26th AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 18 - 21, 2008, Honolulu, Hawaii

Simulator Testing of Longitudinal Flying Qualities with $\mathcal{L}_1$ Adaptive Control *

M. Christopher Cotting,[†] Chengyu Cao,[‡] Naira Hovakimyan,[§]

Lt. Col. Robert J. Kraus,[¶] and Wayne C. Durham^{||}

Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061-0203

A study was conducted to determine if an adaptive controller can recover level 1 handling qualities on a piloted, simulated aircraft in a degraded state. Four different aircraft models of varying handling qualities levels were used as a test data-set to determine if all four could be augmented via the adaptive controller to level 1 handling qualities. Two experienced test pilots were used to judge the aircraft flying qualities using the Cooper Harper Rating Scale, and then an attempt to correlate those results to a handling qualities rating is made.

I. Introduction

Adaptive control algorithms have given hope to a new level of flight vehicle robustness previously unachievable with traditional control methods. Recent Air Force Programs RESTORE (X-36) and JDAM have demonstrated the potential of adaptive controllers for compensation of modeling uncertainties and component failures. However, the major lesson learned during those programs was that the conventional model reference adaptive control scheme is very sensitive to time-delay, especially if one attempts to adapt fast.¹ This has consequently led to a new paradigm for design of adaptive controllers, specifically The Theory of Fast and Robust Adaptation.²⁻⁹ The Theory of Fast and Robust Adaptation provides an ability for a priori prediction of the uniform performance bounds – for transient and steady-state – for system’s input and output signals, and also analytical quantification of the gain and time-delay margin, similar to linear systems’ gain and phase margin concepts. Various architectures of this theory, known as $\mathcal{L}_1$ adaptive controllers, have been flight tested and validated against the theoretical claims.¹⁰⁻¹⁸

While it may be proven that an aircraft can be stabilized when in a degraded or unknown state, the flying qualities of the flight vehicle must be favorable if a piloted system is to be controlled, especially during critical phases such as landing or formation flight (air to air refueling). This paper describes a longitudinal study to evaluate the flying qualities of an adaptive controller used to compensate for a poorly performing aircraft’s handling characteristics. Using a piloted, motion-based flight simulator an evaluation of flying qualities was conducted to collect pilot’s opinions and ratings using the Cooper Harper¹⁹ rating scale. A simplified F-16 model was used as the plant model to evaluate the controller. While simulator evaluations are limited in comparison to full flight test, it is a safe and cost effective way to conduct initial research in a realistic environment.

*Research is supported by AFOSR under Contract No. FA9550-05-1-0157.

[†]Graduate Student, Department of Aerospace and Ocean Engineering, Senior Member AIAA.

[‡]Research Scientist, Department of Aerospace and Ocean Engineering, Member AIAA.

[§]Professor, Department of Aerospace and Ocean Engineering, Senior Member AIAA.

[¶]Lt. Col. USAF and Graduate Student, Department of Aerospace and Ocean Engineering, Member AIAA.

^{||}Emeritus Professor, Department of Aerospace and Ocean Engineering, Senior Member AIAA.

Copyright © 2008 by M. Christopher Cotting. Published by the American Institute of Aeronautics and Astronautics, Inc. with permission.

II. Background

A. $\mathcal{L}_1$ Adaptive Control Architectures and Their Verification and Validation

As mentioned above, adaptive controllers have been successfully flight tested for recovering nominal performance in the presence of modeling and environmental uncertainties.^{1,20} While the stability of these schemes follows from Lyapunov's direct method, the robustness analysis (stability margins) are being determined from Monte-Carlo simulations. It has been observed that increasing the adaptation gain for better performance leads to high-frequency oscillations in the control signal and reduces the system's tolerance to the time-delay in the control and the sensor channels. The recently developed Theory of Fast and Robust Adaptation with its $\mathcal{L}_1$ adaptive control architectures presented and analyzed in References^{4,5,7-9,21-27} has addressed these limitations for a wide class of systems. It allows for fast adaptation with guaranteed, bounded away from zero time-delay margin. The speed of adaptation is limited by the hardware, specifically the computer processor.

Figure 1. $\mathcal{L}_1$ adaptive control architecture.

Originally introduced in References^{22,23} for the class of systems with known high-frequency gain and constant unknown parameters, the underlying design paradigm of $\mathcal{L}_1$ adaptive controller was later extended in^{5,21} to systems with unknown high-frequency gain, time-varying unknown parameters and disturbances without restricting their rate of variation. The analysis in References^{5,21} predicts the uniform performance bounds a priori for the system's input and output signals simultaneously, and also quantifies the stability margins, including the time-delay margin.

