Piloted Evaluation of Modernized Limited Authority Control Laws in the NASA-Ames Vertical Motion Simulator (VMS) [1]

Vineet Sahasrabudhe, Edgar Melkers and Alexander Faynberg
Sikorsky Aircraft Corporation
Stratford, CT

Chris L. Blanken
Army/NASA Rotorcraft Division
Aeroflightdynamics Directorate (AMRDEC)
U.S. Army Aviation and Missile Command
Moffett Field, CA

Abstract

The UH-60 BLACK HAWK was designed in the 1970s, when the US Army primarily operated during the day in good visual conditions. Subsequently, the introduction of night-vision goggles increased the BLACK HAWK's mission effectiveness, but the accident rate also increased. The increased accident rate is strongly tied to increased pilot workload as a result of a degradation in visual cues. Over twenty years of research in helicopter flight control and handling qualities has shown that these degraded handling qualities can be recovered by modifying the response type of the helicopter in low speed flight. Sikorsky Aircraft Corporation initiated a project under the National Rotorcraft Technology Center (NRTC) to develop modern flight control laws while utilizing the existing partial-authority Stability Augmentation System (SAS) of the BLACK HAWK. This effort resulted in a set of Modernized Control Laws (MCLAWS) that incorporate rate command and attitude command response types. Sikorsky and the US Army Aeroflightdynamics Directorate (AFDD) conducted a piloted simulation on the NASA-Ames Vertical Motion Simulator, to assess potential handling qualities and to reduce the risk of subsequent implementation and flight test of these modern control laws on AFDD's EH-60L helicopter. The simulation showed that Attitude Command Attitude Hold control laws in pitch and roll improve handling qualities in the low speed flight regime. These improvements are consistent across a range of mission task elements and for both good and degraded visual environments. The MCLAWS perform better than the baseline UH-60A control laws in the presence of wind and turbulence. Finally, while the improved handling qualities in the pitch and roll axis allow the pilot to pay more attention to the vertical axis and hence altitude performance also improves, it is clear from pilot comments and altitude excursions that the addition of an Altitude Hold function would further reduce workload and improve overall handling qualities of the aircraft.

Introduction

Over twenty years of research in helicopter flight control and handling qualities has shown that as the pilot's visual environment degrades, there is a corresponding degradation in handling qualities for near-Earth tasks. Degraded handling qualities imply reduced task performance and increased pilot workload, which contribute to reduced mission effectiveness and increased accident rates. The same research has also shown that these degraded handling qualities can be recovered by increasing the stability of the helicopter, i.e., by changing the control response type to a higher rank of stabilization. These results and concepts have been incorporated into the US Army's Aeronautical Design Standard – 33 (ADS-33), Handling Qualities Requirements for Military Rotorcraft [Ref. 1] through the Usable Cue Environment (UCE) concept. As the UCE deteriorates from clear day (UCE=1), to a starlit night (UCE=2), to a moonless-overcast night (UCE=3), the helicopter control response must be improved from a rate command, to an attitude command, to a translational rate command response type, respectively, in order to maintain satisfactory handling qualities. In addition, the following outer-loop stability functions may need to be added as the UCE degrades: attitude, direction, height, and position hold.

The UH-60 BLACK HAWK is the US Army's utility-class helicopter. The UH-60A was designed in the 1970s, when the Army primarily operated in the day in good visual conditions. Subsequently, the introduction of night-vision goggles increased the BLACK HAWK mission effectiveness, but the accident rate also increased [Ref 2]. This increase is strongly tied to increased pilot workload as a result of a degradation in visual cues from the goggles. The basic control response of the flight control system has not been upgraded from the original rate-command response type. Operating rate-command response types at night (UCE≥2) results in degraded handling qualities and contributes to increased accident rates. Improving the flight control system to help reduce accident rates has been recognized by the US Army Safety Center as a high priority toward reducing accident rates. A recent Safety Center accident investigation study states that the number one material fix toward reducing Army aviation accidents is to improve the hover and low speed handling qualities. [Ref. 3]

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Recently the US Army has entered into a recapitalization program to extend the service life of the BLACK HAWK for decades to come (UH-60M). On May 2, 2001 the Army contracted with Sikorsky Aircraft Corporation to build four UH-60M prototypes. The upgrades include not only new wide chord rotor blades, but also inclusion of two new digital flight control computers and associated sensors. In the baseline plan, however, these prototypes will fly with flight control laws that are fundamentally similar to existing UH-60A flight control laws. Many years of research have been performed: from documenting the UH-60 relative to ADS-33 [Ref. 4], to developing and evaluating new control concepts [Refs. 5-8] that provide improved handling qualities while retaining the existing partial-authority actuation system. In 2000, Sikorsky initiated a project under the National Rotorcraft Technology Center (NRTC) to develop modern flight control laws while still utilizing the existing partial-authority Stability Augmentation System (SAS) of the BLACK HAWK. Sikorsky's NRTC effort resulted in a set of control laws that incorporate rate command and attitude command response types and have provisions for translational rate command response types.

To advance possible implementation of these modern control laws into the UH-60M, Sikorsky was invited by the US Army Aeroflightdynamics Directorate (AFDD) to participate in a piloted simulation on the NASA-Ames Vertical Motion Simulator (VMS). The objectives of the VMS simulation were to assess potential handling qualities improvements in simulated degraded visual environments and to reduce the risk of subsequent implementation and flight test of these modern control laws on AFDD's EH-60L helicopter. This paper will describe development of the modern control laws, the VMS based piloted simulation evaluation, and associated results.

Modernized Control Laws

This section describes the MCLAWS architecture, the control modes, and the design and analysis techniques. In addition, results are presented from a Sikorsky piloted simulation that was used as a preliminary evaluation in preparation for the VMS experiment.

Basic structure

The basic structure of the Modernized Control Laws (MCLAWS) investigated in this study is shown in Figure 1. The figure shows the pitch axis structure only; the roll and yaw axes have a similar structure. Also shown for comparison is the structure of the current pitch axis control laws that are part of the Stability Augmentation System (SAS) on current UH-60A aircraft. The pitch-SAS is essentially a rate feedback system that augments the damping of the bare airframe dynamics.

The MCLAWS implement a two-mode control system. In the attitude mode the pitch and roll axes have Attitude Command Attitude Hold (ACAH) type responses, while the yaw axis has Rate Command Direction Hold (RCDH) characteristics. The control laws switch to a rate command mode if the helicopter velocities or attitudes exceed the limits shown in Table 1. As the name indicates, in the rate mode the aircraft has a Rate Command (RC) response type. In order to switch back to ACAH mode from rate mode, more restrictive conditions must be met which are shown in Table 1. Note that in this study only the inner loop SAS servos are used to implement MCLAWS. This simplifies the design and limits the changes to the SAS computer - leaving the Flight Path Stabilization (FPS) system untouched. It also allows for a set of control laws that are not inherently dependent on whether or not the pilot has the trim release switch depressed. This approach does not preclude the integration of the outer loop trim servos at a later stage to help re-center the SAS servos in the long term.

When the system switches from attitude mode to rate mode the dashed paths in Figure 1 are gracefully removed, and the systems reverts back to a rate feedback architecture almost identical to the baseline UH-60A SAS control laws. Conversely, when the aircraft re-enters the attitude mode, these paths are brought back in gradually. The overall objective was to retain ACAH characteristics over a useful range of aircraft velocities and attitudes without persistently saturating the SAS.

The MCLAWS have a model following type architecture, where the pilot stick input is passed through a command model to generate desired or ideal rates and attitudes. These are compared to the actual rates and attitudes and the feedback reduces the difference between the two. There are a few key differences from more conventional implementations of the model following architecture. First, instead of just using a commanded attitude both rate and attitude commands are generated and used. Since the basic aircraft responds like a rate command system, using a commanded rate leads to some advantages. Second, unlike a full authority system, the MCLAWS have to contend with a full authority mechanical path that has ten times the authority of the flight control system. Finally, the current implementation uses a unity inverse plant model.

Linear Analysis

The control laws were designed using nine and twenty-two state linear models of the UH-60. The nine state model represents only the rigid body dynamics, while the twenty-two state model adds the flap and lag dynamics and dynamic inflow. The SAS and primary servos were modeled including rate and position limits. Also modeled were computational and filtering delays to account for implementation aspects of the control laws.

The control architecture, linear airframe and other models described above were implemented in a SIMULINK model and the linear analysis was carried out using standard MATLAB tools.

The linear design and analysis of the ACAH mode were driven by ADS-33E bandwidth/phase delay requirements and the more general time domain requirements for a "good" attitude response. Broken loop stability requirements [Ref. 9] were also imposed. An example of the linear analysis carried out is shown in Figure 2. The left half of Figure 2 shows the ADS-33E small amplitude bandwidth/phase-delay pitch and roll axes evaluation for an intermediate design. The right half of the figure shows the gain and phase margins for the pitch and roll axes.

The rate mode was designed to be similar to the existing UH-60A rate feedback system. Considerable effort was spent in making the transition between the attitude and rate modes seamless and transparent to the pilot. This included adjustments to the switching conditions in Table 1 and the addition of faders and transient free switches.

Once the linear design had been completed, a limited amount of numerical optimization was carried out using MATLAB optimization tools. This was done by making selected control system gains variables of the optimization problem and imposing the above design specifications while minimizing actuator activity. The final gains obtained from this process formed the starting point for implementation of MCLAWS in a nonlinear simulation model and subsequent piloted simulation evaluation.

Sample results from reconfigurable and fixed-base

The control laws developed using the linear analysis tools were implemented in the Sikorsky Next-GenHel model of the UH-60. This was done using an automated pictures-to-code framework developed at Sikorsky, which allowed for a short cycle time between control law changes and piloted simulation evaluation.

Once the control laws had been successfully implemented in the nonlinear Next-GenHel model, the simulation was hosted on two separate facilities. Preliminary engineering and piloted evaluations of the control laws were carried out on the Sikorsky Reconfigurable Cockpit Simulator shown in Figure 3(a) while subsequent evaluations were carried out on the Sikorsky Fixed-base simulator shown in Figure 3(b).

Figure 4 shows the results of an evaluation of the MCLAWS as compared to the UH-60 control laws in the Sikorsky Fixed-base simulator. This simulator has a wide field-of-view and actual H-60 cyclic and collective sticks. The aircraft model used was a UH-60A Next-GenHel model at a heavy gross weight of 19,302 pounds. The intention was to evaluate the control laws at a higher gross weight that was more representative of the weights of current and future H-60 variants. The mission task elements (MTEs) evaluated were a subset of those described in ADS-33E and the performance limits imposed on the evaluations were those for the utility configuration. Three pilots carried out the evaluations although due to time constraints only one pilot evaluated the Accel./Decel. MTE. The figure shows the pilot ratings as measured on the Cooper-Harper scale (on this scale numerically lower ratings correspond to better pilot opinion). As the figure shows, across all the MTE's evaluated the MCLAWS earned better pilot ratings on the Cooper-Harper handling qualities rating (HQR) scale [Ref. 10], with a maximum improvement of 2.3 points and an average improvement of 1.1 points.

