SOME PILOTING EXPERIENCES WITH MULTI FUNCTION ISOMETRIC SIDE-ARM CONTROLLERS IN A HELICOPTER

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Abstract

The installation of two side-arm mounted, isometric controllers in the NAE Airborne Simulator, a modified, variable stability Bell 205'A is described, as is the development of various control systems for use with them. The results of two experiments are presented indicating both the feasibility and acceptability of such systems for a wide variety of tasks in a conventional single rotor helicopter, with a minimum of stability augmentation. Areas of future research are indicated.

Introduction

In the fall of 1979, the National Aeronautical Establishment (NAE), a division of the National Research Council Canada, was approached by the Sikorsky Aircraft division of United Technologies, with a proposal for a co-operative project to flight test a pair of isometric side-arm controllers in the NAE Airborne Simulator. This was of sufficient interest to the NAE, relating closely to an area of active research interest, that it was possible to agree to such a program, the results of which were reported in Reference 1. Sikorsky provided the two controllers installed in a seat with side-arm supports, NAE provided the interface between the electrical outputs of the units and the simulator computers and developed suitable control systems, while pilots from both organizations took part in the formal evaluations. This paper will describe the development process that led to the evaluated systems, some of the problems encountered and their solution. Data from the first co-operative experiment and a more recent NAE experiment employing similar controllers will be presented, and intentions for future work in this area will be indicated.

Experimental Hardware

The NAE Airborne Simulator

The NAE Airborne Simulator is an extensively modified Bell 205A-1 with the stabilizer bar removed, the standard hydraulically boosted actuators replaced with dual mode electro-hydraulic actuators (which provide full authority electrical or fly-by-wire control from the right seat or full authority hydraulically boosted mechanical control from the left, or safety-pilot's seat) and extensive hybrid real-time computational capability. The safety pilot, whose controls reflect all computer inputs to the actuator system, can assume control at any time, while a safety system, which monitors the status or condition of many elements of the fly-by-wire system can cause an automatic reversion to left seat control if a 'fault' or 'out-of-limits' condition is sensed.

The on-board hybrid computation system comprises three PDP-11 processors, in mutual communication and operating on a computational cycle of 1/64 second, supported by three fields of analog computation.

The Simulator is equipped with a wide range of motion sensing systems which provide high quality measurements of its velocity relative both to the earth and the ambient airmass. A nose boom carries vanes for angle-of-attack and sideslip measurement, together with a swivelling static pressure source while dynamic pressure is taken from two wide-angle pitot probes, nose-mounted. The usual range of inertial sensors is supported by a doppler radar for earth referenced velocity measurement, while a radio altimeter provides height data, when within some 750 metres of the surface.

Figure 1 shows a simplified block diagram of a typical simulation channel as used in this series of experiments.

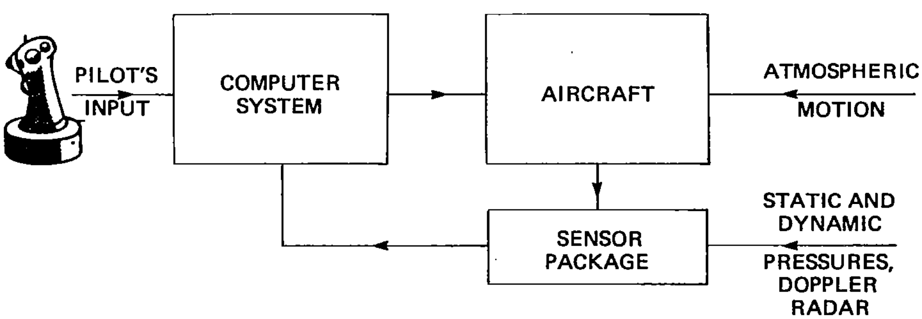

FIG. 1: A TYPICAL SIMULATION CHANNEL FOR THE ISOMETRIC SIDE – ARM CONTROLLER EXPERIMENTS

Side-Arm Controllers

The hand controllers (Fig. 2), standard, commercially available, '4-axis' units were mounted on a standard Bell seat as shown in Figure 3. Each had independant outputs in four control axes, X (fore/aft), Y (lateral), Z (vertical) and θ (torque about the Z axis) as shown in Figure 3, while their transducing characteristics were as listed in Table 1. The controller units themselves exhibited essentially zero compliance in response to forces and moments up to the rated maximum input, but when installed the system showed slight movement due to the compliance of the supporting structure. In addition to the primary force sensing transducers, each unit carried several discrete switches, namely, a trigger, a standard aircraft 'coolie hat' two axis thumb switch, and either side of the latter a simple contact closure push button. The outputs from these were read and interpreted by the on-board computers, while the functions allocated to them were 1) Trigger-communication 2) Coolie hat – progressive trim in X or Y as appropriate 3) Inboard push button – datum reset trim system activation.

Table 1. Controller transducing characteristics.

