NINTH EUROPEAN ROTORCRAFT FORUM
13-15th Sept. 1983 - STRESA - ITALY

PAPER NUMBER : 63

A Piloted Experiment in the Use of Multi-Functions Side-Arm Controllers in a Variable Stability Helicopter

J. Murray Morgan

Airborne Simulation Facility Manager

Flight Research Laboratory

National Research Council of Canada

A PILOTED EXPERIMENT IN THE USE OF A

MULTI-FUNCTION FORCE-SENSING SIDE-ARM CONTROLLER

WITH AN AUTOMATED CONTROL SYSTEM

IN.A HELICOPTER

by

J. Murray Morgan

Airborne Simulation Facility Manager

Flight Research Laboratory

National Research Council of Canada

1. Abstract

Five test pilot's were asked to evaluate the handling characteristics of a helicopter in a set of closely defined tasks using a fully integrated force-sensing side-arm controller. Three levels of sophistication were examined in the yaw channel, while the control systems in pitch, roll and heave were held constant. The data indicated that Level 1 Handing qualities were achieved with automation of the yaw control task and also that, case for case, handling qualities were more favourably evaluated in airborne rather than ground-based simulations.

2. SYMBOLS

Symbol	Parameter
ϕ	Bank angle
p	Roll rate
q	Pitch rate
r	Yaw rate
r	Yaw acceleration
u	Forward speed
F(u)	See text
F1(u)	See text
β	sideslip angle
g	accleration due to gravity
N_{δ_r}	Tail rotor control power
x = A	Roll channel
x = E	Pitch channel
x = P	Collective channel
x = R	Yaw channel

DELx	Controller output
DELxF	Filtered DELx
DELx0	Pre-engage offset in DELxF
Dx	Signal cancelled DELxF
DxNT	Deadbanded Dx
GN	Control System gain
G_o	open-loop gain
PCx	Conditioned Dx
PCRM	Modified PCR
DBx	Dead-band extent
KDx	Forward loop integrator gain
LMx	Linear gain slope
LMx2	Quadratic gain slope
XMAX	Maximum shaping function input
YMAX	Maximum shaping function output
xLIN	Linear slope extent

DLP	Roll damping gain
DMQ	Pitch damping gain

3. INTRODUCTION

The Flight Research Laboratory (FRL) of the National Aeronautical Establishment (NAE) first developed an active research interest in the problems associated with replacing the conventional displacement controls of a helicopter with integrated multi-function force sensing side-arm manpulators as a result of a feasibility study conducted under contract to the Sikorski Aircraft Division of United Technologies Corporation some four years ago.

While the original study (Reference 1) and a subsequent in-house experiment (Reference 2) concentrated on basic feasibility and comparative studies of the new controllers with respect to conventional displacement controls, using primitive, open-loop control systems, recent work has been more concerned with the use of integrated controllers with advanced closed-loop control systems. This move is an obvious progression, since it is probable that any machine designed for this type of controller will implicitly carry sufficient on-board computational capability to support such control systems and the advantages to the designer are sufficient to assume that this capability will be utilised. This assumption is supported by current work in the US Army Advanced Digital Optical Control Systems (ADOCS) program, in which it is accepted that the military missions themselves will largely dictate the level of sophistication needed in the control system to enable the crew to perform the various operational tasks. FRL has developed a close, though informal association with this program, primarily by participating in several series of ground-based simulations in support of it.

In consideration of this it was elected to perform a series of piloted experiments in the NAE Airborne Simulator, using manipulators and control systems similar to those envisaged in ADOCS (Reference 3). Pilots' comments gathered in past work with these controllers at FRL indicated that while the overall workload during a specific task remained much the same whether conventional or force sensing side-arm controllers were used, with the latter there was a general and significant redistribution of that workload amongst the various axes. In particular control of the aircraft in yaw, normally a quite undemanding task, had become a major factor, especially when using the fully integrated configuration, due largely to the requirement to compensate for the many cross coupling disturbances present in yaw. This prompted the selection of the yaw channel as the first for active research. The advantages of this selection are that the yaw channel can be treated in isolation and that the automation of a channel so prone to cross coupling intuitively offers the potential for a significant improvement in handling qualities for a minimal effort. By keeping the simple integral/proportional system of Reference 2 in pitch, roll and collective, a direct comparison between simple and automated systems can be made.

This paper describes such an experiment, the control system and its development are documented and the results are presented. Comparisons are made between the present results and those of References 2 and 3.

4. EXPERIMENTAL DESIGN

While using a fully integrated force-sensing side-arm controller, subject pilots were asked to fly a series of tasks representative of the greater part of a typical generic helicopter flight envelope as well as specific military and Civil-IFR missions. They were asked to give a Cooper Harper rating to each of the tasks, and to repeat them all using, in the yaw channel, three different control systems, a primitive, open-loop integral/proportional system, a rate command and an acceleration command system. The desired performance level for each task was specified. Subject pilots were permitted up to two hours of flight time for training prior to evaluating any system, mainly to provide a reasonable level of competence with the multi-function side-arm controller, while up to one hour refamiliarisation was permitted between the evaluation of different control systems. A copy of the pilot's briefing is in Appendix A, together with expanded notes on individual tasks which are listed in Table 1

Table 1: Experimental Tasks

Task No.	Task Name
1.1	Nap of the Earth (NOE) Segment
1.2	Bob-up and Point Manoeuvre
2.1	Microwave Landing System (MLS) 6° Glideslope Approach
2.2	Missed Approach Procedure
3.1	Acceleration/Stop
3.2	Rearward Translation
3.3	360° Spot turn Left
3.4	360° Spot Turn Right with Hesitations
3.5	Precision Landing
3.6	Right Lateral Translation

5. THE NAE AIRBORNE SIMULATOR

The NAE Airborne Simulator was developed from a Bell 205A single, teetering - rotor helicopter. It has been extensively modified into a four degrees-of-freedom simulator by

a. Removing the stabiliser bar.

b. Removing the cyclic/elevator inter-connect.

c. Replacing the standard hydro/mechanical actuators with full authority, dual function hydro/electro/ mechanical units and providing an individual hydro/ electrical actuator for the elevator.

d. Adding a powerful hybrid real-time computing system consisting of three banks of analogue and three PDP-11/23 based digital processors.

e. Providing a full range of aircraft state sensors interfaced to the computing system.

f. Installing a 64 channel serial digital recording system.

g. Installing a nose-boom with incidence and sideslip vanes and swivelling static pressute source.

The right hand seat is the evaluation pilot's position from which all control inputs whether from conventional or radical systems are read electronically by the computers which in turn drive the aircraft control actuators via experiment-specific software. All computer generated inputs to the actuators are reflected in the conventional controls at the safety pilot's position. He may assume control at any time or, if necessary, over-ride the computer inputs. A comprehensive system health monitor passes control to the safety pilot in the event of a malfunction. A more complete description of the modifications and safety system may be found in Reference 5.

6. THE CONTROLLER

The Controller used for this experiment was a Measurement Systems Inc. model 406, fitted with a NAE designed conformal hand grip. This model is similar to the isometeric unit used in previous FRL experiments, but has the sensor unit spring coupled to the outer case in such a way that the unit shows appreciable compliance in both pitch and roll axes, though very little in yaw and heave. The unit is shown in Figure 1 while its force transducing characteristics were as in Table 2. The controller was mounted on a standard Bell 205 seat as shown in Figure 2, the mounting was adjustable for height and lateral position (swing-in) only.

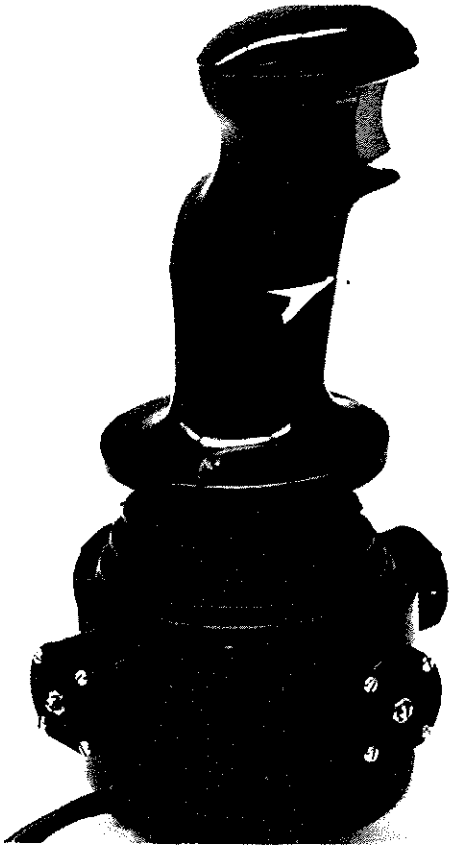


Figure 1: The Controller

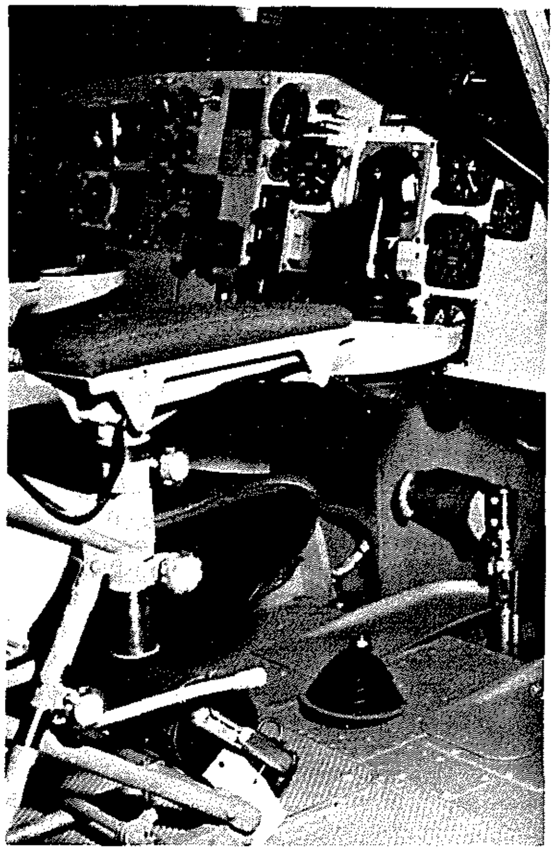


Figure 2: The Controller Mounted in the Airborne Simulator

Table 2: Side-Arm Controller Characteristics

Axis	Sensitivity	Compliance (a)	Maxima
Pitch	0.67 volts/lb(b)	0.26 deg/lb(b)	+8.66 volts(12.9 lb) -9.60 volts (14.3 lb)
Roll	0.72 volts/lb(b)	0.26 deg/lb(b)	+9.78 volts (13.5 lb) -9.25 volts (12.8 lb)
Yaw	0.18 volts/in lb	very low	+10.12 volts (56.2 in lb) -10.66 volts (59.2 in lb)
Heave	0.54 volts/lb	low	+10.60 volts (19.6 lb) -10.31 volts (19.1 lb)

(a) There was no hard stop until well beyond force transducing range.