VMS and Test description

The next phase of the assessment was carried out on the NASA-Ames Vertical Motion Simulator (VMS). The VMS environment includes large-amplitude motion and the ability to simulate both day and degraded visual environments. Handling quality evaluations of five MTEs from ADS-33 were performed with the baseline UH-60A control laws and the MCLAWS in a simulated day environment and a Degraded Visual Environment (DVE). In addition, the baseline and the modern control laws were assessed in the presence of wind and turbulence. This section describes the simulation facility, matrix of configurations, and the conduct of test.

Description of the Facility

The NASA-Ames large-amplitude motion flight simulator is shown in Figure 5. The VMS real-time mathematical model of the UH-60A is based upon the generalized, modularized programs that make up the Sikorsky General Helicopter Flight Dynamics Simulation (GenHel) [Ref. 11]. Off-axis corrections to the model, also termed aerodynamic phase lag, were implemented to correct the low speed off-axis response [Ref. 12]. The overall helicopter weight was set to 16,825 pounds.

The crew station, or cockpit cab, has a single pilot seat mounted in the center of the cab and four-image presentation "windows" to provide outside imagery Figure 6. The cockpit cab was recently modified [Ref. 13] into a UH-60A configured cockpit to support the Joint Shipboard Helicopter Integration Process (JSHIP). The cockpit visual display system consisted of an array of five flat panel screens with each screen abutted against the others in a 220-degree horizontal by 70-degree vertical semicircle. It was masked to represent the pilot's field of view from the BLACK HAWK's right seat. The visual imagery was carefully tailored to contain adequate macro-texture (i.e.. large objects and lines on the ground) for the determination of the rotorcraft position and heading with reasonable precision. The baseline stick-to-visual delay was about 70 msec including a 10-msec math model cycle time. A seat shaker provided vibration cueing to the pilot, with frequency and amplitude programmed as functions of airspeed, collective position, and lateral acceleration. Aural cueing was provided to the pilot by cab-mounted speakers. The aural model, driven by aircraft parameters, provided main rotor noise, tail rotor noise, engine and transmission noise. Standard helicopter instruments and BLACK HAWK grips were installed in the cockpit Figure 7. The cockpit instruments were displayed on two Cathode Ray Tubes (CRTs) mounted on a panel directly in front of the pilot seat. The orientation of the instruments was the same as the actual aircraft and they were compatible with night vision devices. The VMS control loading system (McFadden Systems) is digitally programmed to provide realistic force-feel cues for the cyclic, pedal, and collective controls. The overall VMS motion system capabilities are listed in Table 2.

Matrix of Configurations

The matrix of configurations included the baseline UH-60A flight control laws, the modern control laws, five ADS-33 MTEs, and variations in ambient conditions to include day and night, and calm or with winds/turbulence. The five ADS-33 MTEs included Hover, Vertical Maneuver, Pirouette, Lateral Reposition, and Departure/Abort. Reference 1 provides a detailed description of these MTEs along with the desired and adequate performance standards. The VMS course cueing for these MTEs was carefully matched to the flight test set-up (Figure 8) used in Reference 3. In this way, some comparison could be inferred between the actual flight test results and the UH-60A simulated day conditions on the VMS. Ambient conditions for pilot evaluation of these five MTEs were varied from the day conditions to night. In the night scene, the pilot's vision was aided by wearing night vision goggles (NVGs) (Figure 9). In addition, some MTEs were evaluated in the presence of wind and turbulence. Details of these wind and turbulence models are reported in Reference 14. Table 3 shows the matrix of these configurations.

Conduct of the Test

Participating in the test were five experienced rotary-wing experimental test pilots representing the US Army, NASA, and Sikorsky. The pilots were allowed some time to practice each of the maneuvers to get acquainted with the aircraft's response and with the simulator visual cues. The MTEs were first evaluated in the day scene to allow maneuver training and course cueing familiarization under good lighting conditions. All evaluation runs were carried out with the motion system operational. For evaluation in a DVE, the out-the-window view was severely degraded and the pilots used NVGs to carry out the maneuvers. The simulator has more travel in one horizontal axis as compared to the other and the cab was rotated to take advantage of this depending on the maneuver being evaluated. Initial training sessions were provided prior to at least three data collection records for each maneuver. A structured pilot questionnaire was used to elicit pilot comments and a HQR was provided. Aircraft flight dynamic and control response parameters and task performance data were recorded for display and later analysis. Monitors in the VMS control room provided quick and easy assessment of pilot-task performance relative to the ADS-33 desired and adequate standards Figure 10. This information was relayed to the evaluation pilot in the cockpit to confirm of his perception of task performance based on course cueing. Evaluation sessions were limited to one hour to mitigate fatigue effects.

Results

The results below are presented in terms of HQRs and summary task data for each of the MTEs. Also, SAS actuator saturation data and task time history data are presented for illustration.

Overview of HQRs

Figure 11 and Figure 12 summarize the average HQRs for good and degraded visual conditions respectively for both the baseline UH-60A control laws and the MCLAWS. Figure 11 shows the average HQRs from up to three pilots across five different ADS-33 maneuvers. The patterened bars correspond to baseline UH-60A CLAWS while the dark bars represent MCLAWS. For day (GVE) conditions, there was a consistent improvement in the HQRs across maneuvers and pilots as a result of using MCLAWS instead of the baseline UH-60A CLAWS. It is clear that for each of the five maneuvers evaluated, there wass between a 0.5 and 2.5 point improvement due to the MCLAWS. Averaged over all maneuvers the improvement was slightly more than 1.0 point.

For DVE, on the other hand, several of the maneuvers were too difficult to complete with adequate performance levels with either control system. Pilot comments indicate that this was because of the degraded visual environment being unrealistically degraded and the task cues blending into the background. The result was a series of high HQRs with no ability to distinguish one control system from the other. Pilot debriefs indicated that operations in such conditions are unlikely. A UCE determination was not performed. For other maneuvers however, at least one of the pilots was able to distinguish differences, with the MCLAWS always being superior to the baseline CLAWS. Figure 12 shows the DVE ratings only for those maneuvers where cueing appeared to distinguish between desired and adequate standards. All pilot rating pairs (i.e. ratings for baseline CLAWS and MCLAWS) that were numerically high and equal have been eliminated. The resulting average ratings are shown in the figure. It can be seen that the MCLAWS configuration was rated between 1.0 and 1.5 points better than the baseline and that the average improvement across maneuvers was a little more than one point.

Finally shown in Figure 13 are the HQRs for different wind levels. The patterned group of bars correspond to the baseline UH-60A control laws with the first pattern corresponding to evaluation without any winds and the checked pattern for evaluation in light winds. The shaded bars are for the MCLAWS with the shading corresponding to different levels of wind and turbulence (black is no winds, dark gray is with winds, and light gray is with winds and turbulence) with MCLAWS. It is immediately apparent from the figure that the MCLAWS performed well in rejecting the disturbances and did not show significant degradation as a result of the wind and turbulence. Note that in all MCLAWS cases, the HQRs in the presence of winds and turbulence were still better than the HQRs for the baseline CLAWS without winds and turbulence.

Performance analysis of GVE runs

In order to further understand handling qualities improvements offered by MCLAWS, task performance data were analyzed for both general trends and to provide specific examples of improvement. This subsection presents some of these trends for the GVE runs.

Figure 14 shows the performance summary data for the Precision Hover maneuver for both the baseline UH-60A control laws and the MCLAWS for two pilots. Although the times to achieve a stabilized hover were rather long for both control laws, the MCLAWS evaluations were completed in less time for five out of the six comparisons. The RMS deviations in longitudinal and lateral position, altitude, and heading were less in three out of four cases with the MCLAWS compared to the UH-60A. Looking at the maximum excursions, the lateral position, altitude, and heading were within desired performance standards for nearly all evaluations. However, maximum excursions in longitudinal position ranged from desired, to adequate, to not adequate for both control laws. The problem in controlling the longitudinal axis was a main factor toward degrading the HQR. As the figure shows, only two MCLAWs cases are within adequate time ($\leq$ 8 sec); all the rest are outside of adequate.

Figure 15 shows the performance trends for the Vertical maneuver in GVE. There are some interesting differences between pilots for this MTE. For Pilot 2, all the RMS deviations in longitudinal and lateral position, and heading were less with the MCLAWS compared to the UH-60A evaluations. For Pilot 1, only the RMS deviations in longitudinal position were less with MCLAWS whereas, the lateral position and heading deviations were less with the UH-60A. Looking at the maximum longitudinal and lateral position excursions, evaluations included a mixture of desired and adequate performance with only one falling to not adequate. Six of nine cases with excursions into adequate were with the UH-60A. Maximum heading excursions were nearly all within desired tolerances for both MCLAWS and UH-60A evaluations.

The performance summary for the Pirouette MTE is shown in Figure 16. The time subplot shows both the time to complete the circle and time to stabilize to a hover at the end of the maneuver. Both configurations were roughly equivalent. The RMS deviations show a mixture of less deviation with either MCLAWS or UH-60A depending upon the task parameter and pilot. The maximum radial excursion was within desired tolerance for nearly all evaluations. However, altitude excursions for two-thirds of all evaluations were within the adequate range. Improving the height axis response with the addition of Altitude Hold could be beneficial.

For two-thirds of the evaluations, the heading excursion data show larger deviations with MCLAWS. It should be noted that a MCLAWS—to—GenHel implementation error was discovered after the VMS simulation which caused the MCLAWS heading hold to work well for small deviations, but saturate for larger ones.

Figure 17 shows the performance trends for the Lateral Reposition MTE. The times to complete the maneuver were shorter for the MCLAWS for every comparison with UH-60A even through the times were all similar in duration. For 13--out--of--18 cases, the RMS deviations for longitudinal position, altitude, and heading were less with MCLAWS compared to UH-60A. Maximum excursions for altitude and heading were nearly all within desired performance standards for both MCLAWS and UH-60A. Longitudinal excursions were nearly all within desired for Pilot 2 for both control laws. Although Pilot 1 had mainly adequate performance for longitudinal excursions for both control laws, the MCLAWS evaluations were always significantly better.

