Simulation Evaluation of an Advanced Control Concept for a V/STOL Aircraft

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Two candidate control systems for a vertical/short takeoff and landing aircraft are described, both of which are limited-authority, digital, fly-by-wire variants of a YAV-8B Harrier control system. The performance of these systems was compared with that of an ideal, full-authority system in simulated, adverse-weather shipboard operations using the Ames Research Center's Vertical Motion Simulator. Both systems showed some performance degradation relative to the ideal system, but both were adequate to meet research objectives. The favored system, selected because of safety considerations, was further simulated using a precision visual hovering task that verified its acceptability.

Introduction

THE V/STOL Research Aircraft (VSRA) is a YAV-8B Harrier that is being modified to permit in-flight investigations of V/STOL control and display requirements for terminal-area operations.[1] In particular, attention is being centered on requirements for approach and vertical landing on destroyer-sized ships operating in high seas under conditions of poor visibility. A sequence of ground-based simulations has led to tentative requirements for this task,[2–7] but to date no flight validation has been possible for many of the requirements.

The transition and landing tasks place widely different demands on control system design. For transition, control is required to continuously and smoothly change the state of the aircraft from largely wing-borne flight to fully powered-lift flight, while performing a precision path-tracking task under instrument meteorological conditions (IMC). The landing involves comparatively small changes in aircraft state with precision control of a regulatory nature. These differences between the transition and landing tasks, which must be accomplished with acceptable pilot work load, result in widely different control-mode and display requirements.

It was assumed throughout the previous simulation activities that the control system would be digital, fly-by-wire with high-rate, full-authority actuators. A major problem is that such a control system—with all its implied safety-mandated redundancy—would be prohibitively expensive to install in the single-seat VSRA. However, since the VSRA is aimed at investigating tasks that can be accomplished using mild, low-speed maneuvers within the powered-lift flight envelope, it is conjectured that it may be possible to exploit these restrictions in the design of the VSRA control system in a way that would provide a safe and capable system within budgetary constraints. The purpose of this paper is to describe a modification of the VSRA's control system that is an economical alternative to the full-authority system.

Two candidate modifications to the existing VSRA control system are described, both of which have the potential to meet the operational requirements. Economy is achieved in these systems by reducing the need for high redundancy. Catastrophic hardovers are avoided by using high-rate, low-authority series-servos for stabilization, and low-rate, high-authority parallel-servos for either moderate-to-large amplitude slow maneuvering or for trim. Current research is aimed at demonstrating that this approach provides adequate safety with a single-channel, independently monitored, fly-by-wire control system.[8] There may be, of course, controllability and performance penalties associated with this approach, and a simulation was performed, using the Ames Vertical Motion Simulator (VMS), to compare the performance of the two candidate systems with that of an "ideal" uniformly high-rate, full-authority system. This comparison was made for the same shipboard landing task used in previous simulations. The best candidate control system was identified, and additional comparisons with the ideal system were performed for a simulated precision hover task.

The paper is organized as follows. A summary of the previous shipboard V/STOL simulations is presented to show the scope of the intended VSRA experiments. This is followed by description of the control modes, the candidate control system mechanizations, and the pilot displays. Then follows a discussion of the simulation tasks and simulation results. Finally, conclusions are presented.

Summary of Previous Shipboard V/STOL Simulations

Much of the previous work in the simulation evaluation of flight control concepts for V/STOL shipboard operations investigated the required level of the complexity of the control and cockpit display systems to enable the pilot to perform shipboard landings satisfactorily.[3,5–7] The primary source of data in all the simulation evaluations was pilot ratings and comments.[9]

Reference 7 reviewed the results of several simulation and flight investigations of rotary-wing and fixed-wing V/STOL aircraft performing terminal-area operations, which included decelerating approaches under instrument conditions and recovery to either fixed landing pads or ships. The authors of Ref. 7 concluded that to achieve satisfactory handling qualities for the demanding task of a decelerating approach to hover on instruments, an aircraft with vectored-thrust capability may require some form of decoupled flightpath and longitudinal acceleration command, in addition to attitude command, and a cockpit display that integrates situation and command information, such as flightpath-centered presentations, is desirable. Moreover, they concluded that a velocity-command system would be required to achieve satisfactory flying qualities when making vertical landings under adverse conditions (e.g., land-

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ing on a small ship in bad weather), and that the benefits of control augmentation depend on the size of the available maneuvering area during landing and the amount of motion of the landing pad.

Some data to substantiate these conclusions are shown in Fig. 1. The data are average pilot ratings[6] obtained from previous simulations in which control system augmentation ranging from simple, limited authority attitude damping to all-axes, full-authority kinematic command were evaluated in IMC transition and in landing tasks aboard a *Spruance*-class, DD-963-type destroyer. The transition task (Fig. 1a) pilot ratings show how a decoupled flightpath/acceleration-command system desensitizes the pilot control effort to winds and turbulence. This is evident in the marked improvement of this system over the attitude-command and rate-damping systems at the higher turbulence levels. Data from the landing task (Fig. 1b) indicate the significant improvement in flying qualities of a translational rate-command system over the simpler flight control systems. The head-up displays used in conjunction with the flightpath/acceleration- and translational rate-command systems will be described later.