Axis	Max Input	Sensitivity	Max Output
X	20 lb. F	0.5 volt/lb.	10.0 volts
Y	20 lb. F	0.5 volt/lb.	10.0 volts
Z	40 lb. F	0.25 volt/lb.	10.0 volts
θ	60 in. lb.	0.167 v/in. lb.	10.0 volts

FIG. 2: AN ISOMETRIC CONTROL UNIT

FIG. 3: CONTROLLER/SEAT INSTALLATION

Experimental Software

Modelling

The initial proposal called for a simulation of the Blackhawk helicopter, however, since this would have required a complex, model following procedure and would have caused delays in the program and uncertainties in the validity of the model, it was not undertaken. As a compromise, the basic Bell 205 was used as the baseline model and two levels of SAS were provided, a simple rate-damping augmentation about all axes and a rate command/attitude hold mode in pitch and roll with both stiffness and damping augmentation in yaw and augmented heave damping. This approach had the advantage of being simple and certain in its implementation while presenting a 'real' helicopter, with all the cross-couplings and asymmetries inherent in this class of aircraft.

Control Modes

The experimental software was arranged so that, prior to engagement of the fly-by-wire system, the various outputs from the hand controllers could be assigned to drive different control actuators, enabling a variety of control modes to be investigated. In all, two primary and three secondary control modes were examined (Fig. 4). For the three modes which had duplicated control functions on the two controllers, both inputs were read at all times by the computers and summed, giving the pilot the option of using either hand for the primary control task.

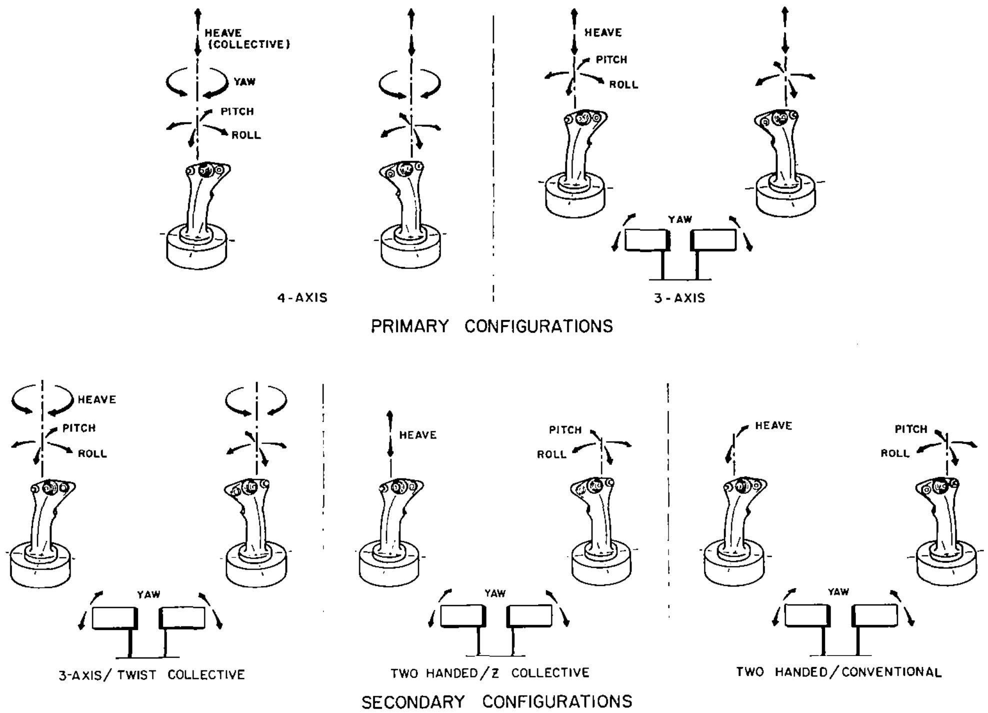

FIG. 4: ISOMETRIC CONTROL CONFIGURATIONS

System Development

Control Signal Shaping

Figure 5 shows three forms of signal shaping which represent the progression in the development process from the first flight to the point at which the system was offered for formal evaluation. The simple dead-band and linear slope of Figure 5a proved to be too sensitive for other than very limited hovering, and even that required a very high pilot workload. The dual slope arrangement in Figure 5b was quite acceptable at the hover, but still produced problems at other points in the manoeuvring flight envelope where the 'knee' became obvious to and created difficulties for the pilot. Therefore the approach shown in Figure 5c, a small linear range blending into a quadratic non-linear characteristic was finally evolved. This gave the pilot the lower sensitivity he desired around neutral, while still permitting large and rapid inputs to be made without any disturbing discontinuities in slope.

The extent of the dead band, and the extent and magnitude of the linear slope segment, which were adjustable in flight with the fly-by-wire system disengaged, were optimized for various control functions and flight conditions. For the formal evaluations a compromise set of characteristics, biased towards operating at and near the hover were used.

During the development flying it was noted that, due to arm/armrest/controller geometry, it was significantly easier to apply a Z force in the up rather than the down direction. Therefore, to provide the pilot with a more subjectively even response in this channel an overall asymmetry was applied to it, effectively magnifying inputs in the UP-Z sense.

