculation. After finding X, Y, M_i, and N_i, the control and the filter gains F_i and K_i were obtained from Eqs. (17) and (18). An FGS controller was then constructed as Eq. (6). To compare the FGS controller with a conventional fixed-structure controller, a linear quadratic Gaussian (LQG) controller was designed at $(H, U) = (4000, 100)$.

Figure 2 shows the responses of $\gamma(t)$ in which the flight condition was $(H, U) = (4000, 100)$ and $(4000, 135)$. At $(H, U) = (4000, 100)$, the response using the LQG controller was superior to the response using the FGS controller from the viewpoint of the settling time. Whereas at $(H, U) = (4000, 135)$ apart from the design point of the LQG controller, the FGS controller showed better performance than the LQG one.

To evaluate the control performance over the entire flight range using the time response, the following index Cost was introduced:

$$\text{Cost} \triangleq \int_0^{50} t|\gamma(t)|\,\mathrm{d}t \tag{21}$$

This index means the integral of time multiplied by absolute value of error criterion during $t \in [0, 50]$. Figures 3 and 4 show Cost using the FGS and LQG controllers, where Cost was limited to 10,000 if Cost was greater than 10,000. Cost using the LQG controller showed high values in the low and high flight velocity regions. In particular, the closed-loop system using the LQG controller was unstable in the regions around $(H, U) = (7000, 50)$ and $(1000, 150)$. On the other hand, Cost using the FGS controller was less than 6000 over the entire flight range. Thus, it is concluded that the FGS controller performed better than the LQG controller over the entire range of the varying parameters.

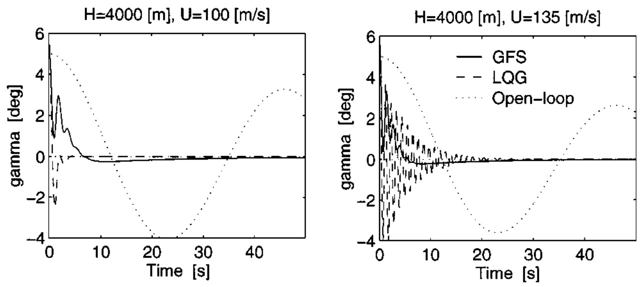

Fig. 2 Time responses comparing FGS controller to a LQG controller.

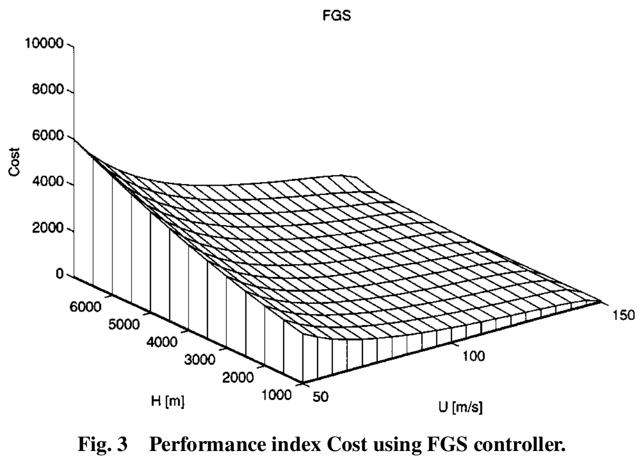

Fig. 3 Performance index Cost using FGS controller.

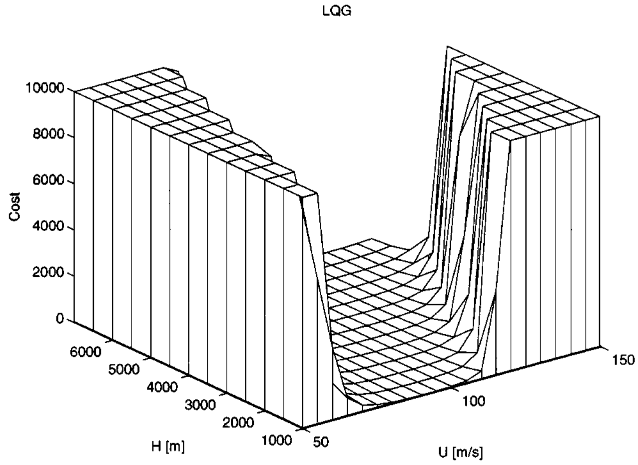

Fig. 4 Performance index Cost using LQG controller.

V. Concluding Remarks

This Note has presented a gain-scheduled control technique, FGS control, in which fuzzy logic was used to construct a model representing an LPV or a nonlinear plant and to perform a control law. LMIs were used to obtain the control and filter gains of the FGS controller, which guaranteed the global stability of the closed-loop system. The proposed method was applied to a numerical example of a longitudinal flight control problem in which the aircraft was regarded as an LPV system; that is, the altitude and the flight velocity were varying. Compared to a conventional LQG controller, the FGS controller showed better control performance over the entire flight region.

In the numerical example, four LTI models were constructed at the corner of the operating range, and the degree of satisfaction was given by Eq. (20) with the membership function shown in Fig. 1. If the number of LTI models is increased, the fuzzy model approximates the characteristics of the original LPV aircraft more closely. However, it becomes harder to find a solution satisfying LMIs in Theorem 1.

