

EFFECTS OF CONTROL SYSTEM AUGMENTATION LEVEL ON PILOT WORKLOAD AND EFFECTIVENESS

Tom Berger, M. Hossein Mansur, and Jeffery A. Lusardi

U.S. Army Combat Capabilities Development Command Aviation & Missile Center, Moffett Field, CA, USA

Carl R. Ott and LTC Wesley R. Ogden

U.S. Army Combat Capabilities Development Command Aviation & Missile Center, Ft. Eustis, VA, USA

COL Ian Curry, Christopher C. Sullivan, CPT Matthew G. D'Alessandro, and Ryan Mackie

U.S. Army Aeromedical Research Laboratory, Fort Novosel, AL, USA

Abstract

A piloted simulation experiment was conducted in the NASA Ames Vertical Motion Simulator to quantify differences in pilot workload and mission effectiveness between different levels of flight control augmentation (ranging from enduring fleet representative to advanced fly-by-wire) during two scout-representative mission vignettes. The study used a combination of experimental test pilots and operational pilots, and data collection included classic (rating scales) and emerging (physiological monitoring) techniques. Four aircraft configurations were included in the study, consisting of two configurations with full-authority fly-by-wire flight control systems representative of current state-of-the-art designs, and two configurations with partial-authority flight control systems representative of those found on enduring fleet aircraft. Overall, the full-authority fly-by-wire configurations showed improvement over partial-authority legacy flight control system configurations in all metrics examined, including improved ability to fly lower and maintain airspeed, reduction in workload, and increase in mission effectiveness.

NOMENCLATURE

AGL	Above Ground Level
BAT	Beta/(Alpha+Theta) brain wave ratio
Coax	Coaxial pusher
DVE	Degraded Visual Environment
EEG	Electroencephalogram
EMF	Explicit Model Following
FBW	Fly-by-wire
FCS	Flight Control System
HQ	Handling Qualities
IWL	Instantaneous Workload Rating
KIAS	Knots Indicated Airspeed
LE	Launched Effects
NOE	Nap-of-the-earth
OPs	Operational Pilots
PAW	Partial-Authority Winged Single Main Rotor
SAS	Stability Augmentation System
SMR	Conventional Single Main Rotor
SWAT	Subjective Workload Assessment Technique
WSMR	Winged Single Main Rotor
XP's	Experimental Test Pilots
ZOH	Zero Order Hold

Presented at 50th European Rotorcraft Forum, Marseille, France, 10–12 September, 2024. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States. Distribution Statement A: Approved for Public Release; distribution unlimited. This work is licensed under the Creative Commons Attribution International License (CC BY).

1. INTRODUCTION

The flight control system (FCS) is a key aspect of modern aircraft and rotorcraft flight vehicles. The FCS takes in pilot inceptor inputs and measured aircraft responses, and drives the actuators to make the aircraft follow the pilot commands. In most of the existing mechanical flight control designs of enduring fleet rotorcraft, the pilot can command 100% of the available primary actuator authority via a mechanical connection to the actuators, while the FCS commands to the actuators are limited to a smaller fraction (e.g., $\pm 10\%$). Such a system is referred to as a partial-authority flight control system. In contrast, many modern fixed-wing aircraft and some rotorcraft use fly-by-wire (FBW), which replaces the mechanical connection between the pilot and actuators with full-authority flight control systems that can command 100% of the primary actuator authority.

Digital FBW FCSs have been in use in fixed-wing military aircraft since the late-1970s (with the F/A-18 being the first production digital FBW aircraft, entering service in 1978), and in fixed-wing commercial aircraft since the 1980s (Airbus A320, 1984). More recently, FBW FCSs have also become prevalent in business jets, with the Dassault Falcon 7X entering service in 2007.

On the rotorcraft side, the adoption of FBW has been more recent. Research efforts began in the 1970s with the Tactical Aircraft Guidance System (TAGS) and XCH-62 Heavy Lift Helicopter (HLH) technology demonstrator programs. Operational rotor-

craft with FBW FCS include the V-22, NH-90, CH-148, and CH-53K, with the civilian Bell 525 and Leonardo AW-609 awaiting certification.

Among the main benefits of full-authority FBW FCSs is the ability to achieve Level 1 Handling Qualities (HQ) and reduce pilot cognitive workload while improving mission effectiveness by tailoring the aircraft response types and hold modes based on mission requirements, usable cue environment, pilot workload, etc. Several studies have looked at implementing the advanced response types and hold modes available in full-authority FBW control systems in enduring fleet partial-authority aircraft (e.g., AH-64 MCLAWS¹, UH-60 MCLAWS^{2,3,4}). While those studies showed HQ improvements over the legacy FCSs, the work was concerned primarily with the hover/low-speed flight regime. Also, those studies used mission task elements (MTEs), which are handling qualities demonstration maneuvers, for pilot evaluations and did not consider operationally relevant mission vignettes. Overall, the limited FCS authority constrained the speeds at which the benefits of improved HQ could be realized.

In the study presented here, a piloted simulation experiment was conducted in the NASA Ames Vertical Motion Simulator to quantify differences in pilot workload and mission effectiveness between different levels of flight control augmentation (ranging from legacy fleet representative to advanced full-authority fly-by-wire) during two scout-representative mission vignettes using classic (rating scales) and emerging (physiological monitoring) techniques.

Data were collected using six pilots. Four aircraft configurations were included in the study, consisting of two configurations with full-authority FBW FCSs and two configurations with partial-authority FCSs representative of those found on enduring fleet aircraft. The full-authority configurations included a lift-offset coaxial-compound helicopter configuration and a winged single main rotor helicopter configuration. The partial-authority configurations included the same winged single main rotor helicopter configuration (but this one with a partial-authority control system), as well as a conventional single main rotor helicopter configuration similar to a UH-60.

Two mission vignettes were developed for the test, representative of scout missions. Both scenarios were roughly 10 minutes long, and were flown by a single pilot in daytime conditions. One scenario had simulated degraded visual environment (DVE) using fog, for a portion of the mission. Task performance for each mission vignette included altitude, airspeed, time en route, and self-reported mission success. Workload was measured using in situ self-reporting, as well as using physiological monitoring.

The remainder of the paper is organized as follows. First, a description of the vehicle models and control laws, as well as the simulation facility used in this study will be provided. Next, the two opera-

tional vignettes used in this study and the qualitative and quantitative data collected will be covered. Finally, the results and conclusions will be provided.

2. VEHICLE DESCRIPTIONS

2.1. Bare-Airframe Models

The flight-dynamics models of the scout-class lift offset coaxial-pusher and winged single main rotor configurations were developed using HeliUM-A, the U.S. Army Combat Capabilities Development Command Aviation & Missile Center (DEVCOM AvMC) in-house flight-dynamics modeling software tool developed as an extension to the University of Maryland HeliUM simulation model^{5,6}. HeliUM-A uses a finite-element approach to model flexible rotor blades with coupled nonlinear flap/lag/torsion dynamics to capture structural, inertial, and aerodynamic loads along each blade segment, a key requirement for these advanced rotorcraft configurations. Blade, wing, and fuselage aerodynamics come from nonlinear lookup tables, and the rotor airwakes are modeled using a dynamic inflow model. A multi-body like modeling approach is used to build the aircraft configuration from its independent components (e.g., fuselage, wing, nacelle, etc.), which allows modeling of arbitrary aircraft configuration with multiple rotors.

The models are generic in nature and do not represent any specific industry designs. The coaxial-pusher configuration (herein referred to as the Coax), shown in Fig. 1(a), was scaled down from a generic utility-class coaxial-pusher configuration⁷. The scaling method used as well as details of the design are provided in Ref. 8. The winged single main rotor (WSMR) model, shown in Fig. 1(b), was derived and scaled from the UH-60A (overall geometries, main rotor and tail rotor properties), as well as the XV-15 and Bo-105 HGH (wing and empennage properties). A detailed description of the development of the WSMR flight dynamics model is provided in Ref. 9.

Linear state-space point models and trim data were extracted from HeliUM-A at a range of airspeeds. The point models were used to develop the flight control systems. In addition, the point models and trim data were combined to form continuous full flight envelope quasi-linear parameter varying (qLPV) stitched simulation models¹⁰. These models were suitable for real-time simulation, and they formed the basis of the simulation models used in the experiment described here.

The conventional single main rotor (SMR) helicopter model was based on the Gen Hel model¹¹.