The Normal Depart-Abort MTE performance summary is shown in Figure 18. For this MTE, all MCLAWs cases were completed within *desired* times whereas only 2 of 7 runs with UH-60A were within *desired*. One UH-60A time was outside of adequate. Smaller RMS deviations in lateral position, altitude, and heading are about equally split between the control law comparisons. For comparisons where large differences in RMS exist, the MCLAWS deviations were always smaller compared to the UH-60A. Maximum altitude and heading excursions for the two control laws were all within desired performance and roughly the same. Lateral excursions were generally less with the MCLAWS compared to UH-60A.

Performance analysis of DVE runs

The performance summary for the Pirouette and Lateral Reposition MTEs in DVE is shown in Figure 19. Similar to the GVE evaluations, the two times associated with the DVE Pirouette were all within the desired tolerances and roughly the same between the two control laws. With the exception of an initial comparison, the RMS excursions in radial position and altitude were significantly less for the MCLAWS cases compared to the UH-60A. RMS heading deviations appear larger with MCLAWS, but this is attributed to the previously mentioned integration error. Looking at the maximum excursion data, trends that mimic the RMS results are seen. It should be noted that nearly all of the altitude excursions were within the adequate performance standards. Once again this points to further improvement possible by addition of an altitude hold function.

The performance summary data for the Lateral Reposition in DVE shows all times were adequate and about the same for both configurations. The RMS deviations for longitudinal position, altitude, and heading are all less with MCLAWS compared to UH-60A cases. Maximum altitude and heading excursions were nearly all within the desired range for both the MCLAWS and UH-60A cases. On the other hand, maximum longitudinal excursions were nearly all in the adequate range for both control laws.

The performance summary data for the Vertical MTE in the DVE is shown in Figure 20. All the evaluations were completed within desired times with all of the MCLAWS cases being slightly better than the UH-60A cases. With the exception of a couple of comparisons, the RMS deviations in position and heading were substantially less with MCLAWS compared to UH-60A. In general, maximum excursions in longitudinal and lateral position were all within desired performance standards with MCLAWS whereas the UH-60A cases were in the adequate range. All of the maximum heading excursions were within desired performance for both sets of control laws.

Actuator saturation

One of the primary concerns when designing control laws for a partial authority system is actuator saturation. In the current implementation of the MCLAWS actuator saturation is addressed directly by switching from an ACAH response system to a RC system before actuator saturation occurs. However, this switching needs to be balanced with the need to maintain ACAH characteristics over a useful range of aircraft velocities and attitudes. As a result at the extreme edges of the ACAH envelope some saturation is expected to occur. Figure 21 shows the percentage of time for which the pitch and roll axis actuator authority was saturated, when performing different MTEs.

As the figure shows, for the lateral reposition the roll axis actuator authority was saturated for approximately 15-20% of the time. Analysis of individual run data shows that most of the saturation occured at the start and the end of lateral maneuver. The saturation in the pitch axis happened primarily during the terminal phase of the maneuver.

During the normal depart/abort maneuver, the lateral axis showed almost no saturation, but there was up to 30% saturation on some runs in the longitudinal axis. Most of this occured when transitioning out from ACAH to RC during the forward acceleration phase of the maneuver and was not extensively commented upon by the pilots.

Finally, during the precision hover maneuver there was minor saturation in the longitudinal axis but none in the lateral axis. The vertical and pirouette MTEs showed no pitch or roll axis saturation for any of the runs with the MCLAWS.

The general trends shown in Figure 21 compare favorably to the results in (Ref. 7). For the precision hover maneuver, the MCLAWS longitudinal saturation is generally at a much lower level. For the lateral reposition and depart/abort maneuvers, it must be pointed out that the more aggressive scout/attack versions of the performance requirements were imposed during the Ref. 7 evaluation and some allowance must be made for this.

Illustrative examples

In order to illustrate the improvements due to the MCLAWS as compared to the baseline UH-60A control laws, Figure 22 compares two individual Precision Hover cases, one for each control system. The top row of subplots shows cyclic stick movement for 30 seconds after the pilot declares a hover capture, while the bottom row shows the task performance in terms of lateral and longitudinal drift. It is immediately apparent that for the MCLAWS run the pilot was expending a smaller effort (as reflected in stick movement) to obtain better position keeping (as reflected in the small drift) when compared to the case with the baseline UH-60A control laws.

Finally, shown in Figure 23 is a comparison of the lateral reposition MTE using the two control laws. The top half shows the ground trace of typical runs for each type as executed by Pilot 1. The figure shows that the performance in terms of longitudinal drift was much smaller with the MCLAWS. The pilot activity as measured by lateral stick Power Spectral Density (PSD) (calculated using CIFER, Ref. 15) was also lower for the MLCAWS case than for the case with baseline UH-60A control laws.

Conclusions

Sikorsky Aircraft Corporation developed modernized flight control laws that incorporate rate and attitude command response types, while utilizing the existing partial authority SAS actuators of the BLACK HAWK helicopter. These control laws were evaluated in a VMS simulation effort, where the objectives were to assess potential handling qualities improvements in simulated degraded visual environments and to reduce the risk of subsequent implementation and flight test of these modern control laws on AFDD's EH-60L helicopter.

The conclusions of this investigation are:

(1) Attitude Command Attitude Hold control laws in pitch and roll improve handling qualities in the low speed flight regime. These improvements are consistent across a range of MTEs and for both GVE and DVE.

(2) The MCLAWS perform better than the baseline UH-60A control laws in the presence of wind and turbulence.

(3) The improved handling qualities in the pitch and roll axis allow the pilot to pay more attention to the vertical axis and hence altitude performance also improves. However, it is clear from pilot comments and altitude excursions, especially during the Pirouette MTE, that the addition of an Altitude Hold function would further reduce workload and improve overall handling qualities of the aircraft.

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Table 1: Attitude to rate mode switching thresholds

	ACAH will engage if:	ACAH will disengage if:
$\lvert\theta\rvert$	<15 degrees , and	>25 degrees , or
$\lvert\phi\rvert$	<10 degrees , and	>35 degrees , or
$\sqrt{U^2+V^2}$	<20 knots	>30 knots

Table 2: VMS Motion System Capabilities

AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	± 30 ft	16 ft/sec	24 ft/sec^2
LATERAL	± 20 ft	8 ft/sec	16 ft/sec^2
LONGITUDINAL	± 4 ft	4 ft/sec	10 ft/sec^2
ROLL	± 18 deg	40 deg/sec	115 deg/sec^2
PITCH	± 18 deg	40 deg/sec	115 deg/sec^2
YAW	± 24 deg	46 deg/sec	115 deg/sec^2

Table 3: Test Matrix of Configurations

ADS-33E-PRF MTEs	Simulated DAY		Simulated NIGHT	
	UH – 60A	MCLAWS	UH – 60A	MCLAWS
Assessed in Moderate Winds:			MTEs in DVE not evaluated in winds	
Hover				
Vertical Maneuver				
Pirouette				
Assessed in Light Winds:				
Hover				
Vertical Maneuver				
Pirouette				
Assessed in Calm Wind:				
Hover				
Vertical Maneuver				
Pirouette				
Lateral Reposition				
Departure/Abort				