The underlying design paradigm of this new theory is the use of a low-pass filter in the feedback path that appropriately attenuates high-frequencies in the control signal typical for fast adaptation rates. Selection of the bandwidth of the filter follows from a small-gain type argument, which in its turn leads to guaranteed bounded away from zero time-delay margin in the presence of fast adaptation. While the adaptation law is still derived from conventional gradient minimization, the error signal $\tilde{x}(t)$ used in that process is the one between the system state and its predictor, Fig. 1. The fact that the adaptive law retains its structure, the upper bound on the norm of $\tilde{x}(t)$ remains proportional to the rate of variation of uncertainties and inversely proportional to the adaptation gain, as in conventional Model Reference Adaptive Control (MRAC). However, with the low-pass filter in the feedback path the $\mathcal{L}_1$ adaptive controller readily avails the opportunity to increase the adaptation rate without leading the system into high-frequency oscillations, while the small-gain theorem invoked for the stability proof leads to uniform performance bounds – inversely proportional to the adaptive gain, and guaranteed, bounded away from zero time-delay margin in the presence of fast adaptation (see the analysis in Reference⁷ for a simple scalar system and References^{5,21} for complete analysis of the closed-loop nonlinear system).

The $\mathcal{L}_1$ adaptive control architecture and its variants have been verified and validated for various systems: flight test of augmentation of an off-the-shelf autopilot for path following,^{10,28} autopilot design and flight test for Micro Air Vehicles (MAV),¹⁴ Tailless Unstable Military Aircraft,^{17,18} Aerial Refueling Autopilot design,^{12,13} flexible aircraft (Sensorcraft),¹⁶ control of wingrock in the presence of faults¹¹ and air-breathing hypersonic vehicles.¹⁵

It is important to note that the $\mathcal{L}_1$ adaptive control system is only intended to be active during a mismatch with desired aircraft performance (when $\tilde{x} \neq 0$). This mismatch may occur first as a transient and then as an error from the desired state that may or may not be constant. The adaptive control system's route taken to drive this mismatch to zero will be key in determining the aircraft flying qualities while the adaptive controller is active. It is important, however, to not only look at an initial transient, but also at the long term response of the controller while active. For example if the adaptive controller is requiring 90% of pitch effectors to keep the aircraft trimmed and stable, a high rate pitch task may not be possible, and aircraft handling qualities would be affected purely by lack of control authority or possibly actuator rate limiting, and not just the dynamic controller response. While total system interaction by structural mode coupling and aeroservoelastic effects would be a major concern in aircraft implementation, it was not investigated in this study due to simulation complexity.

B. Aircraft Model and SAS

The aircraft model used for this study was a simplified F-16 model²⁹ that supports six degree of freedom motion. The aircraft model is a clean F-16 (no external loads), and does not contain math modelling for high lift devices (flaps or slats), landing gear, or ground effects. The model does contain an after-burning turbofan jet engine with appropriate throttle lags modeled. The control inputs are δ_{PLA} , δ_e , δ_a , and δ_r . δ_{PLA} command is the power lever angle command (or throttle position), and its inputs range from 0 (flight idle) to 0.5 (full military thrust) to 1.0 (max afterburner), and is referenced as idle, MIL or MAX thrust, respectively. The three aerodynamic effectors are elevators (δ_e), ailerons (δ_a), and rudders (δ_r) all with a range of $\pm 25^\circ$. The elevators are primarily used for pitch control, the ailerons for roll control, and the rudders for yaw control, with PLA being used as engine control. The aircraft model does not include a sensor model, but relies on use of the actual aircraft states. A simplified atmospheric model was used as well. The aircraft model places the cg location at 35% of the mean aerodynamic chord, resulting in an open loop unstable short period. The aircraft motion is described by the states found in Table 1.

State Index	Name	Description	Units
$x(1)$	V	body axis total velocity	ft/sec
$x(2)$	α	angle of attack	rads
$x(3)$	β	sideslip	rads
$x(4)$	ϕ	roll angle	rads
$x(5)$	θ	pitch angle	rads
$x(6)$	ψ	yaw angle	rads
$x(7)$	p	roll rate	rads/sec
$x(8)$	q	pitch rate	rads/sec
$x(9)$	r	yaw rate	rads/sec
$x(10)$	N	horizontal travel, North	ft
$x(11)$	E	horizontal travel, East	ft
$x(12)$	h	altitude (MSL)	ft
$x(13)$	pow	power, state used to find thrust	0 - 100 %

Table 1. Reference of vehicle states.