2.2. Control Laws

Full-Authority fly-by-wire (FBW) control laws were developed for both the Coax and WSMR helicopters

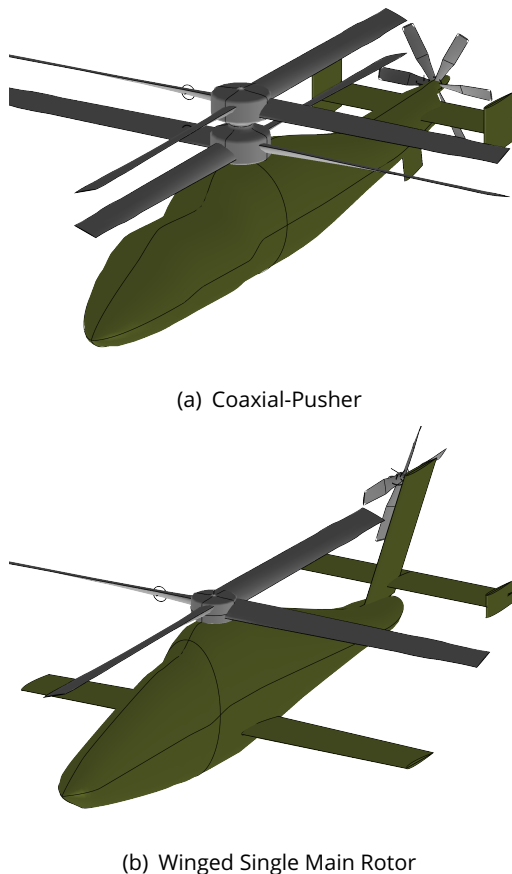


Figure 1: Generic aircraft schematics.

using an explicit model following (EMF) control system architecture¹². The control laws provide pilot-selectable levels of augmentation, with response types ranging from conventional (rate command) to more highly-augmented (attitude command), and hold modes for attitude, position, velocity, heading, and altitude, as shown in Table 1. Additional information about the control laws is provided in Refs. 13 and 14, which discuss previous simulation studies using the same models and control laws.

In addition to the full-authority control laws, partial-authority control laws were also developed for the WSMR configuration, herein referred to as the PAW (Partial-Authority WSMR) configuration. The PAW control laws provide similar pilot-selectable levels of augmentation and hold modes, however the control system is limited to $\pm 10\%$ authority in roll and yaw and $\pm 20\%$ authority in pitch (similar to the AH-64). No augmentation is available in the heave/collective axis. Unlike the full-authority control laws, when the partial-authority system saturates, the aircraft response reverts back to the unaugmented bare-airframe.

The conventional single main rotor FCS includes a stability augmentation system (SAS) which provides rate damping in roll, pitch, and yaw through high-rate, limited-authority ($\pm 10\%$) SAS actuators, and a flight path stabilization system which provides addi-

tional augmentation and outer loop modes through limited-rate, full-authority trim actuators. This system is representative of current enduring fleet aircraft.

Table 1 summarizes the response types and hold modes available for each configuration.

3. SIMULATION OVERVIEW

3.1. Simulation Facility

The experiment was conducted in the NASA Ames Vertical Motion Simulator (VMS) which provides 6-degree of freedom motion with 60 feet of vertical and 40 feet of lateral travel. Figure 2(a) shows a schematic of the simulator facility. The side-by-side rotorcraft cockpit known as T-cab was used, shown in Fig. 2(b). Evaluations were done from the right seat, configured with sidestick, collective stick, and pedal pilot control inceptors.

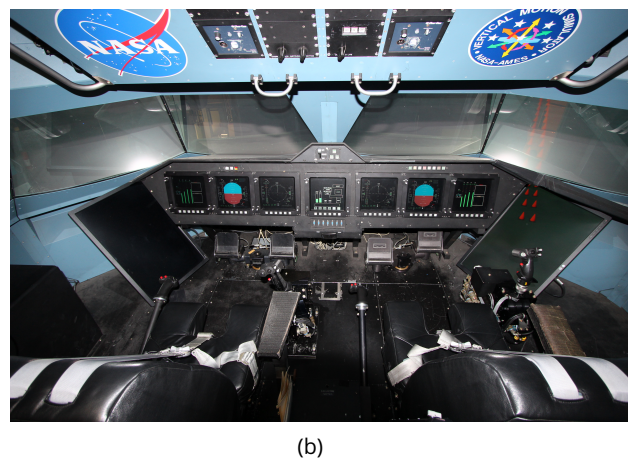
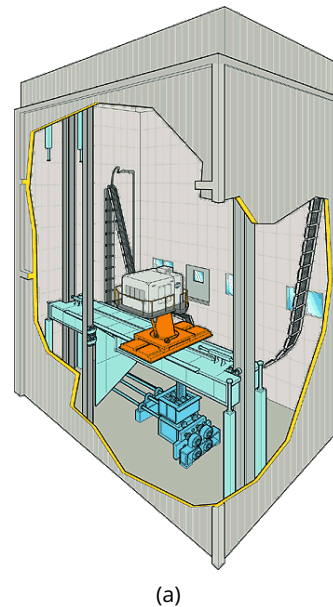


Figure 2: NASA Ames Vertical Motion Simulator

Table 1: Control Law Overview

	Response Types	Hold Modes
<i>Full-Authority</i>		
Coaxial-Compound Helicopter (Coax)	Rate Command	Velocity Hold
	Attitude Command	Position Hold
		Heading Hold
		Altitude Hold
Winged Single Main Rotor (WSMR)	Rate Command	Velocity Hold
	Attitude Command	Position Hold
		Heading Hold
		Altitude Hold
<i>Partial-Authority</i>		
Partial-Authority Winged Single Main Rotor (PAW)	Rate Command	Velocity Hold
	Attitude Command	Position Hold
		Heading Hold
Conventional Single Main Rotor (SMR)	Rate Command	Velocity Hold
	Attitude Command	Heading Hold

3.2. Tasks

The simulation experiment consisted of two scout-representative mission vignettes. The following subsections describe each mission vignette in detail.

3.2.1. Camp Dawson

The first mission vignette was located around Camp Dawson, WV. A map overview of the mission vignette is shown in Figure 3.

To execute the mission, pilots began at point 1 on Fig. 3 and traveled in a river valley along the red route at airspeed not to exceed best range airspeed $V_{BR} = 150$ KIAS (knots indicated airspeed). Once pilots reached point 2 on Fig. 3, they would transition to airspeed not to exceed best endurance airspeed $V_{BE} = 100$ KIAS and fly along the yellow route. At point 3 on Fig. 3, pilots transitioned to nap-of-the-earth (NOE) flight at airspeed ≤ 80 KIAS, and then establish a hover masked behind terrain. The hover location was marked by a pair of radio towers, as shown in the lower left inset in Fig. 3. Pilots would then do a vertical unmask to establish line of sight towards the objective area (marked as the white oval in the upper inset in Fig. 3). They would have to count and report back the number of vehicles in the vicinity of the objective area (which was randomized each run) and deploy a Launched Effect (LE). After remasking vertically, they would transition NOE to point 4 along the magenta route. Once at point 4, pilots would establish a hover behind cover, laterally unmask, establish a stable hover, and deploy a second LE. They would then laterally remask behind terrain and establish a hover at which point the mission would be complete.

The shaded region in Figure 3 indicated an area of the scenario where fog was used to simulate DVE. In

addition, turbulence was used throughout the mission with the addition of steady tail winds at the hover points (3 and 4) to increase pilot workload.

Throughout the mission, pilots were required to remain below 150 ft Above Ground Level (AGL). Whenever pilots had altitude excursions above 150 ft for three or more consecutive seconds, they would receive a threat warning audio and visual cue. This provided a cue for the pilots to reduce their altitude below 150 ft AGL.

The following list shows the key tasks by priority that pilots had to accomplish:

1. Deploy LEs:
 - From vertical unmask at point 3, then re-mask
 - From lateral unmask at point 4, then re-mask
2. Altitude:
 - Maintain less than 150 ft AGL
 - Minimize excursions above 150 ft AGL to < 3 sec
3. Airspeed:
 - ≤ 150 KIAS during red portion of route
 - ≤ 100 KIAS during yellow portion of route
 - ≤ 80 KIAS during magenta portion of route
4. Time to complete mission ≤ 600 sec (≤ 10 min)
5. Report pilot workload via the panel mounted switches

3.2.2. Ojai Valley

The second mission vignette was located around Ojai Valley, CA. A map overview of the mission vignette is shown in Figure 4.

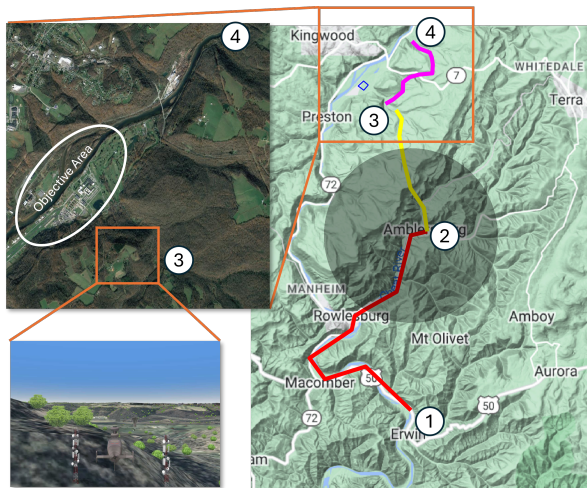


Figure 3: Camp Dawson mission vignette overview.

