

Outer-Loop Development and DVE Flight Test Assessment of a Partial Authority Model-Following Control System for the UH-60

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ABSTRACT

The vast majority of the U.S. Army's helicopter fleet consists of aircraft initially developed in the 1960s and 1970s and which were designed based on the handling qualities and flight control requirements of the time for flight in good visual environments (GVE). The Army today uses helicopters at night and in brownout and other degraded visual environment (DVE) conditions but with the same control laws of the original models; the major exception being the CH-47F and MH-47G DAFCS, which have been highlighted as a successful partial authority flight control system upgrade to provide improved handling qualities. The U.S. Army Aviation Development Directorate–AFDD has partnered with the U.S. Army Utility Helicopter Program Office's Futures Team and the RDECOM DVE Mitigation Program to further develop and test the UH-60 Modernized Control Laws (MCLAWS). Previous work implemented a model following control system architecture which provided an attitude command/attitude hold response-type for hover and low speed flight. This system demonstrated improved handling qualities as compared to the UH-60L SAS/FPS rate command response-type. This paper documents work to integrate an outer-loop position hold with velocity command mode into the MCLAWS. Flight testing of the MCLAWS with position hold demonstrated Level 1 Cooper-Harper handling qualities ratings in simulated DVE conditions. Finally, landing logic has been integrated into the MCLAWS to support DVE landing flight testing.

ACRONYMS

ACAH	Attitude Command/Attitude Hold
DVE	Degraded Visual Environment
GVE	Good Visual Environment
HQR	Handling Qualities Rating
MCLAWS	Modernized Control Laws
MTE	Mission Task Element
PAFCA	Partial Authority Flight Control Augmentation
SAS/FPS	Stability Augmentation System/Flight Path Stabilization
UCE	Usable Cue Environment
WOW	Weight-on-wheel

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INTRODUCTION

In the late 1960s, the U.S. Army began developing requirements for a medium lift, utility helicopter which was to replace the UH-1. In 1972, the Utility Tactical Transport Aircraft System (UTTAS) request for proposals was released and ultimately resulted in the development of the UH-60 Black Hawk helicopter which entered service 1979. The UH-60 partial-authority flight control system was designed to meet handling qualities requirements of the Prime Item Development Specification (PIDS) which was a tailored version of MIL-H-8501A (Ref. 1). As was common at that time, the UH-60 flight control system was designed for daytime flight; neither MIL-H-8501A nor the PIDS had degraded visual environment (DVE) requirements.

ADS-33 (Ref. 2), introduced in 1985 and currently at revision E, specifically addressed flight control and handling qualities requirements for rotorcraft operations in the DVE. Table IV of ADS-33E specifies the minimum response-type required for Level 1 handling qualities in a given usable cue environment (UCE). For example, when the UCE = 2 (DVE), Table IV shows that an attitude command/attitude hold (ACAH) response-type is required in the pitch and roll axes to achieve Level 1 handling qualities. Additionally, the bandwidth specification has different boundaries based on the UCE; also the required agility, which drives other require-

ments, is reduced for DVE operations. Finally, many of the ADS-33E Mission Task Elements (MTEs) have relaxed performance requirements for DVE conditions.

The UH-60 utilizes standard mechanical flight controls consisting of a center cyclic and a collective lever for both pilots. The automatic flight control system (AFCS) consists of a Stability Augmentation System (SAS), Flight Path Stabilization (FPS), and stabilator. The SAS provides rate damping in roll, pitch, and yaw through the high-rate, limited-authority ($\pm 10\%$) SAS servos. The FPS uses the limited-rate ($\pm 10\%/sec$), full-authority trim servos to provide additional augmentation and outer-loop modes consisting of: (1) rate command with attitude retention in the roll axis, (2) airspeed hold at airspeeds greater than 60 knots, (3) rate command/heading hold response-type in the yaw axis, and (4) turn coordination at airspeeds greater than 60 knots. No augmentation is provided in the vertical axis which results in a vertical rate response-type. The introduction of the UH-60M in 2006 added a flight director and collective trim servo to the flight control system which provided additional outer-loop and autopilot modes including attitude hold in pitch and roll, altitude hold, and hover augmentation/gust alleviation, however it retained the rate command response-type and is therefore predicted to receive Level 2 handling qualities ratings in the DVE.

In 2009, the Study on Rotorcraft Survivability (Refs. 3, 4) identified loss of situational awareness (CFIT, DVE, object/wire strike) as a leading cause of combat non-hostile and non-combat helicopter mishaps and noted advanced flight control systems with modern control laws are a key enabling technology in reducing mishaps due to loss of situational awareness. Note, the term “modern control laws” in this paper does not necessarily refer to modern control techniques such as H-infinity (H_∞), Linear Quadratic Regulator (LQR), etc., but rather refers to using modern requirements and hardware to develop control systems with improved handling qualities. The CH-47F DAFCS control laws were highlighted as a successful partial-authority (roughly $\pm 10\%$ in pitch and roll and $\pm 20\%$ in yaw) implementation of an advanced flight control system with modern control laws. ADS-33E requirements were considered during the design of the CH-47F DAFCS and the resulting control system used a digital flight control computer and included airspeed scheduled response-types and gains providing an ACAH response-type at hover and low speed as well as position hold, translational rate command, and altitude hold modes (Ref. 5). During operational testing of the CH-47F DAFCS control laws, a comparison of DVE external load hook-up with a CH-47D (legacy, analog, rate response-type flight control system) and CH-47F DAFCS was conducted. The pilots reported that with its improved handling qualities, the CH-47F DAFCS completed load hook-up 8-10 times faster than the legacy CH-47D.

In recent years, limited new acquisition programs have required the Program Managers to invest in improvements to the legacy systems and several research efforts have been conducted to apply ADS-33E and modern control design methods to legacy aircraft. As opposed to new build aircraft where

full-authority fly-by-wire system can be developed, the following examples were primarily software changes and continued to use the existing limited authority servos. From 2000 to 2003, Sikorsky Aircraft Company and the U.S. Army Aviation Development Directorate–AFDD (AFDD) developed the UH-60 Modernized Control Laws (MCLAWS) (Refs. 6, 7). Flight tests in the GVE demonstrated that the MCLAWS provided improved handling qualities when compared to the legacy UH-60L SAS/FPS. In 2007, AFDD and the U.S. Army Aviation Engineering Directorate (AED) improved upon the MCLAWS approach and applied it to the AH-64D (Ref. 8) demonstrating improved handling qualities in DVE conditions through piloted simulations. In 2011, AFDD and the U.S. Army Armed Scout Helicopter Program Office developed the short-term ACAH gain set for the OH-58D partial-authority ($\pm 10\%$) SCAS which resulted in improved handling qualities in GVE and DVE conditions (Ref. 9). Additionally during the development of the ARH-70, AFDD and Bell collaborated on optimizing the proportional-integral-derivative (PID) stability and control augmentation system (SCAS) which provided a short-term ACAH response within the approximately 15-20% SCAS authority (Ref. 10).

In 2012, AFDD resumed work on the UH-60 MCLAWS (Ref. 11), changing the control law architecture to a model following system and reoptimizing the control laws. Flight tests in brownout and simulated DVE conditions consistently demonstrated that the ACAH response-type provided by the MCLAWS resulted in better handling qualities than the rate response provided by the UH-60L SAS/FPS. This paper will discuss the continuing development of the MCLAWS focusing on the design, analysis, and integration of position hold mode with velocity command and landing logic. The results of a handling qualities assessment using the position hold mode and initial risk reduction testing of the landing logic will be presented and discussed.

OUTER-LOOP DESIGN

The MCLAWS position hold mode with velocity command was designed around the previously developed and optimized MCLAWS V2 inner-loop (Ref. 11). Figure 1 shows how the outer position and velocity loops are integrated into the MCLAWS. As illustrated in Figure 1, the position error generates a velocity command. The velocity error in turn generates a command to the inner-loop, which, through the command model, generates commanded attitudes and rates. This architecture allows the position and velocity loops to use the SAS and trim servos just as the inner-loop does resulting in a faster response as compared to using the trim servos alone.