A simple control system was implemented to modify the short period characteristics of the F-16 model. A block diagram of the system is shown in Figure 2. By feeding back the pitch rate and angle of attack

Figure 2. Augmented F-16 Plant.

the damping ratio and natural frequency of the short period was modified. This modification occurs by manipulating gains K_1 and K_2 . The result is an augmented plant that can be easily changed to match Handling Qualities Ratings that are well documented.^{30,31} Four specific cases that can be found in Table 2 were created at a trim condition of steady, level flight, 10,000 ft MSL, 360 KEAS (709 ft/sec or 0.65 Mach), and an angle of attack of 1 degree.

Case	Natural Frequency ω_n	Damping ratio ζ	K_1	K_2
1	4.63 rad/sec	0.704	0.29	1.25
2	2.47 rad/sec	0.448	0.0	0.444
3	4.0 rad/sec	0.2	0.05	1.25
4	unstable	unstable	0.0	0.0

Table 2. Test Flight Cases

C. Facility

1. Simulator

The simulator used for this study was delivered to the Aerospace and Ocean Engineering Department of Virginia Tech on March 5th of 1996 from NAS Oceana in Virginia Beach. Originally an A-6E Intruder Operational Flight Trainer (OFT), the simulator was declared “in excess” when the Navy retired its A-6E’s and replaced them with F/A-18’s. The transfer was made possible with the help and support of research sponsors at Naval Air Systems Command Headquarters and at the Manned Flight Simulator branch of the Naval Air Warfare Center, Patuxent River, Maryland. A diagram of the simulation system can be found in Figure 3. The left (pilot’s) seat of the trainer cockpit represents the cockpit of a A-6E Intruder. The right seat has been modified to accommodate either an instructor or a flight test engineer with a computer driven CRT which can be custom configured with instrumentation as desired. The simulation computer has been converted to a SGI Origin 2000 computer. This allows the simulation of many different aircraft models, from a F-16 to a Cessna 152 to a Boeing 737 to a F/A-18. The A-6E Intruder aircraft flight controls, instruments, and systems, as well as its visual, aural, environmental, and motion sensations are combined with the desired aircraft software model to create a realistic flight experience. The three window visual display shows the surrounding terrain throughout take-off, maneuvers, and landing approach as a function of the aircraft attitude, altitude, and speed. Motion cues are provided by a three-degree of freedom cantilevered motion system. The simulator was originally procured by the Navy to provide pilot and air crew training for carrier based takeoffs and landings. While heavily upgraded, it retains its original capability.³²

2. IADS

Symvionics Inc. of Arcadia, CA has donated its flight test instrumentation software package called IADS[®] to Virginia Tech for use in their flight simulation laboratory. IADS[®] is a real-time data viewing tool that allows its user to view parameters from the aircraft simulation while the test is occurring. IADS[®] is an industry

Figure 3. Diagram of Virginia Tech Flight Simulation System.

standard tool that is used in flight test by NASA, the US Air Force, and US Navy. IADS[®] also archives the data it displays for analysis purposes after the test. IADS[®] allows the user to customize the data displayed on the computer screen allowing the user to create data screens that are tailored to each test's requirements. IADS[®] has served as an important evaluation tool allowing realtime data visualization during and post flight test. Examples of IADS[®] displays used in this study can be found in Figure 4.

III. $\mathcal{L}_1$ Controller Implementation

A high level diagram of the $\mathcal{L}_1$ architecture implemented for this study can be found in Figure 5. For design and analysis purposes the controller was first implemented as a linear system in Matlab Simulink[®] and then implemented in the nonlinear CASTLE simulation. For both the linear and nonlinear model cases the same $\mathcal{L}_1$ controller was used. The augmentation scheme referenced in Table 2 was also used for both linear and nonlinear plants. The combination of augmentation schemes in Table 2 and the open loop aircraft model were used to create the Stabilized Plant block in Figure 5.

The primary interest of this study was the short period mode of the longitudinal motion. The phugoid was left out of the $\mathcal{L}_1$ design because it had no impact on the short period aircraft response. The lateral-directional states were added to the controller for future use, but since no uncertainty in the lateral or directional motion is incorporated in this study they do not add any augmentation to the aircraft.

For this study the $\mathcal{L}_1$ controller was first designed with a linear system approximation of the aircraft equations of motion. The linear approximation was then replaced with the full nonlinear 6-DOF equations of motion. The general equations for aircraft dynamics can be presented in state space form as:

$$\dot{x}(t) = A_m x(t) + b(\omega u(t) + \theta^T(t)x(t) + \sigma(t)) \quad (1)$$

where A_m corresponds to case 1 in Table 2, and the uncertainties are ω , $\theta(t)$, and $\sigma(t)$. The predictor is

(a)

(b)

Figure 4. Sample IADS[®] data screens used for the study.