Control and Display Description

Control Modes

The control modes and dynamics for the most advanced systems evaluated in the earlier simulations[2–6] are listed in Table 1; the dynamics chosen generally conform to those found to be optimum in previous studies at Ames.[10,11] All control system modes were implemented using algorithms based on the State Rate Feedback Implicit Model Following (SRFIMF) idea discussed in Ref. 2. The SRFIMF achieves a broad class of response dynamics by utilizing high-gain feedback of the commanded state and state rate. An important feature of the SRFIMF is its self-trimming characteristic, which ensures that constant external disturbances produce no steady-state error.

Control System Servo Configurations

To implement the control modes in the candidate control systems, the VSRA's existing limited-authority, high-rate, pitch, roll, and yaw attitude, stability augmentation system (SAS) series-servos, as well as the large-authority, low-rate, pitch and roll trim servos, are employed in a series-parallel

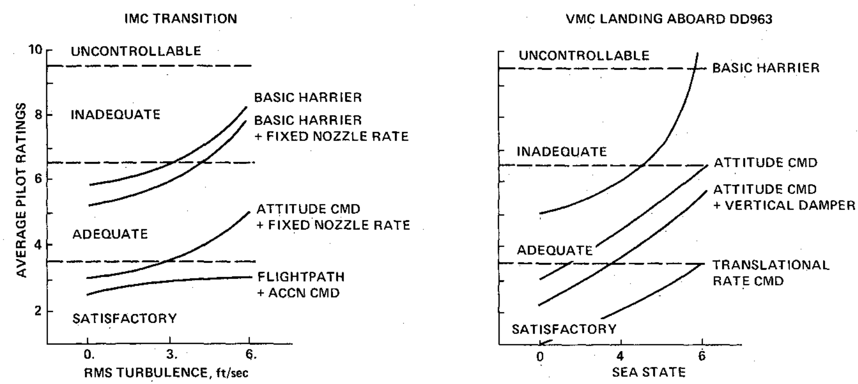


Fig. 1 Pilot evaluations of V/STOL transition and shipboard landing.

Table 1 Control modes and dynamics

Degree-of-Freedom	Transition: Mode type	Transition: Mode dynamics	Hover: Mode type	Hover: Mode dynamics
Pitch	AC	$\frac{\theta}{\theta_c}=\frac{2^2}{(S+2)^2}$	FRT/AH	$\frac{\theta}{\theta_c}=\frac{2^2}{(S+2)^2}$
Roll	RC/AH	$\frac{\dot{\phi}}{\dot{\phi}_c}=\frac{2^2}{(s+2)^2}$	VC	$\frac{V_y}{V_{y_c}}=\frac{1.75^3}{(s+1.75)^3}$
Yaw	ACC/TC	$\frac{a_y}{a_{y_c}}=\frac{4}{s+4}$	RC/AH	$\frac{\dot{\psi}}{\dot{\psi}_c}=\frac{4}{s+4}$
Longitudinal	ACC/VH	$\frac{V_x}{\dot{V}_{x_c}}=\frac{1}{s}$	VC	$\frac{V_x}{V_{x_c}}=\frac{1.75^3}{(s+1.75)^3}$
Vertical	FPC	$\frac{\gamma}{\gamma_c}=\frac{0.88}{s+0.88}$	VC/ALTH	$\frac{\dot{h}}{\dot{h}_c}=\frac{0.88}{s+0.88}$

Command	Stabilization
AC: attitude command	AH: attitude hold
ACC: acceleration command	TC: turn coordination
RC: rate command	VH: velocity hold
FRT: fixed-rate trim	ALTH: altitude hold
FPC: flightpath command	
VC: velocity command	

arrangement. In addition, the aircraft is modified to include either series-parallel or parallel-only servo configurations in the throttle and nozzle propulsion system.

Table 2 shows series- and parallel-actuator authorities and rates for the three systems investigated in the simulation: 1) a hypothetical, ideal system with full-authority, high-rate, series actuators for attitude, throttle, and nozzle; this system is designated the *full-authority* or FA control system; 2) a hybrid system using and the YAV-8B's attitude SAS and trim servos and full-authority, high-rate, parallel actuators for the nozzle and throttle; this system is called the *half-limited-authority*, or HLA control system (in the sense that half of the control system, namely, the attitude, employs limited-authority, series servos); and 3) a uniformly limited-authority, series-parallel system using the YAV-8B's attitude SAS and trim actuators as well as limited-authority, high-rate series, and full-authority, low-rate, parallel servos for the throttle and nozzle; this system is called the *limited-authority*, or LA control system. The series-parallel arrangements employed Schmitt-trigger logic to provide "off-loading" of the series servos by the parallel servos.