The MCLAWS position hold mode is pilot selectable; it can be armed at any time by the pilot through a z-axis plunge on the cyclic trim beeper. Only once the aircraft ground speed drops below 1 kt does the position hold mode engage and select a GPS reference position. If the pilot makes cyclic inputs while the position hold mode is engaged, the aircraft will respond with an ACAH response however the position hold mode will continue to try to hold the last reference position

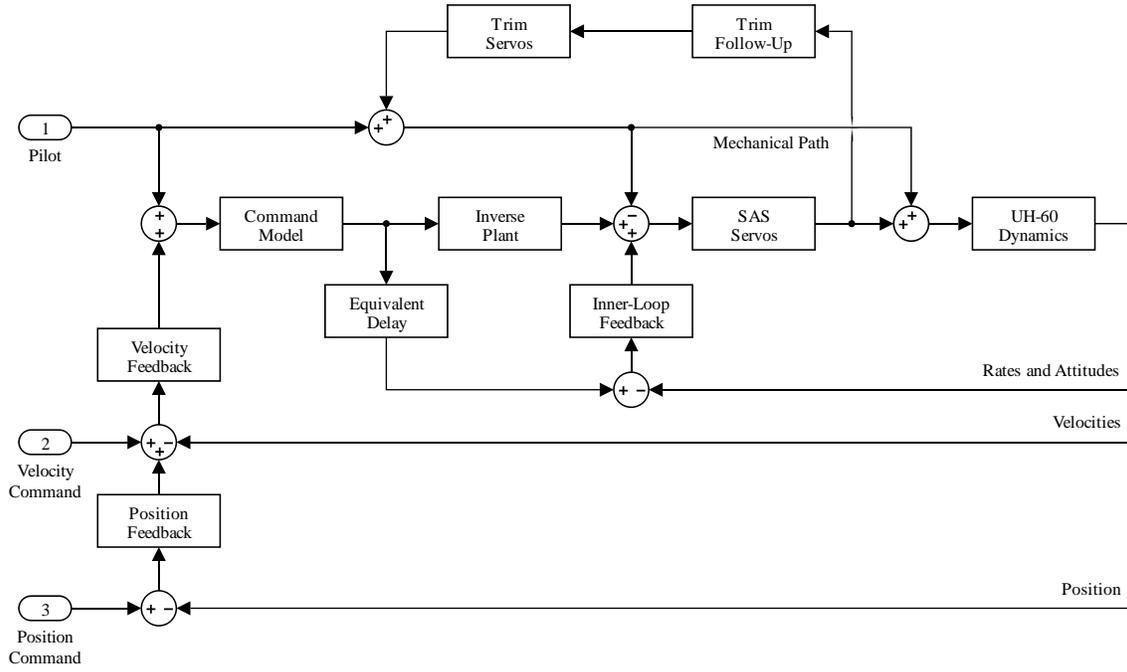


Fig. 1: MCLAWS top level block diagram

until the aircraft ground speed exceeds 5 kt, at which point the position hold mode will disengage but remain armed. Once in position hold, if the pilot holds the beeper in one direction for longer than 0.5 sec, the system will switch into a velocity command.

The position and velocity errors are calculated in level heading axes (i.e. NED coordinate frame rotated by true heading to align with the aircraft direction of flight) such that the x-axis error is always forward/aft and the y-axis error is right/left forming a plane tangent to the ground. While in position hold, the pilot can use the horizontal axes of the trim beeper to bias the position error in increments of 1 ft per beep. In velocity command, while the beeper is held in a direction, the system will command a ground speed of 3 kt in the direction of the beep; it is possible to have both a longitudinal and lateral beep in simultaneously which would result in 3 kt components in each axis resulting in a 4.2 kt command along a 45° direction corresponding to the direction in which the beeper is held. Once the beeper is released, the position hold automatically re-engages and selects the current position as the reference position.

The velocity and position feedback gains were optimized using CONDUIT[®] (Ref. 12). The previously optimized inner-loop feedback gains were held fixed during the outer-loop optimization. The position controller consists of a proportional gain in each axis, while the velocity controller has a proportional and integral gain in each axis resulting in a total of six gains for the outer-loops. In the velocity controller, the integral gains (K_I) were constrained to the value of the proportional gains (K_P) using the relation:

$$K_I = \frac{K_P \omega_c}{5}$$

leaving only four gains to be optimized. These four outer-loop gains were optimized simultaneously against numerous stability and performance requirements using the methods presented in (Ref. 13). Once a baseline set of gains was determined which met the minimum performance requirements, a design margin optimization was conducted to determine if increased performance could be achieved. The result of the design margin optimization (Ref. 12) predicted that disturbance rejection bandwidths slightly higher than the Level 1 boundary values presented in (Ref. 14) could be achieved.

The collective axis outer-loop mode was developed previously (Ref. 11) and was used during the evaluation discussed in this paper. The collective axis outer-loop provides a radar altitude hold mode. The mode is armed by the pilot and engages once the pilot releases the collective trim release trigger and the aircraft vertical velocity is below 60 ft/min. If the pilot releases the trigger with a vertical velocity greater than this threshold, the vertical axis provides rate damping in order to reduce the vertical velocity until the altitude hold mode engages. Using a vertical beeper, it is possible to adjust the altitude reference in increments of 1 ft per beep or with sustained beeps command a 300 ft/min climb or descent rate.

TEST AIRCRAFT

Flight testing of the MCLAWS was conducted on the AFDD EH-60L Advanced QuickFix Black Hawk helicopter, shown in Figure 2. The AFDD Flight Projects Branch (FPB) has removed all external antennas as well as all of the QuickFix equipment with the exception of the inertial navigation unit (INU) and associated navigation control panel and the control display unit (CDU) thus making the aircraft similar to a



Fig. 2: AFDD EH-60L research helicopter

standard UH-60L. Numerous additional sensors have been installed on the aircraft to support various research projects including an EGI; a GPS receiver capable of differential GPS or WAAS; and string potentiometers to measure the positions of the pilot flight controls, the SAS servos, the inputs to the control mixer, and the primary servos.

The Airframe Data System (ADS) is a Windows based PC which is the primary data recording system for the aircraft research systems. The ADS records approximately 120 signals, including analog signals such as string potentiometers for control positions and servo displacements, engine data, and air data measurements; the I01 and I09 groups from the INU (primarily aircraft state data); and DGPS data. The data are recorded in individual data records as commanded by the system operator, where each data record covers a test point.

A programmable display generator (PDG), two 8-inch landscape displays, and video recording equipment have been installed replacing the standard steam gauge instrument panel for the evaluation pilot in the right seat. The Integrated Cueing Environment (ICE) symbology (Ref. 15) was used for all MCLAWS testing. Four control law mode annunciators were added to the ICE displays to provide the pilots insight into the current MCLAWS response type and hold mode status: (1) MCLAWS engaged and response-type, (2) altitude hold armed/engaged and reference altitude, (3) heading hold engaged and reference heading, and (4) position hold armed/engaged.

The Partial Authority Flight Control Augmentation (PAFCA) system was developed in 2000 in order to implement the MCLAWS control law software on the EH-60L. The PAFCA system consists of a SAS/trim interface box, research flight control computer (RFCC), and cockpit control panel. The RFCC is a VME form-factor computer running the Vx-Works real-time operating system which is used to host the MCLAWS software. The RFCC receives aircraft state information from the EGI, pilot control position data from string potentiometers, and discrete signals from the pilot controls and cockpit panels. The MCLAWS software generates servo commands which are sent to the SAS/trim interface box. Digital outputs from the MCLAWS software are used to drive cockpit indicators in the form of lights and the previously discussed annunciators in the ICE symbology. The RFCC also records MCLAWS specific data in a continuous file which is merged post-flight with the individual ADS data records.