Figure 5. Block diagram of L_1 controller.

defined as

$$\dot{\hat{x}}(t) = A_m \hat{x}(t) + b \left(\hat{\omega} u(t) + \hat{\theta}^T(t) x(t) + \hat{\sigma}(t) \right) \quad (2)$$

where the adaptive estimates $\hat{\omega}(t)$, $\hat{\theta}(t)$, and $\hat{\sigma}(t)$ are updated according to the following adaptation laws:

$$\dot{\hat{\theta}}(t) = \Gamma_{\theta} \text{Proj} \left(-x(t) \tilde{x}^T(t) P b, \hat{\theta}(t) \right) \quad (3)$$

$$\dot{\hat{\sigma}}(t) = \Gamma_{\sigma} \text{Proj} \left(-\tilde{x}^T(t) P b, \hat{\sigma}(t) \right) \quad (4)$$

$$\dot{\hat{\omega}}(t) = \Gamma_{\omega} \text{Proj} \left(-\tilde{x}^T(t) P b u(t), \hat{\omega}(t) \right) \quad (5)$$

$$\Gamma = \Gamma_{\theta} = \Gamma_{\sigma} = \Gamma_{\omega} \quad (6)$$

with Γ being the adaptation rate, while

$$P = P^T > 0 \quad A_m^T P + P A_m = -Q \quad Q > 0$$

The projection operator³³ is defined as:

$$\begin{aligned} \Omega_c &\triangleq \{\theta \in \mathbb{R}^n | f(\theta) \leq c\}, \quad 0 \leq c \leq 1 \\ f : \mathbb{R}^n &\rightarrow \mathbb{R} \\ f(\theta) &= \frac{\theta^T \theta - \theta_{max}^2}{\epsilon_{\theta} \theta_{max}^2} \\ \theta^* &\in \Omega_0 \\ \text{Proj}(\theta, y) &\triangleq \begin{cases} y & \text{if } f(\theta) < 0 \\ y & \text{if } f(\theta) \geq 0 \text{ and } \nabla f^T y \leq 0 \\ y - \frac{\nabla f}{\|\nabla f\|} \left\langle \frac{\nabla f^T}{\|\nabla f\|}, y \right\rangle f(\theta) & \text{if } f(\theta) \geq 0 \text{ and } \nabla f^T y > 0 \end{cases} \end{aligned}$$

A control law was then defined to provide command inputs to the augmented aircraft control system:

$$u(s) = -k D(s) r_u(s) \quad (7)$$

$r_u(s)$ is the Laplace transform of $r_u(t) = \hat{\omega}(t)u(t) + \hat{\theta}^T x(t) + \hat{\sigma}(t)$, and $D(s)$ is any transfer function such that it leads to a strictly proper stable

$$C(s) = \frac{\omega k D(s)}{1 + \omega k D(s)} \quad (8)$$

The choice of $D(s)$ and the gain k needs to ensure

$$\|G(s)\|_{\mathcal{L}_1} L < 1, \quad G(s) = (sI - A_m)^{-1} b(1 - C(s)) \quad (9)$$

$$L = \max_{\theta(t) \in \Theta} \sum_{i=1}^n |\theta_i(t)|$$

$$\omega \in \Omega_0 = [\omega_{lo}, \omega_{hi}], \quad \theta(t) \in \Theta, \quad |\sigma(t)| \leq \Delta_0, \quad t \geq 0$$

Letting $D(s) = 1/s$ Equation (8) becomes

$$C(s) = \frac{\omega k}{s + \omega k} \quad (10)$$

For digital implementation, the $1/s$ is approximated by the Tustin approximation where

$$s = \frac{2(z-1)}{T(z+1)}$$

For this particular implementation of the $\mathcal{L}_1$ controller the values used in Table 3 were used to configure the controller.

Controller Parameter	Value
$k(1)$	100
$k(2)$	100
$k(3)$	100
Γ	17000
$D(s)$	$1/s$
θ_{lim}	± 100
σ_{lim}	± 100
ω_{lim}	$[0.5, 2]$

Table 3. Reference of $\mathcal{L}_1$ parameters.

