Adaptive Techniques for Multiple Actuator Blending

By

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Abstract

Advanced missiles employ multiple actuators to enhance maneuverability and to improve the intercept probability against highly maneuverable targets. Actuators employed in such missiles include aerodynamic control surfaces and reaction jets. While the usage of aerodynamic surfaces are not generally constrained, reaction jet usage has to be minimized due to the limited amount of fuel available on-board. A blending logic is employed to optimally allocate the actuators in response to commands from the autopilot. This paper discusses the development of a fuel conservative actuator blending logic that provides relatively invariant actuator performance over widely varying flight conditions. The invariant performance is obtained using the model reference adaptive control technique. Multiple adaptation strategies are employed to ensure rapid convergence and stable behavior. The performance of the model reference adaptive actuator blending strategy is illustrated using a realistic missile model.

1. Introduction

Naval vessels are subject to threats from enemy tactical ballistic missiles and sea-skimming missiles [1]. Protecting the ships against these and other threats will be crucial to the success of future naval operations. Consequently, there is strong interest within the Navy in developing high performance ship/theater defense missiles capable of intercepting tactical ballistic missiles and anti-ship sea skimming missiles during various stages of their flight [2 - 4]. Engagements against airborne threats can occur over a wide range of flight conditions. Successful interception of these

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threats requires the ship/theater defense missiles to be capable of delivering agile performance over a wide range of altitude, Mach number and angle-of-attack flight conditions.

In order to deliver uniform performance over their entire flight envelope, and to take advantage of emerging sensor technologies, these missile may employ multiple non-collocated actuators during certain part of their flight. For instance, fins may be employed during high speed/low angle of attack flight, while reaction jets may be used during high angle of attack/low speed flight. Reaction jets may also be employed just prior to interception in order to accommodate for aim-point shifts [5 - 8] in order to maximize the kill probability. The missile flight control system must be able to seamlessly integrate multiple control actuator usage into the control logic. Unlike the missile models at normal angles of attack, the missile dynamic model is highly uncertain at elevated angles of attack. Uncertainties can arise in aerodynamic data and reaction jet thrust, and can include previously unknown and unquantified coupling effects. Ship/theater defense missile flight control systems must be capable of delivering agile performance while handling nonlinearities and uncertainties in the vehicle model, atmosphere, and ambient winds.

These factors necessitate the development of flight control system design methods that can handle large nonlinearities, uncertainties and multiple actuators. Due to the more stringent performance specifications in ship/theater defense missiles, conventional autopilot design approach may not be capable of achieving the fast response time, stability margin, and flexible-body mode attenuation requirements [2]. This has motivated the application of modern robust feedback control methods such as the H_∞ and μ-synthesis design techniques to the missile flight control problem [2]. The application of emerging nonlinear control methods to the missile autopilot design problem has also been recently reported [9 - 12]. However, strategies for optimally blending the actuators in the control loop has received relatively minor research attention. An initial research effort on the actuator blending problem is given in References 11 and 12. The focus of the present research effort will be on developing a fuzzy logic supervised adaptive actuator blending logic and to evaluate it in nonlinear missile simulation.

Fuzzy logic [13] control has emerged in recent years as an effective methodology for the control of nonlinear, uncertain dynamic system [14 - 26]. Fuzzy logic control concept employs a linguistic approach to control in that the instantaneous value of the control variables depend on the inference derived using a set of IF-Then-Else type rules. The rules are generally derived from state transition relationships. As a result, the fuzzy logic approach can treat linear, nonlinear, continuous and discrete-time systems using the same frame work. Moreover, since fuzzy logic is linguistically based, they can handle uncertainty descriptions that are much more general than those treated by robust control theory. Due to these factors, the fuzzy logic paradigm can help develop control systems that are based on a mix of qualitative and quantitative performance specifications. Application of the fuzzy logic in a few flight control problems have been reported in the literature [23 -25]. Reference 23 has pointed-out that the fuzzy logic paradigm is most effective when used in a supervisory control role. In the missile actuator blending logic design problem, the use of fuzzy logic will permit the inclusion of qualitative performance requirements into the design process. Once the general qualitative features of the actuator blending logic are defined, the fuzzy logic system can be designed using a state space based fuzzy logic rule generation process [27].

The present research employs the missile configuration data, models and control systems discussed in Reference 13. Emphasis will be on using the missile models and nonlinear autopilots from Reference 12 for developing fuzzy logic based the actuator blending strategies.

With this background, this paper discusses the development of a fuzzy logic based adaptive fin/reaction jet actuator blending logic for ship/theater defense missiles. Fuzzy actuator blending logic development uses a nonlinear simulation of the missile, and includes sensor-actuator dynamics. Aerodynamic uncertainties and uncertainties in reaction jet dynamics are included in evaluating the blending logics. The following section will discuss the detailed development of the model reference adaptive actuator blending logic.

2. Actuator Models

The present research employs a rigid body model of the missile described in Reference 12. The fin actuator is assumed to consist of a second order dynamics. The reaction jets are on/off devices, and can be modeled using an on/off nonlinearity follwed by a first-order lag and a dead-time delay. The reaction jets can be operated in a bang-bang mode or in a pulse-modulation mode.

Bang-bang operation of the reaction jets involves turning the reaction jets On or Off based on the sign of the tracking error. Pulse modulation, on the other hand, requires the reaction jets to alternately turn on and off at a selected duty cycle frequency. In the pulse modulation mode, the frequency and pulse widths are governed by the magnitude and direction of the tracking error. Bang-bang mode has the advantage of being fuel-optimal. However, it cannot provide a smooth command tracking. The pulse-modulation mode is attractive because it permits a more precise control of the moments generated by reaction jets. However, it is wasteful in terms of fuel consumption.

Pulse modulation schemes permit the use of on-off actuators in applications requiring continuous variation of control power. Pulse modulators are widely used in electromechanical actuation systems such as remotely piloted aircraft servos and solenoids, and also in precision spacecraft attitude control systems incorporating reaction motors. The advantage of pulse modulation schemes is that once they are integrated with on-off actuators, they can be treated as continuous actuators for the purposes of control system design.

Several pulse modulation schemes have been discussed in the literature [28, 29]. Pulse-width/Pulse-Frequency Modulation, Derived-Rate Modulation, and pure Pulse-Width modulation are a few of the commonly employed schemes. All these have been extensively analyzed, and their static characteristics are well known. Reference 29 has identified the derived rate modulation scheme as being one of the most desirable approaches because it introduces the least phase lag in the control loop. This fact is important to counter the adverse phase lags introduced by the reaction jet On/Off time delays. In all that follows, it will be assumed that the reaction jets are operated using a derived rate pulse modulation scheme.