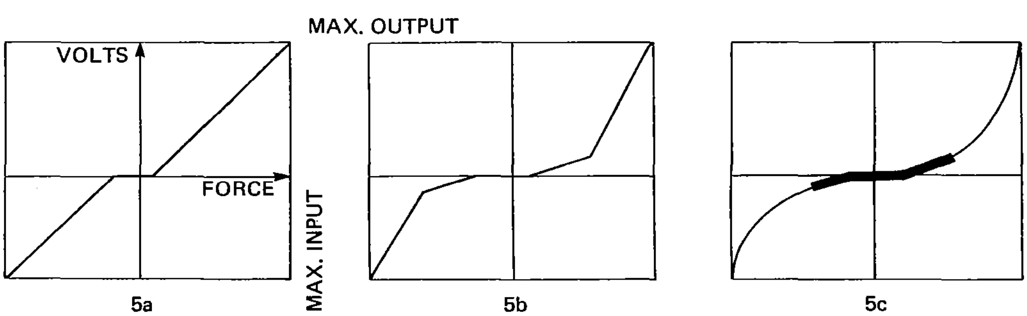

FIG. 5: CONTROL SIGNAL SHAPING

Trimming

Prior to first flight, two trim systems were installed, a progressive, constant rate trim, activated by the 'coolie hat' and applied to the X and Y function of the appropriate controller, and a datum reset system. This latter system was activated by pressing the inboard thumb button on either controller which action disengaged that unit from the drive system, while the inputs to the control channels were held constant by the computer. The pilot was then able to relax any held force and reconnect the controller by releasing the button. Both of these proved to be unsatisfactory. While the progressive system could be used, the force changes associated with repositioning the hand on the controller to make contact with the switch were sufficient to introduce unwanted inputs to the system, thereby making unacceptably large demands on the pilot in terms of the care and physical accuracy of his hand movements. The datum reset was somewhat easier to use, (except that again repositioning the hand and applying sufficient force to the button to overcome its spring generally caused inadvertent inputs), but suffered from a more fundamental problem. If, during the period when the controller was disconnected from the controlled system, the aircraft was externally disturbed, then on reconnection the pilot could find himself with an out of trim condition even greater than that which he had been in the process of relieving initially.

To overcome these difficulties, a selectable, continuous integral trim was devised, which provided an integral-plus-proportional command signal from the hand controller to the system, with the inboard thumb button being reassigned to the activation of this system. The final configuration is shown in Figure 6. As reported in Reference 1, the handling characteristics of this type of system depend on the ratio of integral to proportional gains (K_{ip}), and the optimum value need not remain constant over the entire flight envelope. However, for this experiment a set of constant values was used, and they are reproduced here in Table 2.

Table 2. Integral/proportional gain ratios.

Channel	K_{ip}
Roll	1.0
Pitch	0.5
Yaw	1.9
Heave	1.5

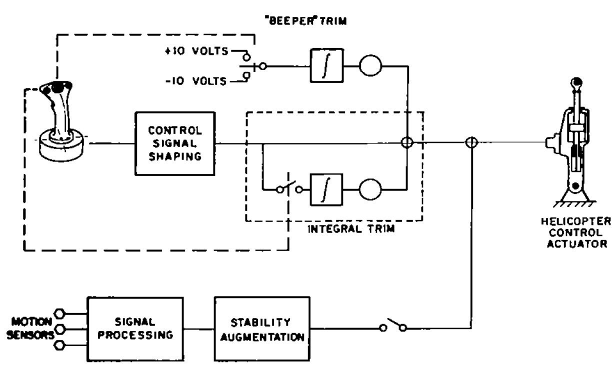

FIG. 6: TYPICAL SIMULATION CONTROL CHANNEL

Control Position Indicators

Late in the evaluation phase of the first experiment, when one of the subject pilots elected to attempt off-level landings and take-offs, a significant and anticipated operational disadvantage of isometric controllers was highlighted. In a conventional helicopter the pilot has a direct bio-mechanical indication of the tip-path-plane orientation; the cyclic position is a direct analog of the normal to that plane. This information is used by and is of great importance to the pilot during all take-offs, but especially when lifting off from a slope. A rigid controller inherently robs the pilot of this important piece of information and, under some circumstances, visual information may not suffice as a replacement. Operational limitations associated with the absence of another performance related cue, tail rotor collective pitch, sensed in a conventional helicopter from pedal displacement, also were evident in these experiments. This information is used by the pilot as an indication of yaw control authority remaining when operating with large yaw rates or in the presence of large sideslip velocities. Figure 7 shows a rudimentary Control Position Indicator (CPI) that was fitted above the instrument panel coaming to compensate for the loss of these cues and while far from ideal (the indicator was adapted from a fixed wing auto pilot trim indicator) it sufficed to expand the useable envelope in the areas indicated above.

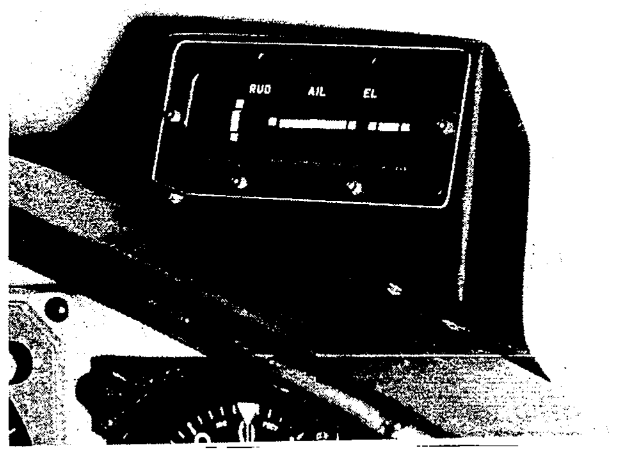

FIG. 7: CPI INSTALLATION

First Experimental Evaluation

Description of the Experiment

A series of tasks, shown in detail in Appendix A and intended to represent the greater part of the flight envelope of the 205, was selected for evaluation by a group of five pilots, two from Sikorsky and three from NAE. Cooper Harper ratings were required for each task and, subsequent to the completion of the experiment the subjects were asked to reply to a general questionnaire; their responses are reported in full in Reference 1.