The SAS/trim interface box contains relays which allow either the commands from the standard UH-60L AFCS or the RFCC through to the SAS and trim servos. This allows the aircraft to be flown in either the standard UH-60 configuration or the MCLAWS configuration without changing out flight control computers. This feature made it trivial to perform a back-to-back comparison of the two flight control systems. It also allows non-MCLAWS research to be conducted without downtime needed to switch flight control computers. The SAS/trim interface box is controlled by a magnetically held switch and release button located on a panel in the cockpit center console within reach of either the evaluation pilot or the safety pilot.

A collective trim servo, which is not a standard part for the UH-60L, has been installed on the EH-60L to allow the MCLAWS to provide vertical augmentation. The collective trim servo is the same model which has been installed on U.S. Air Force HH-60G helicopters as a part of the DRS Advanced Hover Hold Stabilization system. Figure 3 shows collective trim servo installed on the top deck of the EH-60L with the orange linkage connecting the servo to the collective control rod. Aside from different mechanical stop positions, the collective trim servo is nearly identical to the standard roll and yaw trim servos.

The cockpit control grips for both left and right seat have also been changed from the standard UH-60L. The collective grips were replaced with Air Force HH-60G grips which add a collective trim release switch, needed to control the collective trim servo, while maintaining all the original functionality of the UH-60L collective grip. The HH-60G grip also included a thumb COMM/ICS switch which was re-purposed to serve as a vertical and directional trim beeper. The cyclic



Fig. 3: Collective trim servo on the AFDD EH-60L

grips were replaced with UH-60M cyclic grips which provided numerous additional buttons/switches which could be re-purposed for research purposes. Most important was the addition of the z-axis plunge on the cyclic trim release which was used to arm/disarm the position hold mode. The Remote Standby switch was used to provide the pilots an RFCC disengage switch on each cyclic in addition to the disengage switch on the center console.

FLIGHT TEST RESULTS

As a part of the U.S. Army Utility Helicopter Program Office’s Handling Qualities Improvement Project (HQIP), a handling qualities evaluation was conducted at Moffett Field. During the evaluation, five of the ADS-33E hover and low speed mission task elements (MTE) were evaluated on AFDD’s ADS-33E MTE course (Ref. 16): Hover, Vertical Maneuver, Hovering Turn, Lateral Reposition, and Depart/Abort. MCLAWS with outer-loops and the baseline UH-60L SAS/FPS control systems were evaluated back-to-back by three experimental test pilots. The evaluation was conducted in simulated DVE conditions using standard ANVIS-6 night vision goggles modified with a pinhole filter and neutral density filters in each eyepiece to reduce the pilot’s visual acuity to approximately 20/70 which has been shown to correspond to UCE=2 (DVE) (Ref. 17). The addition of a neoprene shroud attached to the helmet as shown in Figure 4 and cockpit window masking in the right chin bubble removed peripheral cues to further simulate NVG flight conditions during the day.

Quantitative Evaluation

Prior to the formal handling qualities evaluation, a series of piloted and automated frequency sweeps were conducted to identify key quantitative metrics of the MCLAWS. Table 1 presents key closed-loop, broken-loop, and disturbance rejection criteria for the inner-loop ACAH response. The pitch phase margin is slightly below the 45° requirement, however no issues which would indicate this was problematic were reported. Also, the roll and yaw disturbance rejection bandwidth (DRB) values are substantially lower (15% and 35% respectively) than the proposed Level 1 boundaries (Ref. 14); all axes satisfy the proposed upper limit of 5 dB for disturbance rejection peak. Throughout the testing, there were no



Fig. 4: NVG setup for simulated DVE

comments from the pilots indicating less than desirable roll attitude hold or heading hold performance. Additionally, the pilots noted that the MCLAWS heading hold performance was very solid.

Table 1: Inner-loop quantitative metrics

Metric	Roll	Pitch	Yaw
Bandwidth	5.0 rad/sec	2.7 rad/sec	3.4 rad/sec
Phase delay	127.0 msec	145.1 msec	92.1 msec
Crossover	3.9 rad/sec	3.3 rad/sec	3.9 rad/sec
Phase Margin	49.2°	43.4°	51.3°
Gain Margin	7.6 dB	6.7 dB	9.2 dB
DRB	0.76 rad/sec	0.58 rad/sec	0.45 rad/sec
DRP	3.8 dB	2.0 dB	3.4 dB

The outer-loop position hold mode and altitude hold mode disturbance rejection criteria are shown in Table 2. All three axes exceeded the proposed Level 1 boundaries for disturbance rejection bandwidth, however the disturbance rejection peak values are all approximately 10% higher than the proposed Level 1 boundaries. The disturbance rejection performance parameters are inversely related, i.e. improving the DRB will result in a poorer DRP. Since the outer-loop disturbance rejection bandwidth values are above the proposed limits, it might be possible in future testing to reduce them slightly in order to meet the proposed 3 dB disturbance rejection peak criteria.

Table 2: Outer-loop quantitative metrics

Metric	X	Y	Z
DRB	0.22 rad/sec	0.23 rad/sec	0.25 rad/sec
DRP	3.3 dB	3.3 dB	3.4 dB

Handling Qualities Evaluation

During the week of 27 April 2015, two U.S. Army and one Sikorsky Aircraft Corporation experimental test pilots participated in a handling qualities evaluation of the MCLAWS at Moffett Field. Prior to conducting the evaluation, each pilot received a familiarization flight in which they flew both the MCLAWS and SAS/FPS control systems, practiced the ADS-33E MTEs, and experienced simulated DVE using the night vision goggles. The handling qualities evaluation was then conducted at least one day later over as many flights as was necessary to complete all five MTEs with both control systems.

During the evaluation flights, the winds were generally out of the west to northwest with speeds between 5-12 kts, light winds as defined by ADS-33E. It was left to each pilot to determine which MCLAWS outer-loop hold mode(s) he felt was helpful during each task. Pilot 1 chose to evaluate MCLAWS with and without position hold engaged for the Hover and Vertical Maneuver MTEs, and without position hold engaged for the Hovering Turn. Pilots 2 and 3 chose to evaluate the MCLAWS only with position hold on for the Hover, Vertical Maneuver, and Hovering Turn MTEs. None of the three pilots used the position hold mode for the Lateral Reposition or Depart/Abort MTEs.

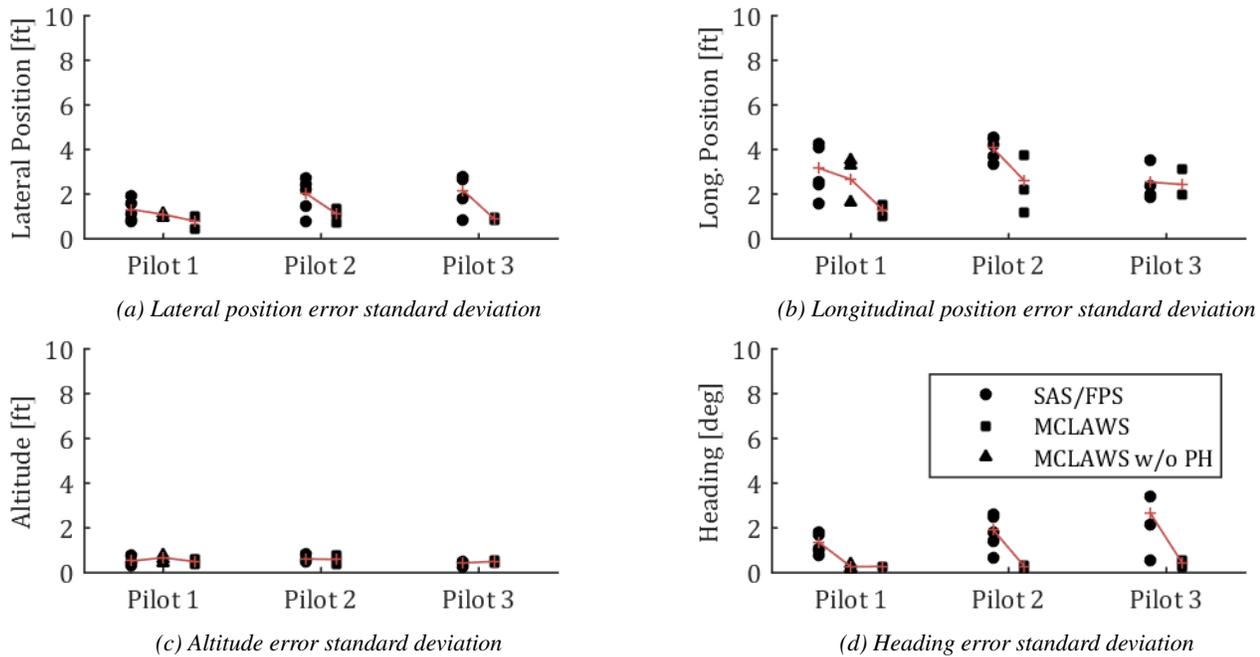


Fig. 5: Standard deviation of errors during 30 second hover portion of Hover MTE (DVE)