3. Actuator Blending Logic

A schematic block diagram of the missile flight control system incorporating blended actuators is given in Figure 1.

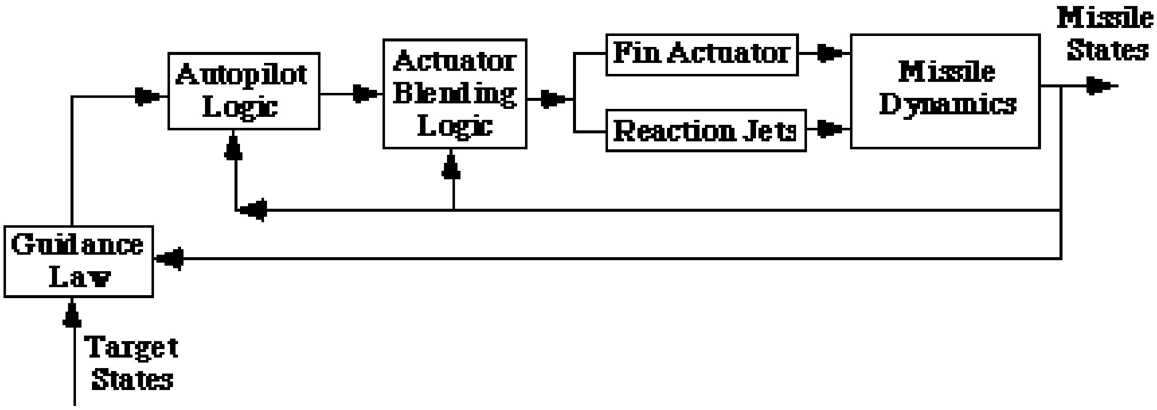


Fig. 1. Missile Flight Control System Using Multiple Actuators

The guidance law uses the target and missile states to generate the commands to the autopilot. The guidance commands to the autopilot are in the form of acceleration components normal to the velocity vector. The autopilot logic generates actuator commands based on the missile states and the guidance command. Aerodynamic control surfaces are used at lower altitude/high speed/ moderate angle of attack conditions. At higher altitudes/lower speeds or when fast transient response is desired, reaction jets are brought-in to augment the control power. However, as indicated in the previous section, reaction jet fuel is available on-board is limited due to weight penalties involved in carrying large reaction jet impulse.

The autopilot design must account for these noncollocated actuators operating in dissimilar control modes. In order to manage the complexity of the design problem, it is desirable to separate the actuator blending problem from the autopilot design problem. Thus, it is desirable that the autopilot be designed using an assumed dynamics of the blended actuators, and the actuator blending logic then designed to realize the assumed dynamics. The following discussions on the actuator blending logics assume the use of such a design philosophy.

3.1. Actuator Blending Logic Specifications

Actuator blending logic has a history spanning five decades. One of the early use of the actuator blending was in the launch vehicle development program during the early 1950's. In some of the launch vehicles, pitch/yaw control at lift-off was provided by secondary-injection thrust vector control (SITVC). As the vehicle accelerates, the control is gradually handed-over to fin actuators, since the on-board secondary injection fluid supply is limited.

More recently, the actuator blending problem in aircraft has received research attention [30, 31]. These research efforts are motivated by the availability of multiple control surfaces on advanced fighter aircraft such as the F/A-18. Actuator blending logics discussed in References 30 and 31 are based on the assumption that redundant controls are available. Moreover, an assumption implicit in these research efforts is that the dynamics of the actuators can be neglected when compared with the dynamics of the autopilot. While such an approach is acceptable for autopilots with bandwidths significantly smaller that the actuator bandwidth, it can have a negative performance impact on high-performance autopilots.

In ship/theater defense missiles, the nature of the actuator blending problem is different from that of high performance aircraft because the question is not which actuator to use amongst a set of redundant actuators, but how the actuators should be used in order to realize a desired transient response while minimizing reaction jet usage. Thus, some of the approaches advanced in the aircraft actuator blending problem are not directly applicable to the missile actuator blending problem.

The performance requirements for the actuator blending logic can be summarized as follows:

1. The actuator blending logic must enable the independent or simultaneous use of the fin and reaction jet actuators as and when demanded by the autopilot.
2. The blending logic must permit the enabling and disabling of reaction jet actuators without adversely affecting the autopilot stability.
3. The blending logic must be relatively robust with respect to actuator model errors.
4. The actuator blending logic must not in any way influence the autopilot stability and tracking characteristics.

Ideally, the actuator blending logic should be designed such that the closed-loop autopilot does not perceive its existence at all. That is, from the autopilot's point of view, the actuators together with the blending logic should appears as one composite actuator with a fixed dynamic behavior. Figure 2 illustrates the proposed concept.

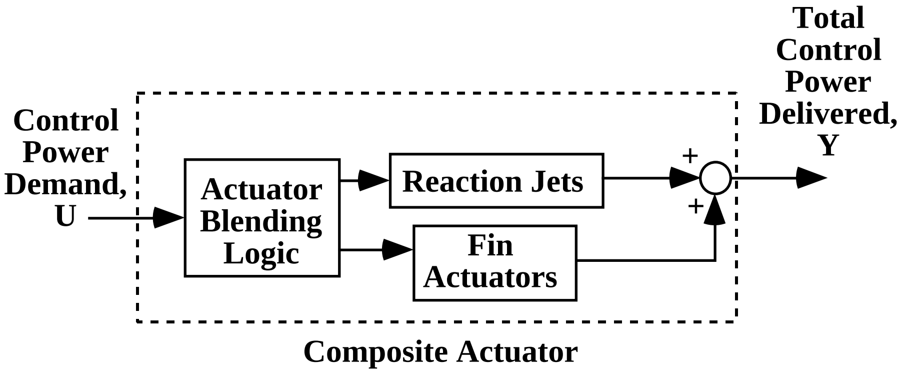


Fig. 2. The Blended Actuator Concept

However, this objective cannot be fully realized because the reaction jets and the fins may not co-located. Moreover, the reaction jets can only be used in an On/Off mode. As a result, the best that can be achieved in this situation is to design the actuator blending logic that closely approximates the dynamic behavior of one of the actuators.

Thus, the objective is to synthesize the actuator blending logic such that the transfer function of the composite actuator with the control power demand U as the input and the total control power delivered Y as the output, remains relatively invariant throughout the operational regime. The main design constraint on the actuator blending logic is that the reaction jets should be used only when the fin actuators are not capable of supplying the desired transient response. Note that this constraint does not compromise the transient performance of the blended actuators.