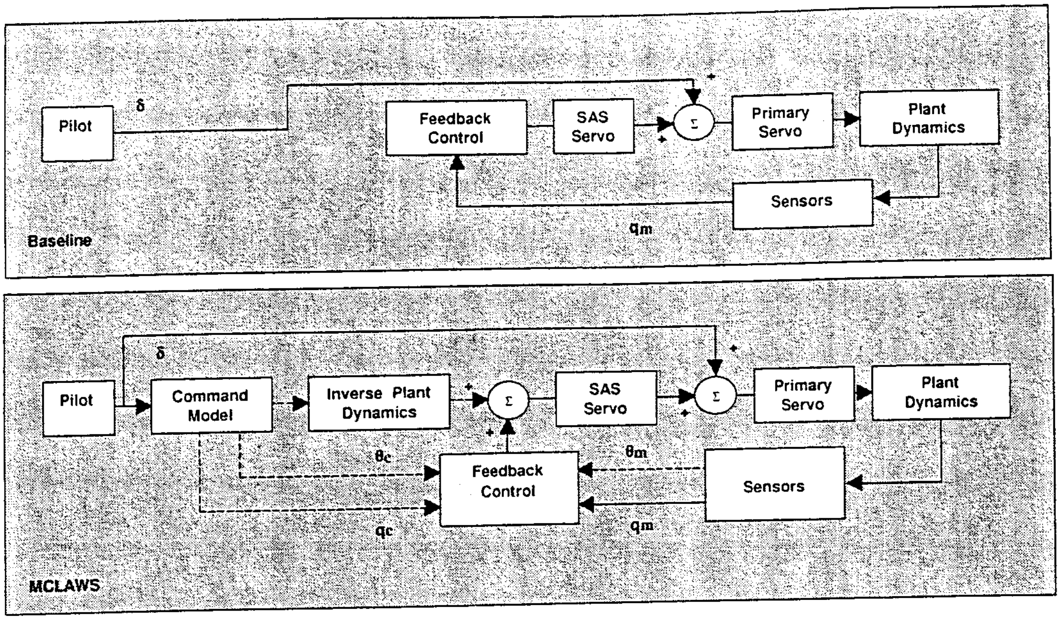


Figure 1: Architecture of MCLAWS compared to baseline UH-60A SAS

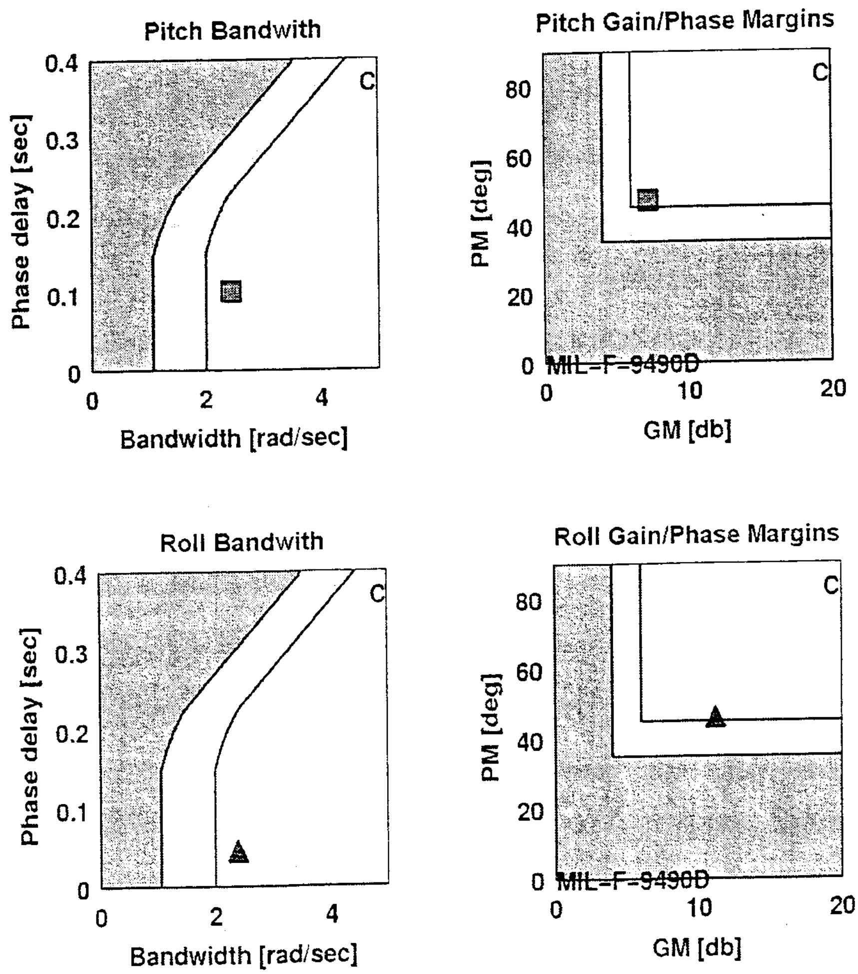


Figure 2: Linear analysis for MCLAWS pitch and roll axes

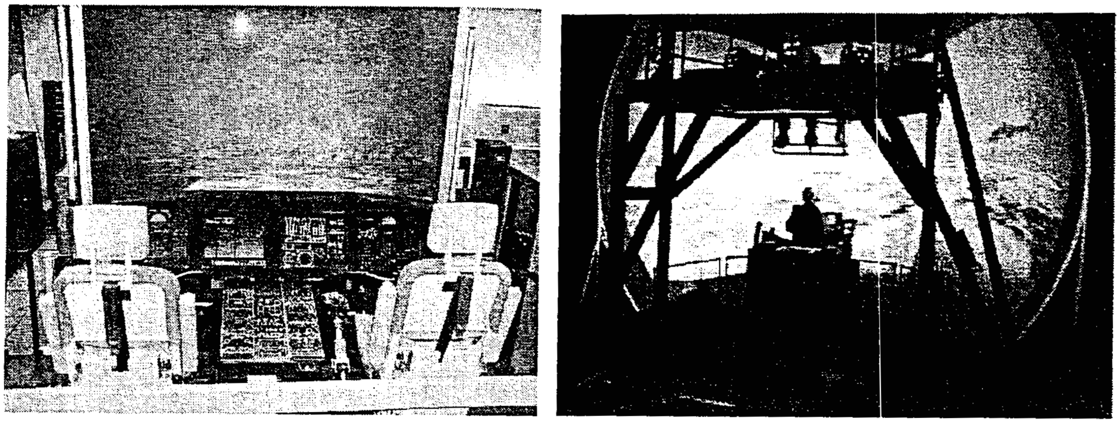


Figure 3: (a) Sikorsky Reconfigurable cockpit simulator; (b) Sikorsky Fixed-base simulator

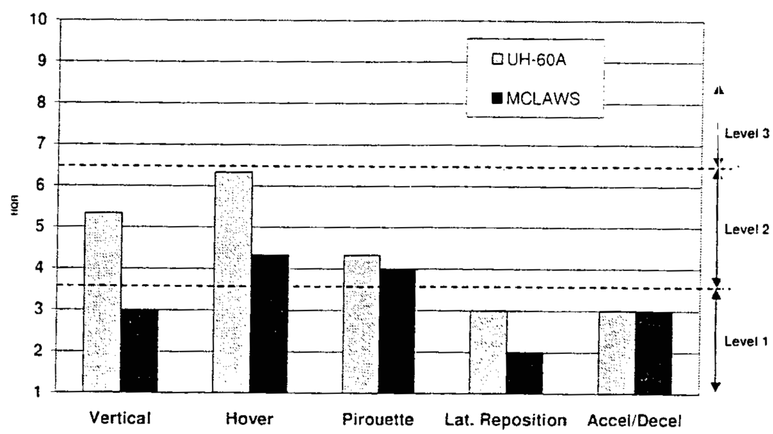


Figure 4: Average pilot HQRs from Fixed-base evaluation at Sikorsky

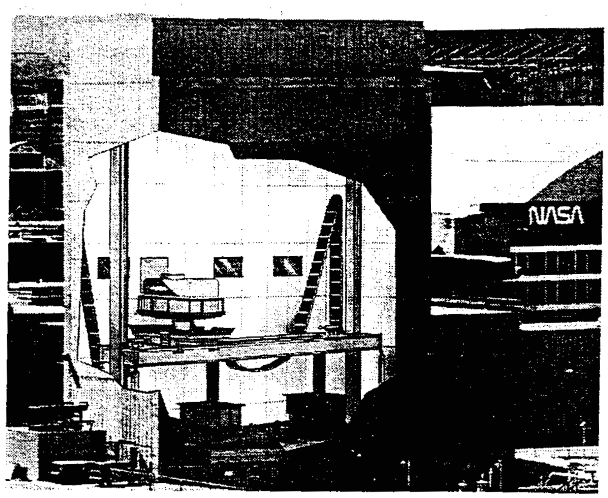


Figure 5: The NASA Ames VMS motion system

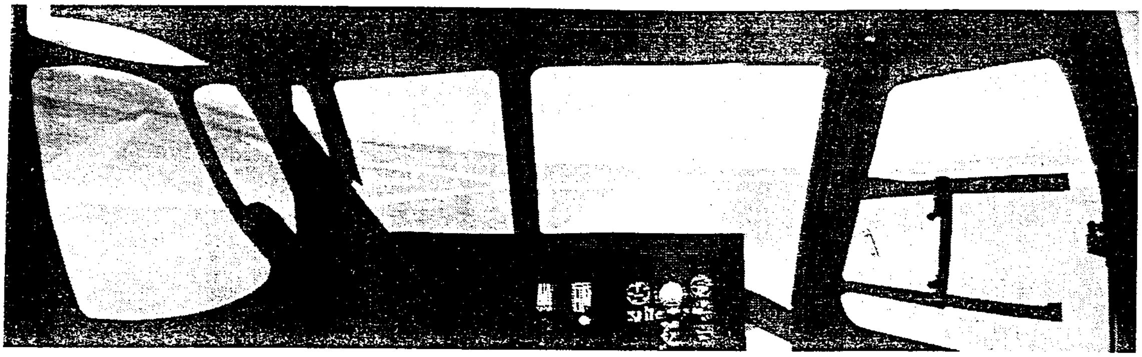
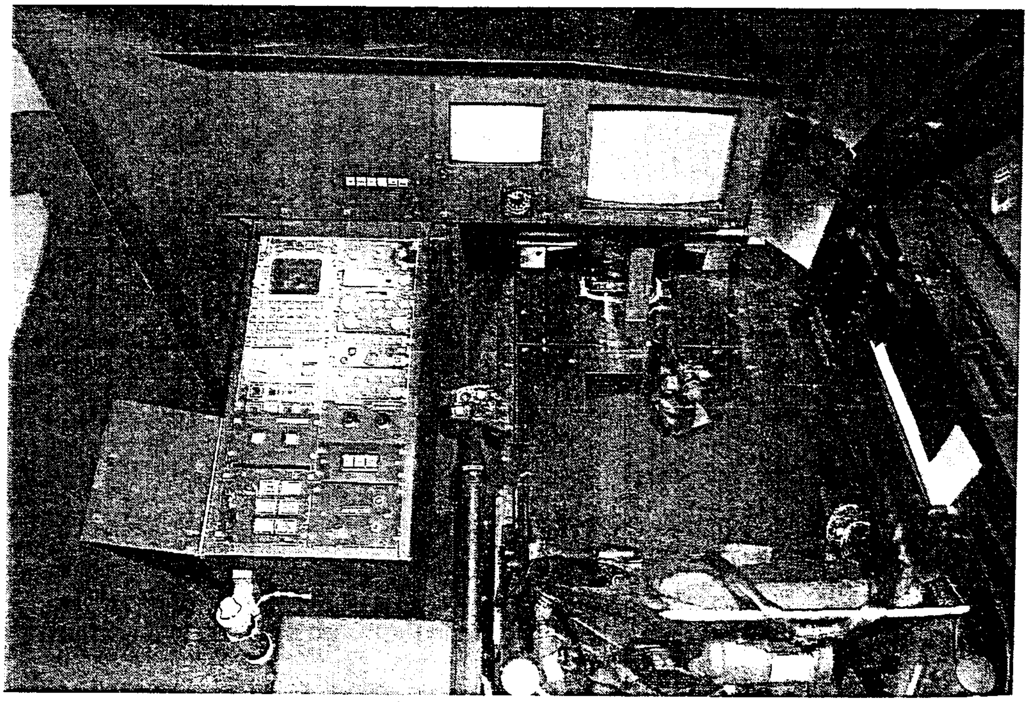