(b) With respect to a force applied at mid grip, 4.25 ins from sensing axis

7. CONTROL SIGNAL PRE-PROCESSING

With conventional controls, the position of the controller with respect to some datum is the pilot's input to the control system. To achieve this input he has to apply forces to accelerate the controller and then decelerate it into the required position. A force sensing controller brings the pilot two integrations closer to the controlled system than this, since his applied force is itself the input quantity. It follows that inputs seen by the control system directly could have a much higher bandwidth than when displacement controllers are in use. Also, force controllers of the type used here, which are not mass balanced about the sensing axes are prone to inertially induced spurious inputs. These factors demand a certain degree of pre-processing of the controller signal before it is used to drive a control system. The pre-processing chain used for this experiment is shown in Figure 3. The 16 rad/sec, (2.54Hz) low pass filter served to 'de-spike' the pilot's inputs and to remove environmentally produced inertial noise; it has been in use since the work described in Reference 1, as has the deadband, which serves both to assist the pilot in achieving an absolute zero input and in removing any residual inertial noise from the controller. The linear/quadratic shaping function (Figure 4) has proved useful in providing pilots with acceptable levels of sensitivity around zero, while permitting large short duration inputs to be made without excessive force. Discrete straight line segments were rejected during development, since the discontinuities in slope were usually detectable by and a distraction to the pilot. Details of the pre-processing procedure are given in Appendix B.

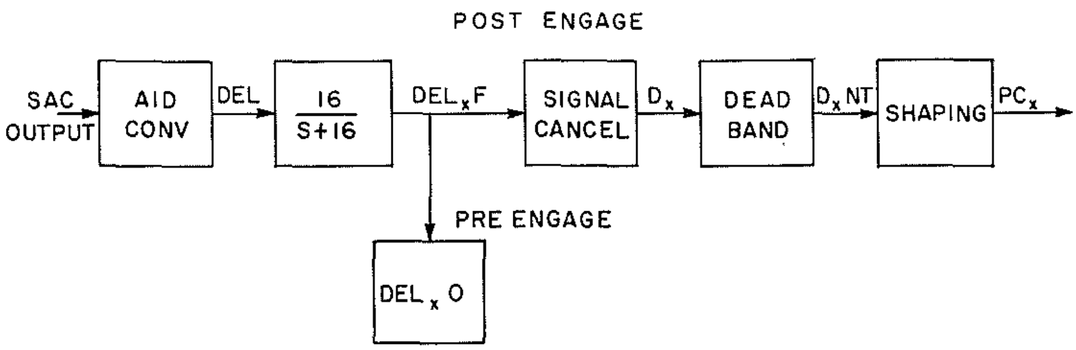


Figure 3: The Signal Pre-Processing Chain

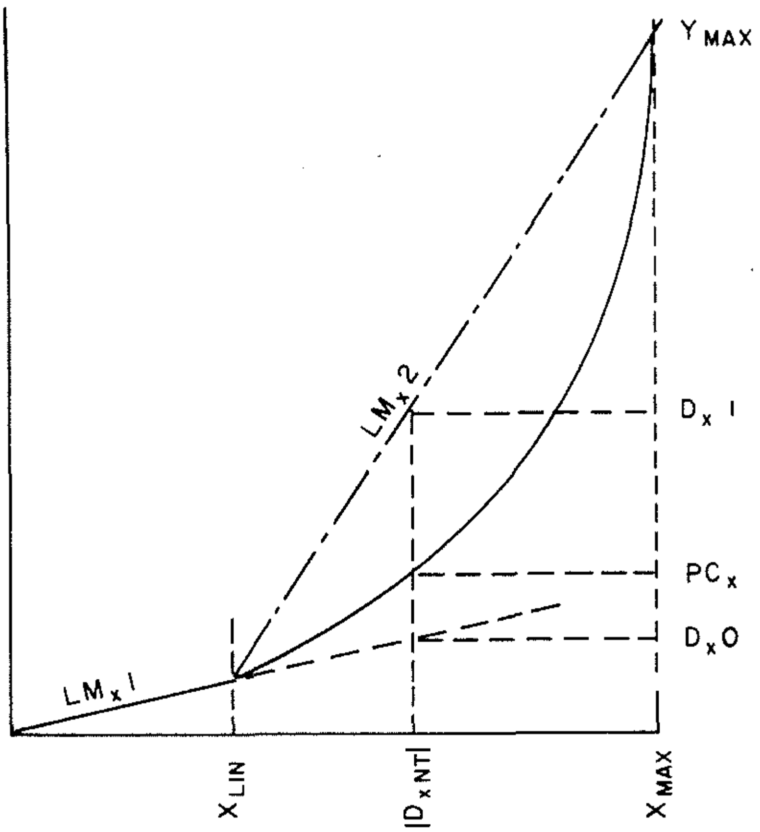


Figure 4: The Signal Shaping Function

8. CONTROL SYSTEMS

In pitch, roll and collective the pre-processing chain was followed by a simple open-loop integral/proportional drive to the actuators. In both pitch and roll, following the work of References 1 and 2 some rate damping augmentation was provided with the intention of removing any significant intrusion into the results of the demands on the pilot to control these axes. This system has been in use at FRL since the beginning of work with force sensing controllers and again is well documented in Reference 1 and 2. It is shown diagramatically in Figure 5.

Figure 6 illustrates the procedure used to achieve both rate and acceleration command systems with the minimum of loop development. A basic high gain rate following loop driven either by a direct output from the hand controller conditioning chain, to produce a rate command system or by a time integral of that signal to give an acceleration command. Subjectively different sensitivity requirements for these two modes of control were accomodated by including additional gain blocks in the direct and integral paths, while an excessively 'spikey' response to yaw rate commands was alleviated by additional low pass filtering of the direct drive signal. The break point of this simple first order filter was set empirically at 1 rad/sec. During development flying the anticipated difficulty inherent in acceleration command systems, that of adequately defining a zero rate, was found to be a major shortcoming of sufficient import that such a 'pure' acceleration command system was not offered for evaluation. The system was modified by the addition of a small dead band to the output of the integrator. This made zero rate definition by the pilot much easier, since he now no longer had to judge the exact magnitude and duration of a counter-rate input to achieve an exact zero input to the rate following system, but merely had to drive the output of the integrator into the dead band. A disadvantage of this solution is an asymemetric response to subsequent control inputs. It was found, however, that a very small dead band (about 2% of full scale) was sufficient to provide the pilot with an adequate zero without this asymmetry being apparent under normal flight conditions.