3.2. Actuator Blending Logic Architecture

Actuator blending logic can be conceptualized as a control law that allocates the fins and reaction jets based on the control moment demand from the autopilot. If this point of view is adopted, nonlinear control techniques [11, 12, 32 - 35] can be used for the synthesis of the blending logic. Two basic approaches can be identified for developing actuator blending logics. Firstly, one can assume that the actuator models are well known, so that an open-loop blending logic can be employed. Such an approach was adopted during previous research efforts [11, 12]. If a more precise control of the blended actuator performance is desired, the blending logic problem can be cast as a closed-loop control problem.

Open-loop blending logics are the simplest. However, their performance depends upon a good knowledge of the actuator dynamics. Casting the actuator blending problem as a closed-loop control problem makes their performance more deterministic. The closed-loop actuator blending logic performance can be expected to be relatively insensitive to actuator parameter variations. Moreover, by employing control system design approaches such as model reference adaptive control, the dynamic behavior of the blended actuator can be guaranteed to remain in a desired range. Thus, closed-loop actuator blending makes it possible to meet all the design requirements set-forth in the previous section. Due to these factors, the present research effort will be on the development of closed-loop actuator blending logics.

However, closed-loop actuator blending logic development is not without attendant difficulties. Firstly, such an approach leads to an increase in the complexity of the blending problem. The second difficulty is that of providing feedbacks regarding the reaction jet performance to the blending logic. This difficulty arises because of the fact that while the fin deflection can be measured, the reaction jet thrust cannot be directly measured. This necessitates the construction of an estimator for reconstructing reaction jet states. Finally, the closed-loop actuator blending logic can become unstable if the actuator dynamics are considerably different from that assumed during the design. Despite these disadvantages, closed-loop actuator blending logics offer significant potential for enhanced performance.

Several candidate architectures can be set-up for the development of closed-loop actuator blending logic. Firstly, it can be treated as a servo problem, wherein the difference between the commanded control moment and the achieved control moment is minimized by selecting appropriate combination of reaction jet and fin actuators. This will ensure that if adequate control moments are not available to achieve a desired transient response using fins, reaction jets will be automatically brought into the control loop.

A second architecture for the actuator blending logic can be based on a model reference adaptive control formalism. In this case, the blending logic not only tracks the commanded moments, but also guarantees a specific dynamic behavior for the blended actuators. The latter feature is valuable to permit the independent design of the missile autopilot and the actuator blending logic.

The present work will employ the model reference adaptive control formalism for realizing the actuator blending logic. Model reference adaptive control [36] seeks to adjust the parameters of a closed-loop system such that the system performance closely approximates that of the

“Reference Model”. The “Reference Model” can be chosen based on the desired dynamic characteristics of the composite actuator model used for the autopilot design. In the present case, the second-order fin actuator dynamics is assumed to be the reference model.

The adaptation scheme used in the control loop can be one of the several available in the literature [36]. Each of these techniques have specific advantages and disadvantages. In order to exploit their individual strengths, two or three adaptation techniques can be combined to improve the system performance. Fuzzy logic [18] can be used to realize the composite adaptation scheme. Such an approach is presented in the following. Figure 3 shows the main components of the fuzzy model reference adaptive actuator blending system discussed in the present research.

It has been pointed out in previous studies [23, 24, 37] that the fuzzy logic approach is most effective when used in a supervisory control role. This observation forms the basis for the development of actuator blending logics presented in the present paper. Note that the application of fuzzy logic in an adaptive control loop has previously been discussed in Reference 38 and 39. However, that work did not include explicit tradeoffs between different adaptation algorithms, as is done in the present research.

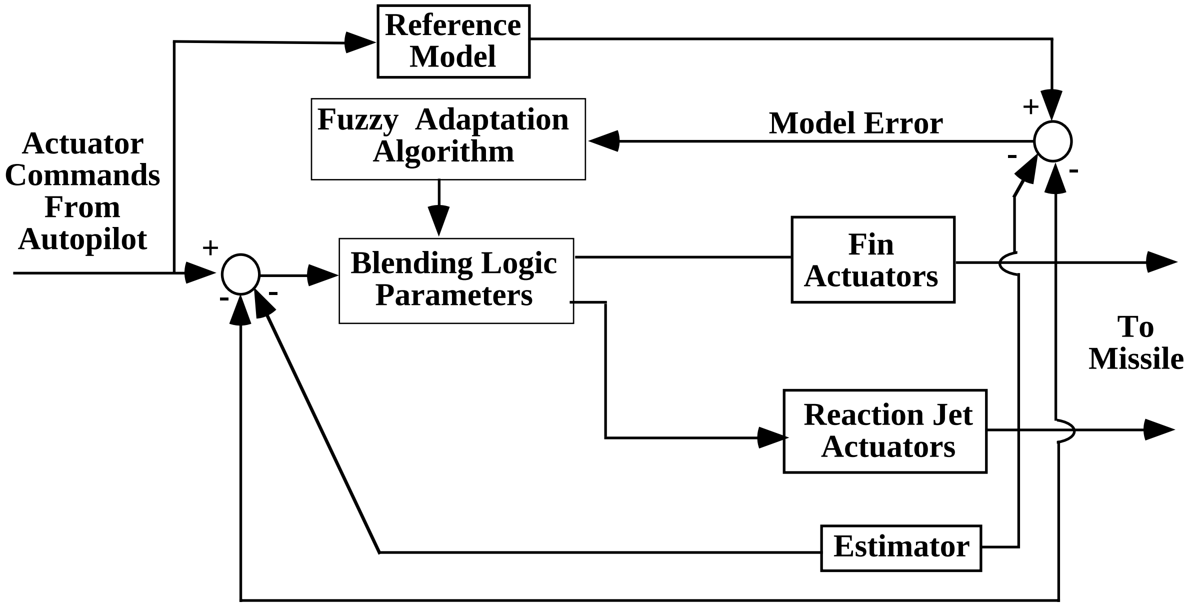


Fig. 3. Structure of the Fuzzy Model Reference Adaptive Actuator Blending Logic

In the model reference adaptive formulation of the blending logic, the actuator commands from the autopilot are simultaneously applied to a reference model and the closed-loop actuator blending logic. The error between the response of the reference model and the closed loop blending logic is used by the fuzzy adaptation algorithm to generate corrections to the blending logic parameters. In the present case, a proportional and derivative gains are the parameters adjusted by the fuzzy adaptation logic. The adaptation scheme ensures that the dynamic behavior of the blending logic stays close to the reference model.