Figure 6: VMS JSHIP cockpit cab

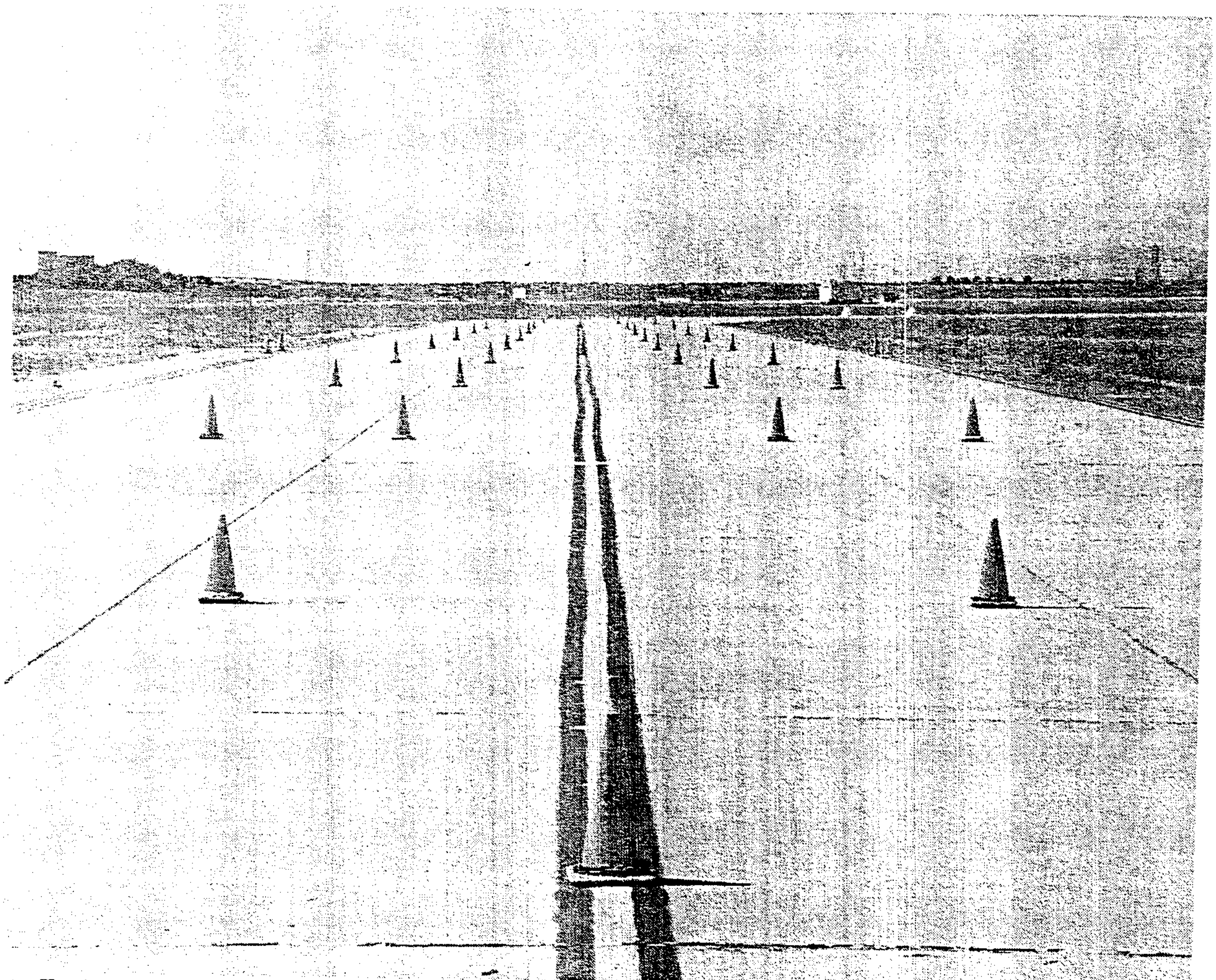
(a) Collective Stick

(b) Cyclic Stick



(c) Cockpit and instruments

Figure 7: Cockpit instruments and inceptors



a) Traffic cones on west parallel taxiway denoting *desired* and *adequate* task performance for the Lateral Reposition maneuver and the Normal Depart/Abort maneuver.

b) Hover MTE – diagonal cones shown in foreground.

c) Hover target/board

Figure 8: Examples of course set-up from the 1999 ADS-33/UH-60A test (Ref. 3)

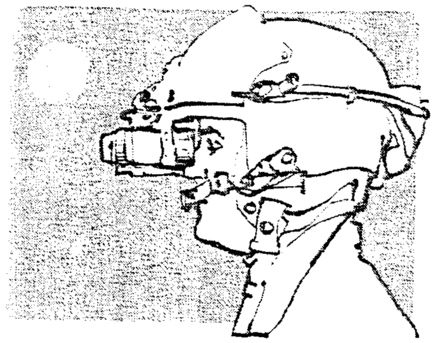


Figure 9: Aviator's night vision goggles

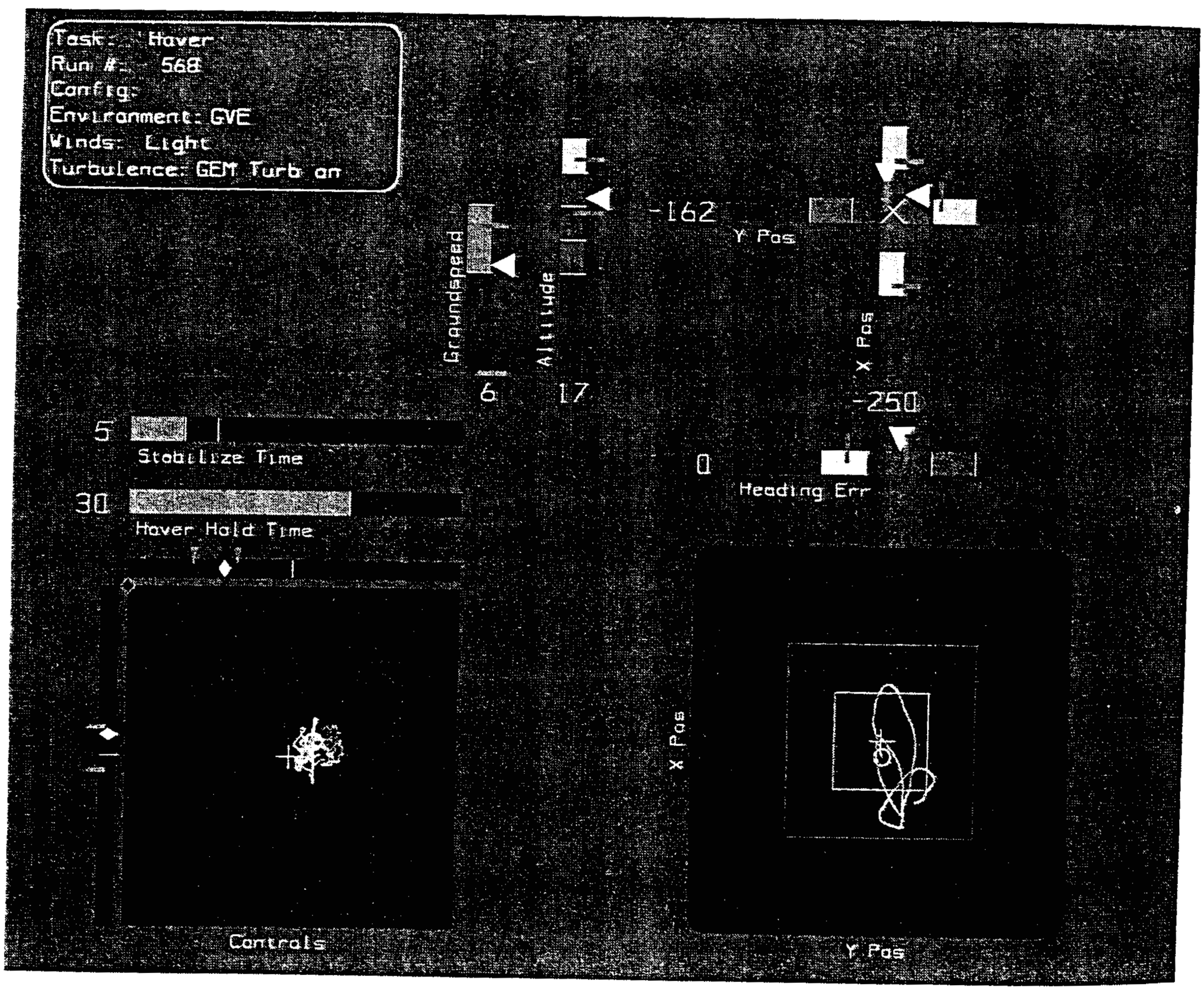


Figure 10: VMS task performance assessment display

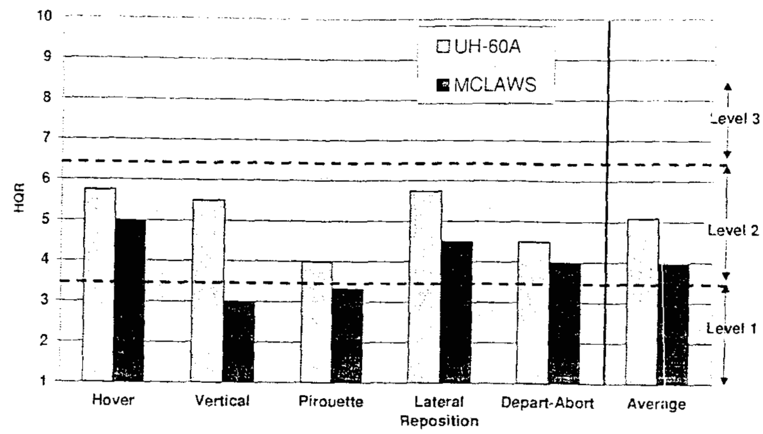


Figure 11: Average Handling Qualities ratings in Good Visual Environment (GVE)

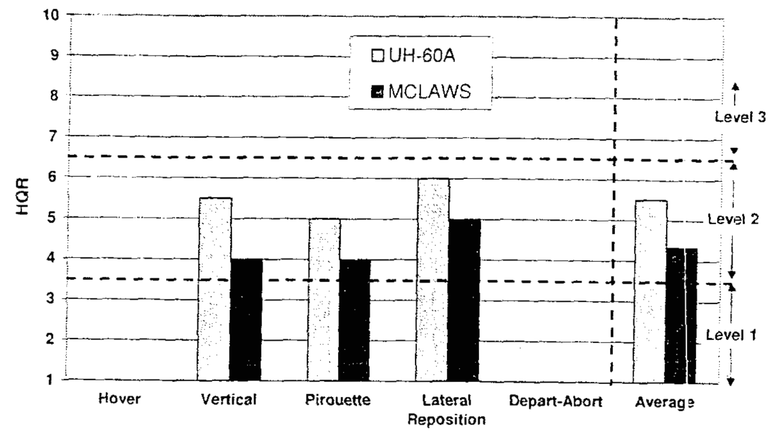


Figure 12: Average Handling Qualities ratings in Degraded Visual Environment (DVE)