To execute the mission, pilots started at point 1 on Fig. 4 and traveled North along the magenta route at best range airspeed $V_{BR} = 150$ KIAS. When pilots reached Highway 33 and the entrance to the valley (point 2 on Fig. 4), they reduced airspeed to best endurance airspeed $V_{BE} = 100$ KIAS and followed Highway 33 through the valley, maintaining airspeed at 100 ± 5 KIAS and altitude below 150 ft AGL. Pilots were required to identify any target vehicles along the route, which were represented by yellow trucks on the road (as seen in the inset in Fig. 4). The number (two or three) and location of the vehicles were randomized for each run. For each target vehicle identified by the pilots, they were required to deploy a LE to maintain surveillance on the vehicle. The route reconnaissance mission was complete after arriving at the helipad next to the tall building at point 3 on Fig. 4 and establishing a stabilized hover. Turbulence was simulated throughout the mission to increase workload.

The following list shows the key tasks by priority that pilots had to accomplish:

1. Deploy LE:
 - Identify number and type of vehicles along Hwy 33
 - Deploy LE in stable forward flight for each target found
2. Airspeed:
 - 150 KIAS max en route to Hwy 33
 - 100 ± 5 KIAS along Hwy 33
3. Altitude:
 - Maintain less than 150 ft AGL
 - Minimize excursions above 150 ft AGL to < 5 sec
4. Report pilot workload via the panel mounted switches

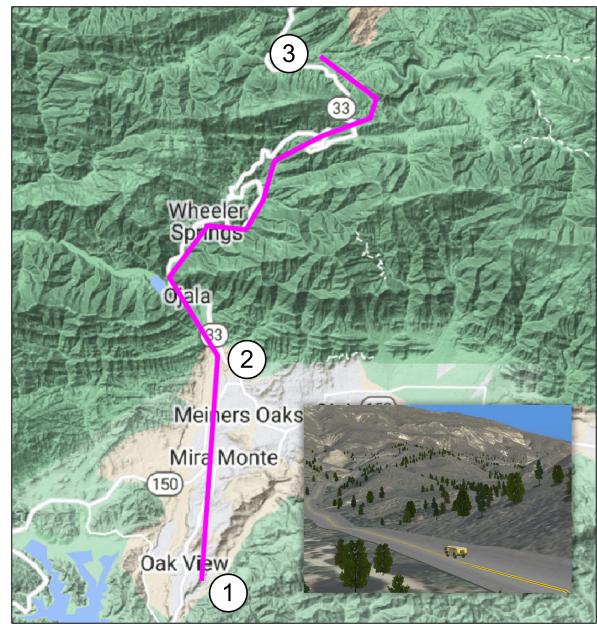


Figure 4: Ojai Valley mission vignette overview.

3.2.3. LE Mode

Both mission vignettes required the pilots to deploy LEs. To do so, pilots first had to engage the LE launch mode by actuating a button on the collective. Once LE launch mode was engaged, LE launch symbology would appear on the HUD and pilots would need to get into launch constraints to be able to launch the LE. The launch constraints are provided in Table 2. The constraints are notional and not representative of an actual vehicle/LE, and were chosen to drive up pilot workload. An altitude of > 100 ft AGL would need to be attained to provide ground clearance for the LE to drop when launched. Additionally, aircraft angular rates would need to be stabilized to less than 5 deg/sec. When launching from a hover, there was an additional constraint to stabilize the altitude with aircraft vertical rate less than 100 ft/min. Finally, a constraint was placed on aircraft airspeed/ground speed to drive up pilot workload. When launching from a hover (in the Camp Dawson mission scenario) pilots would need to stabilize the ground speed less than 3 kts. When launching in forward flight (in the Ojai Valley mission scenario) pilots would need to stabilize the airspeed at 100 ± 3 kts.

Once the launch constraints were met for 3 consecutive seconds, the LE HUD symbology switched to a diamond, indicating the LE was ready to deploy, at which point pilots could launch the LE using the trigger on the sidestick.

3.3. Pilot Demographics and Test Conduct

Six evaluation pilots participated in this study, consisting of four experimental test pilots (XPs) and two operational pilots (OPs). The pilot experience ranged from about 1400 to 5000 hrs (with an average of 3000 hrs) in Army scout/attack and utility platforms.

Table 2: LE launch constraints

Parameter	Constraint
Altitude	> 100 ft AGL
Angular Rates	< 5 deg/sec
Vertical Rate	< 100 fpm (hover only)
Speed stabilized	GS < 3 kts (hover), AS = 100 ± 3 kts (forward flight)

Data collection was done over a two-week period, with three pilots (two XPs and one OP) participating in each week. For each week of data collection, pilots flew one of the full-authority configurations and one of the partial-authority configurations. This was done to allow pilots sufficient time to train on the different configurations and mission scenarios before collecting data. Week 1 pilots flew the full-authority coaxial-compound helicopter (Coax) and partial-authority conventional single main rotor (SMR) configurations, and week 2 pilots flew the full-authority and partial-authority winged single main rotor configurations (WSMR and PAW).

The order of the mission vignettes or configurations (full- vs partial-authority) was not randomized. Pilots always started with the full-authority configurations because those required additional training to cover the different control law modes and response types. Pilots then flew the partial-authority configuration, at which point they had more experience in the simulator and with the two mission vignettes. It is possible that this introduced some bias into the results due to training effects, but the bias would be in favor of the partial-authority configurations.

3.4. Data Collection

This section describes the different types of data that were collected during the experiment. In addition to the quantitative task performance data, pilot rating scales were used to collect qualitative data, and a pilot questionnaire was administered to collect pilot comments. Finally, physiological data was also collected. The rating scales, questionnaire, and physiological data measurements are described below.

3.4.1. Instantaneous Workload (IWL) Assessment Scale

The Instantaneous Workload (IWL) Assessment Scale, shown in Table 3, was developed for this study based on the Bedford Workload Scale. The Bedford Workload Scale was simplified by removing the decision tree and reducing the number of available ratings from ten to five to streamline the process of providing ratings and allow the pilots to

Workload entry buttons

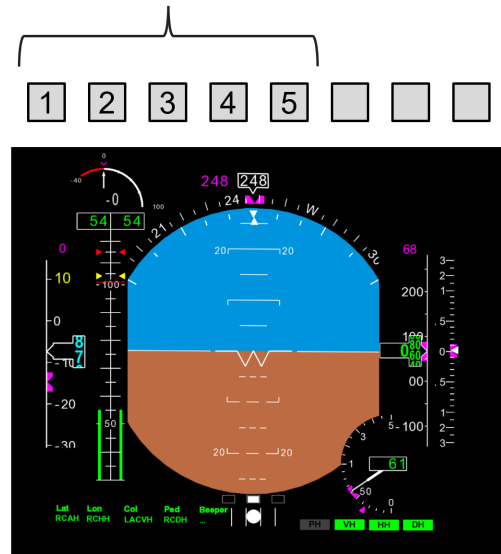


Figure 5: Instantaneous Workload (IWL) Rating entry buttons above the PFD.

enter ratings in real time while flying the mission scenarios.

Pilots were prompted to enter an IWL rating every 30 seconds using five entry buttons above the primary flight display (shown in Figure 5). When pilots would enter a value, the button corresponding to that value would light up. After 30 seconds, the remaining four buttons would begin to flash to cue the pilot to enter another rating.

3.4.2. Estimated Fatigue

An estimated overall fatigue value was derived based on the Instantaneous Workload (IWL) ratings. Figure 6 shows how the discrete IWL ratings were converted to a continuous IWL rating, and then how an estimated value of fatigue was derived, using an example data run.

The top plot in Figure 6 shows when the cue light was on (value of 1), prompting the pilots to enter an IWL rating. The sections highlighted in red correspond to times it took the pilot more than 15 additional seconds to enter an IWL, which will be addressed below.

The second plot shows the IWL ratings entered by

Table 3: Instantaneous Workload (IWL) Assessment Scale

Description	
1	Negligible effort. Workload insignificant.
2	Enough spare capacity for all desirable additional tasks.
3	Reduced spare capacity. Additional tasks cannot be given the desired amount of attention
4	Little spare capacity. Level of effort allows little to no attention to additional tasks.
5	No spare capacity, extremely high workload. Serious doubts as to the ability to maintain level of support

the pilot. When a rating was entered, the cue light turned off for 30 seconds, after which it was turned back on to prompt the pilot for their next rating.

The third plot in Figure 6 shows a zero-order hold (ZOH) reconstruction of a continuous IWL rating based on the discrete ratings provided by the pilot. Specifically, the last rating value is held until the next rating, which is then held until the subsequent rating. This is a simple approach to reconstructing a continuous IWL rating for each run, however, it assumes that the pilot predicts their future workload with each rating, when in fact the ratings tend to be retrospective, or based on the pilot workload up to that point in time. However, fully projecting the ratings backwards in time assumes that the pilot rating changes instantaneously after the pilot enters their WL rating based on their subsequent rating, which is also not accurate.

Therefore, for the analysis done here, the IWL rating value is held centered about when the pilot entered it, as shown in the fourth plot in Figure 6. The dashed blue line shows the ZOH reconstruction of the continuous IWL rating, while the orange line shows the centered reconstruction, which projects the rating forward and backward in time and gives a more accurate representation of the workload when the pilot entered the IWL rating.