3.3. Fuzzy Adaptation Logic

Several adaptation algorithms have been suggested in the literature [36]. Some of the well known approaches are the MIT rules, Lyapunov update rule, and the Newton-Raphson update rule. In order to motivate the development of the fuzzy supervisory logic, each of these rules will be briefly discussed in the following.

3.3.1. MIT Adaptation Rules

MIT rules are variations of the first-order gradient algorithm [40]. These rules are obtained by examining the conditions for minimizing the square of the instantaneous error between the actual system and the reference model:

$$\frac{1}{2} e^2 .$$

e is the error between the reference model and the actual system. If K_1 is the parameter that needs to be tuned by the adaptation algorithm, the parameter update rule is given by:

$$\text{MIT Rule 1: } \frac{dK_1}{dt} = -\gamma e \frac{\partial e}{\partial K_1}$$

where $\partial e / \partial K_1$ is the gradient of the square of the error with respect to the tuning parameter. In linear systems, explicit relationships can be derived for the elements of the gradient vector. These can then be used to carry out on-line computations. The gradient will have to be numerically determined in nonlinear or in high-order linear systems. The fixed parameter γ determines the convergence rate of the method. Too high a value can result in oscillatory behavior near zero values of error. Too small a value can result in unacceptably slow convergence.

Since computing the magnitude of the gradient can be difficult in certain situations, an alternate form of the MIT rule is sometimes used in applications. This second rule is of the following form:

$$\text{MIT Rule 2: } \frac{dK_1}{dt} = -\gamma \operatorname{sign}(e) \operatorname{sign}\left(\frac{\partial e}{\partial K_1}\right)$$

Note that this rule employs only the sign of the error and the gradient, and is sometimes referred to as the sign-sign algorithm [36]. This update rule has a constant convergence rate regardless of the magnitude of the error. Although robust, due to its discontinuous nature, MIT Rule 2 will exhibit limit cycling behavior as the error approaches zero.

First-order gradient algorithms such as the MIT rules are known to have a fast convergence when the parameters are far away from the exact values. However, since the parameter update rate is proportional to the error, the process slows down as the error decreases. The error is driven to zero only as the number of iterations approach infinity. As the parameters approach their true values, the gradient becomes less and less reliable, sometimes leading to wandering motions in the parameters.

3.3.2. Lyapunov Parameter Update Rule

The Lyapunov update technique is based on maintaining the nonpositivity of the rate of change of a Lyapunov function [36]. Quadratic functions of the form:

$$V(e, K_1) = \frac{1}{2}\left[e^2 + (K_1)^2\right]$$

is used as the Lyapunov function, and is known to work well in most situations. The parameter update rule for K_1 is chosen to ensure that the time-rate-of-change of the Lyapunov function remains non-positive, i.e.,

$$\frac{dV}{dt} = e\frac{de}{dt} + (K_1)\left(\frac{dK_1}{dt}\right) \le 0$$

One of the approaches to ensure this is to select: $\frac{dV}{dt} = -\eta e^2$, leading to the Lyapunov update rule:

$$\text{Lyapunov Update Rule: } \frac{dK_1}{dt} = -\frac{1}{K_1}\left[\eta e^2 + e\frac{de}{dt}\right]$$

Since nonpositivity of the rate of change of the Lyapunov function ensures stability of the process, such an approach guarantees that the parameter update process will remain stable in the Lyapunov sense. This property can be important in adaptation systems that are near convergence, because the gradient and the Hessians may be unreliable under these conditions. However, assuring the nonpositivity of the rate of change of a Lyapunov function does not assure satisfactory convergence rate when the parameters are away from their true values. Thus, this technique is primarily useful when the parameters have nearly converged.

3.3.3. Newton-Raphson Parameter Update Rule

Under certain conditions, the Newton-Raphson method [40] can provide a faster convergence rate for generating the parameter updates. This approach uses the first and second gradients (Hessian matrix in the case of multiple parameters) of the square of the error with respect to the parameters to generates the updates. This update formula is of the form:

$$\frac{dK_1}{dt} = -\frac{\partial}{\partial K_1}\left(e^2\right) \Big/ \frac{\partial^2}{\partial K_1^2}\left(e^2\right)$$

If the Hessian matrix can be assured to be positive definite, the process converges at an extremely fast rate. Specifically, in quadratic systems, since the Hessian matrix is constant, it can be shown that the Newton-Raphson technique converges in one iteration if a minimum exists. Slower convergence can be expected in real systems because of nonlinearities and noise sources present. Positivity requirement of the second gradient makes it difficult to apply in situations where the gradient computations are noisy or unreliable. This can often happen when the process is near convergence. However, when the parameters are far from their true values, the Newton-Raphson technique can provide extremely rapid convergence.

3.3.4. Fuzzy Inference System for Adaptation Rule Selection

From the foregoing discussions, it is clear that each of the adaptation algorithms have certain advantages and disadvantages. The desire to exploit the benefits of these algorithms while eliminating their shortcomings to achieve faster, stable, more accurate adaptation algorithm forms the basis for the development of fuzzy adaptation logic. Thus, the fuzzy logic is used to select an appropriate adaptation algorithm based on the magnitudes of the error between the reference model and the closed-loop blending logic, first and second gradients of the parameters with respect to the errors. For instance, if the second gradient is positive, and if the error between the reference model and the system is large, the Newton-Raphson technique can be used. If the error is small and the gradients do not appear accurate, Lyapunov update rule is perhaps the best. The MIT rules are useful in the presence of large errors and nonpositive second gradients.

A block diagram of the fuzzy adaptation rule selection system is illustrated in Figure 4. The fuzzy inference system employs four parameters k_1, k_2, k_3, k_4 to carry out the update rule selection process. These parameters are selected based on the computed values of the model error, gradient vector and the Hessian matrix. De-selected update rules will have zero values for the corresponding parameters. Relative magnitudes of the non-zero values indicate the relative importance of the parameter update rules. The outputs of the parameter weighted rules are combined to get the parameter update for the adaptation process.