IV. Results

A. Predicted HQR of Plant Models

Predicted longitudinal handling qualities were based off of eigenvalue analysis of the short period found in MIL-F-8785C.^{30,31} Cases 1, 2, and 3 in Table 2 were investigated using these criteria to ensure a broad range of airframe characteristics during flying qualities testing. The load factor (n/α) and short period frequency ($\omega_{n_{SP}}$) comparison can be seen in Figure 6(a). Using this criteria alone Cases 1 and 3 appear in the Level 1 category while Case 2 appears in the Level 2/3 category. Investigating Control Anticipation Parameter (CAP) vs. damping ratio ζ_{SP} , the second part of the criteria yields further separation between the cases, as seen in Figure 6(b). From these figures it can be seen that the cases are set to be correlated so that Case 1 has a predicted HQR of level 1, Case 2 has a predicted HQR of level 2, and Case 3 has a predicted HQR of level 3, with Case 4 being not classifiable because the short period is unstable.

Figure 6. MIL-F-8785C Short Period Criteria.

B. Simulation Traces (Linear and Nonlinear)

Simulation test cases were run on each plant test case before $\mathcal{L}_1$ adaptive control was applied and then afterwards to contrast performance with and without $\mathcal{L}_1$ controller augmentation. For brevity only the responses with $\mathcal{L}_1$ are shown here. A double command (Figure 7) was given to both linear and nonlinear models to assure that the $\mathcal{L}_1$ controller and underlying models were behaving similarly. Figure 8 shows responses for all four cases in Table 2. For reference Case 1 is the desired case for all responses. While Cases

2 - 4 do not identically match Case 1, the response in all cases showed similarities, even for the open-loop unstable case. Further the CASTLE (nonlinear model) and the Simulink (linear model) are not identical but very similar as well, showing that the system is responding as desired for both linear and nonlinear models.

Figure 7. Doublet command used to test $\mathcal{L}_1$ controller response.

V. Piloted Simulation Trial

For this study a piloted simulation trial was conducted with two experienced test pilots, referred to as Pilots A and B. One pilot is a retired U. S. Navy Test Pilot with over 3300 flight hours, and a graduate of the Empire Test Pilot School. The other pilot is currently a U. S. Air Force Test Pilot with 3000 flight hours and a graduate of the U. S. Air Force Test Pilot School.

A. Piloted Task Definition

The simulation trial was broken into two parts, the first (referred to as task 1) being a fully disclosed trial where a stick rap impulse was used to excite the different aircraft plant cases, both with and without $\mathcal{L}_1$ augmentation to familiarize the pilot with the different responses from each case. The instruction to the pilot can be found below.

Objective: Observe and qualitatively comment on the short period natural frequency and damping for each airframe. This is not a blind test.

Task: Obtain level flight, 360 KEAS at 10000 ft. Trim aircraft, and verify with hands off stick. Quickly pull aft on the control stick and release to excite the short period mode of the aircraft with an impulse force. Observe and comment on the rise time and overshoot of the response to estimate flying qualities of the aircraft.

After the pilot was introduced to all eight cases (four with $\mathcal{L}_1$ augmentation, and four without $\mathcal{L}_1$ augmentation), a new set of tasks were performed (referred to as task 2). A target aircraft that is another F-16 using the Stevens and Lewis model²⁹ with a maneuver autopilot³⁴ was flown ahead of the piloted aircraft at a constant altitude of 10,000 ft and 360 KEAS (709 ft/sec). The piloted aircraft was positioned 1000 ft behind and 200 ft below the target aircraft. The pilot was to aggressively capture the target aircraft within a bulls-eye found on the cockpit windshield. An example of the pilot's view can be found in Figure 9. The pilot was to rate the difficulty of the task using the Cooper Harper Rating Scale.¹⁹ The pilot was not told which aircraft model he was flying during the testing. The instruction to the pilot can be seen below.

Objective: Evaluate longitudinal flying qualities in a dynamic tracking task using Cooper-Harper rating scale, note this is a blind test.

(a) Angle of attack (α) response from linear and nonlinear models with $\mathcal{L}_1$ controller.

(b) Pitch rate (q) response from linear and nonlinear models with $\mathcal{L}_1$ controller.

Task: Place tail light of lead aircraft just outside of the top ring in the bulls-eye, while maintaining 9800 ft altitude and near level flight, and approximate co-speed with the lead aircraft. When ready pull back on the control stick abruptly to move the target aircraft into the lower ring of the bulls-eye within 1 second. Then move the aircraft into the center of the bulls-eye within 1 second. The entire task should take approximately 2 seconds.

Adequate: Outer Ring

Desired: Inner Ring

Figure 9. Pilot's view for pitch capture task.