Next, the amount of time it took pilots to respond to the cue lights and enter their IWL rating was considered. Pilots were required to enter a rating every 30 seconds. If pilots did not enter a rating for 15 seconds after the cue lights began flashing, it was assumed that their workload was too high to enter a rating, and their IWL rating was defaulted to 5. The value of 5 was held from when the cue lights began flashing until the pilots entered a rating. This is shown in the fifth plot in Figure 6. The red line shows the adjusted ratings, with values of 5 during

the times the pilot did not enter a rating. The adjusted continuous IWL rating value was used in the data analysis presented below.

Finally, an estimated “fatigue” value was derived from the IWL ratings. This was done based on the assumption that fatigue is a function of both workload and time (e.g., working very hard for a short period of time would result in similar fatigue as working less hard but for a longer period of time). Therefore, to estimate fatigue, the area under the IWL rating curve was integrated over the time of each run (as shown in the shaded region in the last plot in Figure 6):

$$(1) \quad \text{“Fatigue”} = \frac{1 \text{ hr}}{3600 \text{ sec}} \int_0^{T_{\text{run}}} (IWL(t) - 1) dt$$

where T_{run} is the total time in seconds of each run and $IWL(t)$ is the adjusted continuous IWL rating curve. Note that 1 (the lowest IWL rating) is subtracted from the IWL rating value, such that any time spent at the lower IWL rating did not contribute to fatigue. The metric was then scaled to be in units of workload-hour (through the $1/3600$ scale factor).

3.4.3. Subjective Workload Assessment Technique (SWAT)

A modified Subjective Workload Assessment Technique (SWAT) was used to collect pilot workload ratings on a multi-dimensional rating scale at the end of each individual run. The SWAT rating scale is based on Ref. 15, but modified here to streamline the rating process and make providing ratings more efficient for pilots. At the end of each run, pilots provided a 1–3 rating in the areas of Time Load, Mental Effort Load, and Psychological Stress Load. Table 4 shows the descriptions accompanying each rating of the scale.

Table 4: Subjective Workload Assessment Technique (SWAT) Scale

AREA	VALUE	DESCRIPTION
Time Load	1	Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.
	2	Occasionally have spare time. Interruptions or overlap among activities occur infrequently.
	3	Almost never have spare time. Interruptions or overlap among activities are very frequent or occur all the time.
Mental Effort Load	1	Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.
	2	Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention is required.
	3	Extensive mental effort and concentration are necessary. Very complex activity required total attention.
Psychological Stress Load	1	Little confusion, risk, frustration, or anxiety exists and can be easily accommodated
	2	Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.
	3	High to very intense stress due to confusion, frustration, or anxiety. High extreme determination and self-control required.

3.4.4. Mission Effectiveness Rating Scale

At the end of each mission set, pilots provided a single Mission Effectiveness rating for the particular aircraft configuration and mission scenario combination. The scale was developed for this study to get a quantitative assessment of how pilots rated their own mission effectiveness. Before providing a Mission Effectiveness rating, the pilots' mission performance (e.g., time to complete the mission, time spent above the threshold altitude, time spent off the nominal airspeed) was reported back to them.

Table 5 shows the Mission Effectiveness Rating Scale.

3.4.5. Questionnaire

The following is a list of questions provided to the pilots to collect pilot comments:

After the completion of each mission set:

- Rate your effectiveness in completing all mission elements.
- What was the critical sub-phase of the mission or major determining factor in the effectiveness rating?
- Comment on any compensation strategies that you had to use in order to complete any of the mission tasks.

Additional debrief questions after each simulator session:

- Describe the contributing factors in your assessment of the workload required to complete the mission in this configuration. Include any features or characteristics of the aircraft that may have contributed to decreasing the workload of piloting tasks.

- Did you experience any mode confusion or times when you were unaware of how the aircraft would respond to your control inputs?
- Comment on any other factors that may have influenced your assessment of the workload and effectiveness of the aircraft.

3.4.6. Physiological Data

Physiological data were collected using a B-Alert X10 to measure Electroencephalogram (EEG) / Electrooculogram (EOG) and a Polar H10 to measure Electrocardiogram (ECG), to subsequently calculate HRV. The recorded EEG data were used to calculate Alpha, Beta, and Theta wave power spectral densities, which were used to calculate the BAT ratio: $\text{Beta}/(\text{Alpha}+\text{Theta})$. The BAT ratio has been used to estimate Engagement Index (EI) to study alertness and task engagement^{16,17}, mental attention investment¹⁸, and mental effort¹⁹. Higher BAT ratio values correspond to higher workload and cognitive engagement.

Preliminary analysis of the EEG (Alpha, Beta, and Theta power spectral densities) data is included in this report. Further analysis of EEG and HRV data is provided in an upcoming publication²⁰

4. RESULTS

4.1. Camp Dawson

Figures 7 through 10 show the task performance, pilot ratings, and BAT data for the Camp Dawson mission scenario for the full-authority and partial-authority configurations. Mean values for the metrics are also summarized in Table 6.

Figure 7 shows task performance metrics for the Camp Dawson mission scenario for the full-authority configurations (Coax and WSMR, blue circles) vs the

Table 5: Mission Effectiveness Rating Scale

Description		
1	Highly Effective	Able to complete mission with little to no excursions outside of task parameters.
2	Mostly Effective	Some infrequent or large excursions outside of task parameters during mission.
3	Somewhat Effective	Mission completion possible with frequent excursions outside parameters.
4	Marginal Effectiveness	Some mission tasks were shed in order to control aircraft.
5	Ineffective	Unable to complete mission; control of aircraft requires full attention of pilot.

Table 6: Camp Dawson Results Summary

	Full-Authority [*]	Partial-Authority [*]	Improvement ^{**}
<i>Task Performance</i>			
Total time	563.79 (18.1) sec	584.83 (20.01) sec	3.5%
Time above 150 ft	4.12 (4.70) sec	7.55 (8.53) sec	45%
Number of ASE alerts	0.50 (0.83)	1.04 (1.33)	52%
Percent time above airspeed	25.51 (8.19) %	28.51 (7.87) %	11%
Time spent in hover	45.17 (12.19) sec	62.32 (17.39) sec	28%
Time to launch LE	11.67 (8.96) sec	13.59 (11.11)	14%
<i>Pilot Ratings</i>			
Time Load	2.0 (0.28)	2.15 (0.46)	7%
Mental Effort	2.07 (0.38)	2.41 (0.50)	14%
Psychological Stress	1.22 (0.42)	1.78 (0.51)	31%
Average SWAT	1.77 (0.26)	2.11 (0.38)	16%
Effectiveness	1.43 (0.53)	2.14 (0.69)	33%
Instantaneous Workload	3.09 (0.63)	3.30 (0.66)	6.5%
Mean fatigue	0.31 (0.06)	0.37 (0.05)	17%

^{*} Results shown as mean value followed by standard deviation in parentheses.

^{**} Percent improvement of Full-Authority as compared to Partial-Authority (positive values represent an improvement in the metric, negative values represent a degradation in the metric).

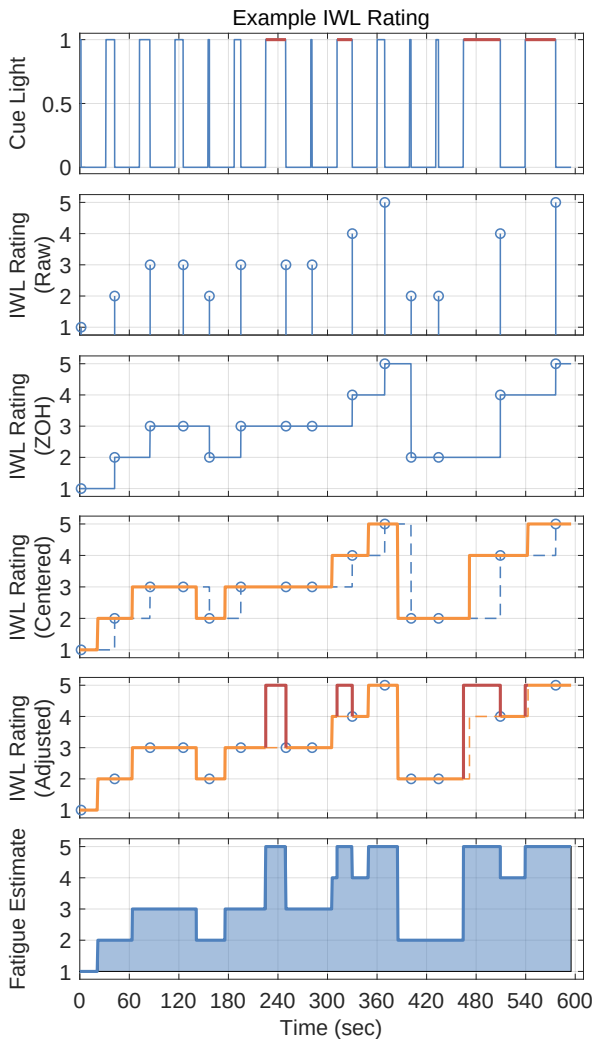


Figure 6: Instantaneous Workload (IWL) rating and estimated fatigue derivation.

partial-authority configurations (SMR and PAW, red squares). The first plot shows the total time to complete each run of the mission scenario. On average, pilots completed the scenario in 563.8 sec in the full-authority configurations and 584.4 sec in the partial-authority configurations. This corresponds to an 3.5% improvement for the full-authority configurations as compared to the partial-authority configuration, which although small, demonstrates the ability of the full-authority configurations to reduce mission times while completing the same objectives.