The decision was made to introduce the subjects directly to the two primary control configurations rather than to train them via a force analog of a conventional displacement system. To provide an overall comparison, one of the NAE pilots, with some five years experience on the aircraft was asked to rate the tasks using the basic, unaugmented, aircraft and displacement controls. The experience levels of the evaluation pilots are shown in Table 3.

Table 3. Evaluation pilot experience levels.

Pilot	Total Hours	Helicopter/Fixed Wing
A	3500	3250/250
B	5700	400/5300
C	6900	900/6000
D	6500	4000/2500
E	5600	1550/4050

Results of the First Experiment

Cooper Harper Ratings

Figures 8 to 10 are plots of the Cooper Harper ratings obtained during the experiment. All data points have been used and they are coded by task rather than pilot so that any effect of task on opinion can be examined.

Summary of Pilots Comments

As a supplement to the numerical opinions obtained during the experiment, the following summary of the subjects' written and verbal comments for which there was reasonable commonality is produced below:

1) When using a three axis configuration, force rather than displacement pedals were preferred. the need to use leg and foot movement when applying only forces with the hand generally being judged less natural than applying forces to all controls.

2) The assignment of collective to a twist function was not liked since it tended to be prone to inputs in the incorrect sense, and the instinctive relationship between input and control response, present when collective was driven via the Z axis, was absent.

3) All subjects felt that the more fully supported and erect posture inherent in the side-arm controller installation reduced fatigue compared to the conventional helicopter seating position.

Pilot Adaptation

With one exception, discussed in more detail below, all subject pilots adapted easily to the multi-function configurations, to the extent that the majority of them elected to commence data runs before the allotted training period was complete.

Discussion of Results of First Experiment

Four Axis System

Consider Figure 8 and ignore, for now, the circled data points. While the degree of acceptability increased with increasing stability augmentation, as might be expected, the main point of interest is that even the most primitive form of augmentation brought the peak of the rating distribution to the acceptable side of the 3.5 boundary. Note too, that the data in the left hand column suggest that there is little difference between the basic, unaugmented, aircraft when flown with displacement and isometric, four function controllers. Also, the spread of points due to individual tasks suggests that no particular portion of the manoeuvring flight envelope examined produced opinions radically different from any other.