The following sections present and discuss the standard deviations of the position errors, altitude error, and heading error; handling qualities ratings; and pilot comments for each of the five MTEs collected using the questionnaire developed by Lusardi et. al. (Ref. 18) and shown in (Ref. 13). The standard deviation plots also show the average standard deviation for all of the runs by a given pilot as the red + symbols which are connected by the red line to show trend information.

Hover MTE For the Hover MTE, all three pilots evaluated the MCLAWS with the altitude hold and heading hold modes engaged for the entire maneuver, and the position hold mode engaged for the 30 second hover maintenance portion of the task. Pilot 1 also evaluated the MCLAWS without the position hold engaged during the hover maintenance portion of the task; the altitude and heading hold modes were still engaged.

Figure 5 shows the standard deviations of the position, altitude, and heading errors during the 30 second hover maintenance portion of the Hover MTE. MCLAWS with the position hold shows a 40%-60% reduction in lateral error as compared to both the SAS/FPS and MCLAWS without position hold. With the lateral and vertical cues directly in front of the pilot, it is fairly easy for the pilot to keep the lateral position error to a minimum. Conversely, the longitudinal cue is out the right side of the aircraft and due to the lack of peripheral vision enforced by the simulated DVE setup, the pilot must rotate his head 90° in order to see the cue. Due to this, the longitudinal position error was generally greater than the lateral error. For Pilots 1 and 2, a 40% to 60% reduction in longitudinal error standard deviation was seen when using the MCLAWS with position hold; for Pilot 3 the standard deviations were similar with both MCLAWS and SAS/FPS.

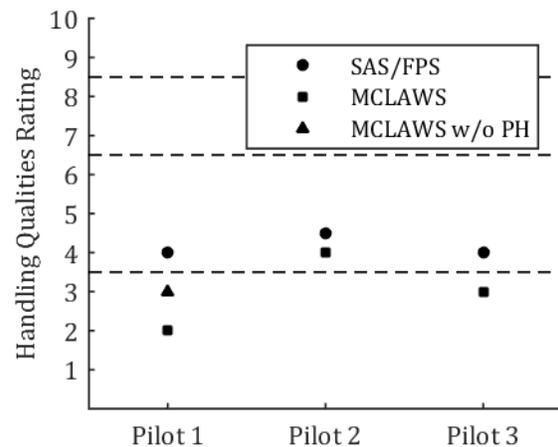


Fig. 6: Cooper-Harper handling qualities ratings for Hover MTE (DVE)

The altitude error standard deviation is consistently low with no noteworthy difference between the configurations. This is to be expected as during the hover maintenance portion of the task, the aircraft attitude changes are small, resulting in minimal altitude changes. Finally, the heading error standard deviation plot shows that the MCLAWS, with or without position hold, produced substantially (80%) less heading error than the SAS/FPS. This confirms the earlier findings (Ref. 11) of improved heading hold performance in MCLAWS.

Figure 6 plots the Cooper-Harper handling qualities ratings provided by each of the pilots after completing the Hover MTE. As noted previously, Pilot 1 evaluated MCLAWS both with and without the position hold mode and provided a rating for each, both of which were Level 1 ratings. All three pi-

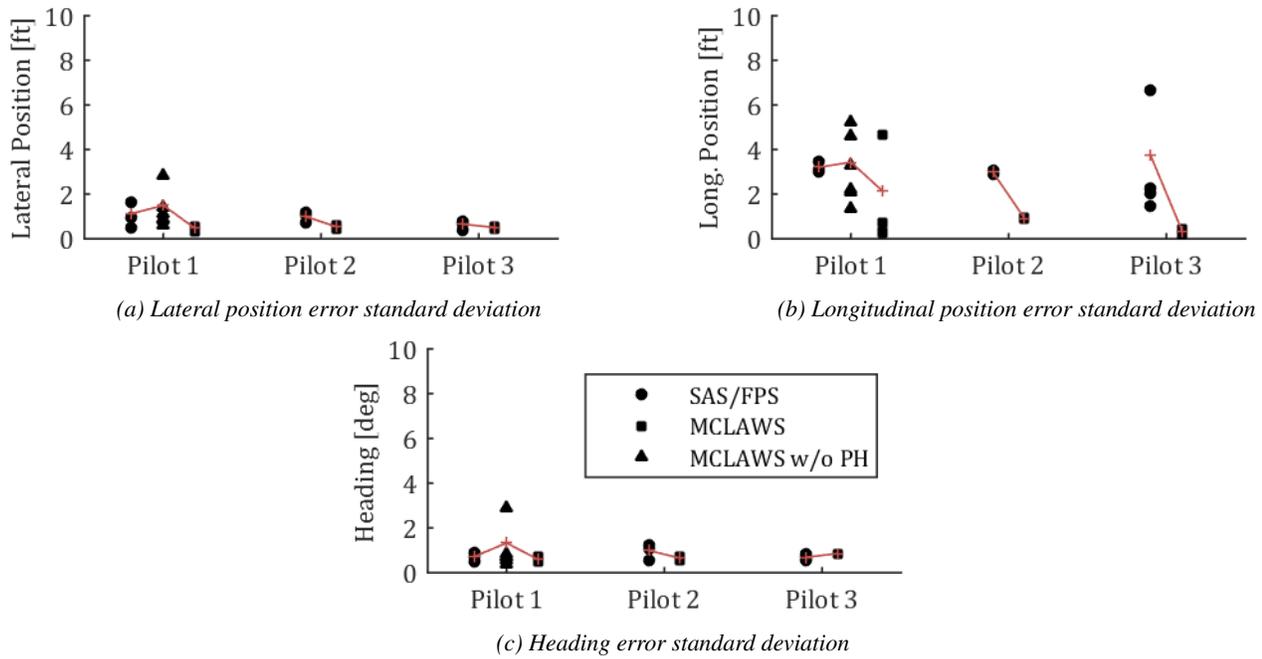


Fig. 7: Standard deviation of errors during Vertical Maneuver MTE (DVE)

lots gave MCLAWS better ratings than the baseline SAS/FPS system. The loss of peripheral vision/cues caused by the simulated DVE setup resulted in increased workload associated with maintaining the longitudinal position, especially with SAS/FPS or MCLAWS without position hold. The pilots generally adopted a scan strategy in which they would turn to check the longitudinal cue every 1-2 sec. With SAS/FPS, the pilots generally found that they were using the entire length of the desired box. All three pilots noted that the position hold mode in MCLAWS was a significant benefit, resulting in reduced pilot workload and therefore improved ratings. Pilot 2 felt that the trim beeper, which was used to fine tune the reference position once position hold was engaged, was not quick or responsive enough. Due to this, Pilot 2 felt the need to stay in the loop on the cyclic, mainly in the lateral axis, in order to ensure meeting the ± 3 ft requirement resulting in increased workload and the Level 2 rating.