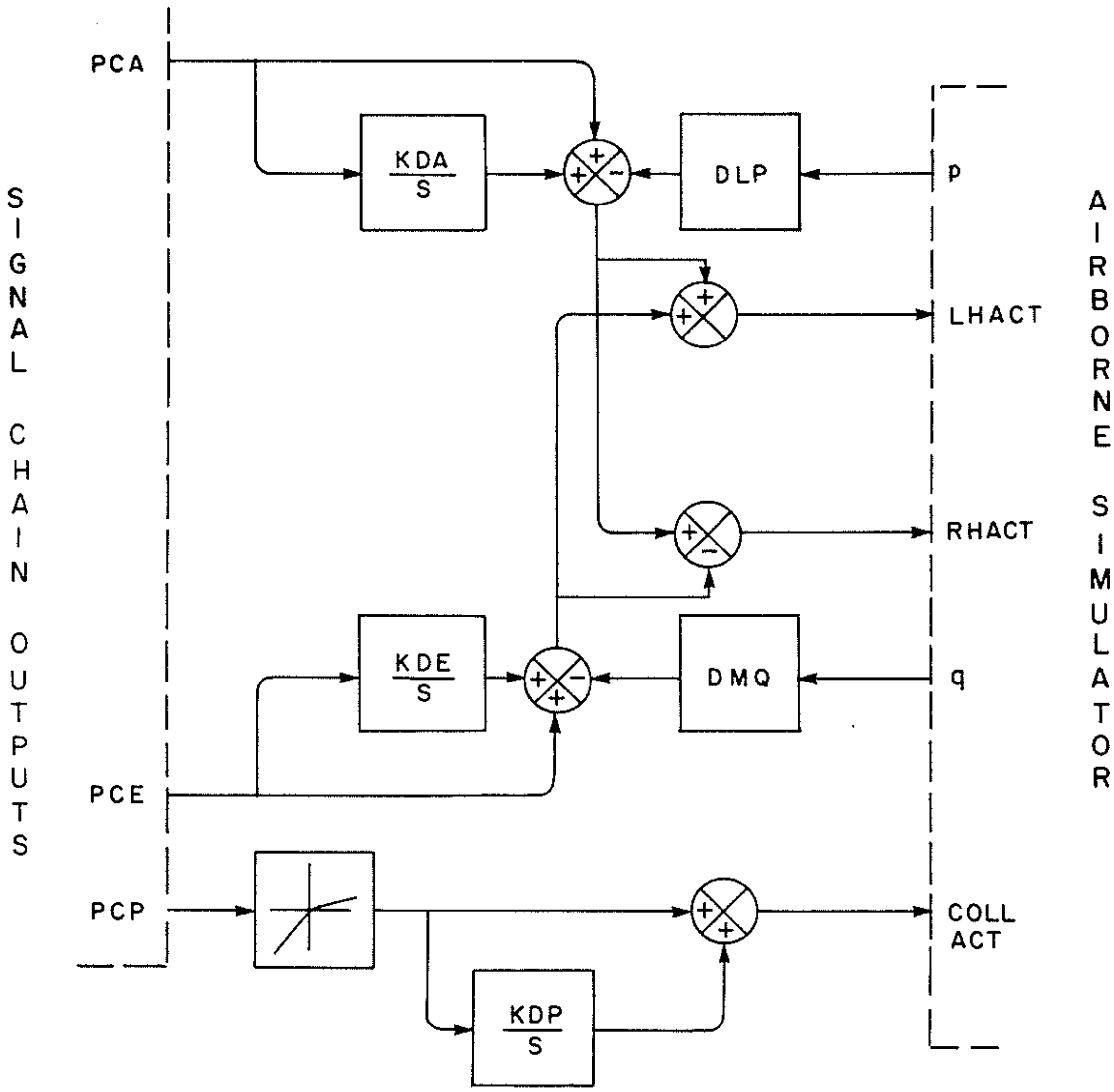


Figure 5: Pitch, Roll and Heave Control Systems

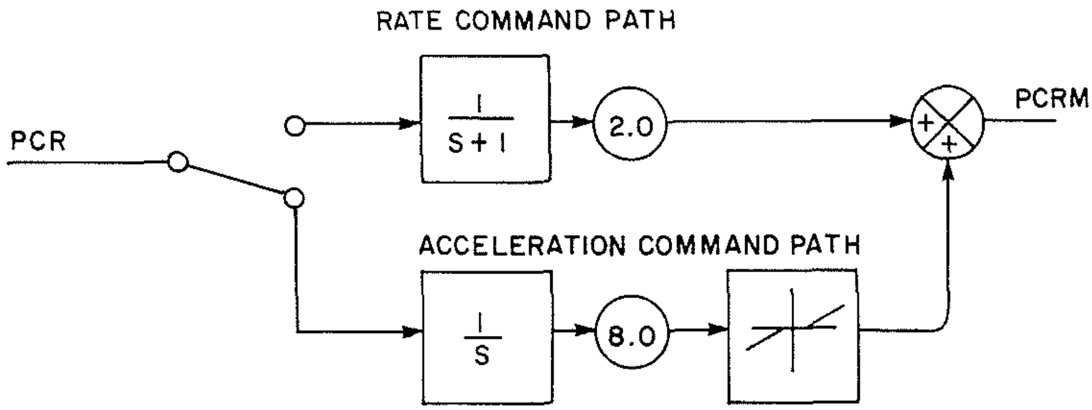


Figure 6: Rate or Acceleration Command Processing

The rate following system is shown in Figure 7. This is a basic type 1 system, with gain scheduling to accomodate the large changes in N_r and N_r with forward speed that are characteristic of the Bell 205A. Two gain scheduling functions were used,

$$F(u) = \frac{u-30}{20} \Big| \; 0 \leq F(u) \leq 1$$

$$F_1(u) = \frac{80-u}{50} \Big| \; 1 \geq F(u) \geq 1$$

These were used to vary gains as speed varied between 30, and 50 or 80 Kt. The Airborne Simulator does not provide a reliable value for airspeeds less than 30 KT, therefore below that speed constant gains, set following Reference 4, were used. The variable range for F(u) was selected to enable turn coordination and sideslip suppression signals to be blended in or out as quickly as possible without the changes being obvious to the pilot. $F_1(u)$ was intended to act as a scheduling function for those parameters which varied continuously throughout the speed range anticipated for this experiment. Linear functions were employed in the interests of computer processing time. A switch was used to provide a 'landing and take-off' mode, inhibiting the error integration for ground contact operations. Without this any unsatisfied command or error condition with the aircraft motion constrained would cause the loop to drive the tail rotor collective pitch to full travel. Decoupling moment demands were fed into the loop to reduce the demands on the system to control large but predictable extraneous moments.

During development a difficulty was encountered due to an asymmetry inherent in the tail rotor system. The effective control power in yaw increases markedly when the tail rotor is subjected to large values of positive lateral airspeed, specifically in lateral flight to the right or high rate yawing manoeuvres to the left. This effective increase in open-loop gain was sufficient to drive the closed loop unstable when gain levels derived from Reference 4 were used. Not wishing to degrade steady state command tracking by an overall gain reduction, this instability was controlled by applying a 'rate of rate' (r) damping loop to the system and accepting the implicit reduction in bandwidth in such a procedure. The gain of the yaw acceleration loop was set empirically so that the system remained stable except under extremely high values of lateral velocity which were not expected to be encountered during evaluation flying.

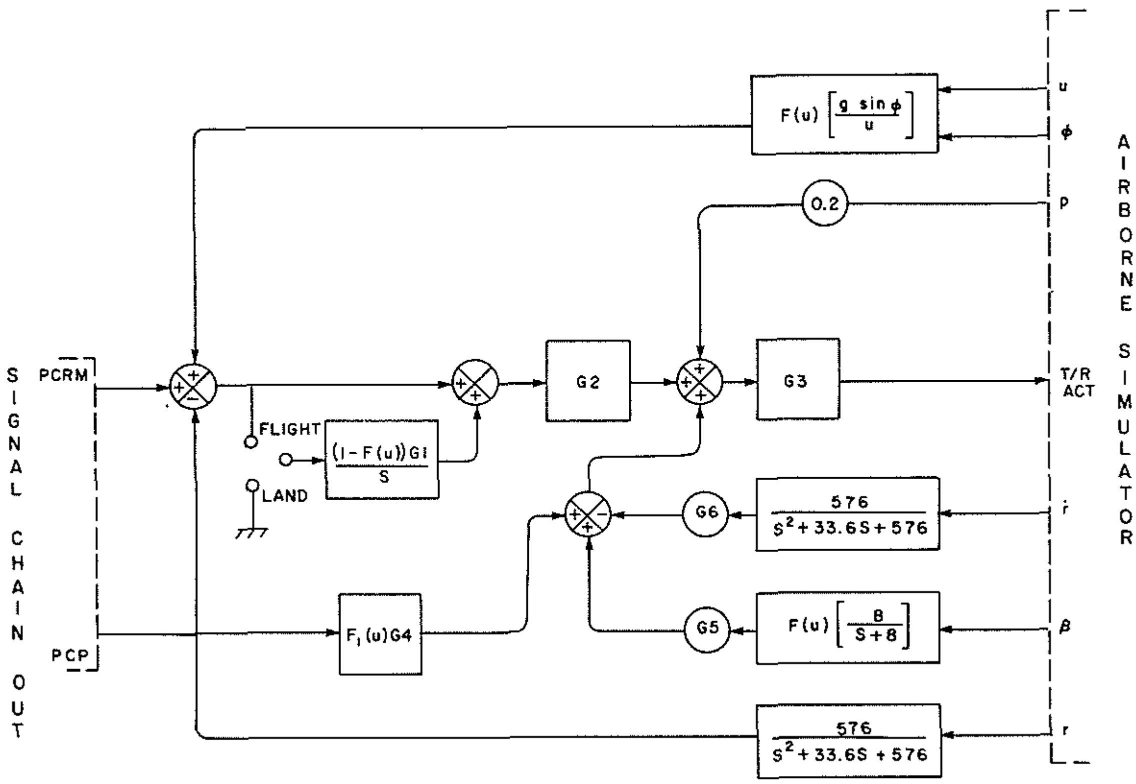


Figure 7: The Yaw Rate-Following Control System

The second order low pass filtering in r and r was applied to reduce excessive noise in the yaw acceleration signal due to various airframe and transmission modes while maintaining the essential phase relationship between the two parameters.

9. RESULTS

Figures 8 to 18 are plots of the raw Cooper Harper (CH) ratings coded by pilots together with the same data as mean and standard deviation. In reading these data it should be remembered that the pilots were evaluating the whole vehicle each time, not yaw control in isolation, and that for comparison purposes the configuration marked 'INTEGRAL TRIM' indicates an aircraft with an integral trim control system in yaw as well as in pitch and roll; this configuration is identical with the rate damped configuration of References 1 and 2.

10. DISCUSSION OF RESULTS

From these plots, some interesting trends are noticeable. It would appear that under conditions of high forward speed, there is a definite preference for a rate command system in yaw. This is evident in tasks 1.1, 2.1 and 2.2. For low speed manoeuvring, that is in tasks 1.2 and 3.1 to 3.6, there is a mild tendency to prefer an acceleration command system.

Taken as a whole, these data support the indications of References 1 and 2 that Level 1 handling qualities can be achieved with fully integrated side-arm controllers and quite low levels of control system sophistication. This conclusion, now supported by three piloted experiments, should be examined in comparison with present similar research work being conducted on ground-based simulators.In the experiment described herein experiment there were three visual flight task for task correspondences with the work of Reference 3, task 1.1 (NOE RUN), 1.2(BOB-UP) and 3.1 (ACCEL/STOP). In the reference, five levels of sophistication were examined in the pitch and roll channels, ranging from acceleration command with rate stabilisation as the most primitive, through attitude command with attitude stabilisation, to linear velocity command with position hold as the most advanced. Either rate or acceleration command systems were available in the yaw channel, while vertical velocity or vertical acceleration command systems were used in heave.

Although these two experiments were not designed to produce comparative data, and although there were significant differences between them (eg. The host vehicle for Reference 3 was a mathematically modelled Blackhawk) there was also sufficient commonality to enable the data be read together. Especially is this true since none of the compared tasks were aircraft performance dependent while when using highly automated control systems the basic handling qualities of the host aircraft tend to become transparent to the pilot. There was also some overlap in the pilot sample, since both the NASA pilot and the author participated in both experiments. Finally, the hand controller and control channel allocation used in this experiment were identical to the configuration denoted by (4+0) SD in Reference 3. The purpose of this comparison is in no way to denigrate the value of the data reported in Reference 3, but is to highlight the observed fact that evaluators tend to find low altitude manoeuvring tasks more difficult in ground-based simulators than in the air; indeed, the authors of the reference seem very much aware of this since their discussion concentrates on trends and effects rather than absolute values.