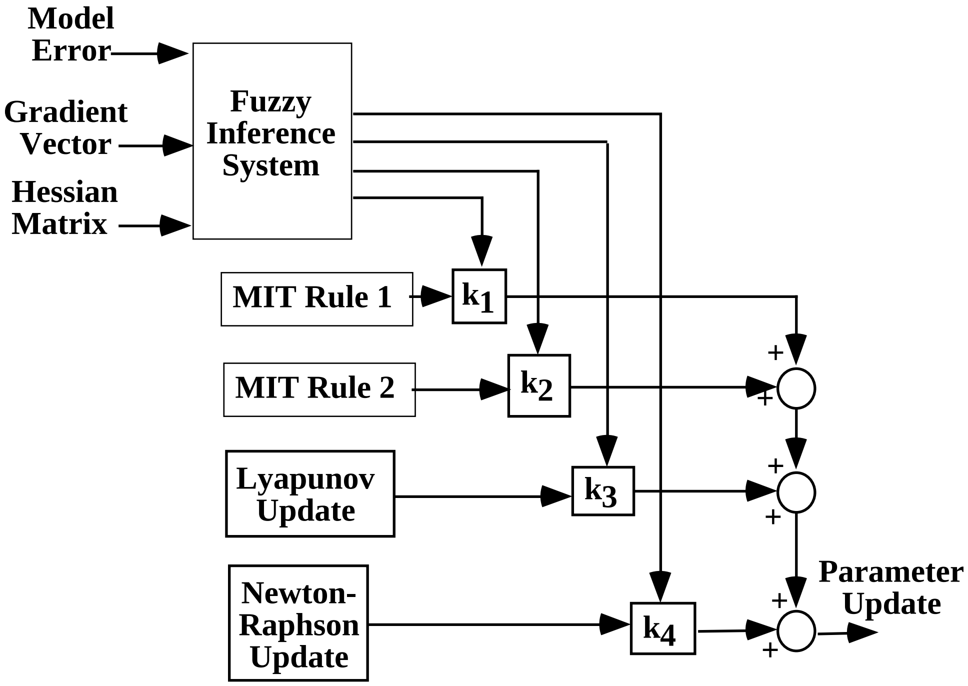
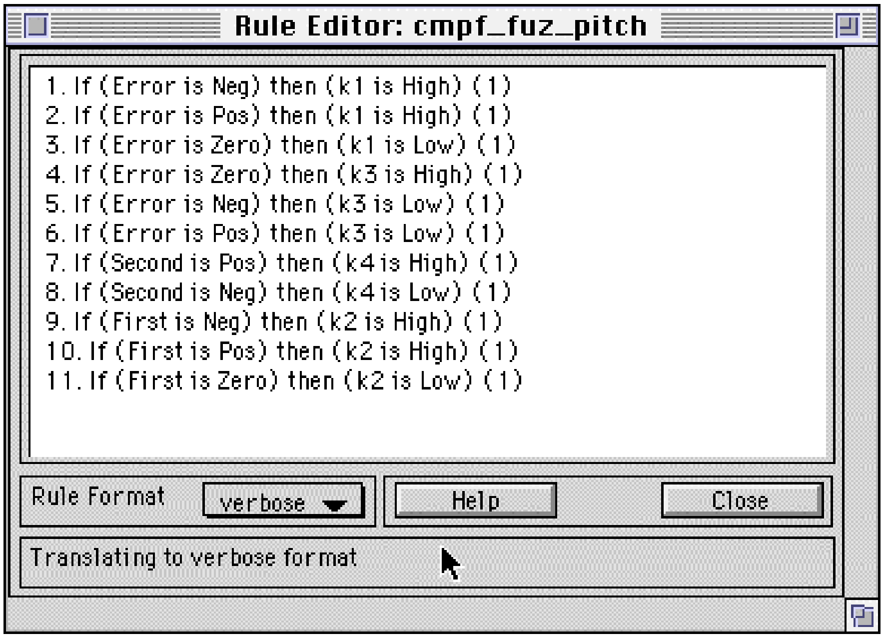


Fig. 4. Fuzzy Adaptation Logic for Model Reference Actuator Blending

The fuzzy logic toolbox of MATLAB® [20] is used to set up the fuzzy adaptation methodology. Three trapezoidal membership functions are used for each of the inputs and two sigmoidal membership functions are used for each of the outputs. The fuzzy logic rules incorporated in the fuzzy inference system are listed in Figure 5.



1. If (Error is Neg) then (k1 is High) (1)
2. If (Error is Pos) then (k1 is High) (1)
3. If (Error is Zero) then (k1 is Low) (1)
4. If (Error is Zero) then (k3 is High) (1)
5. If (Error is Neg) then (k3 is Low) (1)
6. If (Error is Pos) then (k3 is Low) (1)
7. If (Second is Pos) then (k4 is High) (1)
8. If (Second is Neg) then (k4 is Low) (1)
9. If (First is Neg) then (k2 is High) (1)
10. If (First is Pos) then (k2 is High) (1)
11. If (First is Zero) then (k2 is Low) (1)

Translating to verbose format

Fig. 5. Fuzzy Adaptation Rules

The fuzzy adaptation logic is next incorporated in the closed-loop actuator blending logic and evaluated in nonlinear simulations as described in the following section.

3.4. Numerical Results

The block diagram of the fuzzy model reference adaptive actuator blending using pulse modulated reaction jets is given in Figure 6. As motivated elsewhere in this paper, due to the unavailability of the reaction jet thrust measurements, an estimator has to be included in this channel. Moreover, in order to match the first-order dynamics of the reaction jet with the second-order fin dynamics, a lead-lag compensator is included in the reaction jet channel. The lead-lag compensator is chosen such that, if the time-delay was zero, the dynamics of the reaction jet, together with the lead-lag compensator will be identical to that of the fin dynamics. A proportional plus derivative control law is then used to achieve closed-loop actuator blending. A priority ordering is imposed in the control loop to ensure that reaction jets will be used only when the fin commands saturate, indicating that fins alone may not be able to deliver the desired transient response. The priority ordering is imposed by using a saturation nonlinearity in the fin command, and using the difference between the input and output of this nonlinearity to command the reaction jets. The closed-loop system topology and the design process will remain unchanged in this case.

As indicated in the forgoing, the reference model is chosen to be identical to that of the fin actuator dynamics. The model reference adaptive actuator blending logic is required to adjust the proportional gain K_1 and the derivative gain K_2 such that the blended actuator appears as a fin actuator to the autopilot.

The evaluation of the fuzzy model reference adaptive blending logic proceeds in two steps. Firstly, the actuator blending logic is evaluated in a standalone, control moment tracking mode. If this tracking performance is found to be acceptable, the blending logic is integrated with the three time-scale autopilot from Reference 12, and evaluated with respect to acceleration tracking characteristics. The present paper will only discuss the control moment tracking performance of the adaptive blending logic.

Figures 7 through 12 show the performance of the fuzzy model reference adaptive actuator blending logic using pulse modulated reaction jets. Note that the blending logic tracks the commanded moments with good accuracy. Although not presented here, the present adaptive blending logic yielded good performance when integrated with a three time-scale autopilot discussed in Reference 12.

Fig. 6.