Simulated Flight Hardware and Software

The YAV-8B control system and the additions and modifications required for the VSRA are shown schematically in Fig. 2. The major additions to the YAV-8B include the nozzle and throttle actuators mentioned above, a primary flight-control digital computer, an independent monitor digital computer, a servo control unit (SCU), sensors and pilot controls required for the advanced flight-control laws, and a color, head-down display (HDD). The YAV-8B display symbol generator is replaced by a programmable unit. The SCU routes commands from the primary flight-control computer to the appropriate servos. A vital element in this single-channel system is the independent monitor computer, which checks the integrity of the flight-control computer hardware and software by comparing the actual closed-loop aircraft dynamics with the desired dynamics. A detailed description of this independent monitor is given in Ref. 8. All of the items previously mentioned, with the exception of the HDD, were simulated in this experiment.

The arrangement for a single-degree-of-freedom controller for the control systems is shown in Fig. 3 for the case of the

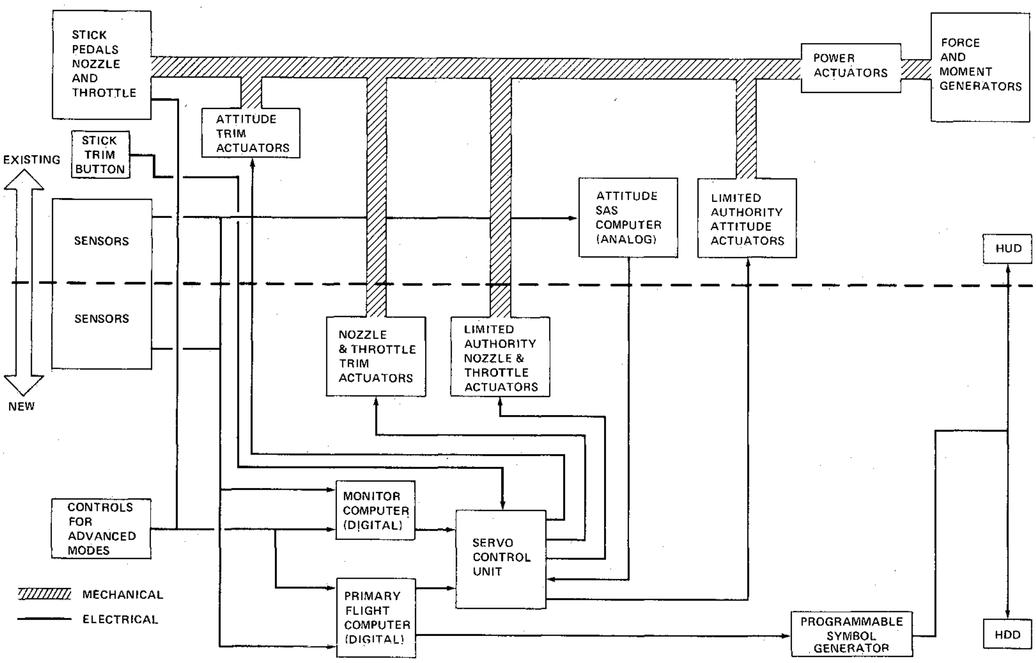


Fig. 2 VSRA control-display system schematic.

Table 2 Control system servo configurations

System type	Force and moment producer	Actuator authority and rate: Series		Parallel	
Full-authority (FA)	stabilator and pitch RCS[a]	−11.5 deg, +12.5 deg	60 deg/s	—	—
	aileron and roll RCS	−27 deg, +12 deg	80 deg/s	—	—
	rudder and yaw RCS	±15 deg	60 deg/s	—	—
	thrust (PSA)[b]	0 deg, 75 deg	100 deg/s	—	—
	nozzle	2 deg, 98.5 deg	90 deg/s	—	—
Half-limited authority (HLA)	stabilator and pitch RCS	±1.5 deg	60 deg/s	−4 deg, +7.5 deg	2.2 deg/s
	aileron and roll RCS	±2.0 deg	80 deg/s	−6 deg, +4 deg	1.0 deg/s
	rudder and yaw RCS	0, 1.75 in.^{2}	35 in.^{2}/s	—	—
	thrust (PSA)	—	—	0 deg, 75 deg	100 deg/s
	nozzle	—	—	2 deg, 98.5 deg	90 deg/s
Limited-authority (LA)	stabilator and pitch RCS	±1.5 deg	60 deg/s	−4 deg, +7.5 deg	2.2 deg/s
	aileron and roll RCS	±2.0 deg	80 deg/s	−6 deg, +4 deg	1.0 deg/s
	rudder and yaw RCS	0, 1.75 in.^{2}	35 in.^{2}/s	—	—
	thrust (PSA)	±5.0 deg	100 deg/s	0 deg, 75 deg	2.8 deg/s
	nozzle	±5.0 deg	90 deg/s	2 deg, 98.5 deg	4.8 deg/s

[a]RCS—reaction control system. [b]PSA—power spindle angle.

series-parallel servo arrangement. By executing the flight-control-mode algorithms, the flight controller generates servo commands corresponding to pilot and sensor inputs. The additional command input pilot controls (thumbwheels, buttons, etc.) for use with the advanced control modes are mounted on the existing YAV-8B stick and throttle. The servo commands pass directly to the series position servos and are also processed to provide signals to control the constant-rate parallel servos.