Figure 19 shows the same data as Figures 8, 9 and 13, overplotted with a range of data appropriate to each task derived from Reference 3, Figure 23. The shaded areas show(a) the total range of CH ratings achieved for all control systems and (b) the range achieved with the two least sophisticated systems in the experiment of Reference 3. These plots suggest that in the airborne case even the most primitive model, that with open-loop control was assessed as having handling qualities of the same level as those achieved in ground-based simulation with highly automated control systems in all axes, while applying active closed-loop control to a single axis is sufficient, in the Airborne Simulator, to improve the handling qualities at least to the levels achieved in the most sophisticated ground-based simulations with one exception. The BOB-UP manoeuvre remained predicatably easier in the ground-based simulations when either Attitude Command/velocity Stabilised or Velocity Command/Position Hold control systems were used therein. In this manoeuvre the Airborne Simulator was evaluated at the same level as the ground-based simulation employing an Attitude Command/Attitude Stabilised system (Ref. 3, and Fig. 18). It is also worthy of note that in all the visual flight data reported in Reference 3 appropriate to a fully integrated controller with small displacements (ie, data for configuration (4+0) SD), Level 1 handling qualities were only observed with the most sophisticated control system appropriate to the specific task.

The observations above underline the importance of complementing ground-based simulations with flight validation in fundemental handling qualities research. The supreme advantages of the ground-based devices are, without doubt, their ability to present a large matrix of models in quick succession, to operate in a constant or controlled environment that is absolutely repeatable and their high utilisation potential. On the other hand the airborne simulator has the characteristics of a real visual environment, absolute correlation of visual and motion cues and the full complement of peripheral cues associated with a real aeroplane (noise, vibration etc.). There is also the less well defined but important 'risk factor' - an evaluation pilot in an airborne simulator knows that the consequences of error, or loss of control could be catastrophic, there is no reset button.

The pilots of helicopters operating close to the surface use very fine grain visual cues indeed, and by and large a general impression of the terrain is insufficient for that level of control precision required by many of the tasks they are required to perform. Despite the many advances in simulated visual displays in recent years they are not capable of presenting the fine grain detail necessary for good low altitude visual cueing. This suggests that early flight validation should be considered important in this area of research. However, the limited availability of airborne simulators and the relative difficulty in mounting large matrix experiments in them requires a compromise approach to the problem, possibly with the a greater mass of data being acquired through ground-based simulation, but with a sufficiency of validation comparisons being flown in airborne facilities to effectively benchmark the results or to discover any simulator dependencies in observed trends or biases.

11. CONTINUATION

The observations made above encourage continuation of these experiments using, whenever possible, tasks and configurations directly comparable to those used to establish similar data in ground-based simulation. Extension of automated control systems to the pitch, roll and vertical channels is planned and partially implemented with this type of activity in mind.

Additional work planned includes a study of the gain/filter-lag effect on pilot performance and opinion using advanced control systems about all axes.

Proposed instrumentation development in the Airborne Simulator includes a low speed sensor system of sufficient quality to permit a study of velocity demand and position hold systems as a part of the general advanced control system program, as well as the installation of a high resolution ground position sensor. Signal transmission from the experimental controllers to the computer system will be converted to an intelligent digial/optical medium within the next year.

12. PARTICIPATING PILOT'S

The subject pilot's for this experiment were:

S. Kereliuk	NAE
D. Sattler	NAE
Capt. R. Kobieski	CDF
G. Tucker	NASA (Ames)
J. Erickson	FAA

13. ACKNOWLEDGEMENTS

The author wishes to recognise the material contributions made to the production of this paper by Mr. K. Davidson (NAE) Instrumentation Technician and Safety Pilot, Mr. G. Burton (NAE), Instrumentation Technician and Mr. B. Macdonald (RAF) who calibrated the controller. This work was partially funded by the Canadian Department of National Defence under the Aeronautics Technology Program.

14. SUMMARY

Using a fully integrated side-arm controller configuration, with primitive open-loop control systems in pitch roll and heave, Level 1 handling qualities were achieved by automation of the yaw channel. This was a consistent result throughout a series of tasks which addressed a large portion of a representative single-rotor helicopter flight envelope.

15. REFERENCES

1.	Sinclair,M Morgan, M.	An Investigation of Multi Axis Isometric Side-Arm Controllers in a Variable Stability Helicopter. NAE LR-606, NRC No. L9629, August 1981.
2.	Morgan, J.M.	Some Piloting Experiences with Multi Function Isometric Side-Arm Controllers in a Helicopter Proceedings of the joint NASA/AHS Helicopter Handling Qualities Specialists Meeting NASA CP 2219, April 1982.
3.	Landis, K.H. Aiken, E.W.	An Assesment of Various Side-Stick Controller/Stability and Control Augmentation Systems for Night Nap-of-Earth Flight Using Piloted Simulation. NASA CP 2219, April 1982.
4.	Heffley, R.K.A et al.	Compilation and Analysis of Helicopter Handling NASA Qualities Data, Volume 1:Data Compilation CR 3144, August 1979.
5.	Sinclair, M. Roderick, W. Lum, K.	The NAE Airborne V/STOL Simulator. Proceedings of the AGARD Flight Mechanics Panel Syposium on Rotorcraft Design. AGARD CP 233.