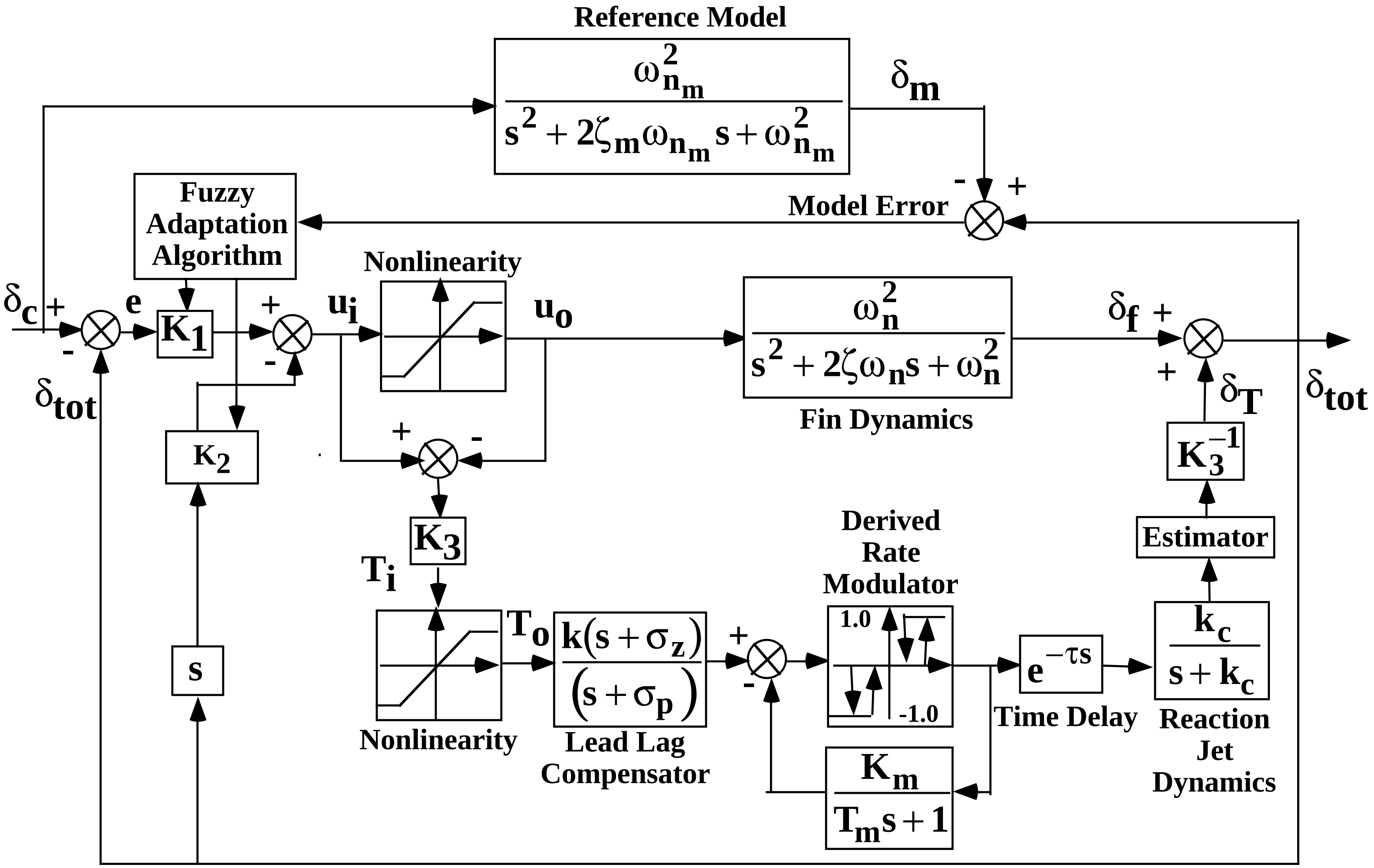


Fig. 4.4. Fuzzy Model Reference Adaptive Actuator Blending Logic Using Pulse Modulated Reaction Jets

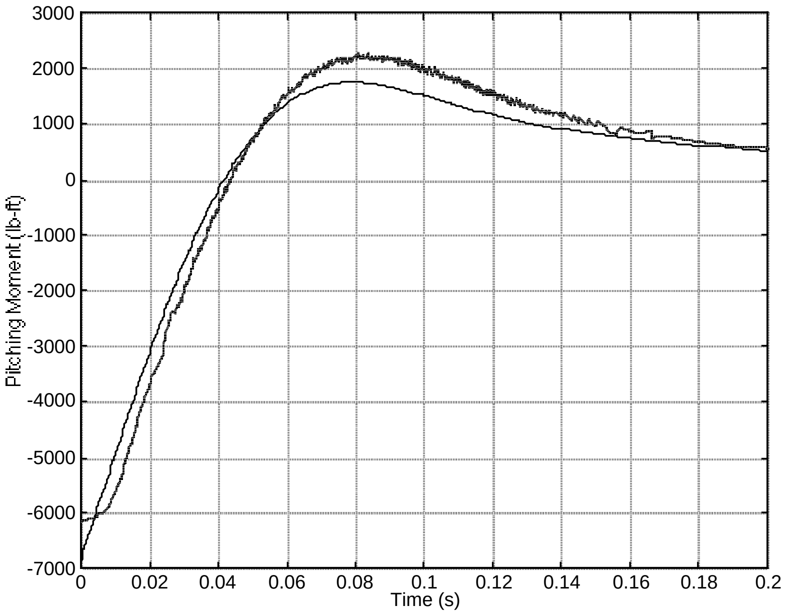


Fig. 7. Pitch Moment Tracking Response of the Fuzzy Model Reference Adaptive Blending Logic with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)

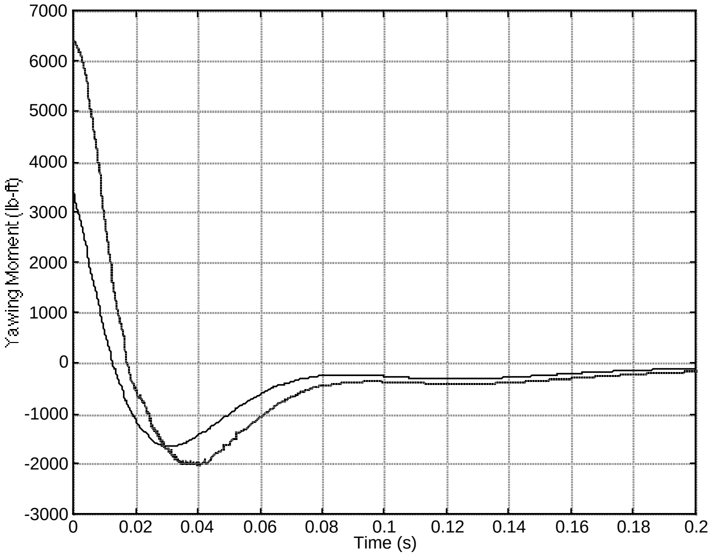


Fig. 8. Yawing Moment Tracking Response of the Fuzzy Model Reference Adaptive Blending Logic with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)