Control System Mechanization

The relationships between the control modes, pilot controllers, and force/moment producers for the three control system mechanizations are shown in Table 3 (transition), Table 4 (hover) and Fig. 4. The FA control system uses pilot controls that are all mechanically disconnected from the force and moment producers. Furthermore, all signals from the flight-control computer are applied to full-authority, high-rate, series actuators. The FA control system is used here only as a hypothetical high-fidelity standard with which to gauge the effectiveness of the two candidate systems proposed for the VSRA.

In the HLA and LA systems, the existing YAV-8B mechanical links between the cockpit controls and the primary force/moment generators are retained. An inherent limitation of this arrangement is that pilot inputs cannot be made through the mechanical controls, since such inputs could easily overpower the effect of the series-servo and result in degraded model-following. To overcome this limitation, additional controllers are used to provide electric command signals for some of the desired control modes. In the HLA system, an auxiliary vertical-controller (VC) lever is required, because the pilot is precluded from placing his hand on the rapidly moving throttle lever (due to the action of the high-rate, full-authority, parallel servo).

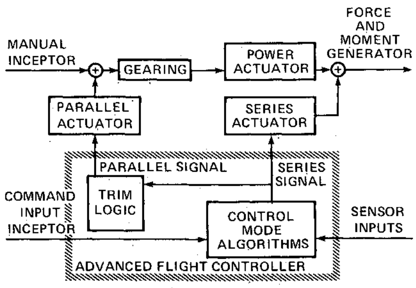


Fig. 3 Basic single-degree-of-freedom VSRA controller.

Display

The head-up display (HUD) format used throughout the simulation evolved from work reported in Refs. 3, 5, and 6. Two distinct HUD formats are used. The symbols present during the transition and the landing phases are shown in Figs. 5 and 6, respectively. These HUD displays provide the pilot with the guidance, command, and situation information needed to perform the shipboard landing task in zero-zero visibility.

Table 3 Transition control-mode/actuator/controller relationships

		Pilot's control		
Transition control mode	Force/moment producer	Full-authority, FA	Half-limited-authority, HLA	Limited-authority, LA
flightpath angle cmd	engine thrust	VC[a] lever thumbwheel	VC lever thumbwheel	throttle lever thumbwheel
longitudinal accel cmd/vel hold	engine nozzle deflection	stick thumbwheel	stick thumbwheel	stick thumbwheel
roll rate cmd/bank angle hold	aileron and roll RCS[b]	lateral stick	lateral stick	lateral stick
pitch att cmd	stabilator and pitch RCS	longitudinal stick	none	none
fixed-rate pitch trim	stabilator and pitch RCS	longitudinal trim switch	longitudinal proportional thumb button[c]	longitudinal proportional thumb button[c]
sideslip cmd/ turn coordination	rudder and yaw RCS	rudder pedal	rudder pedal	rudder pedal

[a]VC—vertical controller. [b]RCS—reaction control system. [c]Proportional thumb button converted to ON/OFF trim switch by software.

Table 4 Hover control-mode/actuator/controller relationships

		Pilot's control		
Hover control mode	Force/moment producer	Full-authority, FA	Half-limited-authority, HLA	Limited-authority, LA
vertical vel cmd/ altitude hold	engine thrust	VC[a] lever	VC lever	throttle lever thumbwheel
lateral vel cmd	roll angle	lateral stick	lateral proportional thumb button	lateral proportional thumb button
longitudinal vel cmd	engine nozzle deflection	longitudinal stick	longitudinal proportional thumb button	longitudinal proportional thumb button
fixed-rate pitch trim	pitch RCS[b]	long trim switch	VC lever switch	throttle lever switch
yaw rate command	yaw RCS	rudder pedal	rudder pedal	rudder pedal

[a]VC—vertical controller. [b]RCS—reaction control system.

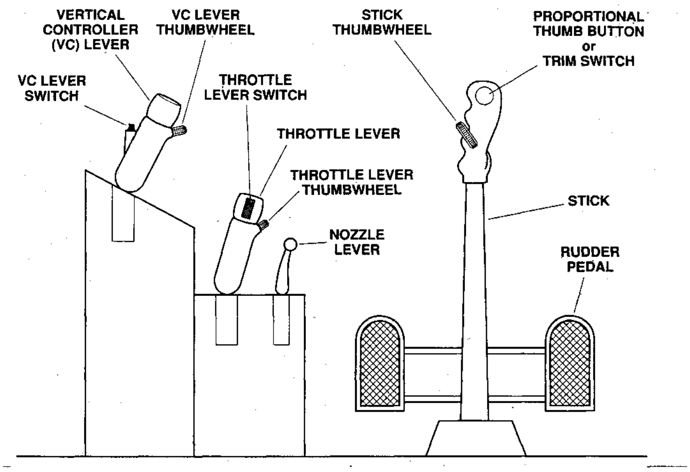


Fig. 4 Cockpit controller arrangement.