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Windshear Recovery Using Fuzzy Logic Guidance and Control

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I. Introduction

THE generic term *windshear* refers to a rapid change in the wind speed and/or direction.[1] The microburst, a dangerous form of windshear, is produced by a strong sudden downdraft of cool air, which strikes the ground and outflows in all directions. The hazard of the low-altitude microburst arises from the rapid change from a performance increasing headwind to a strong performance decreasing tailwind and downdraft. To cope with the headwind, the pilot intuitively, or the autopilot automatically, takes actions to prevent the aircraft from climbing. Next, these actions are compounded by the energy loss caused by the ensuing downdraft and tailwind. The sudden energy loss poses a serious risk to arriving and departing aircraft.

As windshear may exceed the performance capability of aircraft, avoidance has been emphasized. Because of the recent advances in windshear forward-looking detection systems, timely recognition and avoidance has helped to reduce the hazard significantly.[2] However, because of the short-lived, transient nature of this phenomenon, timely detection might not be always possible. Hence, certain procedures and techniques should be applied to cope properly with the energy loss in case of an encounter. For the guidance and control problem during the windshear phenomenon, it is proposed to apply a fuzzy logic controller based on energy principles that is extended to convey tight energy control and flight envelope protection.

II. Microburst Windshear Hazard

Windshear can be considered as an energy management problem in which the energy decrement of the aircraft results in a loss of either potential energy (altitude) or kinetic energy (airspeed). Because the windshear affects, in particular, the longitudinal motion of an aircraft, the total energy balance in the vertical plane is considered.[3] The airplane total specific energy or potential altitude h_p is defined as

$$h_p = E/mg = \left(V_A^2/2g\right) + h \tag{1}$$

where V_A is the airspeed, mg is aircraft weight, and h is the altitude. Differentiating this expression and using the general equations of motion yields

$$\begin{aligned}\dot{h}_p &= (V_A/g)\dot{V}_A + \dot{h}\\ &= V_A\left(\frac{T\cos\alpha - D}{mg} - \frac{\dot{w}_x}{g}\cos\gamma_A - \frac{\dot{w}_h}{g}\sin\gamma_A + \frac{w_h}{V_A}\right)\end{aligned} \tag{2}$$

where T is the thrust in the direction of the x axis of the body frame, D is the aircraft drag, w_h and w_x are the time derivatives of the vertical and horizontal wind velocity components, α is the angle of attack (the angle between the x axis of the body frame and the air-mass direction of V_A), and γ_A is the air-relative flight-path angle. The first term is the airplane's excess thrust-to-weight ratio. The subsequent three wind terms describe the windshear impact on the aircraft energy state. The three terms can be combined into the so-called $\mathcal{F}$-factor[2]

$$\mathcal{F} = (\dot{w}_x/g) - (w_h/V_A) \tag{3}$$

A positive $\mathcal{F}$-factor can be physically interpreted as the loss in available excess thrust-to-weight ratio. From Eqs. (2) and (3), it can be seen that the aircraft loses energy if the windshear (associated) energy loss cannot be compensated by an energy-increasing positive thrust change $\Delta T/mg$ because of a limited maximum excess thrust-to-weight ratio. In such a condition, the aircraft descends and/or loses airspeed. In a landing situation, the windshear problem also involves the decision whether to initiate an escape maneuver[4] or to continue the landing. Several optimal guidance schemes and control laws have been developed for safe flight through windshear during abort landing[5] and penetration landing.[6,7,8] In most penetration landing studies, the descending flight path is controlled by pitch/elevator and the airspeed (or inertial speed) by thrust, both with high gains. Miele et al.[6] have performed an extensive optimization study and have provided practical guidance and control laws. The guidance laws include the control of flight path, which is done by angle of attack determined as function of windshear intensity, and the control of airspeed, which is done by thrust, also as a function of windshear intensity. In the guidance laws, tracking the flight path is preferred above airspeed. Psiaki and Park[7] use a pitch steering strategy, which controls the flight path in conjunction with a thrust guidance, which controls the minimum of airspeed and inertial velocity (often referred to as groundspeed). This is done to prevent the energy loss due to the headwind. The idea of explicitly controlling air-relative energy during the penetration of a windshear is also considered by KrishnaKumar and Bailey.[8] The importance of proper energy distribution is emphasized as well. However, the energy partition in this energy-based controller is fixed, i.e., an a priori choice is made on how to distribute the available energy. The recovery concept in this Note proposes a variable energy distribution according to the margins with respect to a stall situation and a minimum altitude. A smooth and variable energy distribution, for each flight mission, is conveyed through the application of fuzzy logic.

III. Generic Flight Recovery Concept

The basic philosophy of this recovery concept is that a compromise between airspeed and altitude is pursued continuously during the encounter with respect to the associated safe operating altitude and stall speed margins, regardless of the specific flight mission, the guidance strategy, and the microburst intensity.[9,10] This protection mechanism can be easily integrated in the longitudinal fuzzy controller of Refs. 11 and 12, which is based on total energy principles.[13] This controller has been designed and extensively tested with respect to other control law designs in a recently formulated civil aircraft benchmark problem.[14]

In Fig. 1, the extended controller is shown. According to the total energy concept, where both airspeed and altitude are controlled simultaneously, thrust T increases the total energy E, whereas an exchange between kinetic (airspeed) and potential energy (altitude) is achieved by pitch angle changes (via elevator). Two inputs to the controller are velocity error V_e, the difference between a reference airspeed $V_{A,\mathrm{ref}}$ and the actual airspeed V_A, and altitude error h_e, the difference between a reference altitude h_{ref} and the actual altitude h.

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