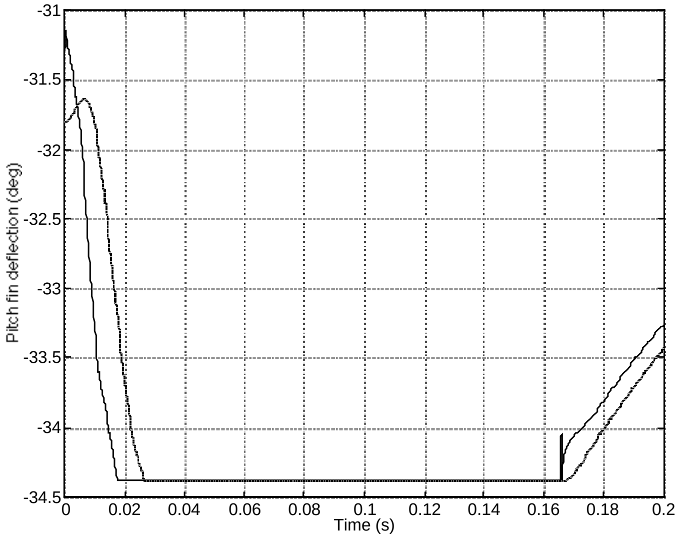


Fig. 9. Pitch Fin Deflection for Moment Command Tracking:
Fuzzy Model Reference Adaptive Blending Logic
with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)

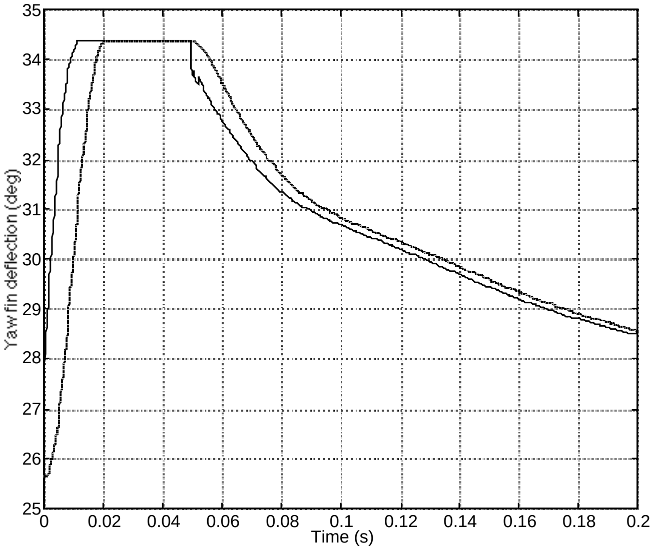


Fig. 10. Yaw Fin Deflection for Moment Command Tracking:
Fuzzy Model Reference Adaptive Blending Logic
with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)

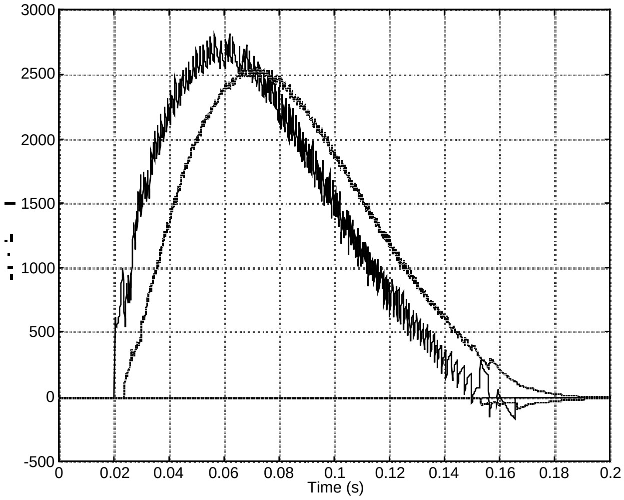


Fig. 11. Pitch Reaction Jet Thrust for Moment Command Tracking: Fuzzy Model Reference Adaptive Blending Logic with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)
Pitch-Up Reaction Jet > 0
Pitch-Down Reaction Jet < 0

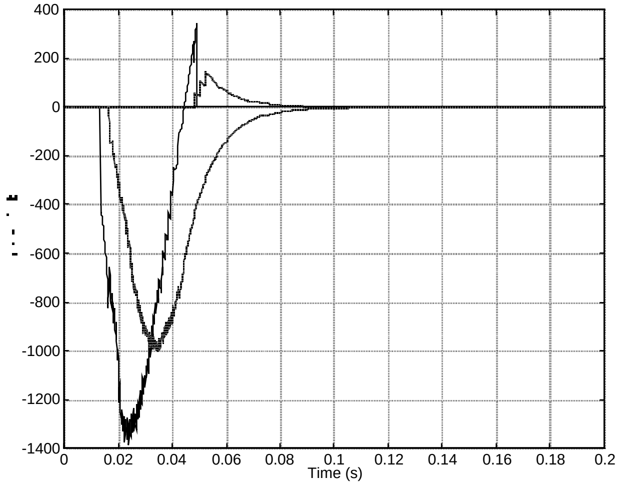


Fig. 12. Yaw Reaction Jet Thrust for Moment Command Tracking: Fuzzy Model Reference Adaptive Blending Logic with Pulse Modulated Reaction Jets
(solid line: command, dashed line: actual)
Yaw-Right Reaction Jet > 0
Yaw-Left Reaction Jet < 0

3.5. Advantages of Fuzzy Model Reference Adaptation Logic

The quantitative benefits in employing fuzzy logic for actuator blending will be briefly discussed in this section. The fuzzy logic paradigm permits the designer to include qualitative performance requirements in the control loop. Any control approach that exploits this particular feature of the fuzzy logic paradigm will be able to demonstrate performance benefits. In situations where the design requirements can be strictly quantified, and no knowledge-base is needed for the operation of the dynamic system, fuzzy logic technology is unlikely to deliver any additional benefits over the modern control theoretic techniques.