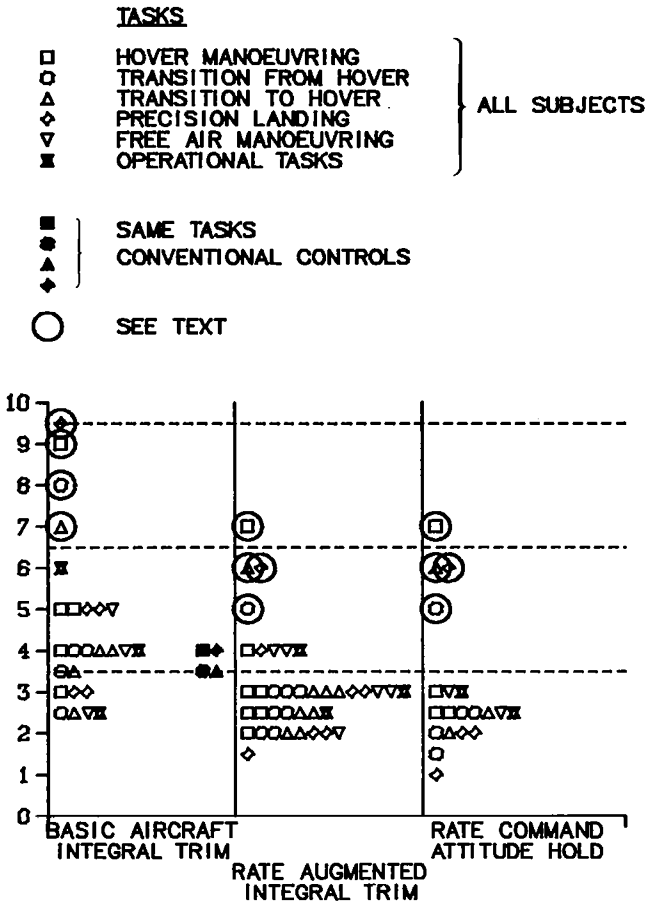

FIG. 8: 4 FUNCTION, RIGHT HAND, EVALUATIONS

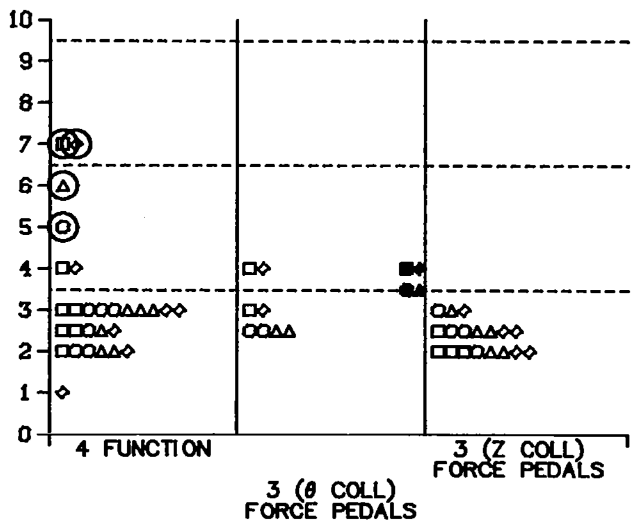

FIG. 9: RATE AUGMENTED, INTEGRAL TRIM

The circled data points are of special interest, and may have a particular significance. They were all contributed by a single subject, who was the exception to the general pattern of easy adaptation to the isometric, multi function system. It is possible that he may represent a sub-group in the piloting body who will adapt only with great difficulty to such systems, and if so, this could have significance in the areas of trainee selection or training washout.

Effect of Control Configurations

From the evidence of Figure 8, the rate damped model was selected to examine the effects of various control configurations on pilot opinion, the results being plotted in Figure 9. Of the two primary configurations there is a slight preference for the three-plus-pedals over the four-axis mode, with all data points for the former configuration being on the acceptable side of the 3.5 boundary.

The Effect of Increasing Stability

The final plot in this series shows the effect of increasing stability when using the preferred control configuration. It suggests that while the tendency for acceptability to increase with increasing stability augmentation is present, even the 'basic aircraft' is within the fully acceptable boundary with this control system.

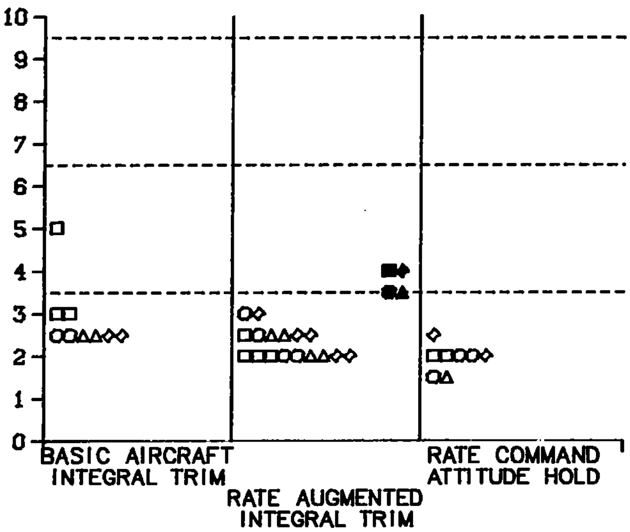

FIG. 10: 3 FUNCTION, Z COLLECTIVE, FORCE PEDALS

Biasing Factors

When interpreting the above data, two factors should be considered. The possible sense of euphoria experienced by the pilots on discovering that they could not only fly, but fly well, with such a radically new control system may have introduced a favourable bias in the ratings. On the other hand their very low experience level at the time of rating (no more than some 10 hours each by the end of the flight phase, with the exception of the development pilot, who had about 22 hours) might have been expected to produce the reverse effect. These effects are reasonably expected to diminish as work in this area proceeds.

The Interim Period

From the end of the initial experiment to the summer of 1981, no formal investigations were carried out, but the controllers were flown quite frequently, often riding 'piggy-back' on other experiments or for the purpose of demonstration to pilots from other organizations and countries. In this period too, they were flown in the IFR environment, where the ability to free one hand for ancilliary tasks, without having to abandon the control task met general approval. The pattern of relatively easy adaptation for the majority of pilots was maintained.

Development of an Alternate Hand Grip

Both during the initial experiment and subsequent flying, it had been noticed that, although the controller units themselves had little inherent cross-talk, in use there were several coupling tendencies, the dominant ones being a nose-up pitch with UP-Z commands and a roll into yaw. Both these effects appeared to be, if not due to, at least exacerbated by the hand grip design. Figure 11a shows the original hand grip supplied with the isometric controller. If a lightly cupped hand applies a force to this grip in the UP-Z direction, the pressure point on the handle is sufficiently displaced from the force sensing axis to result in an appreciable moment in the nose-up sense. Similarly roll inputs, generally applied with the inside edge of thumb or forefinger produce a moment about the Z axis, hence producing a yaw command.