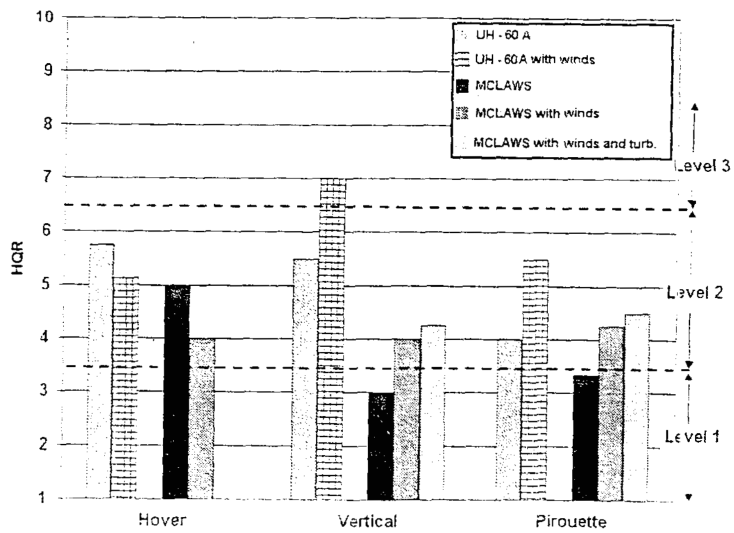


Figure 13: Average Handling Qualities ratings in winds

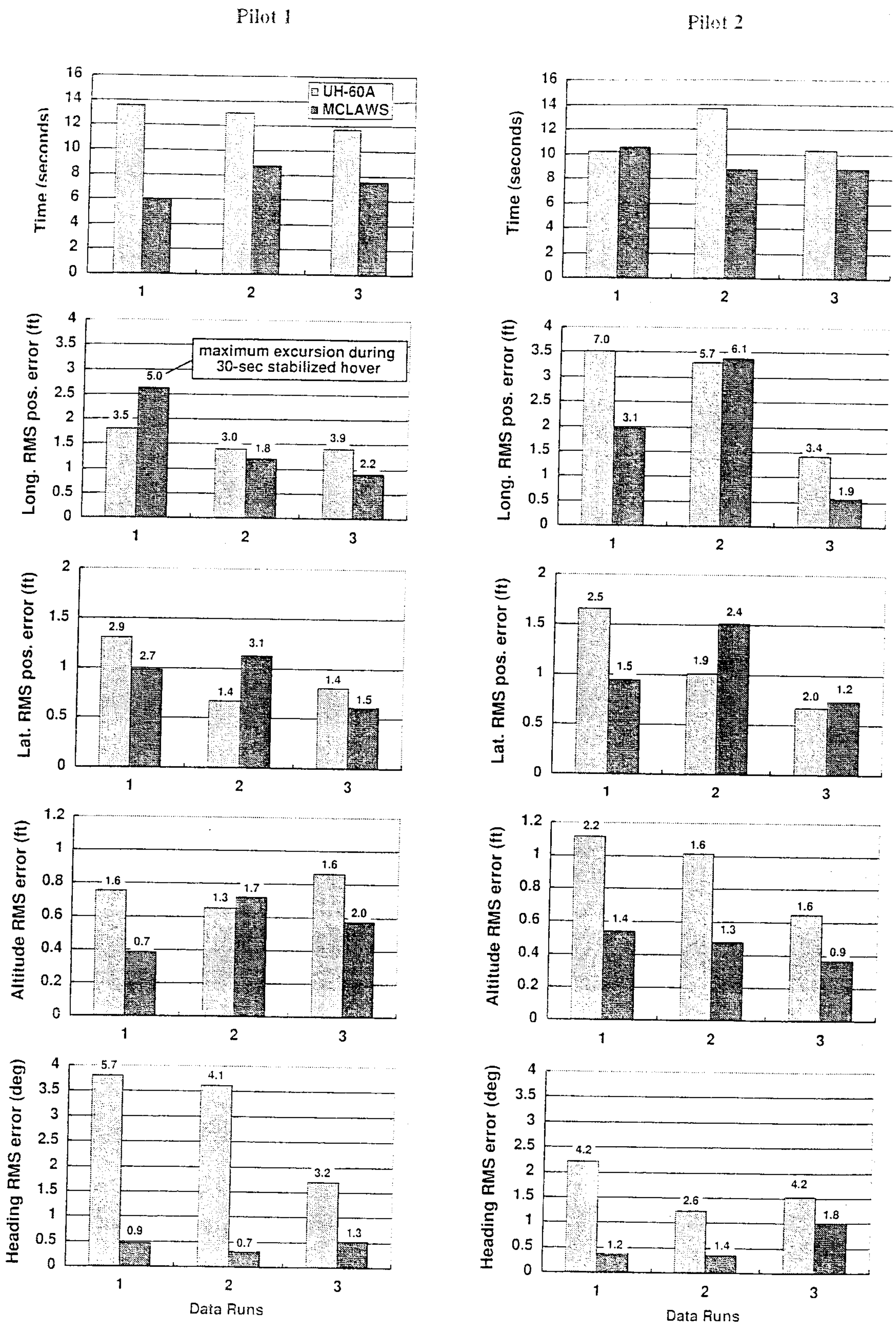


Figure 14: Hover MTE performance summary data in GVE.

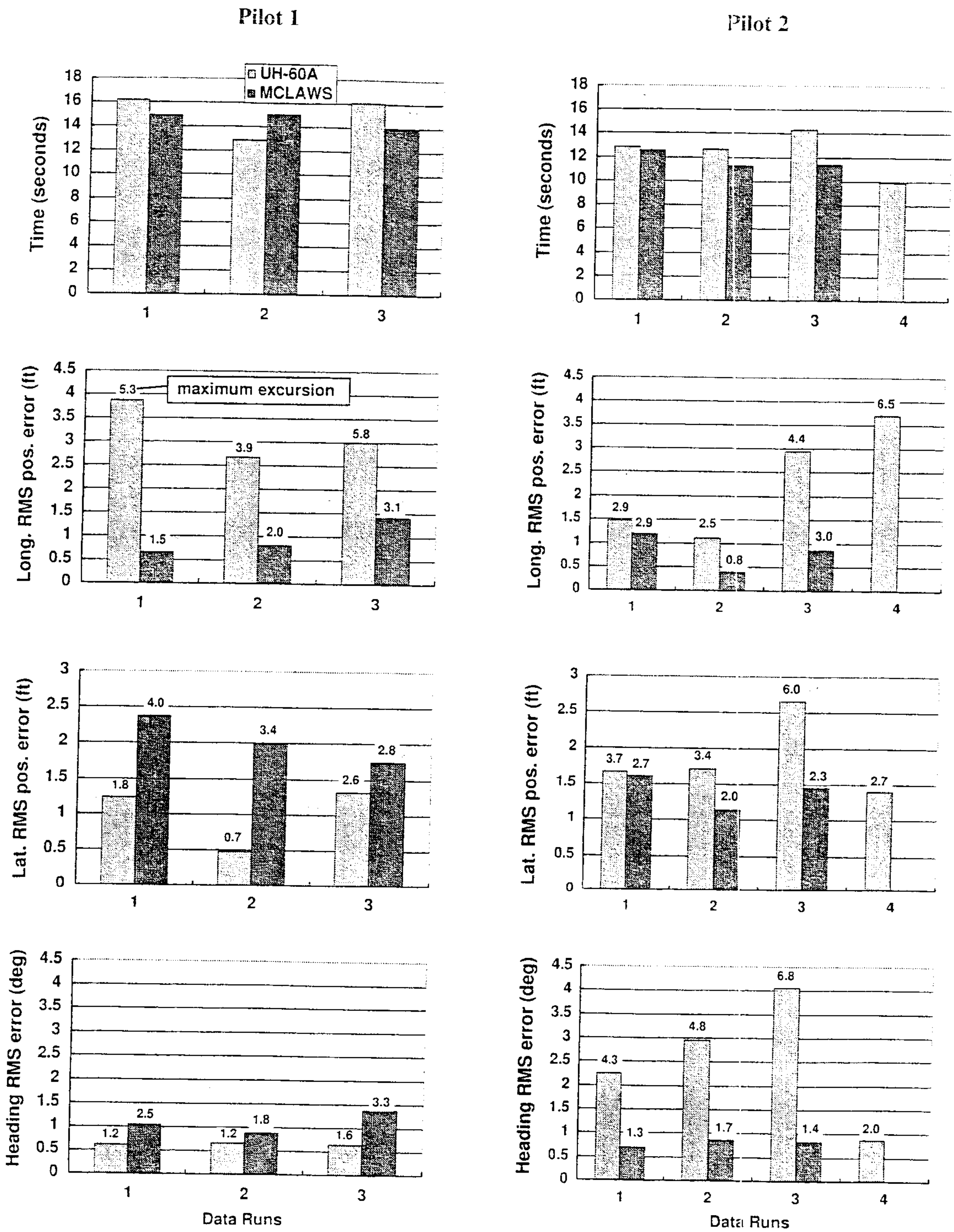


Figure 15: Vertical MTE performance summary data in GVE.

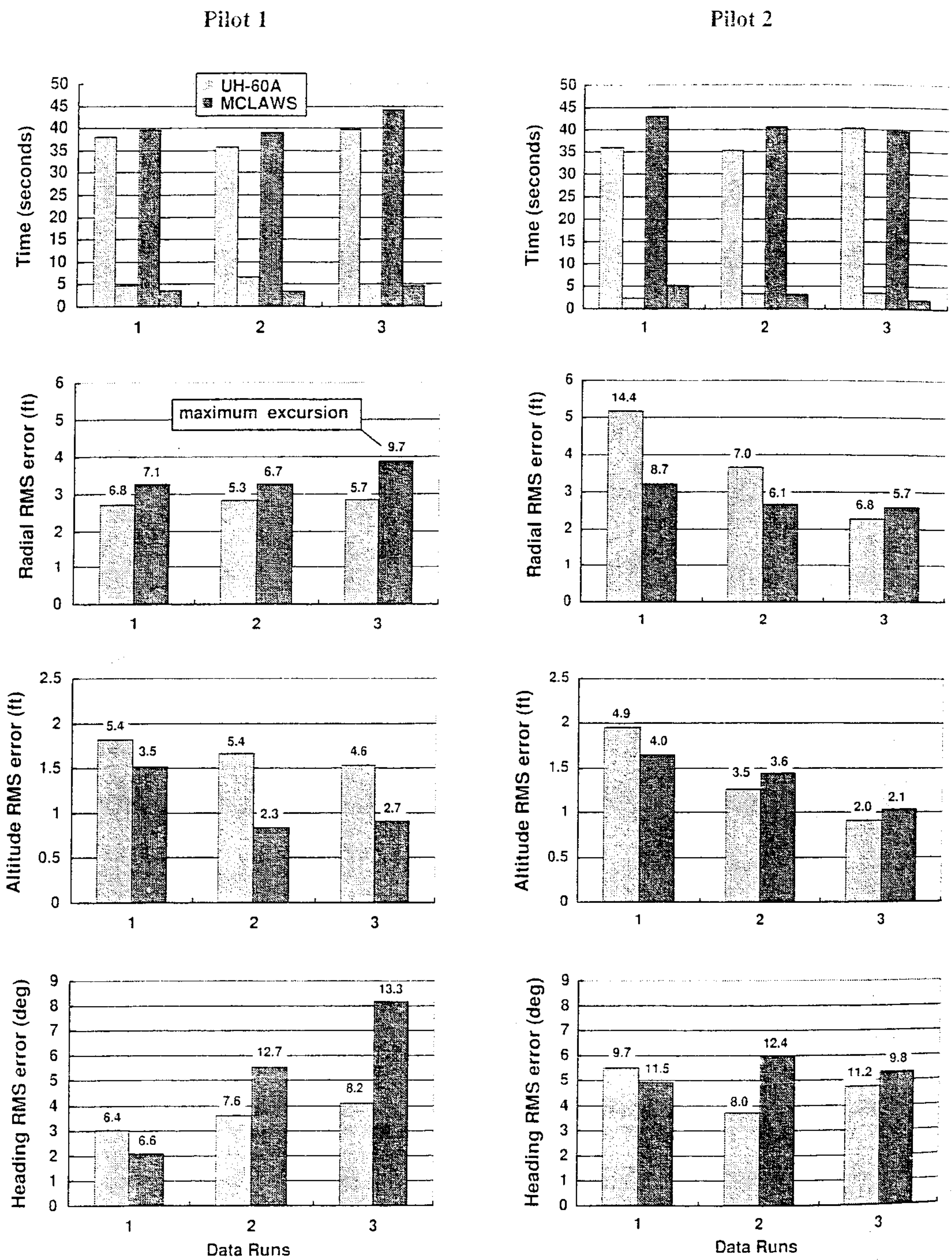


Figure 16: Pirouette MTE performance summary data in GVE.