The second plot in Figure 7 shows the cumulative time of each run spent above the threshold altitude of 150 ft AGL. On average, pilots spent 4.1 sec above 150 ft AGL in the full-authority configurations and 7.5 sec above 150 ft AGL in the partial-authority configurations. This corresponds to a 45% improvement for the full-authority configurations as compared to the partial-authority configuration, demonstrating the increased survivability of the full-authority configurations by being able to more consistently fly at a lower altitude.

The third plot in Figure 7 shows the number of threat alerts that pilots received while flying the mission scenario. Recall that threat alerts occur when pilots stayed above the threshold altitude for longer than three consecutive seconds. On average, pilots received 0.5 threat alerts in the full-authority configurations and 1.04 threat alerts in the partial-authority configuration. This corresponds to a 52% reduction in threat alerts for the full-authority configurations as compared to the partial-authority configuration, again demonstrating the increased survivability of the full-authority configurations by being able to more consistently fly at a lower altitude.

The fourth plot in Fig. 7 shows the percent of time spent above the desired airspeed in the different segments of the mission. Desired airspeed were chosen based on best-range and best-endurance speeds, and so time above these airspeeds corresponds to reduced range and endurance. On average, pilots spent 25.5% time above airspeed in the full-authority configurations and 28.5% time above airspeed in the partial-authority configurations. This corresponds to an 11% improvement for the full-authority configurations as compared to the partial-authority configuration.

The fifth plot in Fig. 7 shows the time spent in a hover while flying the Camp Dawson mission scenario, and the sixth and final plot shows the time from engaging LE mode to deploying the LE. Pilots were able to minimize time in hover by meeting the LE launch constraints 14% more quickly with the full-authority configurations (Fig. 7, sixth plot). On average, pilots spent 45.2 sec in a hover in the full-authority configurations and 62.3 sec time in hover in the partial-authority configurations. This corresponds to an 28% improvement for the full-authority configurations as compared to the partial-authority configuration, demonstrating the benefits of the im-

proved stability provided by a full-authority control system.

Figure 8 shows the pilot SWAT and Effectiveness ratings for the full-authority and partial-authority configurations, with lower scores being better. For the Time Load element of the SWAT rating scale, pilots rated the full-authority 2.0 and partial-authority 2.15 on average (7% improvement for the full-authority configurations over the partial-authority configurations). For the Mental Effort element of the SWAT rating scale, pilots rated the full-authority 2.07 and partial-authority 2.41 on average (14% improvement for the full-authority configurations over the partial-authority configurations). For the Psychological Stress element of the SWAT rating scale, pilots rated the full-authority 1.22 and partial-authority 1.78 on average (31% improvement for the full-authority configurations over the partial-authority configurations). The average SWAT scores were 1.77 for the full-authority configurations and 2.11 for the partial-authority configurations (16% improvement for the full-authority configurations over the partial-authority configurations). The average Effectiveness scores were 1.43 for the full-authority configurations and 2.14 for the partial-authority configurations (33% improvement for the full-authority configurations over the partial-authority configurations).

Figures 9(a) and 9(b) show Instantaneous Workload (IWL) Ratings metrics for the full-authority and partial-authority configurations throughout the mission scenario. Lower IWL Ratings indicate lower workload. The mean IWL Ratings are plotted separately for the full-authority and partial-authority configurations, along with the standard deviation and min/max ratings. In addition to receiving on average higher IWL Ratings, the partial-authority configurations also received more IWL 5 Ratings for more time than the full-authority configurations.

Figure 9(c) shows a coplot of the average Instantaneous Workload (IWL) Ratings for the full-authority and partial-authority configurations throughout the mission scenario. On average, the full-authority configurations had lower or equal IWL Ratings compared to the partial-authority configurations for 80% of the mission duration. Mean estimated fatigue values were 0.30 for the full-authority configurations and 0.37 for the partial-authority configurations (17% improvement for the full-authority configurations over the partial-authority configurations).

Figure 10 shows the preliminary physiological data analysis for the Camp Dawson mission scenario. The figure shows the Beta/(Alpha+Theta) (BAT) brain wave ratio, which is a measure of cognitive engagement. The raw EEG data were averaged over 30 sec windows for each record. Then, the means for all full-authority configuration runs and all partial-authority configuration runs were taken and are shown in Figure 10. Overall, the full-authority configuration had lower BAT ratios than the partial-authority configuration, indicating pilots were able

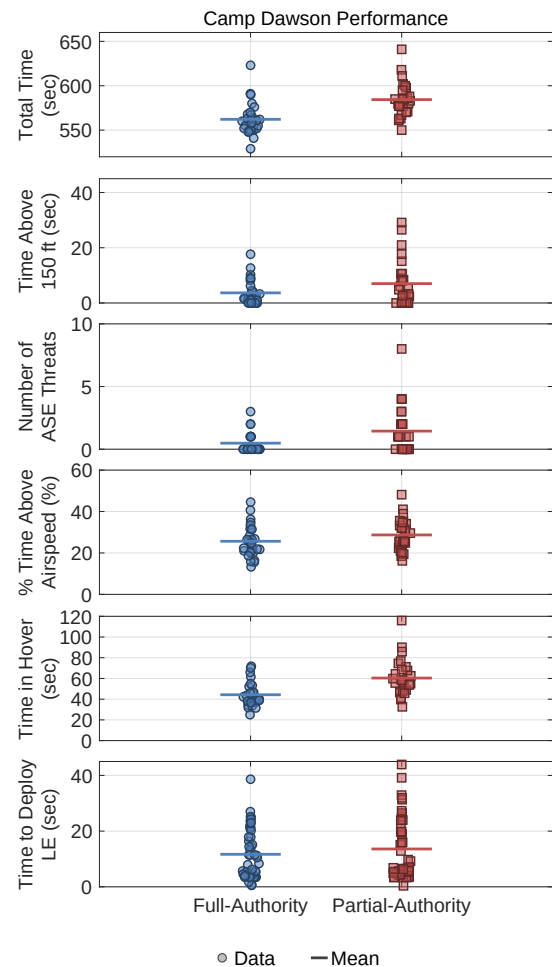


Figure 7: Full-authority vs partial-authority task performance (Camp Dawson).

to complete the mission scenario (with better performance as demonstrated above) with lower workload and cognitive engagement.

In addition to the task performance, pilot ratings, and physiological data, pilots were also asked to provide comments. Below is a sample of the comments provided for the full-authority and partial-authority configurations.

Full-authority:

- Coax: "On [the] yellow route, going to velocity hold was helpful [to hold V_{BE}]."
- Coax: "The pusher propeller can be positive [when managing airspeed and entering or exiting the hover points] or negative [if you try to be too fancy with it, it can add workload]. I think that by the time you have 1000 hrs in this aircraft would feel very natural. I have around 10 hrs of coax time and it felt natural."
- WSMR: "Heading hold was critical to coming into the hover points. Heading hold really impressive, did not need pedal inputs gong into hover

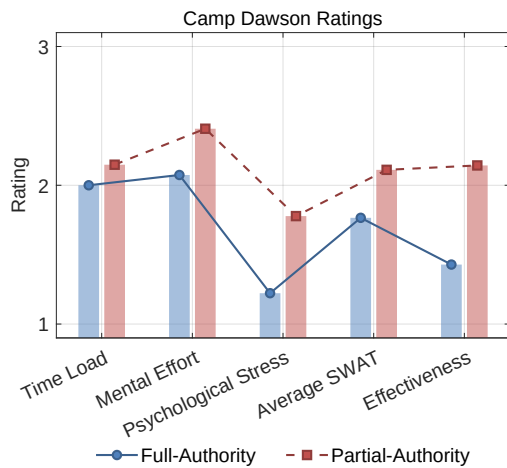


Figure 8: Full-authority vs partial-authority pilot ratings (Camp Dawson)

or during flight when making big power inputs. Never felt it was not under control in heading, even with turbulence.”

Partial-authority:

- SMR: “Airspeed changes from 150 to 100 kt during S-turn and staying below 150 ft were difficult without help... Hover point deceleration to hover was more difficult than coax since not assisted.”
- SMR: “Constantly having to cross-check altitude and airspeed in terrain flight. There were no features [of the FCS] that decreased workload.”
- SMR: “High workload maintaining altitude and airspeed, LE constraints, and hover position without CLAW hold modes.”
- PAW: “Not quite as carefree deceleration to hover and position hold as the Full-Authority WSMR.”
- PAW: “Significant coupling – aggressive collective pull resulted in pitch, had to compensate with longitudinal stick input. Hit pedal stop on every run in the sideward slide [when laterally unmasking] and due to collective-yaw coupling.”