Vertical Maneuver MTE For the Vertical Maneuver MTE, all three pilots evaluated MCLAWS with the heading hold and position hold modes engaged for the entire maneuver. Due to the nature of the task, altitude hold was not engaged during the maneuver. Pilot 1 also evaluated MCLAWS without position hold engaged.

Figure 7 shows the standard deviations of the errors for the Vertical Maneuver MTE; since there was not a reference altitude during the maneuver, the altitude error is not plotted. Similar to the Hover MTE, the lateral and longitudinal position error is substantially reduced (20%-80%) with the MCLAWS as compared to SAS/FPS. Without the position hold engaged, the position errors for MCLAWS and SAS/FPS are roughly the same, demonstrating the benefit of a position

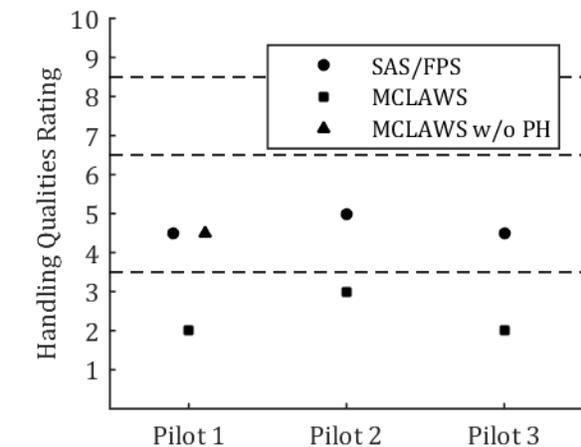


Fig. 8: Cooper-Harper handling qualities ratings for Vertical Maneuver MTE (DVE)

hold mode for the Vertical Maneuver MTE. Also similar to Hover MTE, the longitudinal error was greater than the lateral error due to the cues and loss of peripheral vision; however, this was exacerbated in the Vertical Maneuver MTE as the longitudinal cue was extremely difficult to see while at the apex of the maneuver; the position hold mode reduced the longitudinal error by 30%-80%. In the yaw axis, the heading error was generally low for both the SAS/FPS and MCLAWS. The outlier for Pilot 1 using MCLAWS without position hold is related to fact that it was the first run and the pilot had difficulty with some of the cues; the other runs all show consistently lower heading error.

Figure 8 plots the handling qualities ratings for the Vertical Maneuver MTE. SAS/FPS received Level 2 ratings while

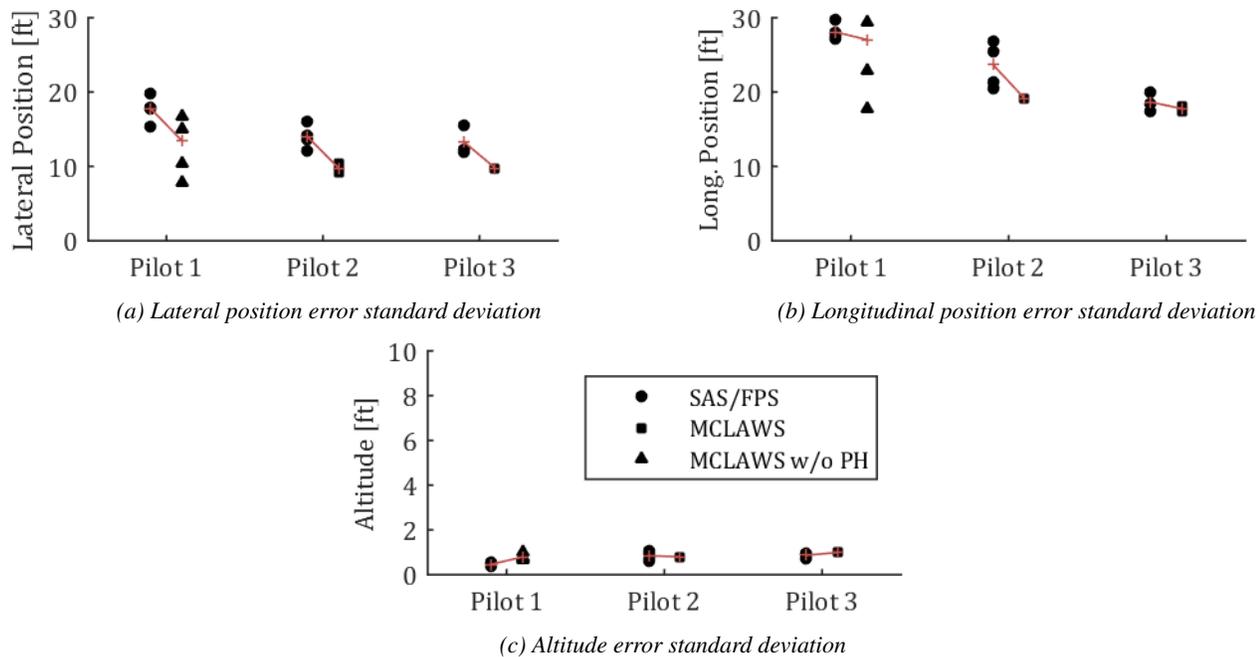


Fig. 9: Standard deviation of errors during Hovering Turn MTE (DVE)

MCLAWS with position hold received Level 1 ratings with an improvement of two HQRs and crossing the Level 1/Level 2 boundary. Pilot 1 again evaluated MCLAWS both with and without position hold engaged; without position hold, the rating was the same as SAS/FPS indicating the importance of the position hold mode in reducing workload and improving performance. As mentioned previously, the highest workload portion of the task, especially for SAS/FPS and MCLAWS without position hold engaged, was the longitudinal position maintenance, especially near the top of the maneuver when the longitudinal cue was difficult to see. This is reflected in the ratings of HQR 4.5 or HQR 5 for the SAS/FPS or MCLAWS without position hold indicating considerable pilot workload was required to meet desired or that the pilots had to accept adequate performance.

When performing the maneuver with MCLAWS and position hold, the pilots noted that it was nearly a single axis (vertical) task. Pilot 2 commented that attitude command (MCLAWS) seemed to tame the angular rates achieved for a cyclic input. Pilot 3 noted that while evaluating the SAS/FPS there was a trade-off between the size of the collective input, and therefore task completion time, with the longitudinal drift; larger collective inputs resulted in more longitudinal drift. He noted that it was necessary to size the collective input so as to just be able to make the desired time while keeping the longitudinal drift as low as possible.

Hovering Turn MTE For the Hovering Turn MTE, Pilots 2 and 3 evaluated MCLAWS with the altitude hold position hold and modes engaged for the entire maneuver while Pilot 1 performed the evaluation without position hold engaged. Due to the nature of the task, heading hold was not engaged during the maneuver.

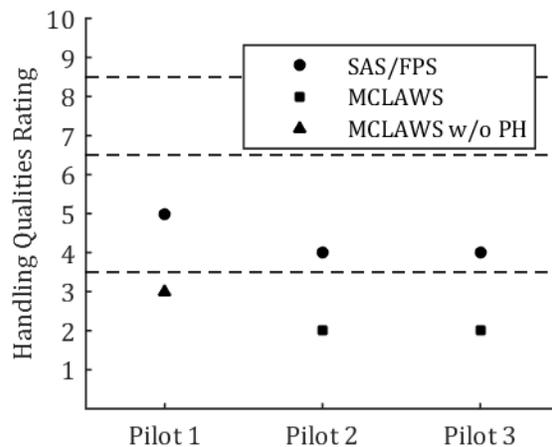


Fig. 10: Cooper-Harper handling qualities ratings for Hovering Turn MTE (DVE)

Figure 9 plots the standard deviation of the errors during the Hovering Turn MTE. This figure has two differences from the plots shown for the other maneuvers. First, the lateral and longitudinal error are in runway (inertial) coordinates, not body coordinates; the runway and body coordinates are aligned at the end of the maneuver. Second, the scale on the lateral and longitudinal error is greater as there is not a single point about which the aircraft is rotating so the error represents deviations about the mean aircraft position through the task.