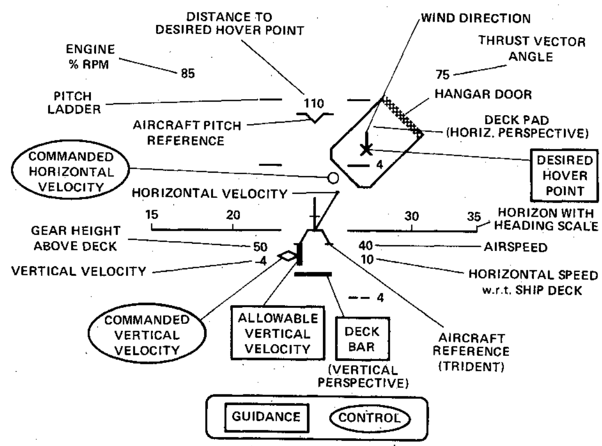


Fig. 6 HUD format in hover.

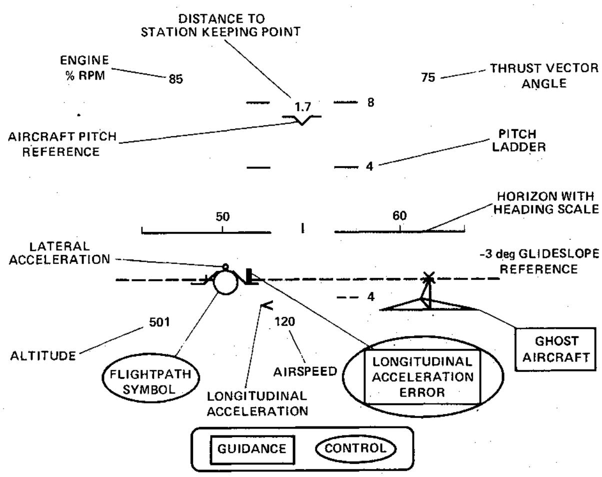


Fig. 5 HUD format in transition.

In transition (Fig. 5), symbols representing a ghost aircraft and a longitudinal acceleration error contain the primary guidance information. The display is based on the principle of pursuit guidance.[12,13] The ghost aircraft identifies the position of a phantom aircraft located ahead of the real aircraft and performs the task perfectly. The pilot maneuvers his aircraft vertically and laterally, using the appropriate controls (Table 3), until the flightpath and ghost aircraft symbols coincide. The aircraft then corrects to the reference flightpath flown by the ghost aircraft. Deceleration is established by the pilot operating the stick thumbwheel to zero the acceleration-error ribbon. The length of this ribbon represents the error between the aircraft's deceleration and the constant deceleration required to bring the aircraft to a hover at a predetermined initial-station keeping point. A piecewise-constant, two-step deceleration was chosen to be the guidance command provided to the pilot, and was based on previous transition task simulations conducted at Ames. Situation information that accompanies the flightpath and ghost aircraft symbols includes aircraft attitude, speed, altitude, engine percent rpm, thrust vector angle, longitudinal acceleration, heading, and distance to the initial-stationkeeping point.

The hover display format (Fig. 6) is a superposition of vertical and horizontal (plan view) aspects. The central element is a fixed "trident" symbol that represents a plan view of the aircraft showing the correct relative locations of the landing gear and nose boom. The landing pad is presented in both horizontal and vertical aspects. In the horizontal aspect, the pad symbol is geometrically similar to the *Spruance*-class destroyer pad and is scaled in both size and relative position to match the trident. In the vertical aspect, the pad (deck bar) is shown "edge on" at a distance below the trident that is proportional to the altitude above the deck. The primary guidance information in hover is contained in symbols representing the desired hover point, height above the deck (deck bar), and vertical velocity allowable within a prescribed landing gear limit. In operation, the pilot, using the appropriate controls (Table 4), moves a commanded-horizontal-velocity symbol over to the desired hover point and holds it there while maintaining a rate of descent close to zero, as shown by a commanded-vertical-velocity symbol. When the aircraft is at the desired hover point, the pilot establishes a vertical descent rate, within the limits of the allowable-vertical-velocity ribbon, until touchdown. The allowable-vertical-velocity ribbon is especially useful when the ship deck is heaving because it combines the velocity of the deck with that of the aircraft. Attitude, airspeed, velocity of airplane with respect to ship, engine percent rpm, thrust-vector angle, heading, hangar door position, and wind direction are provided as situation information.

Simulation Conduct

Facility

The VMS provides large-amplitude vertical and longitudinal translation capability, and provides high-fidelity motion cues. A continuous, three-window, computer-generated imaging (CGI) system (no window mullions) provides unobstructed views of outside scenes.

Simulation Tasks

Shipboard transition and landing (Fig. 7), and land-based precision hover tasks were used for the evaluation of the candidate control systems. The shipboard tasks consisted of three distinct phases: transition to hover, translation to a point over the ship's landing pad, and final, descent to landing (the term "landing" includes the last two phases).