Overall, the pilot comments reinforce the benefits of full-authority fly-by-wire flight control systems over partial-authority flight control systems seen in the quantitative (task performance) and qualitative (pilot rating) data.

4.2. Ojai Valley

Figures 11 through 14 show the task performance, pilot ratings, and BAT data for the Ojai Valley mission scenario for the full-authority and partial-authority configurations. Mean values for the metrics are also summarized in Table 7.

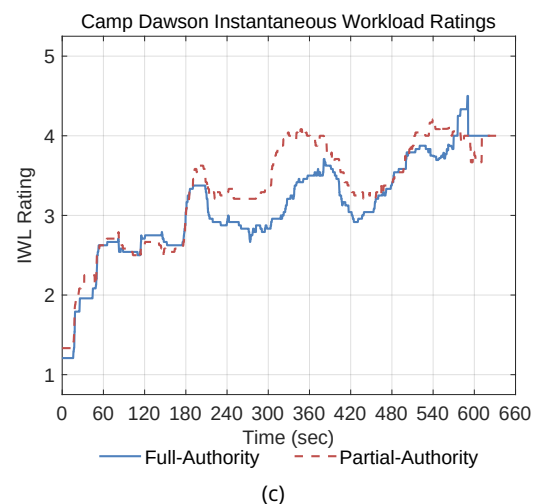
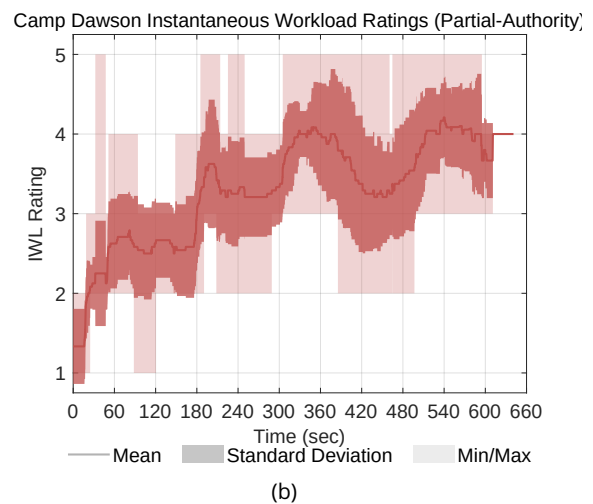
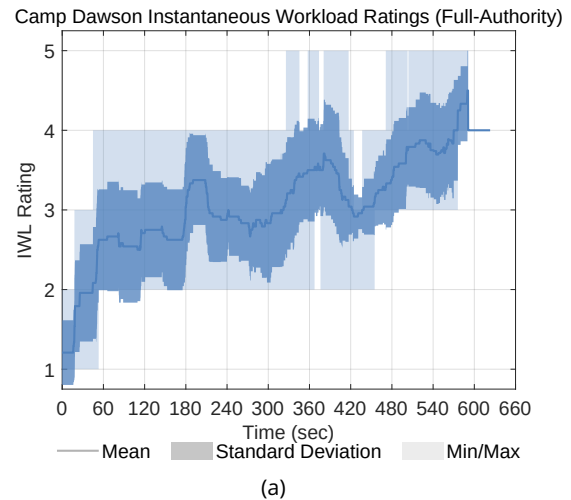


Figure 9: Full-authority vs partial-authority task performance Instantaneous Workload (IWL) Ratings (Camp Dawson).

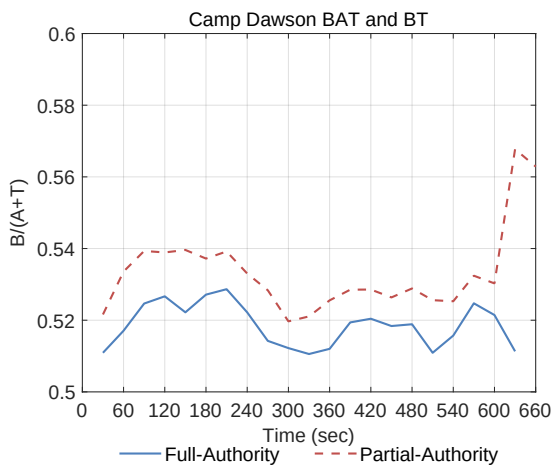


Figure 10: Full-authority vs partial-authority pilot EEG data (Camp Dawson).

Figure 11 shows task performance metrics for the Ojai Valley mission scenario for the full-authority configurations (Coax and WSMR, blue circles) vs the partial-authority configurations (SMR and PAW, red squares). The first plot shows the cumulative time of each run spent off the target best endurance airspeed V_{BE} of 100 kts (time airspeed was outside 100 ± 5 kts). On average, pilots spent 6.7 sec off the target airspeed in the full-authority configurations and 37.2 sec off the target airspeed in the partial-authority configurations. This corresponds to an 82% improvement for the full-authority configurations as compared to the partial-authority configuration, demonstrating the ability of the full-authority configurations to maximize endurance by maintaining V_{BE} more consistently.

The second plot in Figure 11 shows the cumulative time of each run spent above the threshold altitude of 150 ft AGL. On average, pilots spent 28.9 sec above 150 ft AGL in the full-authority configurations and 57.6 sec above 150 ft AGL in the partial-authority configurations. This corresponds to a 50% improvement for the full-authority configurations as compared to the partial-authority configuration, demonstrating the increased survivability of the full-authority configurations by being able to more consistently fly at a lower altitude.

The third plot in Figure 11 shows the number of threat alerts pilots received in each run. Pilots received a threat alert when they were above 150 ft AGL for more than 5 consecutive seconds. On average, pilots received 1.6 threat alerts in the full-authority configurations and 4.1 threat alerts in the partial-authority configurations. This corresponds to a 61% improvement for the full-authority configurations as compared to the partial-authority configuration, again demonstrating the increased survivability of the full-authority configurations by being able to more consistently fly at a lower altitude.

The fourth plot in Figure 11 shows the percent of

time pilots were in LE mode that launch constraints were met. Recall the launch constraints were to have altitude above 100 ft AGL, aircraft angular rates < 5 deg/sec and airspeed within 100 ± 3 kts for 3 consecutive seconds. For both full- and partial-authority configurations, some pilots flew the entire run in LE mode, which skews some of the percent times lower. Other pilots only engaged the LE mode when they saw a target. Overall, pilots were able to meet the LE launch constraints for 42.8% of the time they were in LE mode in the full-authority configurations, as compared to 37.2% of the time in the partial-authority configurations. This corresponds to a 15% improvement for the full-authority configurations as compared to the partial-authority configuration, demonstrating the benefits of the improved stability provided by a full-authority control system.

The fifth and final plot in Figure 11 shows the number of LE launches as a percent of the number of targets in each run. Achieving 100% required the pilots to identify all of the targets and be able to get into the launch constraints to deploy a LE. On average, pilots deployed a LE for 83% of the targets in the full-authority configurations and 78% of the targets in the partial-authority configurations. This corresponds to a 6.4% improvement for the full-authority configurations as compared to the partial-authority configurations, again demonstrating the benefits of the improved stability provided by a full-authority control system.

Figure 12 shows the pilot SWAT and Effectiveness ratings for the full-authority and partial-authority configurations, with lower scores being better. For the Time Load element of the SWAT rating scale, pilots rated the full-authority 1.92 and partial-authority 2.25 on average (15% improvement for the full-authority configurations over the partial-authority configurations). For the Mental Effort element of the SWAT rating scale, pilots rated the full-authority 2.0 and partial-authority 2.38 on average (16% improvement for the full-authority configurations over the partial-authority configurations). For the Psychological Stress element of the SWAT rating scale, pilots rated the full-authority 1.29 and partial-authority 1.79 on average (28% improvement for the full-authority configurations over the partial-authority configurations). The average SWAT scores were 1.74 for the full-authority configurations and 2.14 for the partial-authority configurations (19% improvement for the full-authority configurations over the partial-authority configurations). The average Effectiveness scores were 1.5 for the full-authority configurations and 2.33 for the partial-authority configurations (36% improvement for the full-authority configurations over the partial-authority configurations).

Figures 13(a) and 13(b) show Instantaneous Workload (IWL) Ratings metrics for the full-authority and partial-authority configurations throughout the mission scenario. In addition to receiving on average

higher IWL Ratings, the partial-authority configurations also received more IWL 5 Ratings for more time than the full-authority configurations.

Figure 13(c) shows a coplot of the average Instantaneous Workload (IWL) Ratings for the full-authority and partial-authority configurations throughout the mission scenario. On average, the full-authority configurations had lower or equal IWL Ratings compared to the partial-authority configurations for the entire mission duration. Mean estimated fatigue values were 0.19 for the full-authority configurations and 0.25 for the partial-authority configurations (23% improvement for the full-authority configurations over the partial-authority configurations).