B. Simulation Trial Results

1. Task 1

When asked to characterize the four aircraft models without $\mathcal{L}_1$ augmentation both pilots were able to give responses that correlated with predicted model behavior. Pilots A and B both described model 1 as “deadbeat.” Both pilots noticed the lower damping and slower frequency in model 2 as well. Pilot A responded that model 3 had “a lot of overshoot” and “poor damping” and that “the aircraft felt like it was going to diverge but did not.” Pilot B concurred that model 3 had poor damping as well. Pilot A referred to model 4 as having an “aperiodic divergence.” When the $\mathcal{L}_1$ controller was engaged Pilot B could not tell any difference in all four model responses, although he did state that the controls felt “heavier.” He further noted that all four models felt deadbeat, and “right on.” Both pilots noted that the aircraft had to be re-trimmed with $\mathcal{L}_1$ engaged. With $\mathcal{L}_1$ engaged Pilot A noticed small differences between models 3 and 4 but felt that models 1 and 2 behaved the same when $\mathcal{L}_1$ was engaged.

2. Task 2

The Cooper Harper ratings given by each pilot are presented in two forms in Table 4 and in Figure 10. Pilot ratings as presented in Figure 10 do show that a significant improvement in aircraft handling does occur with $\mathcal{L}_1$ off versus $\mathcal{L}_1$ on. Further, agreement between aircraft model 1 with $\mathcal{L}_1$ off is found with all $\mathcal{L}_1$ on aircraft model cases. Both pilots judged all $\mathcal{L}_1$ controller cases as well as case 1 $\mathcal{L}_1$ off (baseline reference case) as being either a 3 or 4 on the Cooper Harper scale. Pilot B correctly identified cases where the $\mathcal{L}_1$ controller was on versus off with the exception of the $\mathcal{L}_1$ off aircraft model 1 case. As Pilot A was given more exposure to the different airframes with $\mathcal{L}_1$ controllers he noted that he was “learning the airplane” and that the task became easier. With airframe case 2 and $\mathcal{L}_1$ on, Pilot A remarked “nothing to it,” and with airframe case 4 and $\mathcal{L}_1$ on he remarked “very easy,” although some pilot compensation was required. Pilot A

felt that the task as described for the case 2 and case 4 airframes with no $\mathcal{L}_1$ compensation was not achievable.

Aircraft Model	Pilot A		Pilot B	
	$\mathcal{L}_1$ Off	$\mathcal{L}_1$ On	$\mathcal{L}_1$ Off	$\mathcal{L}_1$ On
1	3	4	3	4
2	10	2	8	3
3	6	3	9	4
4	10	3	9	3

Table 4. Cooper Harper Ratings from Flying Qualities Test of $\mathcal{L}_1$ controller augmenting Short Period.

Figure 10. Piloted Cooper Harper Ratings Results.

Overall comments from both pilots on the eight different aircraft models presented noted that there was a considerable amount of re-trimming required for each aircraft model presented. Also, a lack of control harmony between the pitch and roll axes caused both pilots to pay more attention to the lateral aircraft response than expected. In general, a considerable separation between ratings were found with the $\mathcal{L}_1$ controller on vs off for all but the case 1 airframe.

According to MIL-F-8785C, Level 1 flying qualities are “clearly adequate for the mission Flight Phase,” Level 2 flying qualities are “adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness or both,” and Level 3 flying qualities are “such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both.” Taking this as guidance, and to simplify data correlation, this study will take achievement of desired criteria (Cooper Harper rating of 1 - 4) as a level 1 flying quality, achievement of adequate criteria (Cooper Harper ratings of 5 and 6) as level 2 flying quality, and Cooper Harper rating of 7 - 9 as Level 3 flying quality. Using this as a correlation between Cooper Harper rating and flying quality rating, all $\mathcal{L}_1$ cases were level 1, although several were on the lower edge of level 1. Most $\mathcal{L}_1$ off cases, however were level 3.

While aircraft simulation and flying real aircraft are similar, deficiencies in a simulation will make drawing direct conclusions from flying qualities data imprecise. This principle may explain why aircraft model case 1 was a marginal level 1 flying quality aircraft, although preliminary analysis shows it lying directly in the

heart of the MIL-F-8785 level 1 envelope. Further complicating the analysis of the pilot rating is that only one pilot rated one airframe as a Level 2 flying quality aircraft although by prediction using MIL-F-8785C both pilots should have rated aircraft model case 2 as level 2 and case 3 as level 3. Noting that the majority of $\mathcal{L}_1$ off cases were rated as level 3 by the pilots also raises the possibility that the task assigned may have been too difficult and over exposed the weaknesses of the predicted level 2 and level 3 aircraft.