Transition

The transition starts at a speed of 120 knots relative to the ship, along a reference flightpath with a glide-slope of -3 deg. The reference deceleration is approximately 3 ft/s^2, stepping down to approximately 1.5 ft/s^2 when 1000 ft away from the initial stationkeeping point. In plan view, the reference approach is curved with a total track angle change of 55 deg. The transition ends at an initial stationkeeping point located 100 ft to port and 100 ft aft of the mean position of the desired touchdown point, and at a gear height of 75 ft above sea level. The transition task was conducted in atmospheric turbulence levels ranging up to 6 ft/s rms gusts.

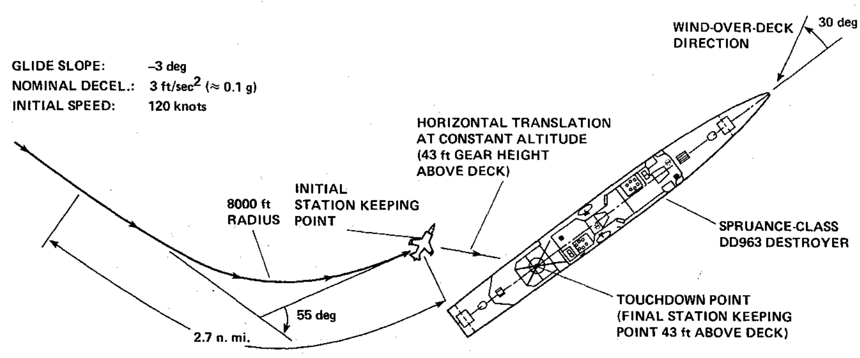
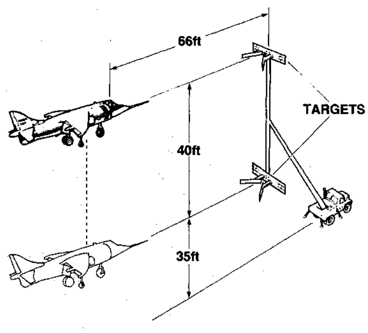
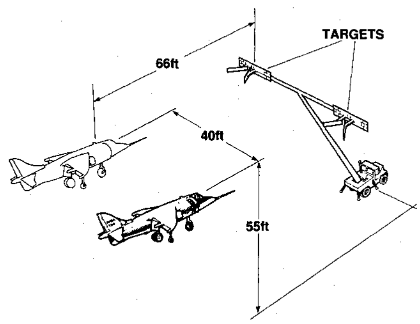


Fig. 7 Transition profile and shipboard landing task.



a) Precision hover vertical position control task



b) Precision hover lateral position control task

Fig. 8 Precision hover task setup.

Landing

Landing maneuvers involve translating the aircraft at a constant altitude of 75 ft (gear height) above the sea from the initial stationkeeping point to the final stationkeeping point located 43 ft (gear height) vertically above the mean position of the desired touchdown point on the deck of the ship. A final, vertical descent to touchdown at a nominal 3 ft/s descent rate completes the task. The landing task was carried out using a simulated *Spruance*-class, DD-963-type destroyer driven by a six-degree-of-freedom ship motion model with accompanying ship air-wake turbulence.[14] Environmental conditions during the landing ranged from calm seas with 15 knots wind-over-deck (WOD) (sea state 0) to heavy seas with WOD of 43 knots (sea state 6). At sea state 6, and 3σ values for roll angle and heave velocity are 9 deg and 13 ft/s, respectively. The landing gear limit of the VSRA is 12 ft/s.

Precision Hover

Precision hover tasks on a land-based vertical takeoff and landing (VTOL) pad were performed to compare the FA system and the better of the limited-authority systems. There were two tasks: a vertical translation between hover targets, and a horizontal translation between hover targets (Fig. 8). In both cases the task is to acquire one of the targets, translate to the other target while maintaining a nominal 66-ft target-to-pilot eyepoint distance, acquire the second target with minimum overshoot, and then repeat the cycle until a handling-qualities evaluation can be made. Reference 8 provides a detailed discussion of the use of the precision hover task to validate the simulation model in hover.

Simulation Results

Pilot comments and ratings for the three control system implementations were obtained. The pilot ratings (PR) were based on the Cooper-Harper Handling Qualities Rating Scale.[9] Three Ames Research Center test pilots participated in the simulation. The pilot most experienced in Harriers has been extensively involved in the control and display development process for previous V/STOL simulation efforts at Ames in both engineering and test pilot roles. The second pilot has been involved in the development of flightpath symbol and control schemes for short-takeoff and landing (STOL) aircraft before becoming involved with V/STOL simulation and flight test evaluations of the Harrier. The third pilot has been active in the development of flightpath symbology and control concepts for conventional takeoff and landing (CTOL) and STOL aircraft as both a research engineer and test pilot; he has no Harrier flight time but has participated in previous V/STOL simulations.