Figure 14 shows the preliminary physiological data analysis for the Ojai Valley mission scenario. The figure shows the Beta/(Alpha+Theta) (BAT) brain wave ratio which is a measure of cognitive engagement. Unlike the results seen in the Camp Dawson mission vignette, here the full-authority configurations had higher BAT ratios than the partial-authority configurations, indicating pilots had higher cognitive engagement, which does not track with the self-assessed report of the workload seen in the SWAT and IWL ratings. There are two possible reasons for this. The first is that for the Ojai Valley mission scenario, pilots generally flew the full-authority configurations in a control law mode which provided velocity hold but came with an attitude-command response type in the pitch and roll axes. This is a response type that most pilots have less experience with than a more conventional rate-command response type, which may have driven up cognitive workload and engagement as pilots concentrated to modify their control strategy. The second possible reason that pilots had higher BAT ratios while flying the full-authority configurations is linked to their improved performance, which may have required more concentration. However, it should be pointed out again that these results do not match the self-assessed workload which was lower for the full-authority configurations. Further investigation into the physiological results here is needed.

Below is a sample of the comments provided for the full-authority and partial-authority configurations.

Full-Authority:

- Coax: "Decreasing workload: [velocity hold] for airspeed maintenance."
- Coax: "Velocity hold [was] repeatable and reliable."
- Coax: "Big fan of the pusher propeller and airspeed hold."
- WSMR: "Airspeed hold, set it and forget it, as long as you do not contaminate longitudinal inputs."
- WSMR: "I was able to get all the performance I wanted, maybe more, with attitude command but [was] going to the limit."

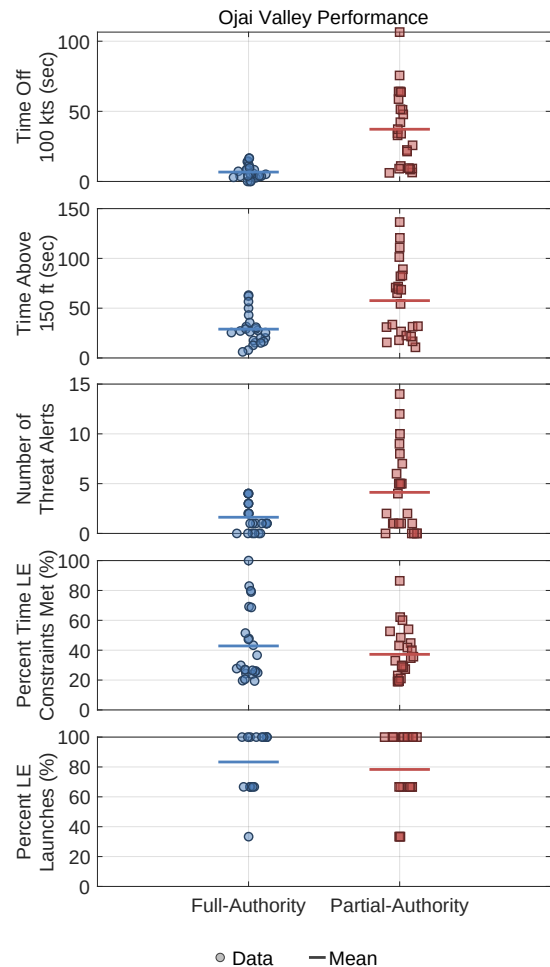


Figure 11: Full-authority vs partial-authority task performance (Ojai Valley).

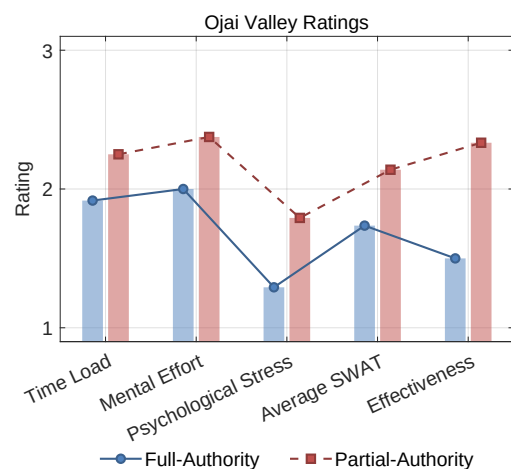


Figure 12: Full-authority vs partial-authority pilot ratings (Ojai Valley).

Table 7: Ojai Valley Results Summary

	Full-Authority [*]	Partial-Authority [*]	Improvement ^{**}
<i>Task Performance</i>			
Time off 100 kts	6.70 (4.99) sec	37.23 (26.23) sec	82%
Time above 150 ft	28.94 (15.91) sec	57.59 (36.85) sec	50%
Number of ASE alerts	1.63 (1.44)	4.13 (4.12)	61%
Percent time launch constraints met	42.84 (24.15) %	37.22 (17.05) %	15%
Percent LE launches	83.33 (21.08) %	78.33 (24.84) %	6.4%
<i>Pilot Ratings</i>			
Time Load	1.92 (0.50)	2.25 (0.44)	15%
Mental Effort	2.00 (0.42)	2.38 (0.49)	16%
Psychological Stress	1.29 (0.46)	1.79 (0.51)	28%
Average SWAT	1.74 (0.37)	2.14 (0.32)	19%
Effectiveness	1.50 (0.55)	2.33 (0.82)	36%
Instantaneous Workload	2.47 (0.45)	2.97 (0.63)	17%
Estimated Fatigue	0.19 (0.06)	0.25 (0.06)	23%

^{*} Results shown as mean value followed by standard deviation in parentheses.

^{**} Percent improvement of Full-Authority as compared to Partial-Authority (positive values represent an improvement in the metric, negative values represent a degradation in the metric).

- WSMR: "During the task, even with turbulence, was backed out of the system, even went hands off to readjust harness at some point...And during run in to [hover at the end] was low workload."
- WSMR: "Velocity hold helped a lot. I did not have to glance at airspeed. After you get used to Attitude Command it was not bad."
- WSMR: "Control laws help a lot for this particular mission."

to get a little frustrated and warm with this configuration. Did have to calm myself down after Run 27. Psychological issues of dealing with aircraft that is much harder to hold in constraints."

As with the Camp Dawson mission scenario, the pilot comments for the Ojai Valley mission scenario reinforce the benefits of full-authority fly-by-wire flight control systems over partial-authority flight control systems seen in the quantitative (task performance) and qualitative (pilot rating) data.

Partial-Authority:

- SMR: "[Highest workload was] having to control all axes simultaneously (pitch, roll, collective, and to a lesser extent yaw); aggravated by having to get into LE constraints. Got some help from force trim if set correctly."
- SMR: "Manual inputs required for airspeed and altitude maintenance while looking for target vehicles."
- PAW: "Damped rate aircraft with no hold modes gets you into forcing [increased] scan pattern and longitudinal cyclic stick activity. Ride quality suffered. Interesting that I was able to do better on altitude with this one, but I did more control in the pitch axis."
- PAW: "Airspeed hold on Full-Authority WSMR was very easy. Here had to synchronize inputs between pitch and collective. Deploying LEs took longer. I had similar performance to Full-Authority WSMR but I was working harder."
- PAW: "More like a juggling act. Workload much higher than Full-Authority WSMR...Was starting

5. CONCLUSIONS

A piloted simulation experiment was conducted in the NASA Ames Vertical Motion Simulator to quantify differences in pilot workload and mission effectiveness between different levels of flight control augmentation (ranging from enduring fleet representative to advanced fly-by-wire) during two scout-representative mission vignettes. The results of the study support the following conclusions:

1. Full-authority fly-by-wire (FBW) Flight Control Systems (FCSs) provided task performance and mission effectiveness benefits over partial-authority FCS. These benefits included reduced variability in mission task performance, improved ability to fly lower, and improved ability to maintain best endurance and range airspeeds. These benefits were also evident in a 35% increase in mission effectiveness score for the full-authority configurations over the partial-authority configurations.