In the present situation, since the adaptation rules have qualitative features that make each of them superior under certain conditions, using a supervisory fuzzy logic can be shown to clearly provide an advantage. In order to bring-out the superiority of the fuzzy logic-based model reference adaptive control, moment tracking responses using the four different adaptation algorithms and the fuzzy logic algorithm are presented in Figures 13 and 14.

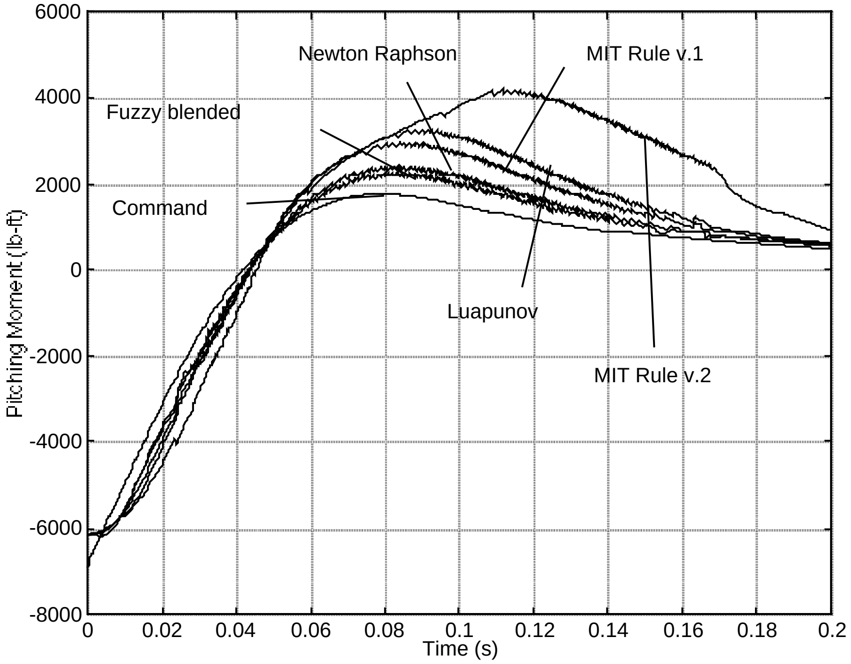


Fig. 13. Pitching Moment Tracking Response Comparison Between Adaptation Schemes

From these figures, it may be observed that fuzzy logic-based adaptation algorithm provides the best compromise between the four adaptation rules. Fuzzy adaptation algorithm appears to combine the best features of the four adaptation rules.

It should be pointed-out here that once the adaptive blending logics are integrated with the autopilot, the differences between various adaptation algorithms will not be quite as dramatic as indicated in Figures 13 and 14. This is because of the fact that closed-loop systems tend to compensate for variations occurring within the control loop.

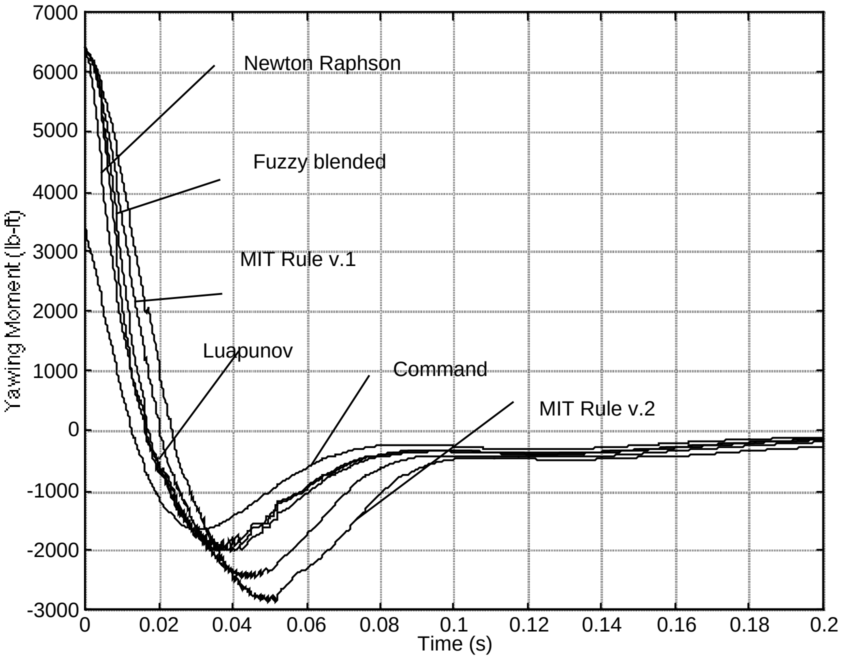


Fig. 14. Yawing Moment Tracking Response Comparison Between Adaptation Schemes

Conclusions

This paper discussed the development of a fuzzy logic supervised model reference adaptive actuator blending logic. Actuator blending is needed in this application in order to provide uniform control power during terminal homing at high altitudes.

The blending problem is non-trivial because the actuators are not collocated. Further, the reaction jets can only be operated in an On/Off mode. The actuator blending was formulated as a model reference adaptive system. A fuzzy logic supervisory system was used to combine four different adaptation rules. The performance of the fuzzy blending logic was demonstrated through simulations.

Due to the richer dynamic behavior obtainable, closed-loop adaptive actuator blending strategies can provide good performance from the blended actuators even under off-design parameter values. However, closed loop blending strategies require the use of estimators to determine the reaction jet actuator outputs and are computationally more demanding than open-loop strategies.

The following summarizes some of the general observations about the application of the fuzzy logic technology for the development of missile actuator blending logic.

1. Fuzzy logic enables the designer to include heuristic information in the flight control loop. This capability is useful in not only developing new controllers, but also in improving the performance of existing control systems.

2. The fuzzy logic design involves a trial and error process for the selection of the fuzzy logic rules and membership functions. Thus, it is helpful to start the design process using “crisp” implementations. This way, the fuzzy logic system can be assured to have a performance at least equal to that of the crisp implementation.

3. Due to the trial and error nature of the fuzzy logic system development, the designer must make every attempt to minimize the number of inference rules and membership functions. Otherwise, multiple interacting rules and membership functions can quickly overwhelm the designer’s ability to make adjustments to the system. This will lead to increased design time. Moreover, large number of rules and membership functions will also make the fuzzy logic system computationally expensive.

4. Fuzzy logic appears to be most effective when used in a supervisory role. This is because of the fact that while the fuzzy logic technique provides significant potential for incorporating

intelligence about the system operation, it cannot provide stability guarantees essential in high performance flight control systems.

Future work will focus on comparing the fuzzy actuator blending logic performance with more conventional blending logics. An assessment of the computational resources required for the implementation of the adaptive blending logic is also a future research item.

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