VI. Conclusions

A $\mathcal{L}_1$ controller was successfully implemented into the piloted simulator at Virginia Tech. This simulator now has the basic building blocks to serve as a test bed for future $\mathcal{L}_1$ flying qualities research. Using the developed simulation, the flying qualities of the test airframes were shown to be enhanced by the $\mathcal{L}_1$ controller in cases where the aircraft model was predicted to have deficient flying qualities. While pilot ratings are often more qualitative than quantitative, the overarching results show that using $\mathcal{L}_1$ control aided in achieving the desired task with pilot control. With these promising results, future work should continue to investigate $\mathcal{L}_1$ performance in a piloted environment. A better understanding of the correlation between predicted flying qualities and test results is desired. Future work should include reevaluating the piloted task as well as including more pilots to enlarge the pilot evaluation sampling. An expansion of the work here should also include incorporating $\mathcal{L}_1$ control into a more complex aircraft model as well as investigation into lateral directional aircraft flying qualities.

References

- ¹Wise, K., Lavretsky, E., and Hovakimyan, N., "Adaptive Control in Flight: Theory, Application, and Open Problems," *In Proceedings of American Control Conference*, 2006, pp. 5996–5971.
- ²Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel $\mathcal{L}_1$ Adaptive Controller, Part I: Control Signal and Asymptotic Stability," *Proceedings of the 2006 American Control Conference*, June 14-16 2006.
- ³Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel $\mathcal{L}_1$ Adaptive Controller, Part II: Guaranteed Transient Performance," *Proceedings of the 2006 American Control Conference*, June 14-16 2006.
- ⁴Cao, C. and Hovakimyan, N., "A Novel $\mathcal{L}_1$ Neural Network Adaptive Control Architecture with Guaranteed Transient Performance," *IEEE Transactions on Neural Networks*, Vol. 18(4), July 2007, pp. 1160–1171.
- ⁵Cao, C. and Hovakimyan, N., "Guaranteed Transient Performance with $\mathcal{L}_1$ Adaptive Controller for Systems with Unknown Time-Varying Parameters: Part I," *Proc. of American Control Conference*, New York, NY, July 2007, pp. 3925–3930.
- ⁶Cao, C. and Hovakimyan, N., "Stability Margins of $\mathcal{L}_1$ Adaptive Controller, Part II," *American Controls Conference*, 2007.
- ⁷Cao, C., Patel, V., Reddy, K., Hovakimyan, N., and Lavretsky, E., "Are the Phase and Time-delay Margins Always Adversely Affected by High-gain?" *Proc. of AIAA Guidance, Navigation and Control Conf.*, 2006, AIAA-2006-6347.
- ⁸Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Output Feedback Controller for Systems with Time-varying Unknown Parameters and Bounded Disturbances," *American Control Conference*, 2007, pp. 486–491.
- ⁹Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Output Feedback Controller for Systems of Unknown Dimension," *American Control Conference*, 2007, pp. 1191–1196.
- ¹⁰Cao, C., Hovakimyan, N., Kaminer, I., Patel, V., and Dobrokhodov, V., "Stabilization of Cascaded Systems via $\mathcal{L}_1$ Adaptive Controller with Application to a UAV Path Following Problem and Flight Test Results," *American Control Conference*, 2007, pp. 1787–1792.
- ¹¹Cao, C., Hovakimyan, N., and Lavretsky, E., "Application of $\mathcal{L}_1$ Adaptive Controller to Wing Rock," *In Proc. of AIAA Guidance, Navigation and Control Conference*, 2006, AIAA 2006-6426.
- ¹²Wang, J., Cao, C., Patel, V., Hovakimyan, N., and Lavretsky, E., " $\mathcal{L}_1$ adaptive neural network controller for autonomous aerial refueling with guaranteed transient performance," *In Proc. of AIAA Guidance, Navigation and Control Conference*, 2006, AIAA 2006-6206.
- ¹³Wang, J., Patel, V., Cao, C., Hovakimyan, N., and Lavretsky, E., " $\mathcal{L}_1$ adaptive neural network controller for autonomous aerial refueling in the presence of unknown actuator failures," *In Proc. of AIAA Guidance, Navigation and Control Conference*, 2007, AIAA 2007-6313.
- ¹⁴Beard, R., Knoebel, N., Cao, C., Hovakimyan, N., and Matthews, J., "An $\mathcal{L}_1$ Adaptive Pitch Controller for Miniature Air Vehicles," *Proc. of AIAA Guidance, Navigation & Control Conf.*, Keystone, CO, 2006, AIAA-2006-6777.
- ¹⁵Lei, Y., Cao, C., Cliff, E., Hovakimyan, N., Kurdila, A., Bolender, M., and Doman, D., "Design of an $\mathcal{L}_1$ Adaptive Controller for an Air-Breathing Hypersonic Vehicle Model with Unmodelled Dynamics," *Proc. of AIAA Guidance, Navigation & Control Conf.*, Hilton Head Island, SC, 2007, AIAA 2007-6527.
- ¹⁶Gregory, I., Patel, V., Cao, C., and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Control Laws for Flexible Wind Tunnel Model of High-Aspect Ratio Flying Wing," *Proc. of AIAA Guidance, Navigation & Control Conf.*, Hilton Head Island, SC, 2007, AIAA 2007-6525.
- ¹⁷Patel, V. V., Cao, C., Hovakimyan, N., Wise, K., and Lavretsky, E., " $\mathcal{L}_1$ Adaptive Controller for Tailless Unstable Aircraft," *In Proc. of American Control conference*, 2007, pp. 5272–5277.