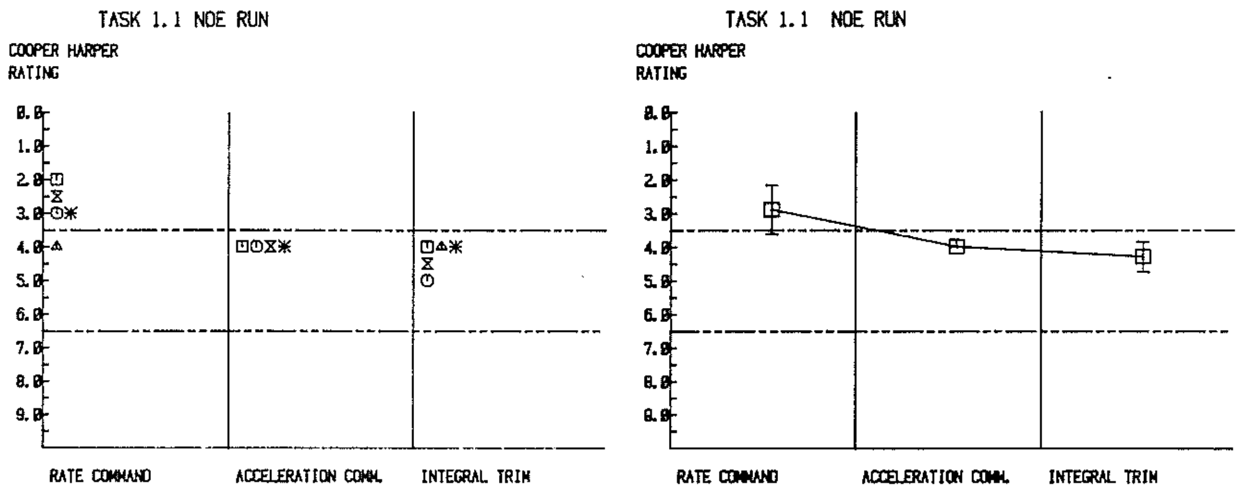


Figure 8: Task 1-1, NOE Course, Data

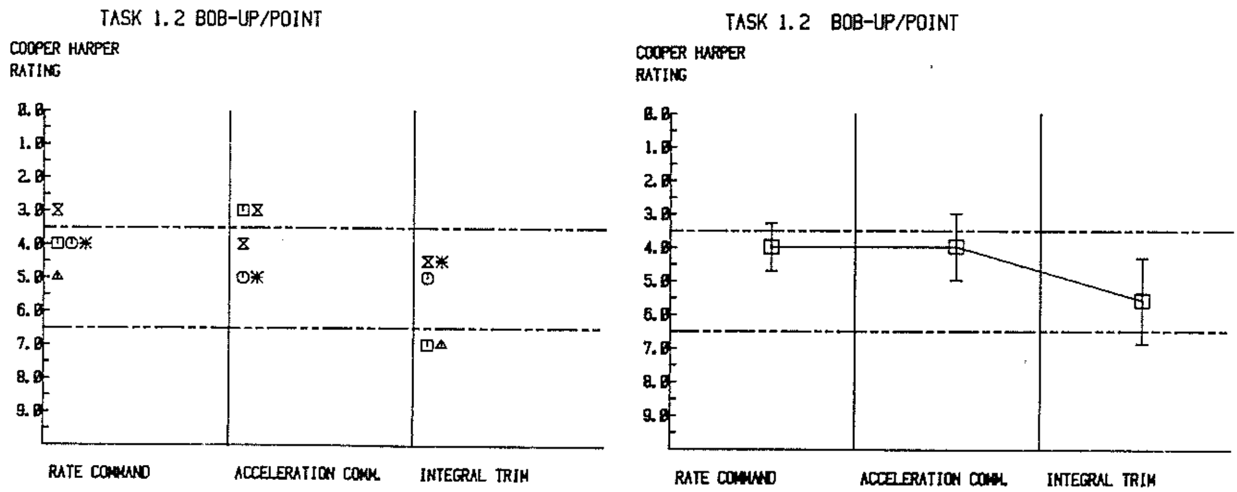


Figure 9: Task 1-2, BOB-UP, Data

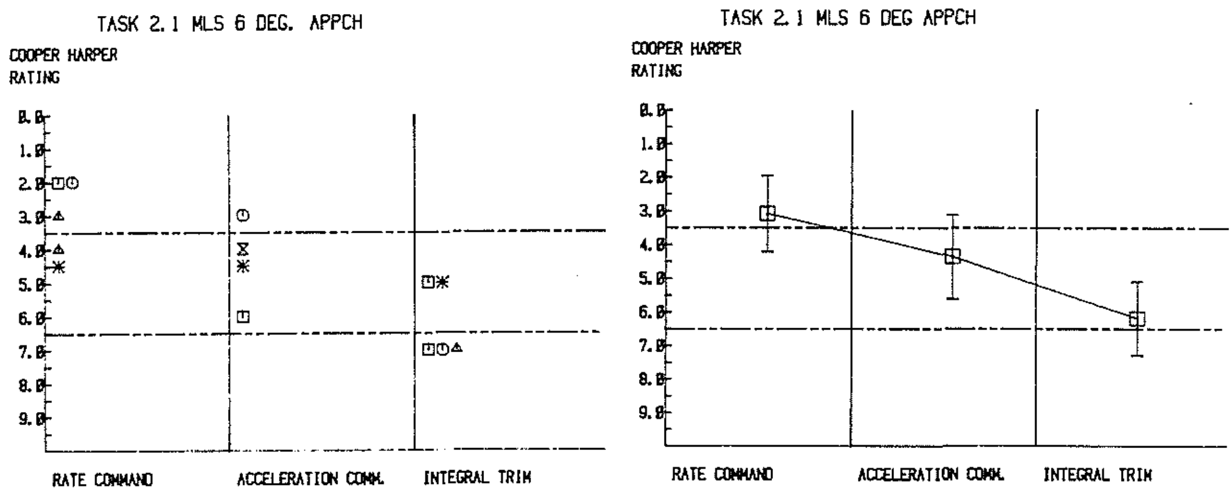


Figure 10: Task 2-1, MLS Approach, Data

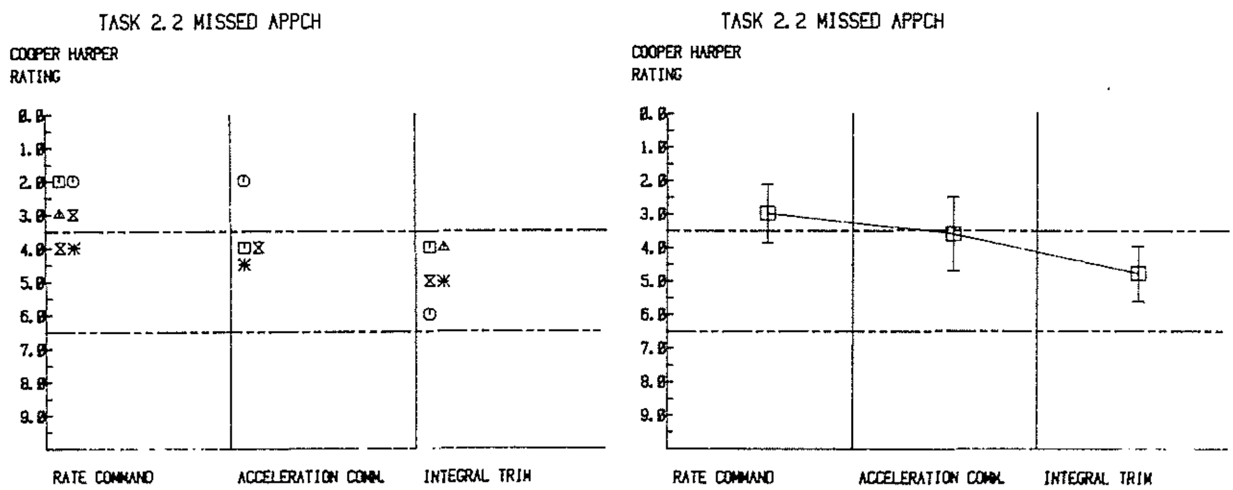
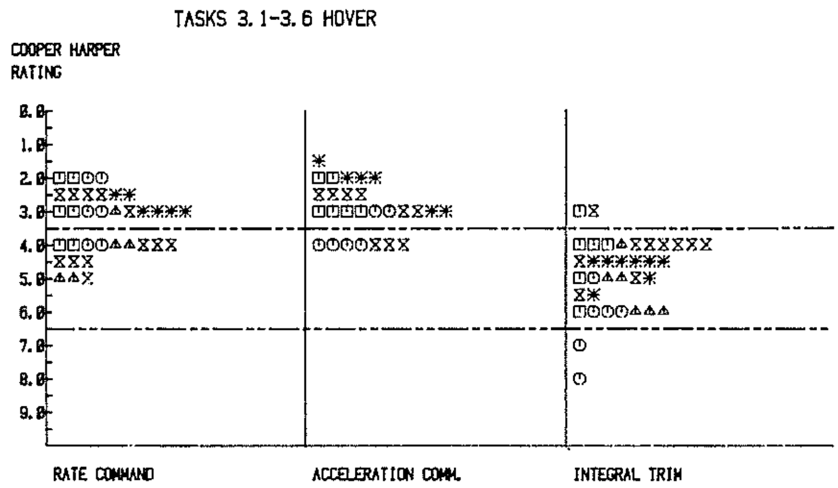