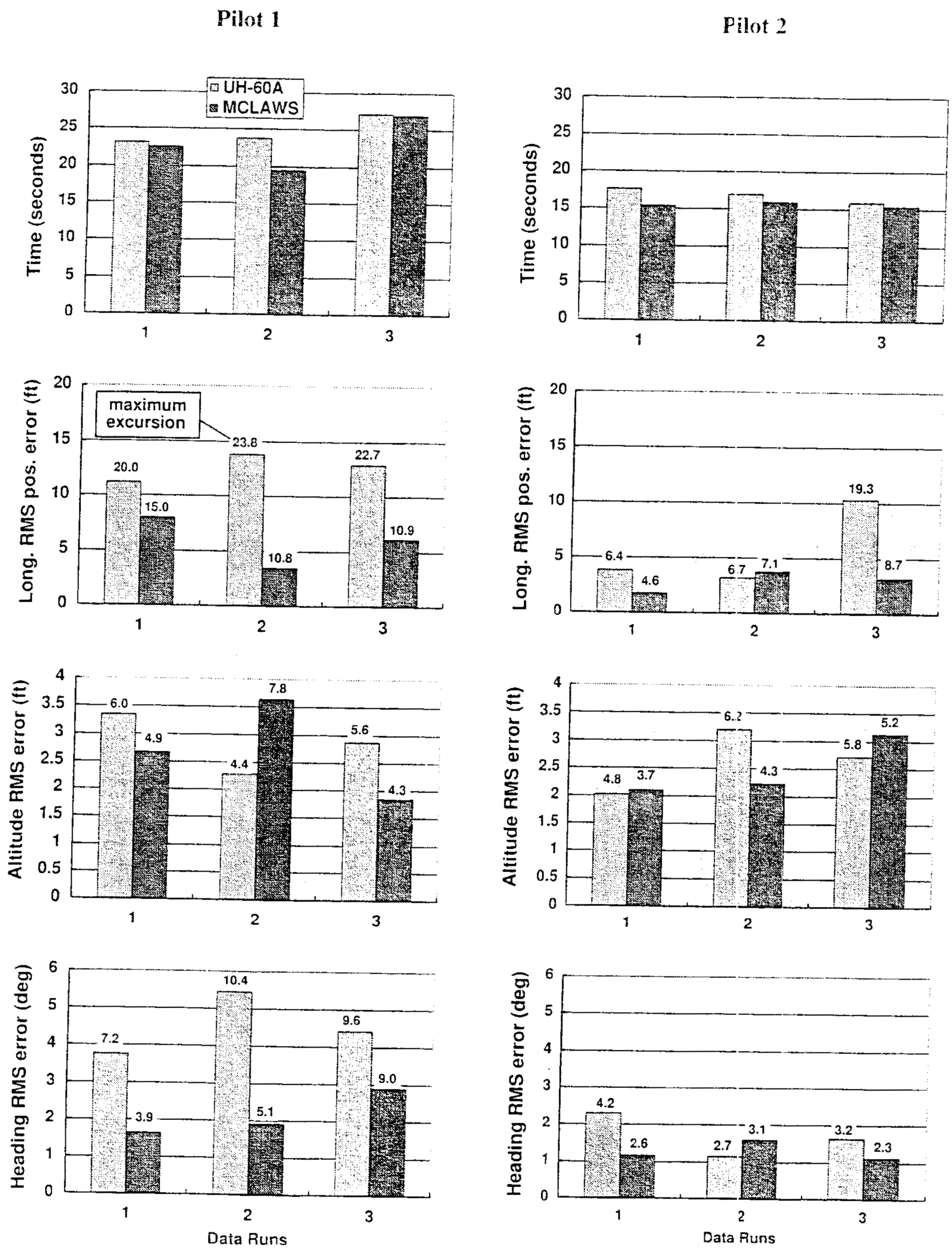


Figure 17: Lateral reposition MTE performance summary data in GVE.

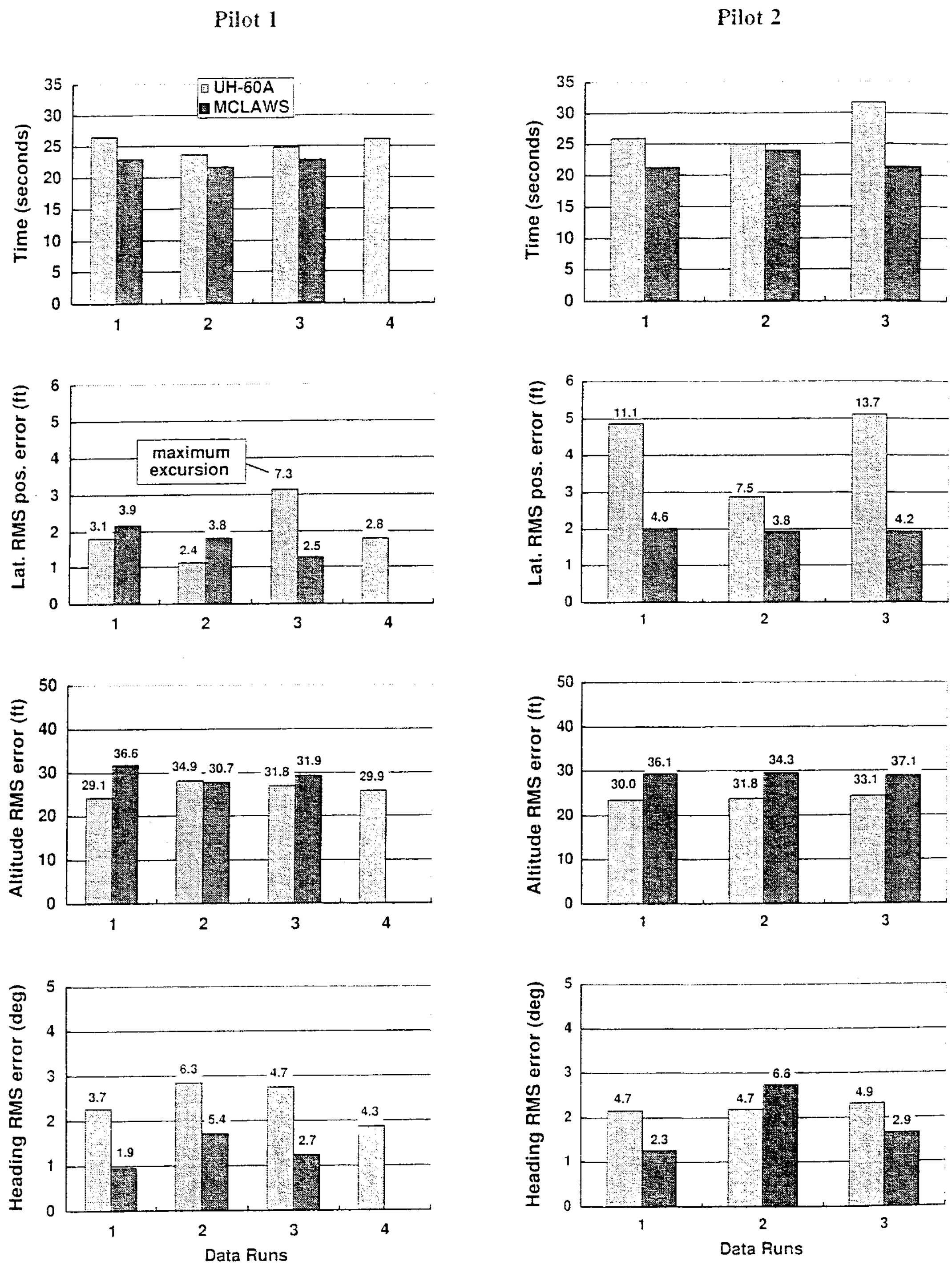


Figure 18: Departure-Abort MTE performance summary data in GVE.