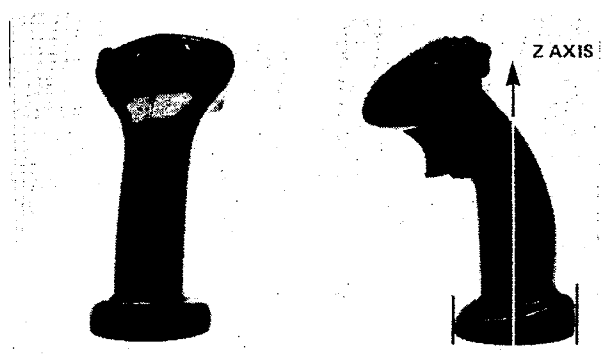

FIG. 11a

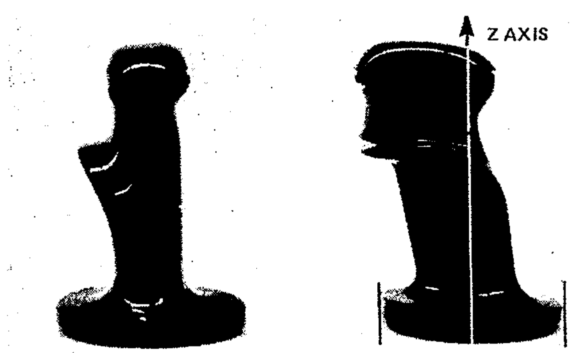

FIG. 11b

FIG. 11: HAND CONTROLLER CONFIGURATIONS

One other problem noted with the original grip was that the slimness and almost circular cross section of the lower portion of the design made the application of larger yaw inputs relatively more difficult than inputs in the other three axes. This was one action for which it was necessary to grip the handle firmly, a most undesirable technique which leads to both rapid hand fatigue and undesired inputs, both pilot and environment induced.

To eliminate, or at least reduce the effects of these undesirable characteristics, the handle shown in Figure 11b was designed and manufactured at the NAE. Its main features are the elimination of the curvature in the X-Z plane, a somewhat ovoid cross section and, to assist in the application of a 'clean' Z force, a much larger base flange and a good sized thumb/finger support table.

While no formal evaluations of this design have been made, it has found general acceptance among the project pilots and has been used in a recent series of tests.

The Second Experiment

Following the initial work with these controllers, it was felt important that a more direct comparison between the multi-axis, isometric systems and conventional controls should be made. To this end an experiment was designed and flown in the summer and fall of 1981.

Description of the Experiment

Using the marked ground course, shown in Appendix A, pilots were required to fly, in a single run, an accelerate/stop segment, rearward, lateral and quarter translations, two 'pedal' turns, a precision touch-down and a lift-off. The briefing to them included instructions to pay close attention to height-keeping and tracking, and to fly the course 'briskly'.

Qualitative and quantitative data were recorded using both the aircraft data acquisition system and ground observation. The pilots were also asked to provide a subjective assessment of the relative ease and precision of the task when using the multi-function controllers, compared to the conventional controls.

The subjects were required to fly the course alternating two runs with conventional controls and two runs with either the four-axis or the three-axis plus pedals configurations using the isometric side-arm controllers. Each flight consisted, generally, of one practice and eight data runs. Two complete sets of runs were flown with each isometric configuration and refamiliarization was permitted for each pilot between his evaluating with the different side-arm controller systems.

The data were analyzed for precision, control activity and time as a means of investigating the relative performance of a particular subject as he moved from one control system to another.

The subject pilots for this exercise were all from NAE and Table 4 summarizes their relevant experience to the end of this experiment.

Table 4. Pilot flying experience at the end of the second experiment

Pilot	Total	Helicopter/Side-Arm
C	7200	995/37
B	6054	432/70
G	905	313/13
H	4002	4002/9

Results

While most of the data from this experiment still awaits analysis, some preliminary results are presented in Figures 12 to 14, specifically, the pilots' subjective opinions, track deviations in the lateral translation segment, and touch-down scatter.

Pilot Opinions

As illustrated in Figure 12, the pilots generally considered isometric control to be more difficult and less precise, in this type of closely bounded task, than conventional control. There is also a suggestion that this judgement is less severe in the case of the three axis system than in that of the fully integrated, four axis configuration. However, the greater number of opinions fall between the 'same/more difficult' and 'same/less precise' responses, indicating no great difference from displacement controls. The relatively very short exposure of the subject pilots should also be considered when looking at these replies.