Figure 11: Task 2-2, Missed-Approach, Data



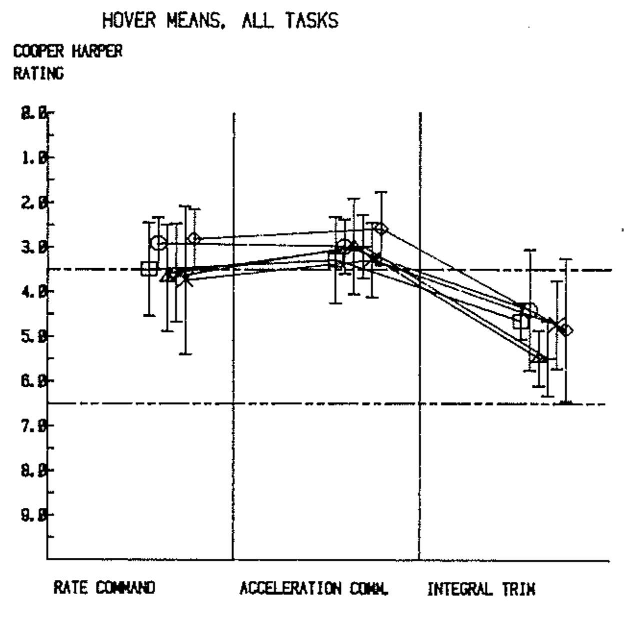


Figure 12: Hover Manoeuvring, Consolidated Data

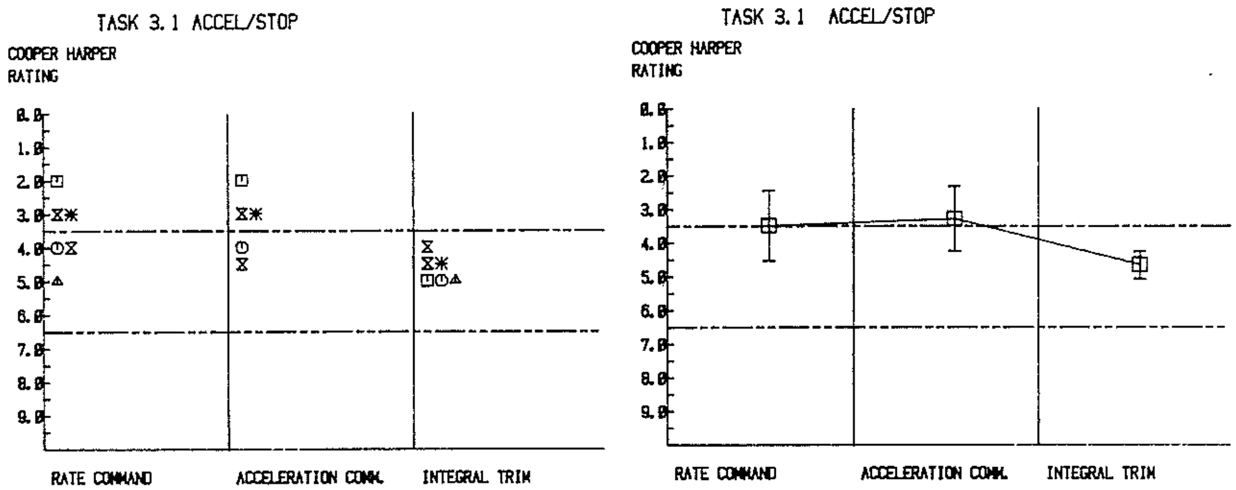


Figure 13: Task 3-1, Accel - Stop, Data

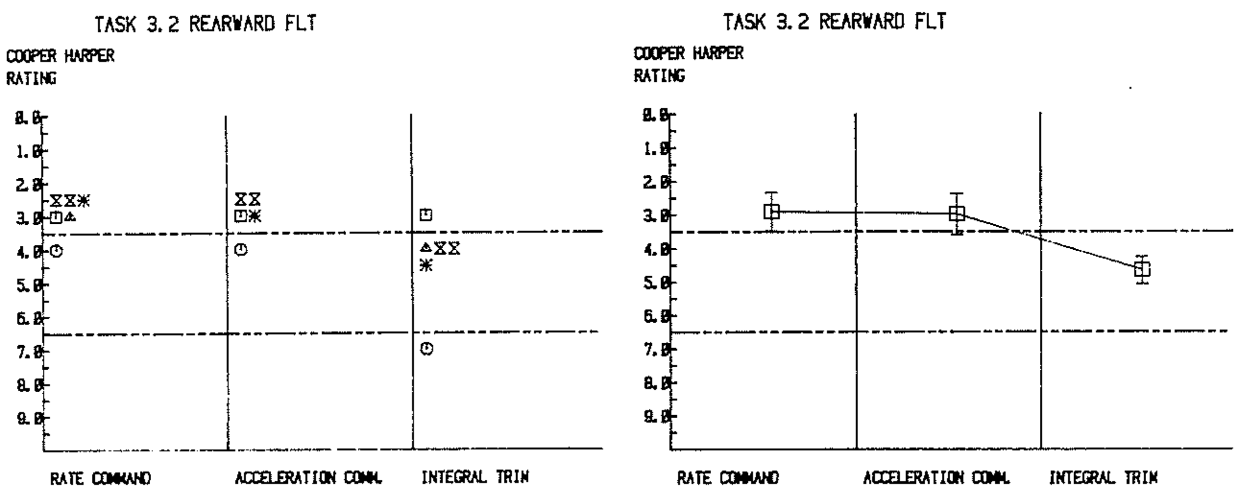


Figure 14: Task 3-2, Rearward Translation, Data

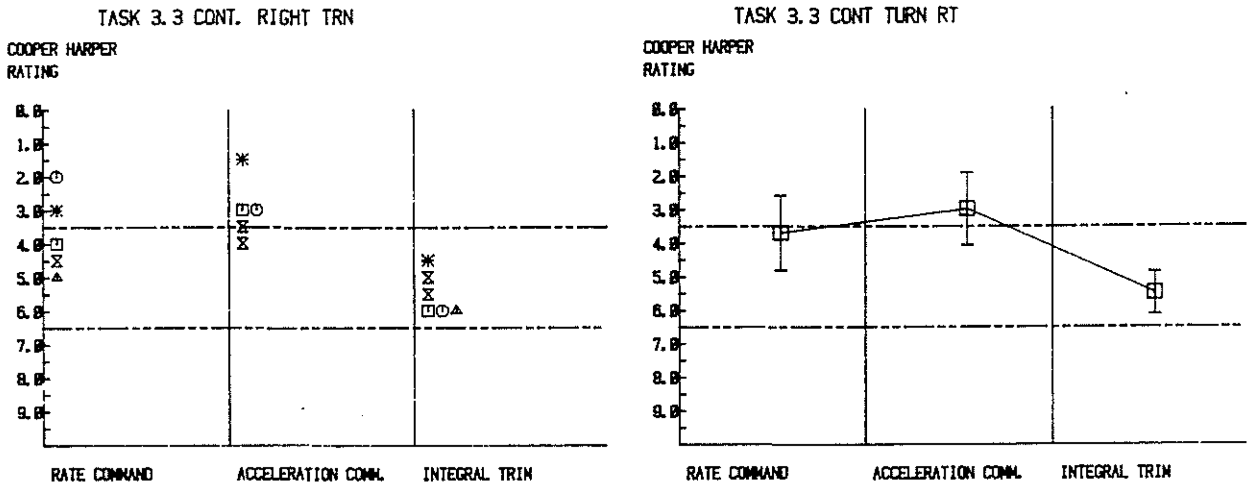


Figure 15: Task 3-3, 360 Turn Left, Data

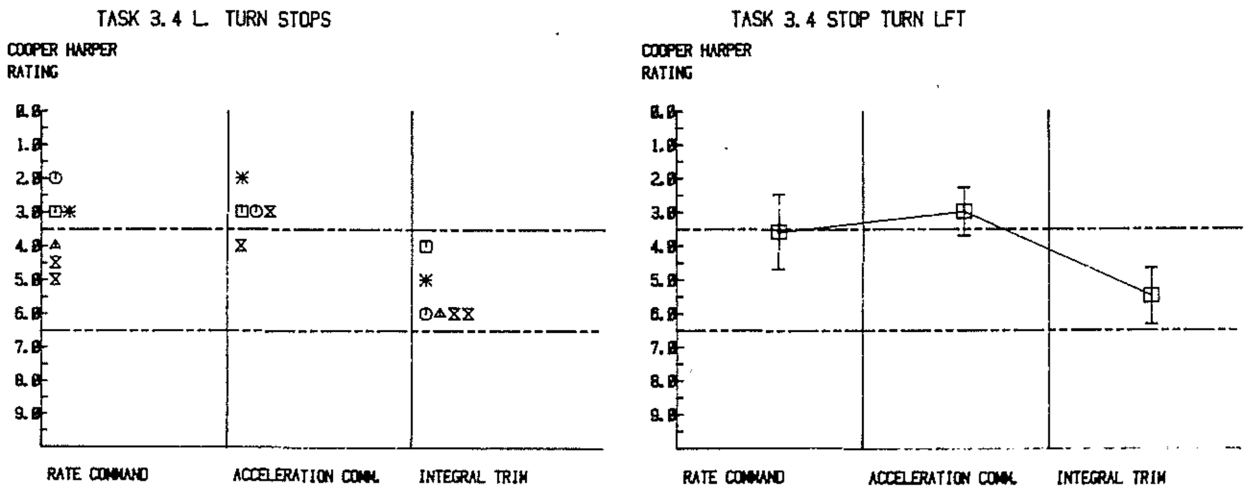


Figure 16: Task 3-4, 360 Degree Turn Right with Hesitations, Data

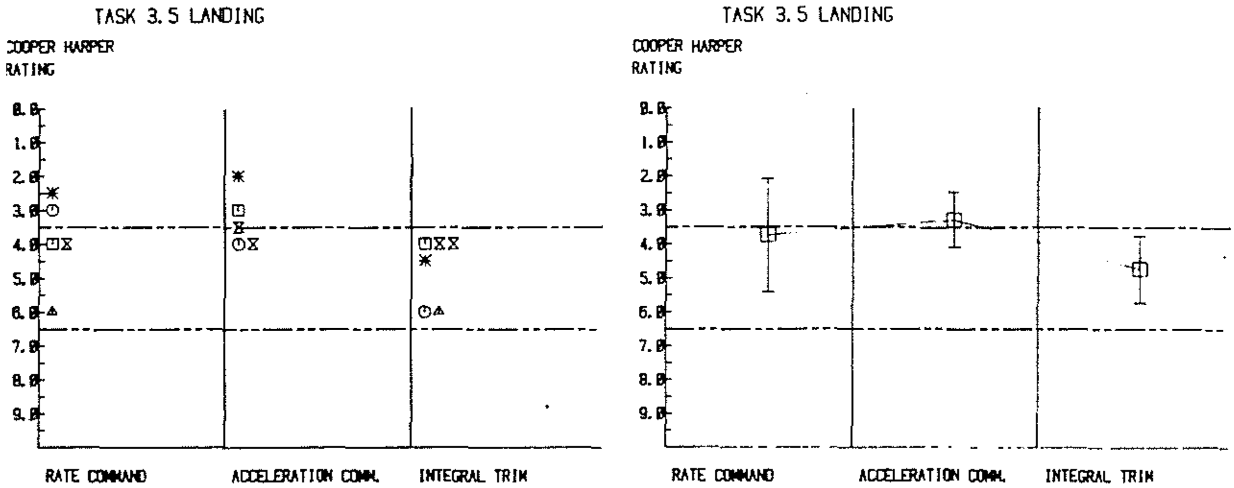


Figure 17: Task 3-5, Precision Landing, Data

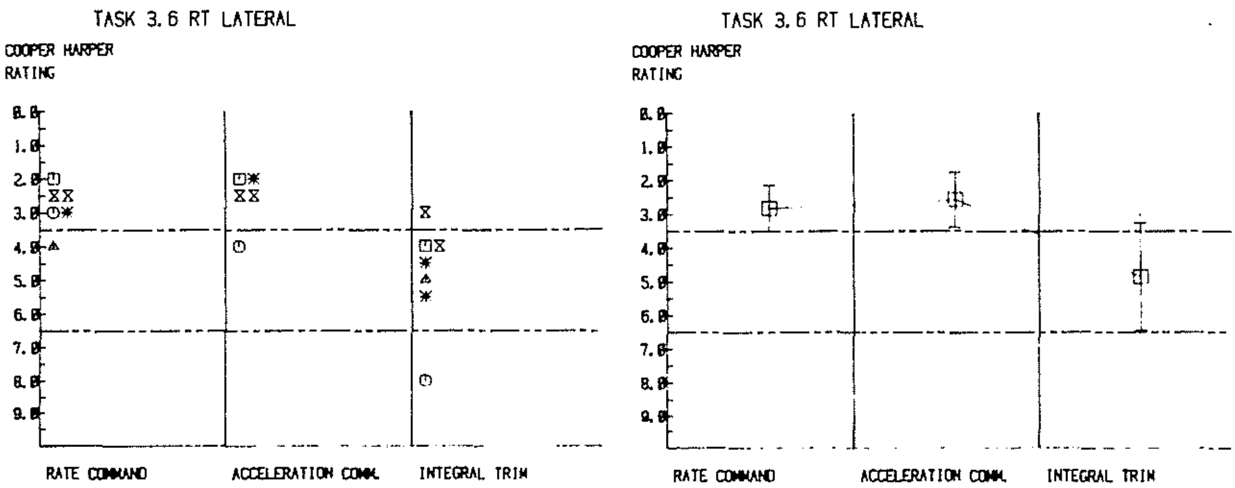


Figure 18: Task 3-6, Right Lateral Translation, Data

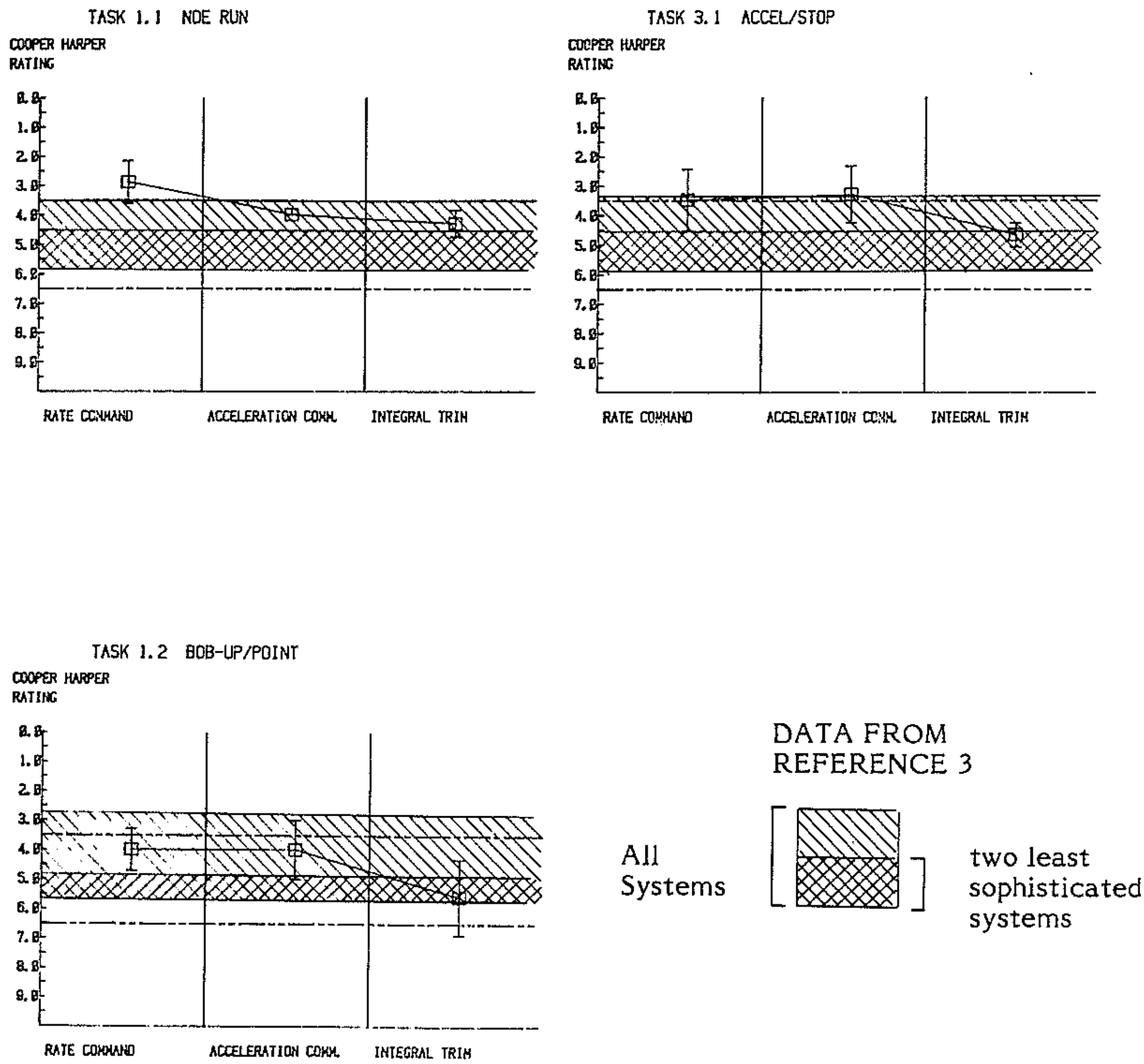


Figure 19: Comparison Between the Data of this Experiment and those of Reference 3 for three Corresponding Tasks.