The lateral and longitudinal position errors are generally lower with MCLAWS than they are with SAS/FPS. With the MCLAWS, the lateral error is reduced by approximately 25% and the longitudinal error is reduced by 5%-20%. The altitude

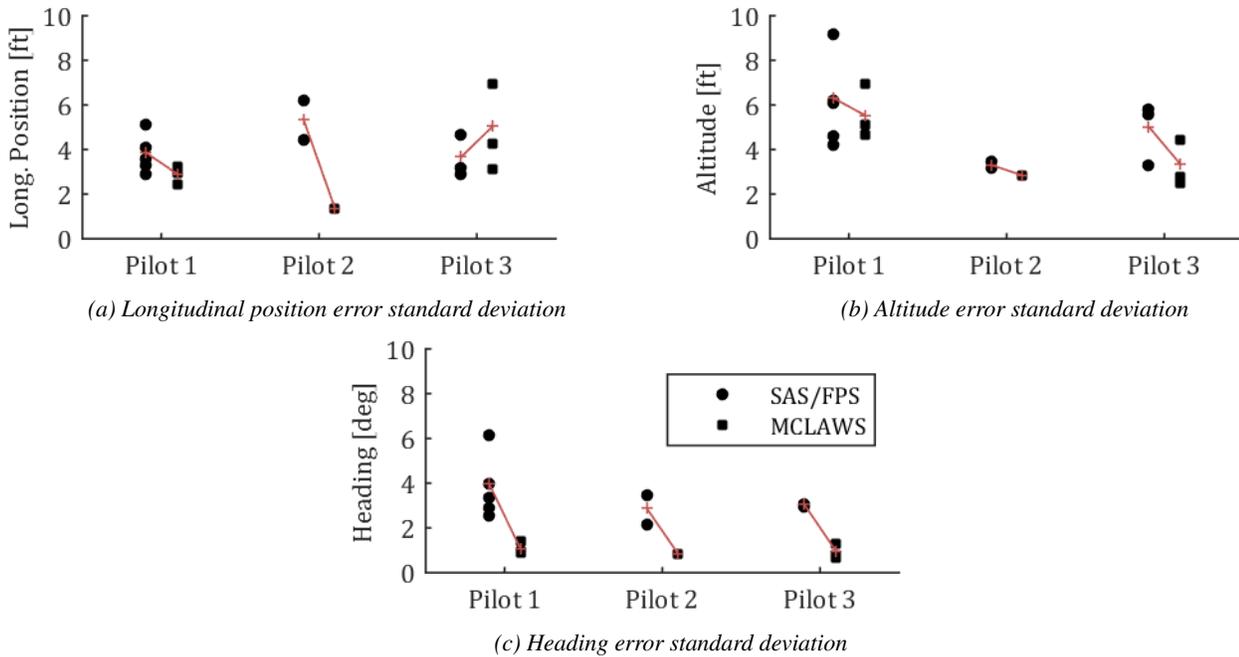


Fig. 11: Standard deviation of errors during Lateral Reposition MTE (DVE)

errors for MCLAWS and SAS/FPS were similar and low for all three pilots. The heading error was not plotted since there was not a reference heading for this maneuver.

Figure 10 shows the pilot ratings for the Hovering Turn MTE. The ratings for SAS/FPS are all Level 2 while the ratings for MCLAWS are all Level 1 with MCLAWS showing a significant improvement over SAS/FPS of two HQRs and crossing the Level boundary. For this MTE, Pilot 1 did not provide ratings with the position hold mode engaged in MCLAWS. With SAS/FPS, all the pilots noted that while desired was achievable, there was significant workload associated with maintaining horizontal position through the maneuver. Pilot 1 noted that for MCLAWS with the position hold on, he felt a slightly lower yaw rate was required in order for the position hold to keep up. For that reason, he decided to go without the position hold and increase the yaw rate. Without the position hold mode, he noted that only a couple of lateral inputs were required through the maneuver resulting in reduced pilot workload compared to SAS/FPS. Pilot 2 and Pilot 3 both used the position hold with MCLAWS and found that they were able to meet the desired requirements without needing to be in the loop on the cyclic.

Lateral Reposition MTE For the Lateral Reposition MTE, all three pilots evaluated MCLAWS with the altitude hold and heading hold modes engaged for the entire maneuver. Due to the nature of the task, position hold was not engaged during the maneuver.

The standard deviations of the errors for the Lateral Reposition MTE are plotted in Figure 11. The longitudinal position error is greatly reduced for Pilots 1 and 2 (25% and 75% respectively) when using MCLAWS as compared to SAS/FPS.

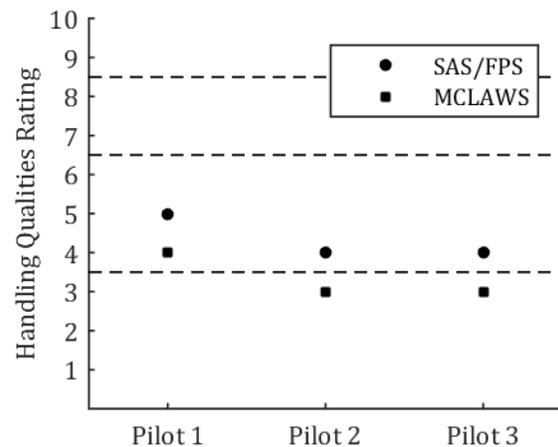


Fig. 12: Cooper-Harper handling qualities ratings for Lateral Reposition MTE (DVE)

For Pilot 3, the runs with SAS/FPS showed reduced longitudinal position error of approximately 40%. The altitude error is fairly similar for both MCLAWS and SAS/FPS with MCLAWS showing a 10%-30% improvement. The heading error is substantially (70%) reduced with the MCLAWS as compared to SAS/FPS. This confirms pilot comments from previous testing (Ref. 11) that the MCLAWS heading hold is much tighter than the heading hold in SAS/FPS.

Figure 12 shows the pilot ratings for the Lateral Reposition MTE. MCLAWS was consistently rated one HQR better than SAS/FPS. All the pilots found the heading hold to be sufficient for the task with both SAS/FPS and MCLAWS. In the vertical axis, the MCLAWS altitude hold helped to reduce the workload but it still required some minor corrections by the pilots

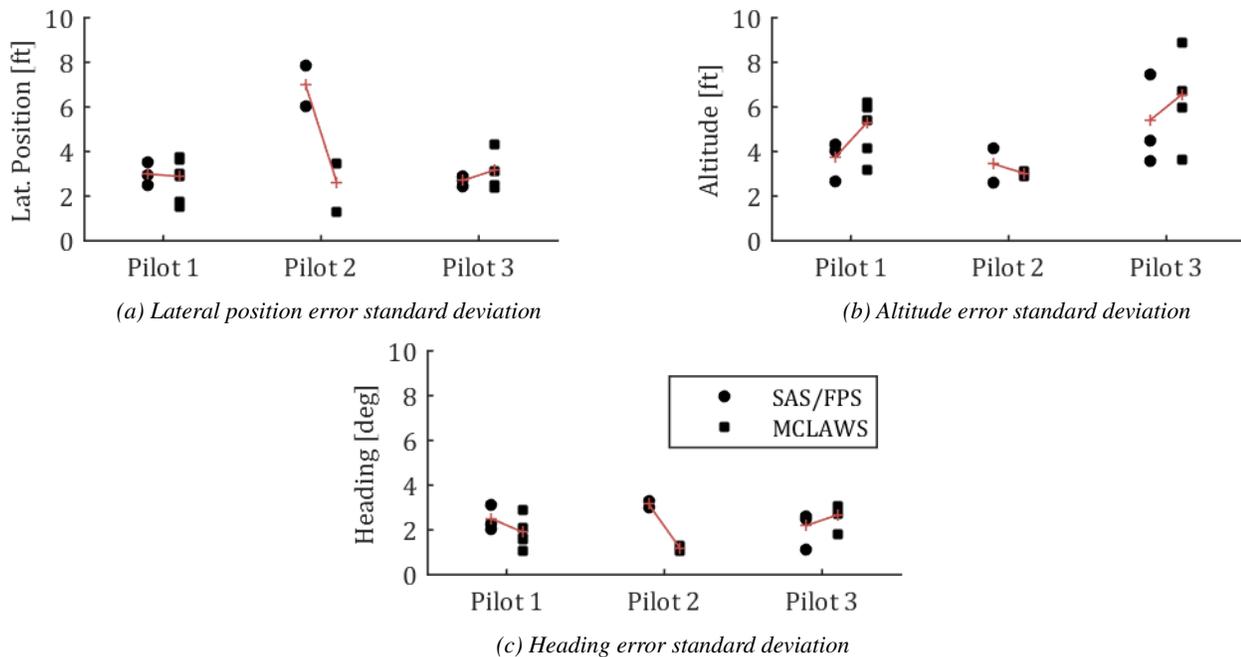


Fig. 13: Standard deviation of errors during Depart/Abort MTE (DVE)