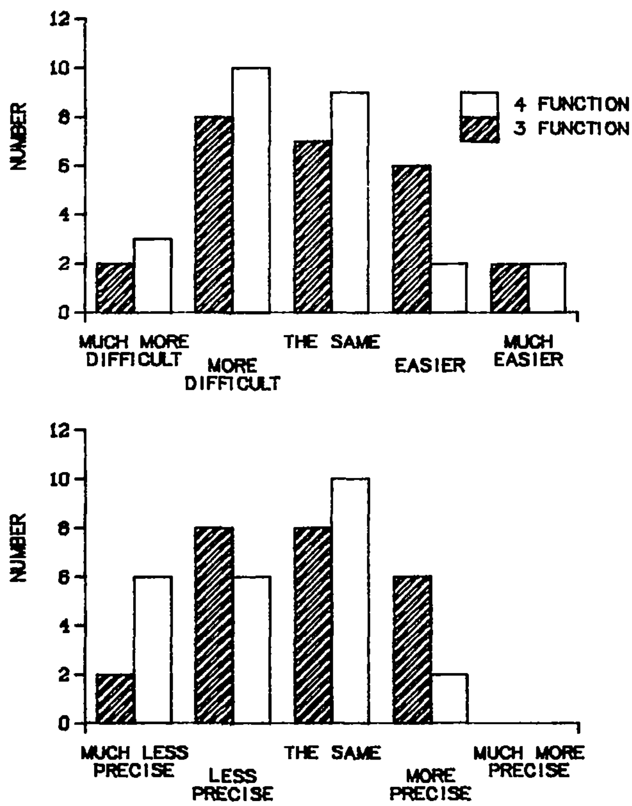

FIG. 12: PILOT'S SUBJECTIVE ASSESSMENTS

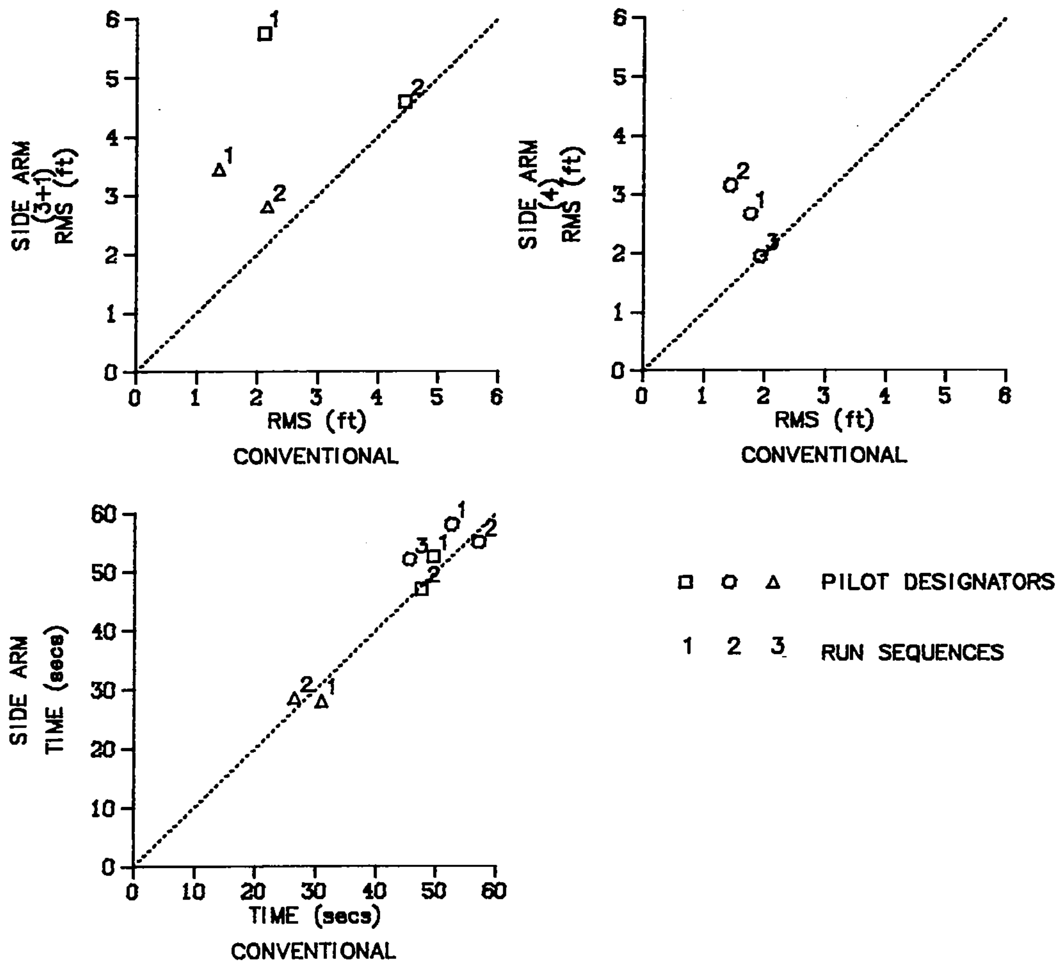

FIG. 13: PERFORMANCE COMPARISONS, CONVENTIONAL AND SIDE-ARM CONTROLLERS LATERAL TRANSLATION TRACKING

Lateral Tracking

To obtain the data plotted in Figure 13 time-adjacent pairs of runs were analysed for RMS deviations and plotted one against the other, thereby eliminating, as far as possible, any effects due to changing atmospheric conditions or pilot fatigue.

While the general tendency is towards a more unsteady tracking performance with the isometric controllers, it is possible that learning curve effects are still present, since there is a consistent tendency for the RMS values for the two control systems to approach one another the later into each flight the data are taken. It is noteworthy that there is no indication of any time penalty when using the force controllers, which may suggest that even though the subjects considered the tasks to be more difficult, and their performance to be less precise with the isometric than with the conventional system, the level of degradation was not such as to cause them to proceed with unusual caution.

Landing Accuracy

Figure 14 compares landing accuracy of systems, and a definite degradation in performance is noted for the isometric systems. (It should be emphasized that the control system being flown in these tests had not been specifically optimized for the landing task.) There is an interesting difference in the pattern of landing errors between the systems; using conventional controls the errors tend to lie along the lateral axis of the aircraft, while with the isometric systems, there is a definite slew towards the longitudinal. This may be due to a change in the type of visual cues required by a pilot when landing with isometric systems compared to those he habitually uses when operating with displacement controls. This may demand that more of his visual attention be directed towards the front of the aircraft than to the side and, considered in combination with a natural tendency to drift the aircraft along the line of sight, may have caused this dispersion pattern. (It is worthy of note that in the Simulator the evaluation pilot sits on the right, and that there are no errors either to the left or the rear with any control system.)