APPENDIX A

TASKS AND TASK ENVIRONMENT

A1. NAP-OF-THE-EARTH

A short natural Nap-of-the-Earth course was selected close to the NAE hangar, it consisted of a low double hill dropping into a wooded area forming a gully between the hillside and the tree line. This course is shown in Figures A-1 and A-2. The major demands on the pilot mode by this course were two long (90 degree) turns to the left and two lesser turns (about 45 degrees), one left and one right. Vertical workload was created by the requirement to negociate the col between the two hills.

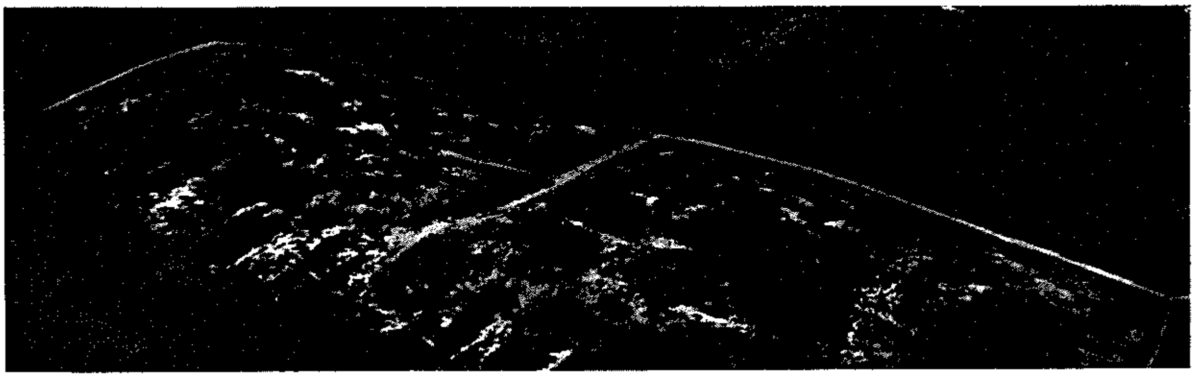


Figure A-1: The NAE NOE Course, General View

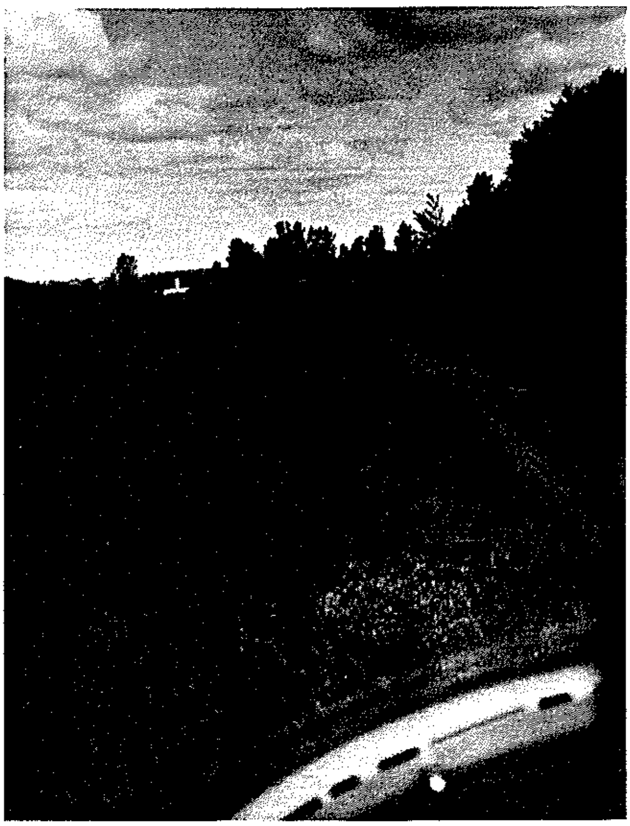


Figure A-2: The NOE Course, Pilot's View

A2. MLS APPROACH

The NAE COSCAN installation was used, set for a 6 degree glideslope angle. Pilots were placed, by the safety pilot, in a suitable position for localiser interception about 1/2 nm prior to the glideslope intercept. The approach and missed-approach were flown with simulated IMC screens in place. Raw displacement information was fed to the panel displays and there was no flight director.

A3. HOVER TASKS

Tasks 3.1 to 3.6 were flown on the NAE ground-marked 'Hover Course' shown in Figure A-3.

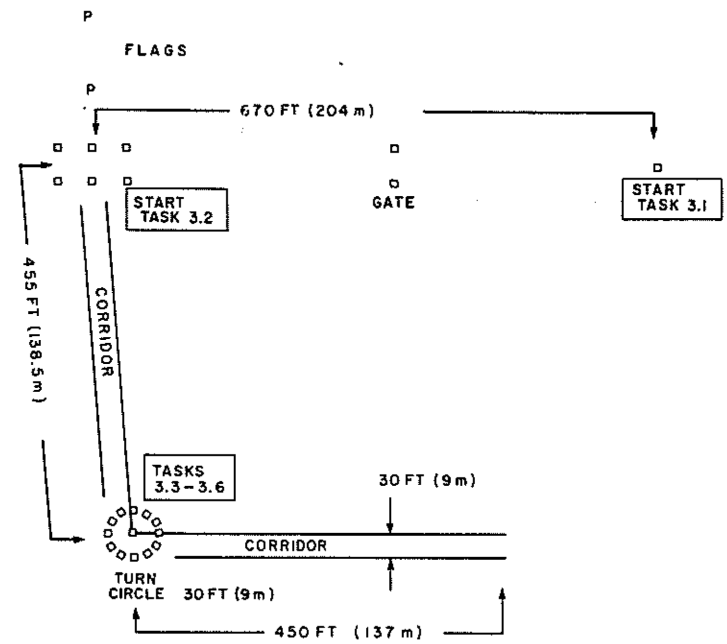


Figure A-3: The Layout of the NAE Hover Course

A4. PILOT'S BRIEF

(The remainder of this Appendix is a slightly edited version of the written brief given to each of the subject pilots.)

GENERAL

1. The flying for this experiment is dividied into three main sections: training; evaluation of non-hover tasks; and evaluation in and around the hover. The order in which flights are arranged is intended to reduce as far as possible in the time available, the effects of learning during the evaluation phases and also to lessen the effects of cross contamination between control modes.

2. Pilots who have had previous exposure to multi function side-arm controllers will patently require less fundamental training than those who have not, nevertheless all subjects will be offered the same training opportunities.

3. In flying a force sensing system, remember that any applied force is felt as a control demand. A relaxed hand and a loose grip on the controller will generally prevent any tendency to overcontrol or to produce "spikey" actuator inputs. This is especially important to remember when attempting precision manoeuvres at or near the hover.

4. Remember that the flight control systems in pitch, roll and collective remain the same for all yaw channel configurations. During flights 1 and 2 you may, if you so wish, set up gains in these channels to your personal taste.

TRAINING

5. Flight 1. Rate command in yaw. General air work for familiarization, NOE segment, MLS approaches, free hovering. If adequate proficiency with rate command system achieved, brief examination of acceleration command at hover.

NOTE: In rate command, constant torque on controller produces constant rate of yaw below 30 KIAS and applies bias against sideslip at higher speeds. Above 30 KIAS full sideslip suppression and turn coordination are built into the system and no yaw inputs are required unless it is wished to fly with sideslip.

6. Flight 2. Primitive integral trim system in yaw. Flight content as in flight 1.

EVALUATION FLIGHT CONTENTS

7.

Flight NUMBER	YAW CONTROL SYSTEM	CONTENT
3	Rate Command	NOE Segments, Bob-up and Point, MLS Tracking, Missed Approach
4	Acceleration	As Flight 3
5	Rate Command	Hover Course, Accel/ Stop Rearward Translation 360 Right 360 Left, pause every 90, Right Lateral Translation

6	Acceleration Command	As Flight 5
7	Integral Trim	As Flight 3
8	Integral Trim	As flight 5

NOTE: The required time for the evaulation tasks in each flight is quite short and subjects may practise the required tasks before evaluation if they feel that this will ensure their confidence in their ability to evluate. If needed or wished, an additional training flight can be flown between evlaution flights 6 and 7.

NOTES ON INDIVIDUAL TASKS

8. Task 1.1 NOE Segment.

Commence from hover, accelerate to 45 kt IAS and decelerate to approx 20 kt for first turn. Fly second leg at about 30 kt, around second turn, accelerate to 40 kt between dead saplings, and convert to left three-quarter translation at low speed between hillocks.

Accelerate to approximately 30 kt towards gate, to return to hover short of gate.

9. Task 1.2 Bob-up Manoeuvre.

Vertical climb, yawing right until silo visible (about 100 degrees). Hold silo ahead, with aircraft stabilized on heading, for 3 seconds. Return to hover on original heading (i.e. left yaw during descent).