to stay within the desired altitude. With SAS/FPS, the collective required constant monitoring and adjustments through the maneuver. In the longitudinal axis, all the pilots noted that with SAS/FPS, constant activity was required on the cyclic to maintain desired performance. Longitudinal pilot inputs were reduced with MCLAWS.

While answering the questionnaire immediately following the task, Pilot 1 noted that desired performance was obtained with MCLAWS but he felt that it did require moderate workload. After completing the questionnaire, he went on to say that a rating of HQR 3 was a possibility, but during the post flight debrief, he felt a rating of HQR 4 was correct due to the amount of pilot compensation required. The compensation noted by Pilot 1 consisted of lateral inputs to initiate and terminate the maneuver, and longitudinal inputs during the translation. Pilot 2 commented that the aircraft response with MCLAWS was “crisp and clean” and that the attitudes achieved were commensurate with the stick forces applied. Pilot 3 noted that with the MCLAWS, there was a more jerky lateral response which he attributed to maintaining the cyclic out of detent through the maneuver and the possibility of biodynamic feedback causing the jerkier response.

Depart/Abort MTE For the Depart/Abort MTE, all three pilots evaluated MCLAWS with the altitude hold and heading hold modes engaged for the entire maneuver. Due to the nature of the task, position hold was not engaged during the maneuver.

Figure 13 plots the standard deviation of the errors for the Depart/Abort MTE. Unlike the previous MTEs, the error data do not show one control system which consistently provided improved performance. Pilots 1 and 3 saw gener-

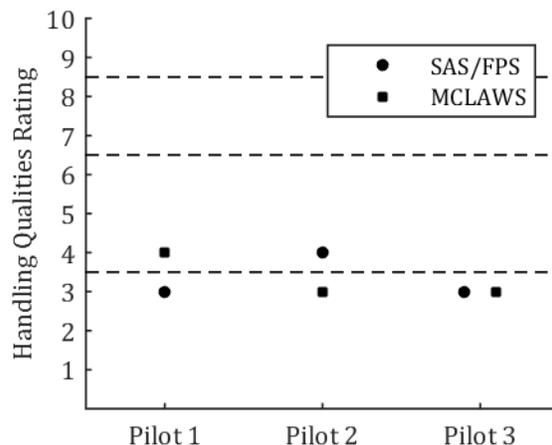


Fig. 14: Cooper-Harper handling qualities ratings for Depart/Abort MTE (DVE)

ally similar lateral position performance with both MCLAWS and SAS/FPS. They also saw improved altitude performance with the SAS/FPS at the cost of increased workload. The MCLAWS altitude hold, with some minimal help from the pilot during the flare, was able to meet the altitude requirements and thus the pilots traded reduced, though still desired, altitude performance for reduced pilot workload in the vertical axis.

Figure 14 shows the handling qualities ratings for the Depart/Abort MTE. Unlike the previous tasks, there was no clear consensus from the pilot ratings during the Depart/Abort MTE. The pilots all commented that the MCLAWS altitude hold was helpful but still required monitoring, especially during the flare at the end of the maneuver. Pilot 1 noted that the

ride was slightly jerkier with MCLAWS due to holding the cyclic out of detent and the bio-dynamic feedback (very similar to Pilot 3’s comments for lateral reposition). Pilot 2 noted that SAS/FPS allowed him to be too aggressive during the initial acceleration and final deceleration and required additional mental workload in order to keep his cyclic input aggressiveness in check. He also noted that the SAS/FPS seemed looser compared to the MCLAWS and that the MCLAWS had a smoother response and seemed more easily able to capture pitch attitudes. Pilot 3 commented that the MCLAWS attitude hold in the roll axis helped reduce cross-coupling during the final deceleration.

Discussion

A back-to-back handling qualities evaluation comparing the MCLAWS attitude command/attitude hold response type with position hold mode against the UH-60L rate response SAS/FPS control system demonstrated that the MCLAWS provided improved handling qualities. During four of the five ADS-33E MTEs which were evaluated, the MCLAWS demonstrated improved task performance and reduced pilot workload as compared to the baseline UH-60L SAS/FPS control system.

Pilot 1 noted that the Depart/Abort MTE is not the sort of task which would be performed in the DVE conditions due to the maneuver’s aggressive nature. When performing a departure in DVE conditions, the pilot would hover the aircraft straight up to a safe height above the ground before accelerating at a slower rate. When questioned, Pilot 2 and Pilot 3 agreed that the level of aggressiveness required for the Depart/Abort MTE is greater than would normally be used in DVE conditions. The pilots also noted that the GVE and DVE standards for the MTE in ADS-33E are identical which is different than the other four MTEs which were evaluated.

After the handling qualities evaluation was completed, it was discovered that the phase margin for the heading hold mode was 30.5°, well below the requirement. The value presented in Table 1 is for the piloted response when heading hold is not active. For future testing, the heading hold gains will be re-optimized to provide sufficient heading hold phase margin.

Throughout the evaluation, all the pilots noted that while they mainly preferred the ACAH response of MCLAWS in the simulated DVE, it was too sluggish for normal operations in GVE. This matches previous research (Ref. 19) which has demonstrated the ability for ACAH to provide Level 1 ratings in GVE, however pilot preference is still for a rate command response type when good visual cues are available to the pilot. This points to the need for response types to be pilot selectable.

LANDING LOGIC DEVELOPMENT AND TESTING

Future MCLAWS and DVE Mitigation research will require the ability to land the aircraft with the MCLAWS engaged.

Unlike the baseline SAS/FPS computers, the MCLAWS uses integral attitude feedback which must be disabled when the aircraft is on the ground. The EH-60L has a single weight-on-wheel (WOW) switch in the left main landing gear which is used to disable modes in the SAS/FPS computer when the aircraft is on the ground, however this was insufficient for the MCLAWS which needed to know the state of each of the three landing gear. In order to detect when the right main gear or tail gear contacts the ground, additional weight-on-wheel switches were needed. This was addressed by installing UH-60M Upgrade left and right main gear and tail gear struts, each of which has three, dual redundant weight-on-wheel switches which are triggered as the landing gear strut is compressed. This allowed the baseline left main gear switch to be unaltered for use with the SAS/FPS.

Control Law Modifications

The landing logic implemented in MCLAWS is based on the Advanced Digital/Optical Control System (ADOCS) (Ref. 20) landing logic. The MCLAWS landing logic has three states: Flight, Any WOW, and Constrained. In the Flight state, none of the weight-on-wheel switches have been triggered and the control law response is the standard MCLAWS response. For the Any WOW state, when any one weight-on-wheel switch is triggered, the system fades out all attitude feedback (proportional and integral) over a 1 sec period resulting in a baseline SAS-like rate command response type. Lastly the Constrained states remove all feedback in an axis as shown in Table 3. When all three gear are in contact with the ground, all three axes will be constrained and the response will be stick to head to allow for taxiing.