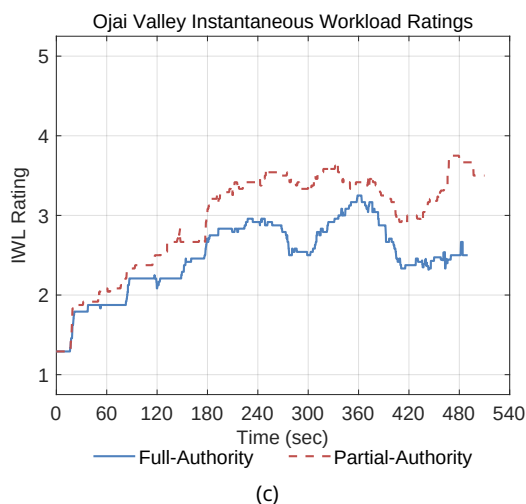
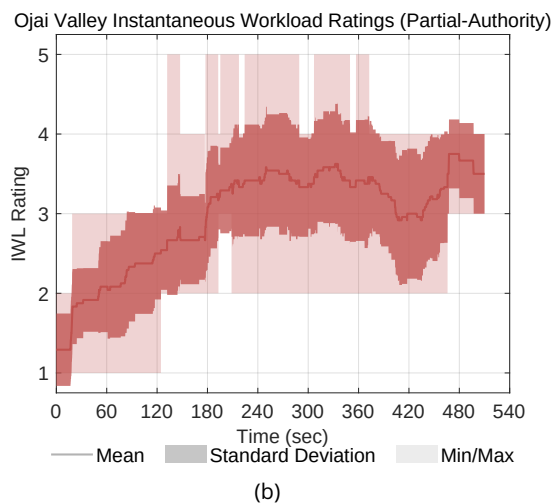
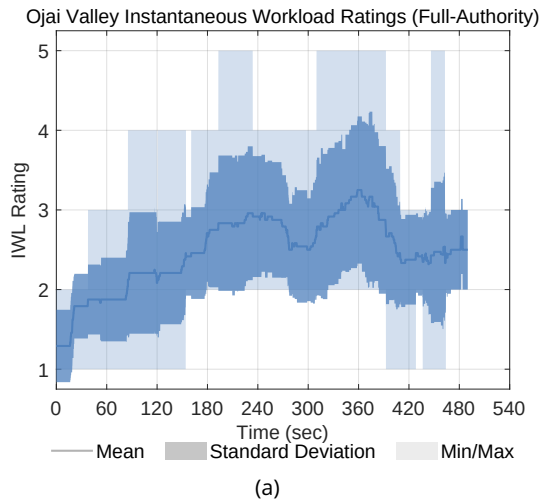


Figure 13: Full-authority vs partial-authority task performance Instantaneous Workload (IWL) Ratings (Ojai Valley).

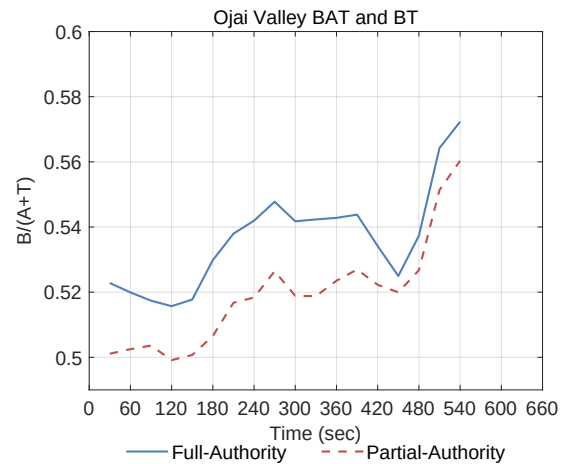


Figure 14: Full-authority vs partial-authority pilot EEG data (Ojai Valley)

2. Full-authority FBW FCSs also provided self-assessed workload benefits over partial-authority FCS. These benefits included a reduction in Instantaneous Workload of 12%, a reduction in Fatigue Estimate of 20%, and a reduction in Subjective Workload of 18%.
3. Physiological data were collected and used to compare Beta/(Alpha+Theta) (BAT) brain wave ratios. For the Camp Dawson scenario, the BAT ratios supported the self-assessed workload ratings provided by the pilots. However, for the Ojai Valley scenario, the BAT ratios had the opposite trend than the self-assessed workload ratings. Several potential reasons for this were discussed, and additional work should be done to correlate between self-assessed and physiological workload data.
4. Overall, the data show that pilots had improved mission performance and effectiveness and increased survivability and range/endurance, with lower cognitive workload while flying configurations with full-authority FBW FCSs.

COPYRIGHT STATEMENT

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ERF proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.

REFERENCES

- [1] Harding, J. W., Moody, S. J., Jeram, G. J., Mansur, H., and Tischler, M. B., "Development of Modern Control Laws for the AH-64D in Hover/Low Speed Flight," American Helicopter Society 62nd Annual Forum Proceedings, Phoenix, AZ, May 2006.
- [2] Tischler, M. B., Blanken, C. L., Cheung, K. K., Swei, S. S., Sahasrabudhe, V., and Faynberg, A., "Modernized Control Laws For UH-60 BLACK HAWK Optimization and Flight-Rest Results," *Journal of guidance, control, and dynamics*, Vol. 28, (5), 2005, pp. 964-978.
- [3] Fujizawa, B. T., Tischler, M. B., Ott, C., and Blanken, C. L., "UH-60 Partial Authority Modernized Control Laws for Improved Handling Qualities in the Degraded Visual Environment," American Helicopter Society 70th Annual Forum Proceedings, Montreal, Quebec, Canada, May 2014.
- [4] Fujizawa, B. T., Tischler, M. B., and Minor, M. J. S., "Outer-Loop Development and DVE Flight Test Assessment of a Partial Authority Model-Following Control System for the UH-60," American Helicopter Society 72nd Annual Forum Proceedings, West Palm Beach, FL, May 2016.
- [5] Juhasz, O., Celi, R., Ivler, C. M., Tischler, M. B., and Berger, T., "Flight Dynamic Simulation Modeling of Large Flexible Tiltrotor Aircraft," American Helicopter Society 68th Annual Forum Proceedings, Fort Worth, TX, May 2012.
- [6] Celi, R., "HeliUM 2 Flight Dynamic Simulation Model: Developments, Technical Concepts, and Applications," American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May 2015.
- [7] Berger, T., Juhasz, O., Lopez, M. J. S., Tischler, M. B., and Horn, J. F., "Modeling and Control of Lift Offset Coaxial and Tiltrotor Rotorcraft," *CEAS Aeronautical Journal*, Vol. 11, (1), January, 2020, pp. 191-215, DOI: 10.1007/s13272-019-00414-0.
- [8] Padthe, A. K., Lopez, M. J. S., Berger, T., Juhasz, O., Tobias, E. L., and Glover, E. D., "Design, Modeling, and Flight Dynamics Analysis of Generic Lift-Offset Coaxial Rotor Configurations," Vertical Flight Society's 78th Annual Forum Proceedings, Forth Worth, TX, May 2022.
- [9] Lopez, M. J. S., Padthe, A. K., Glover, E. D., Berger, T., and Tobias, E. L., "Seeking Lift Share: Design Tradeoffs for a Winged Single Main Rotor Helicopter," Vertical Flight Society's 78th Annual Forum Proceedings, Forth Worth, TX, May 2022.
- [10] Tobias, E. L. and Tischler, M. B., "A Model Stitching Architecture for Continuous Full Flight-Envelope Simulation of Fixed-Wing Aircraft and Rotorcraft from Discrete-Point Linear Models," U.S. Army AMRDEC Special Report RDMR-AF-16-01, April 2016.
- [11] Howlett, J. J., "UH-60A Black Hawk Engineering Simulation Program - Volume I - Mathematical Model," NASA CR 166309, December 1981.
- [12] Tischler, M. B., Berger, T., Ivler, C. M., Mansur, M. H., Cheung, K. K., and Soong, J. Y., *Practical Methods for Aircraft and Rotorcraft Flight Control Design: An Optimization-Based Approach*, AIAA, Reston, VA, 2017.
- [13] Berger, T., Dotson, B. N., Gong, A., Lusardi, J. A., Mansur, M. H., Ott, C. R., Ogden, W. R., and Miller, M. L., "Effects of Linked vs. Unlinked Cyclic Controllers on Crew Coordination," Vertical Flight Society's 79th Annual Forum Proceedings, West Palm Beach, FL, May 2023.
- [14] Berger, T., Gong, A., Lusardi, J. A., Mansur, M. H., Boehringer, R. P., Ogden, W. R., Ott, C. R., Brown, D. R., Daniels, D. A., and Borden, C. C., "Proposed Yaw-Axis Target Acquisition and Tracking Handling Qualities Requirement Updates," Vertical Flight Society's 80th Annual Forum Proceedings, Montréal, Québec, Canada, May 2024.
- [15] Reid, G. B. and Nygren, T. E., "The Subjective Workload Assessment Technique: A Scaling Procedure for Measuring Mental Workload," *Advances in Psychology*, Vol. 52, 1988, pp. 185-218.
- [16] Pope, A. T., Bogart, E. H., and Bartolome, D. S., "Biocybernetic system evaluates indices of operator engagement in automated task," *Biological psychology*, Vol. 40, (1-2), 1995, pp. 187-195.
- [17] Freeman, F. G., Mikulka, P. J., Prinzel, L. J., and Scerbo, M. W., "Evaluation of an adaptive automation system using three EEG indices with a visual tracking task," *Biological psychology*, Vol. 50, (1), 1999, pp. 61-76.
- [18] MacLean, M. H., Arnell, K. M., and Cote, K. A., "Resting EEG in alpha and beta bands predicts individual differences in attentional blink magnitude," *Brain and cognition*, Vol. 78, (3), 2012, pp. 218-229.
- [19] Smit, A. S., Eling, P. A., Hopman, M. T., and Coenen, A. M., "Mental and physical effort affect vigilance differently," *International Journal of Psychophysiology*, Vol. 57, (3), 2005, pp. 211-217.
- [20] D'Alessandro, M. G., Mackie, R. C., Berger, T., Ott, C. R., Sullivan, C. C., and Curry, I., "Real-time Neurophysiological and Subjective Indices of Cognitive Engagement in High-Speed Flight," *Aerospace Medicine and Human Performance*, Accepted for publication on July 3, 2024.