10. Task 2.1 MLS Approach.

From steady speed at 80 kt IAS at 1500 ft indicated, intercept localizer (250 heading). Decelerate to 60 kt at glideslope interception, track localizer and glideslope to 550 ft indicated (200 ft radalt).
Desired performance:

Initial height +/- 100 ft
IAS +/- 5 kt
Localizer +/- 1/2 dot
Glideslope +/- 1 dot

11. <u>Task 2.2 Missed Approach.</u>

Set 43 psi torque while maintianing 60 kt IAS. Commence right turn before 1000 ft indicated, to end at 1500 ft, heading 080, accelerate to 80 kt IAS.
Desired performance:

IAS +/- 10 kt
Vertical speed greater than 1000 ft/min
Final height +/- 100 ft
Final heading +/- 5 degrees

12. <u>Task 3.1 Accel/Stop.</u>

From hover, accelerate to 35 kt IAS at the gate, return to hover.
Desired performance:

IAS +/- 5 kt
End position within marked zone
Height keeping +/- 5 ft

13. <u>Task 3.2 Rearward Translation.</u>

Line-up on red flags. Commence rearward translation. Maintain speed no greater than about 10 kt groundspeed (safety consideration). Attempt to maintain ground track within corridor, constant heading, constant height.
Desired performance:

Ground track within corridor
Heading +/- degrees
Height +/- 5 ft

14. <u>Task 3.3 360 Turn Right.</u>

Centre aircraft over circle. Commence tail rotor turn right aiming to complete turn in 30 seconds (mean rate 12 deg/sec). Attempt to maintain constant height and turn rate.
Desired performance:

Rate 12 deg/sec mean, constant
Height +/- 2 ft
Final heading +/- 5 degrees

15. <u>Task 3.4 360 Left Turn with Stops.</u>

Start as in para 14. Initial heading 320 degrees, commence tail rotor turn left, stopping for 2 seconds on headings of 230, 140, and 050 degrees, terminate on 320 degrees.
Desired performance:

As above, but with no reversals of turn direction at intermediate stops.

16. Task 3.5 Precision Landing.

From stabilized hover over circle, attempt to land aircraft smoothly in centre. Use heading depending on wind direction.
Desired performance:

> Touchdown point within 4 ft of centre, no yaw excursions once skids have touched.

17. Task 3.6 Lateral Translation.

Hover over circle and line-up with centre of corridor on 320 degree heading. Right lateral translation with constant speed no greater than 15 kt (safety). Attempt to maintain constant heading, height and speed.
Desired performance:

> Height +/- 2 ft
> Heading +/- 5 degrees
> Ground track - remain within corridor.

APPENDIX B

CONTROL SYSTEMS DETAIL

B1. Filtering

All digital filtering was of the simple discrete sample approximation type, illustrated in the case of the first order low-pass below.

From

$$V_o = V_i \left(\frac{\alpha}{S+\alpha}\right)$$

we write

$$V_{o\cdot} = \frac{\alpha}{S}(V_i - V_o) = \alpha\int_0^t (V_i = V_o)\,dt$$

Assuming $\int_0^t x\,dt \simeq \sum_{I=0}^{I=t/\Delta T} X_I * \Delta T$

for discretely sampled data where ΔT is the time interval between successive samples, we impliment the above as:

$$V_{o_n} = V_{o_{n-1}} + (V_{i_n} - V_{o_{n-1}}) * \frac{\alpha}{64}$$

Where n and n-l refer to the values in the current and previous comptuational cycles, while 1/64 seconds is the cycle time of the Airborne Simulator digital system.

B2. Signal Pre-Conditioning

Signals from the side-arm control unit were all subjected to the same form of pre-conditioning, though parameteric values were changed from function to function. After sampling, the process was

$$DELxF = DELx \qquad \text{SPIKE SUPPRESSION}$$

Pre fly-by-wire engagement

$$DELx0 = DELxF \qquad \text{FOR SIGNAL CANCELLING}$$

Post fly-by-wire engagement

$$Dx = DELxF - DELx0 \qquad \text{SIGNAL CANCELLING}$$

$$DxNT = Dx * (Dx - DBx) \qquad \text{DEAD BANDING}$$

$$PCx = \frac{DxNT}{|DxNT|}\left[Dx0 + \left(\frac{|DxNT| - XLIN}{XMAX - XLIN}\right) * (Dxl - Dx0)\right] \qquad \text{SHAPING}$$

$$Dx0 = |DxNT| * LMx$$

$$Dxl = YMAX - (XMAX - |DxNT|) * LMx2$$

The complexity of implimentation of the shaping function was in the interests of flexibility, since while the form of the function remained the same, that is, a short linear slope blending tangentially into a quadratic function arranged so that a maximum input resulted in a maximum output, the experimenter was able to adjust both the slope and extent of the linear portion by entering new values of LMx and XLIN. Figure 4 shows the details of this implimentation.

In this general description x represents A,E,R or P, designators for the various control channels.

B3. Control Systems

Figure 5 shows the primitive open loop control systems used in pitch, roll and collective channels. Although the quantities DLP and DMQ give the diagram the appearance of a rudimentary rate command system, their values were set so that while the rate damping of the helicopter was augmented by approximately 100% at the hover, the gains were too low to ameliorate significantly the pilot input demands. The asymmetric function in the collective channel was provided to accommodate the differences in ease with which a pilot can apply a vertical force to the controller in the up and down directions with the fore-arm constrained by an arm rest.

Referring to Figure 7, the main loop has a DC gain determined by the product G2.G3 with respect to rate error, and by G3 alone for de-coupling moments. These values are themselves functions of speed such that

$$G3 = G3B + F_1(u) * G3I$$

The total effective open loop gain is

$$G_o = G2 * G3 * 10.24 * N_r$$

Where N_{δ_r} is the tail rotor control power in rads/sec^2/volt (0.3172 N_{δ_r} rad/sec^2/inch) and 10.24 is a factor introducted by the digital to analogue conversion and error signal input scaling.

From Reference 4, N_{δ_r} (rad/sec^2/volt) varies from - 0.3694 at the hover to -0.5408 at 100 KIAS, while N_r (1/sec) moves from -0.7102 to -1.604 in the same speed range. An approximate compensation to achieve a constant open loop gain of approximately 7.5 was achieved by using the values in Table B-2. The resulting open loop gain is shown in Figure B-1.

Table B-1, G2 & G3 components

G2B	2.08
G2I	0.42
G3B	0.68
G3I	0.15

Table B-2 summaries the full parameter set used in the control system

Table B-2 Yaw System Gains

	Hover	Cruise
G1	0.25	0.0
G2	2.50	2.08
G3	0.83	0.68
G4	0.40	0.20
G5	0.0	1.25
G6	0.1	0.1

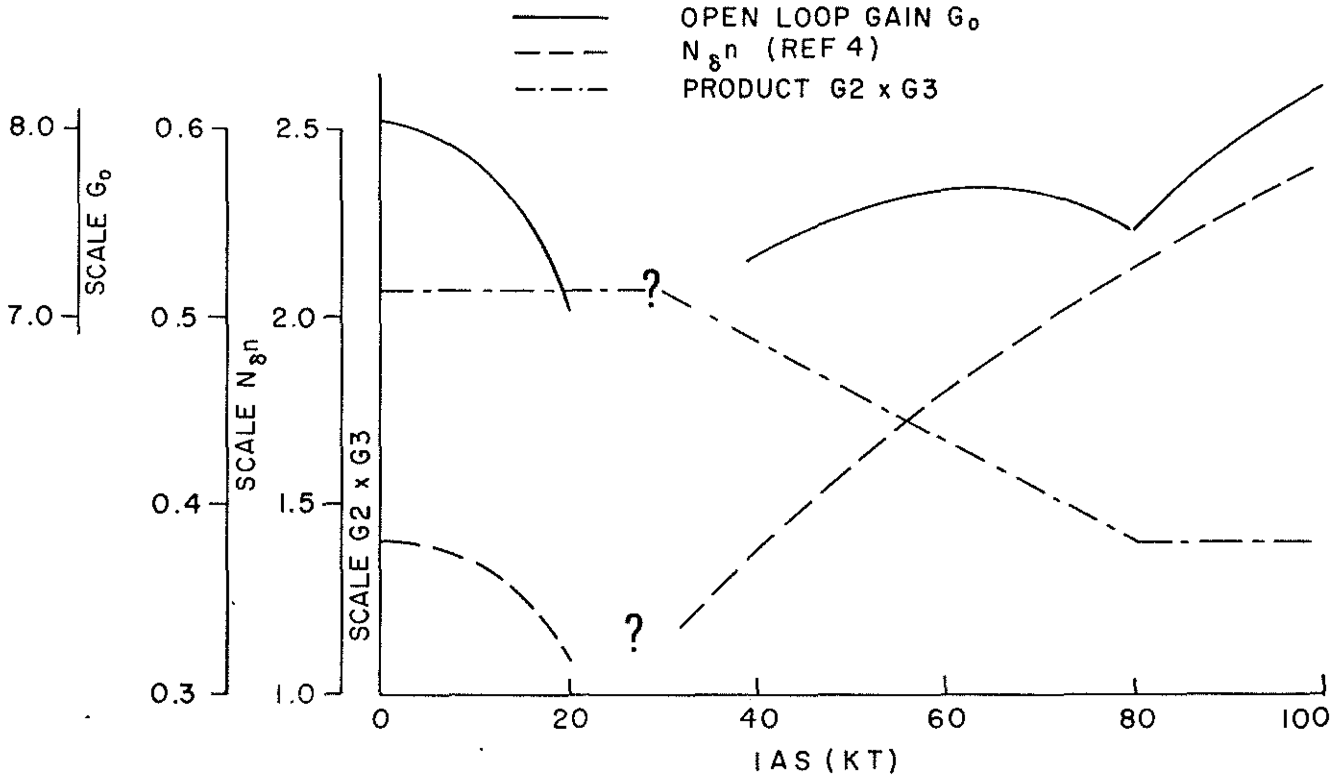


Figure B-1 Yaw Control System, Open-Loop Gain

NOTE: The query (?) indicates a region in which data from Reference 4 is unsufficient to provide reasonable quidance as to the value of N_{δ_r}