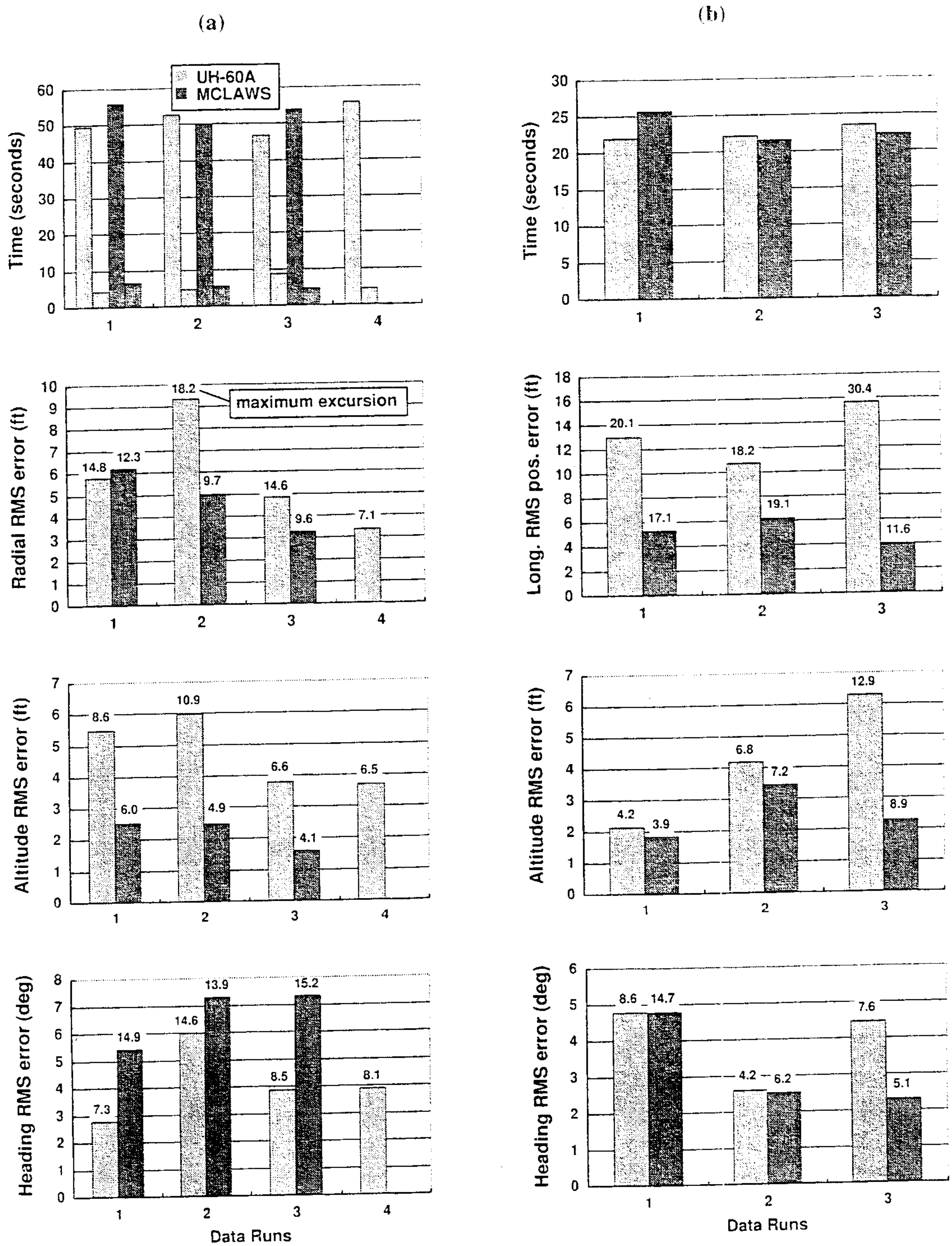


Figure 19: (a) Pirouette MTE performance summary data in DVE (Pilot 2):
(b) Lateral Reposition MTE performance summary data in DVE (Pilot 2).

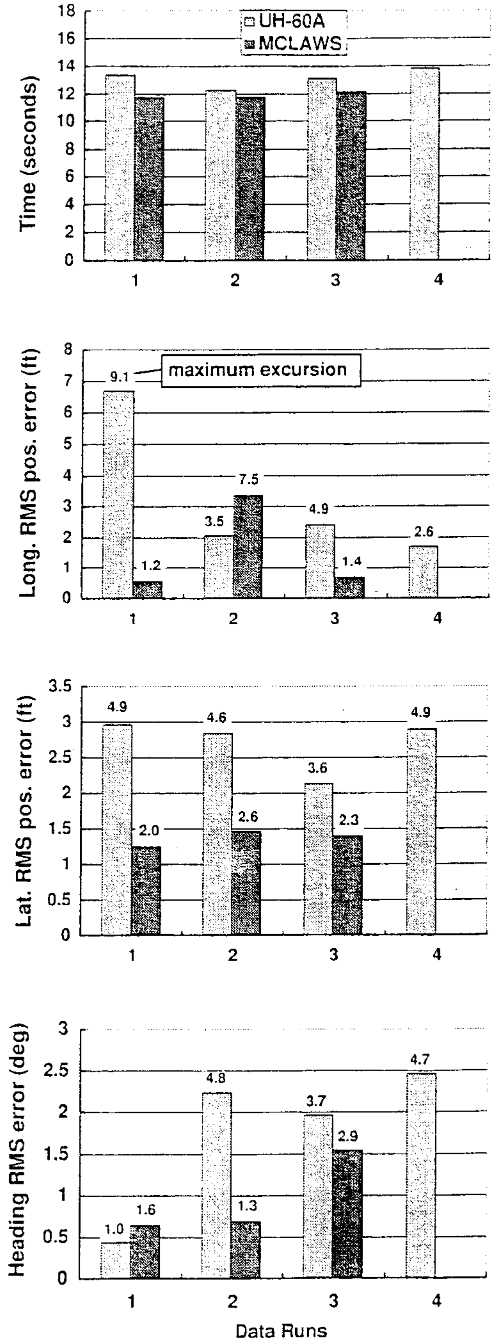


Figure 20: Vertical MTE performance summary data in DVE (Pilot 2).

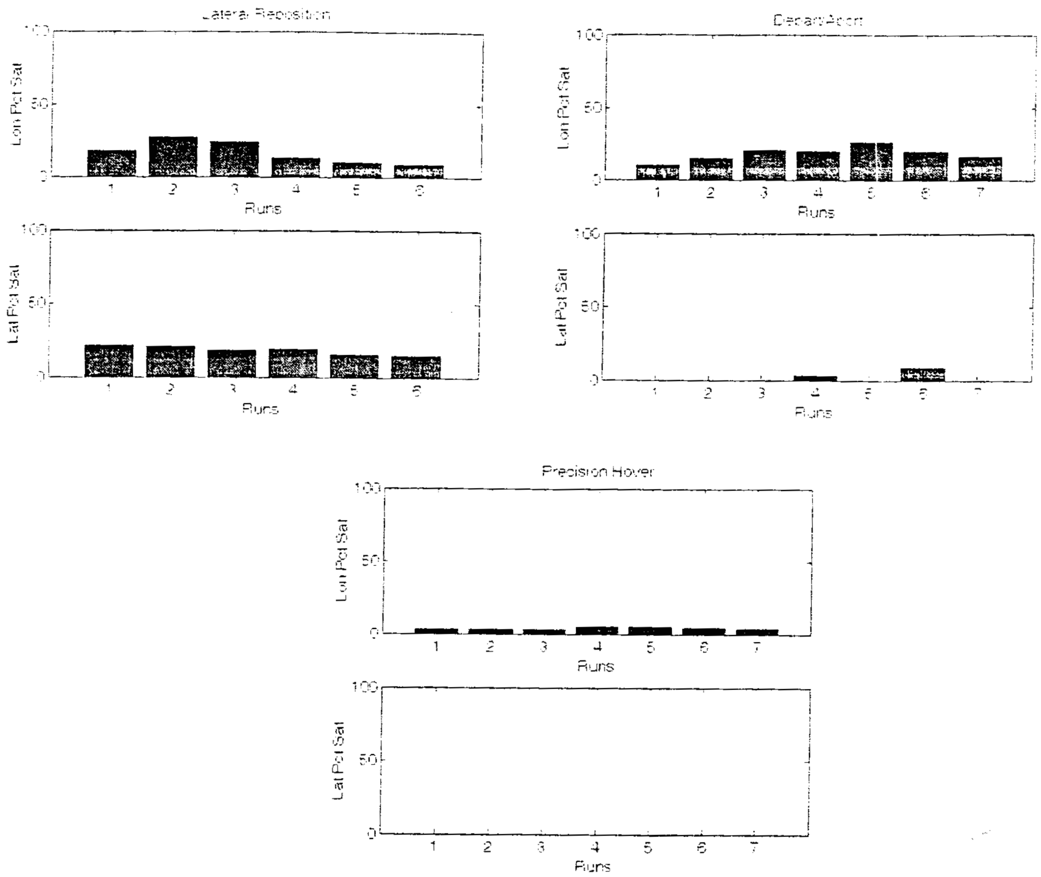


Figure 21: Longitudinal and Lateral SAS authority saturation percentages for individual runs for different MTEs using MCLAWS

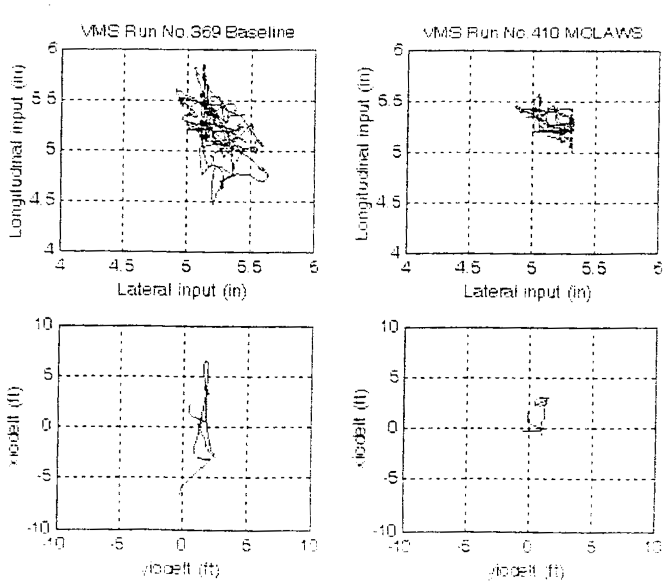


Figure 22: Cyclic inputs (top row) and horizontal position keeping (lower row) for baseline control laws and MCLAWS during hover MTE

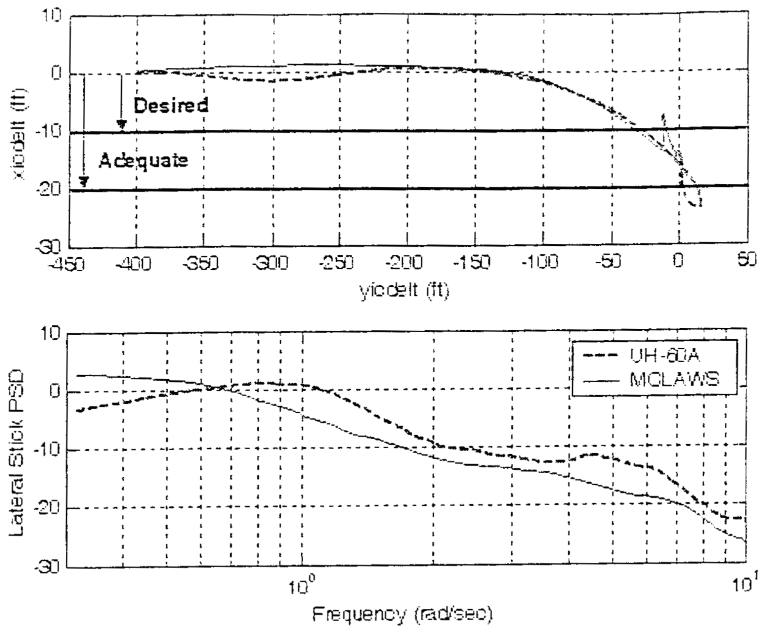


Figure 23: Comparison of Lateral Reposition MTE by Pilot 1 using MCLAWS and baseline UH-60A control laws