- ¹⁸Patel, V., Cao, C., Hovakimyan, N., Wise, K., and Lavretsky, E., " $\mathcal{L}_1$ Adaptive Controller for Tailless Unstable Aircraft in the Presence of Unknown Actuator Failures," *Proc. of AIAA Guidance, Navigation and Control Conf.*, Hilton Head Island, SC, 2007, AIAA 2007-6314.
- ¹⁹Cooper, G. and Harper, R., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," Tech. Rep. TN D-5153, NASA, April 1969.
- ²⁰Wise, K. and et al, E. L., "Adaptive Flight Control of a Sensor Guided Munition," *Proc. of AIAA GNC Conf.*, 2005.
- ²¹Cao, C. and Hovakimyan, N., "Stability Margins of $\mathcal{L}_1$ Adaptive Controller: Part II," *Proc. of American Control Conference*, New York, NY, July 2007, pp. 3931–3936.
- ²²Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel $\mathcal{L}_1$ Adaptive Control Architecture, Part I: Control Signal and Asymptotic Stability," *Proc. of American Control Conference*, Minneapolis, MN, June 2006, pp. 3397–3402.
- ²³Cao, C. and Hovakimyan, N., "Design and Analysis of a Novel $\mathcal{L}_1$ Adaptive Control Architecture, Part II: Guaranteed Transient Performance," *Proc. of American Control Conference*, Minneapolis, MN, June 2006, pp. 3403–3408.
- ²⁴Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Controller for Systems with Unknown Nonlinearities: Part I," *Submitted to IEEE Conference on Decision and Control*, 2007.
- ²⁵Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Controller for Nonlinear Systems in the Presence of Unmodelled Dynamics: Part II," *Submitted to IEEE Conference on Decision and Control*, 2007.
- ²⁶Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Controller for Systems in the Presence of Unmodeled Actuator Dynamics," *Submitted to IEEE Conference on Decision and Control*, 2007.
- ²⁷Cao, C. and Hovakimyan, N., " $\mathcal{L}_1$ Adaptive Controller for Multi-Input Multi-Output Systems in the Presence of Unmatched Disturbances," *Submitted to IEEE Conference on Decision and Control*, 2007.
- ²⁸Kaminer, I., Yakimenko, O., Dobrokhodov, V., Pascoal, A., Hovakimyan, N., Patel, V. V., Cao, C., and Young, A., "Coordinated path following for time-critical missions of multiple UAVs via $\mathcal{L}_1$ adaptive output feedback controllers," *AIAA Guidance, Navigation and Control Conference*, 2007.
- ²⁹Stevens, B. L. and Lewis, F. L., *Aircraft Control and Simulation*, Wiley, 2nd ed., 2004.
- ³⁰anon, *MIL-STD-1797*, Department of Defense, March 1987.
- ³¹anon, *MIL-F-8785C*, Department of Defense, November 1980.
- ³²Scalera, K. C. and Durham, W. C., "Modification of a Surplus Navy 2F122A A-6E OFT for Flight Dynamics Research and Instruction," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, No. AIAA-1998-4180, AIAA, Boston, MA, August 10-12 1998.
- ³³Pomet, J.-B. and Praly, L., "Adaptive Nonlinear Regulation: Estimation from the Lyapunov Equation," *IEEE Transactions on Automatic Control*, Vol. 37, No. 6, June 1992, pp. 729 – 740.
- ³⁴Cotting, M. C. and Cox, T. H., "A Generic Guidance and Control Structure for Six-Degree-of-Freedom Conceptual Aircraft Design," *AIAA Aerospace Sciences Meeting and Exhibit*, No. AIAA20050032, Reno, NV, January 2005.