All three control system mechanizations (FA, HLA, LA) were tested in transition, with turbulence levels of 0, 3, and 6 ft/s rms, and in shipboard landings in sea states 0, 4, and 6. Following the shipboard landing tests, the FA and LA control systems were tested using the precision hover task in calm winds.

Transition

The variation of pilot ratings with turbulence levels for the transition task is shown in Fig. 9a. Except for the half-limited system as originally configured (1.5 deg of stabilator series-servo authority), all three of the implementations received pilot ratings indicating Level I or Level II flying qualities, with the FA system consistently being rated in the Level I area. Uncoupled flightpath and acceleration-command modes, along with a clear indication of guidance errors on the HUD, contributed to the generally desirable flying qualities achieved by all three implementations. It is evident that the penalty incurred in going from the FA to the LA system is about a $1–1\frac{1}{2}$ PR degradation for the three levels of turbulence simulated, yielding Level II flying qualities for the LA system in high turbulence. Comparison with Fig. 1 shows that the PR's given to the FA system compare very well with the averaged PR's of previous simulations. The $1–1\frac{1}{2}$ penalty in PR obtained using the LA system is significant since this system is evidently comparable in pilot acceptance to a full-authority attitude command and fixed-rate nozzle system (Fig. 1).

Most of the pilots' criticisms of the LA system were directed at the uncommanded movement of the stick in the pilot's hand

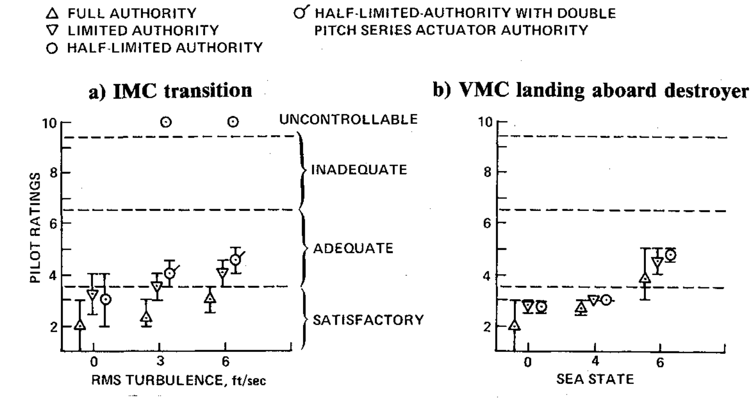


Fig. 9 Control system comparison in transition and shipboard landing: a) flightpath/acceleration command in transition; and b) translational velocity command in hover.

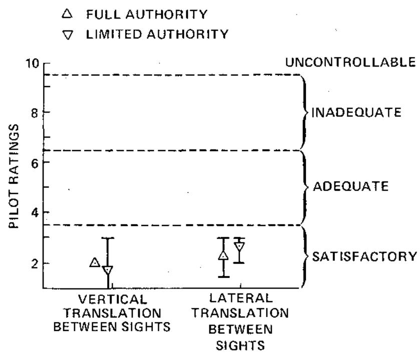


Fig. 10 Control system comparison in precision hover.

(caused by the action of the parallel servos), and the degradation of the roll-control response when compared with the FA system. In general, the low rates at which the parallel servos "off-loaded" the series servos caused a detectable degradation in the pitch and flightpath response, as determined by the uncommanded movements of the flight-path symbol on the pilot's HUD. At the higher levels of turbulence, there was an excessive and disproportionate (relative to the stabilator and nozzle) amount of activity and saturation of the throttle series servo.

The HLA system as originally configured (Table 2) suffered from incipient turbulence-induced pitch-thrust closed-loop instability and was given PR's of 10. The root causes of this problem are the pitch-thrust coupling of the basic aircraft, and the large difference in authorities and rates of the pitch and throttle actuators. In turbulence, the vertical controller moved the throttle quickly and through large amplitudes—by means of the high-rate, full-authority, parallel servos—in an attempt to maintain the commanded flightpath. These large power changes induced corresponding pitching moments that forced the limited-authority, high-rate pitch series-servos to saturate. Although the pitch parallel-servo moved to unsaturate the series servo, its rate was too low to relieve the saturation quickly enough. The problem did not occur in the LA system because the pitch- and power-actuator authorities and rates are better matched. The problem was alleviated in the HLA system by doubling the pitch series-servo authority to 3 deg of stabilator. This modification produced pilot ratings comparable to those of the other two systems, but the pilots still noted a tendency for larger pitch and flightpath excursions in turbulence.

Landing

The variation in pilot ratings for the landing task in sea states 0, 4, and 6 is shown in Fig. 9b. Level I flying qualities in sea states as high as 4 were achieved by all the control system implementations. The FA implementation was consistently rated best. Parallel-servo-induced stick movements in the LA and HLA systems interfered somewhat with the precision in which the pilot could operate the stick-mounted proportional thumb button, though only minor penalties in pilot ratings resulted.