Table 3: WOW conditions for constrained states

Gear in contact with ground	Axis Constrained
Left Main and Right Main	Roll
Tail and (Left Main or Right Main)	Pitch
Tail	Yaw

SAS Hard Over Testing

All previous testing has been conducted with a 25 ft AGL floor for MCLAWS engaged flight. This limitation was based on the fact that the RFCC was a non-redundant system running research software leading to a concern that a SAS servo hard over would cause the aircraft to impact the ground before the pilot or safety pilot could react and recover the aircraft. This limitation was an institutional legacy from the RASCAL program and was based on full-authority servo hard over failures.

Considering that the MCLAWS is a ±10% partial-authority system, the severity of the aircraft response after a SAS servo hard over is expected to be less than in a full authority system and therefore a test program was conducted to demonstrate safe aircraft recovery from SAS servo hard overs

using the PAFCA system to inject hard overs. A build up approach was taken where hard overs of $\pm 2.5\%$, $\pm 5\%$, $\pm 7.5\%$, and finally $\pm 10\%$ were injected. After the hard over was injected, two different pilot response strategies were evaluated: 1) immediate pilot response to recover the aircraft 2) recovery after a 3 sec delay in accordance with ADS-33E divided attention requirements.

Figure 15 shows the pilot and aircraft response to a 10% roll SAS servo hard over with a 3 sec delay before the pilot initiates recovery. The hard over is triggered just after 5 sec and the pilot does nothing to correct the aircraft movement until 8 sec. During the 3 sec delay, the roll rate quickly builds to $20^\circ/\text{sec}$, the roll attitude exceeds 30° , and nearly 25 ft of altitude is lost. Both pilots commented during this phase of testing that the hard over was very apparent and it was hard to wait for 3 sec before recovering the aircraft. Even with divided attention, it would not take 3 sec for the pilot to recognize something was amiss and correct for it.

Further hard over testing was conducted on simulated approaches to landing. Using the ICE displays and landing guidance, a simulated landing pad was placed at 50 ft AGL over a taxiway and numerous approaches were conducted. During these approaches, a SAS servo hard over in any or multiple axes would be triggered without warning to the pilot. A SAS servo hard over was not triggered on every approach to provide a randomness to the testing. Upon detecting the servo hard over, the pilot was expected to initiate a climb, disengage the RFCC thus returning the aircraft to the baseline UH-60L SAS clearing the hard over, and execute a go around.

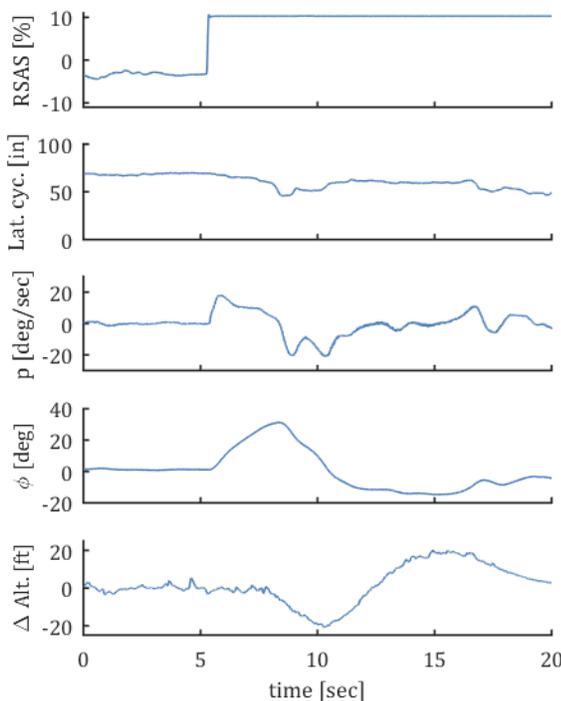


Fig. 15: Roll SAS servo hard over with 3 sec pilot delay

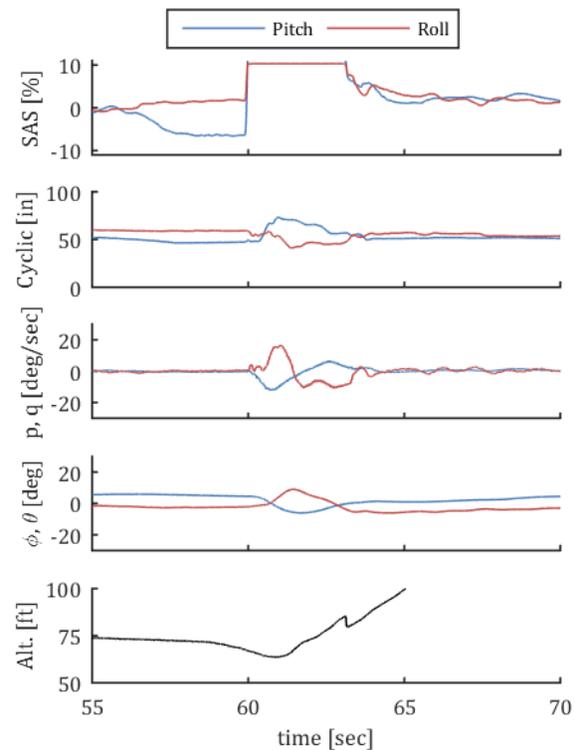


Fig. 16: Pitch and roll SAS servo hard over on simulated landing approach

During the approaches, the pilot was following the ICE Landing Guidance in an attempt to create divided attention operations as the guidance has the effect of increasing the pilot workload in order to achieve a precise landing. As noted previously, the hard overs, when injected, were quite apparent. Figure 16 plots the pilot and aircraft response to unannounced, simultaneous pitch and roll SAS servo hard overs which occur at 60 sec. From the stick traces, it can be seen that the pilot quickly acts to stabilize the aircraft and the angular rates do not exceed $15^\circ/\text{sec}$ while the attitude changes by less than 10° . As this is a simulated landing, the aircraft is descending at the moment of the hard overs, however the aircraft only descends an additional 3 ft after the hard over. By 63 sec, the pilot has disengaged the RFCC and has reverted to the UH-60L SAS response type as he continues to climb.

MCLAWS Engaged Landings

Based on the data collected from the SAS servo hard over testing, airworthiness approval was obtained to conduct MCLAWS engaged landings using the landing logic discussed previously. The first MCLAWS engaged landing was conducted on 25 November 2015. Through 31 January 2016, over 50 MCLAWS engaged landings have been conducted in GVE, including landings from IGE/OGE hover, roll on landings up to 40 kt, a 4° lateral slope landing, and numerous standard and Type IV (over simulated obstacles in approach path) landings using the ICE symbology. Pilot comments have indicated that the MCLAWS engaged landings were no different than landings with the legacy SAS/FPS control system.

CONCLUSIONS

A position hold mode with velocity command and landing logic have been integrated into the UH-60 Modernized Control Laws. Based on the flight test results, the following conclusions can be drawn:

1. In back-to-back flight test comparison, the MCLAWS with position hold mode received predominantly Level 1 Cooper-Harper handling qualities ratings during the five hover and low speed ADS-33E MTEs conducted in simulated DVE conditions as compared to Level 2 ratings for the legacy UH-60L SAS/FPS system.
2. Four of the five MTEs were consistently conducted with increased precision using the MCLAWS. In the fifth MTE (Depart/Abort) neither control system was more precise however it was noted that this maneuver might not be relevant for DVE testing where the benefit of MCLAWS is most noticeable.
3. The MCLAWS and the ACAH response type should be available as a pilot selectable mode such that the control laws provide the improved stability of ACAH in DVE, and the faster response of a rate command response-type for GVE flight.
4. A 10% SAS servo hard over is a noticeable event, even when the pilot is concentrating on following landing guidance for a precise landing. Pilot recovery from a SAS hard over results in minimal aircraft attitude change or altitude loss. GVE landings with the non-redundant research flight control computer and MCLAWS landing logic have been safely demonstrated permitting further MCLAWS landings in DVE.

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