All the pilots noted rapid, large-amplitude movement of the nozzle and throttle levers with the HLA system. Movement of the throttle in the pilot's hand with the LA system was not objectionable. In fact, it was the preferred control arrangement from a safety viewpoint in that after a failure it allowed the pilot to apply full power quickly to recover from a hazardous condition. Hardover failures of the HLA system's full-authority throttle and nozzle servos in the vicinity of the destroyer's superstructure were found to be too severe for a simplex fly-by-wire implementation. Furthermore, the pilot reaction time was increased due to having to move his hand from the VC lever to the throttle to initiate a recovery. These failure considerations eliminated the HLA system as a candidate control system since safe recovery could not be ensured when operating near the ship.

In sea states 0 and 4 there was little difference in the pilot ratings for both the LA and HLA implementations, largely because the pilot technique was basically the same using either system. In these lower sea states, ship heave was relatively mild, and there was rarely any need to adjust an established constant descent rate. In sea state 6, however, the ship heave was severe enough to require arresting the descent rate and even required a rapid increase in altitude to avoid gear damage by the rapidly rising deck. The work load associated with continuously varying vertical velocity during the descent contributed to the significant increase in average pilot ratings and resulted in Level II flying-qualities ratings for all the systems. The pilots generally preferred controlling descent rate through the VC lever rather than through the throttle-mounted thumbwheel provided in the LA system. However, the rapid, high-amplitude movements of the full-authority throttle and nozzle parallel servos used in the HLA system were irritating to the pilots who indicated that such a phenomenon could be quite distracting in a real operational environment.

Precision Hover

A precision hover positioning task, described previously, was used for the evaluation of the relative capability of the FA and LA system mechanizations. Figure 10 shows the pilot ratings obtained for these tasks for the two systems.

With decoupled translation and attitude dynamics provided by the control modes, the tasks were accomplished satisfactorily (Level I) using either implementation. The vertical translation task brought out a minor deficiency in the LA system. Because of the throttle's low-rate parallel actuators and low-authority series actuators, the desired first-order, vertical dynamic-response (Table 1) was sluggish even when commanding quite moderate (3–5 ft/s) vertical velocities. The 5 deg throttle series-servo authority only provided about 0.08 g of acceleration in hover. Series-servo saturation caused some altitude overshoot when attempting to acquire and stabilize at a target. With the high-rate, full-authority, throttle series-servo used in the FA implementation, virtually deadbeat height response was achieved in the vertical axis, even when commanding vertical velocities considerably higher than 5 ft/s.

Using either system, lead compensation in lateral velocity had to be generated by the pilot when performing the lateral translation task in order to keep overshoots to a minimum. Minor deficiencies with the LA system when performing this task were 1) a slight cross-control tendency when using the proportional thumb button, which resulted in unwanted longitudinal drift; 2) unintentional horizontal velocity changes that resulted when an unexpected stick movement caused the pilot to make inadvertent inputs through the proportional thumb button; and 3) a nonlinear lateral-velocity sensitivity to lateral thumb button input that caused larger (with respect to the FA system) lateral overshoots and greater difficulty in acquiring the targets. Relatively high stick force gradients for the FA implementation were seen as a minor deficiency, but the use of stick for commanding translational velocity was preferred over the thumb button.

Conclusions

An evaluation of two candidate limited-authority implementations of an advanced control concept for the NASA V/STOL Research Aircraft was performed in a piloted, moving-base simulation. The principle measure of the operational penalty associated with implementing the candidate *limited-authority* and *half-limited-authority* control systems was the difference in pilot ratings between the candidate control systems and an ideal full-authority control system.

Level I and Level II flying qualities were achieved by both the candidate systems for shipboard transition and landing tasks. The limited-authority and half-limited-authority candidate mechanizations were given pilot ratings $1–1\frac{1}{2}$ units worse in transition, and $\frac{1}{2} - 1$ unit worse in shipboard landing than the *full-authority* system.

In general, the half-limited-authority system (with its full-authority throttle and nozzle parallel servos) was actually found inferior to the limited-authority system. An acceptable half-limited-authority control system (in the sense of pilot ratings indicating adequate or satisfactory flying qualities) for the transition task required a stabilator series-actuator authority double that of the existing V/STOL Research Aircraft stabilator series-servo. This difference was the result of significant pitch-thrust coupling in transition and was particularly evident when appreciable levels of turbulence were present.

Hardover command failures in the half-limited-authority implementation presented a safety problem if a simplex computer system were used. Pilot reaction time in transferring control from the vertical controller lever to the throttle lever contributed significantly to the time delay in initiating recovery from failure.

A precision hover task showed that Level I flying qualities were obtainable with the limited-authority control system, with a difference in pilot rating (performance penalty) of about $\frac{1}{2}$ unit worse than the full-authority system.

V/STOL shipboard landing and precision hover tasks showed that although there are small performance penalties (as measured by pilot ratings) associated with the limited-authority control system, the highly augmented control modes required for these tasks could be realized on the V/STOL Research Aircraft. Furthermore, these penalties are sufficiently small that the performance that could be obtained with a full authority can be inferred from the performance of an aircraft fitted with a limited authority system, with good confidence, by referring to the simulation results.

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