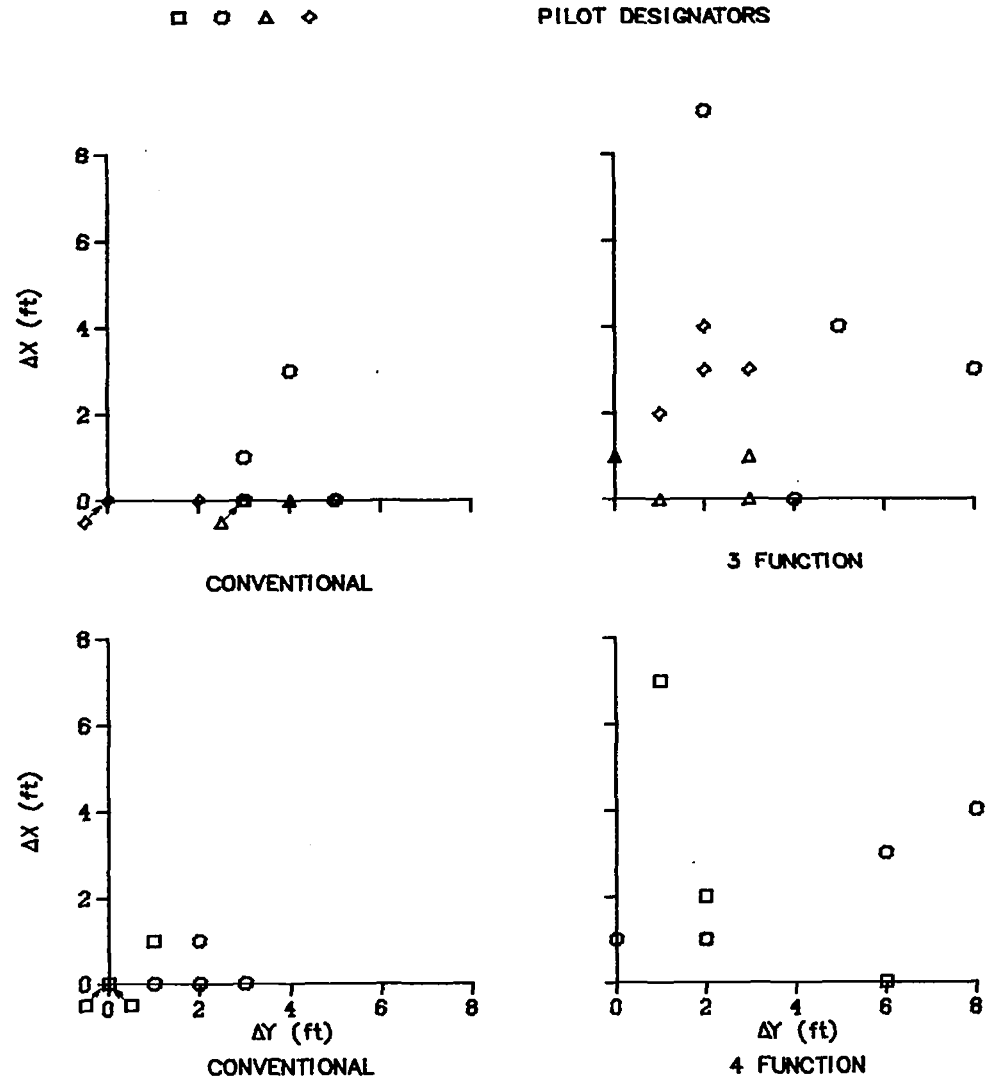

FIG. 14: TOUCHDOWN SCATTER COMPARISONS

Future Intentions

The National Aeronautical Establishment will continue its investigation of integrated, multi-axis control systems as part of the aircraft flight systems and flight mechanics research program. At the time of writing, for example, a controller, similar to the one described in this paper but with some compliance, is being prepared for installation in the Airborne Simulator. The potential merits of limited motion will be investigated.

It is expected that the main areas of interest for future study will be:

1) Evaluation of the limited motion controller.
2) An investigation into more sophisticated control systems, including mission and task level optimization, and adaptive or scheduled variations in control system characteristics.
3) Further direct comparisons between displacement, limited compliance and isometric controllers.
4) Investigations of integrated control/display systems using multi-axis controllers and advanced electronic displays.

Conclusion

The work at the NAE over the last two years has demonstrated both the feasibility and acceptability of using multi-function, isometric, side-arm controllers to perform a wide variety of tasks in a conventional helicopter, with the minimum of stability augmentation. While these two short test programs do not provide definitive answers to all of the questions which the designer must ask about such radically unconventional control systems, they do indicate that this will be a fruitful area for future research efforts.

Acknowledgement

The names of the subject pilots, in alphabetical order, with their affiliations are:

K. Davidson	NAE
S. Kereliuk	NAE
G. Kohler	Sikorsky Aircraft
M. Morgan	NAE
R. Murphy	Sikorsky Aircraft
D. Sattler	NAE
A.D. Wood	NAE

Reference

Report–Sinclair, M., and Morgan, M., "An Investigation of Multi-Axis Isometric Side-Arm Controllers in a Variable Stability Helicopter", National Research Council Canada, Aeronautical Report LR-606, August 1981.

APPENDIX

SOME PILOTING EXPERIENCES WITH MULTI FUNCTION ISOMETRIC SIDE-ARM CONTROLLERS IN A HELICOPTER

Task Details for the Two Experiments

First Experiment

Table 1 details the tasks required to be performed by the subject pilots in the first experiment. A single Cooper Harper rating was requested for each task, with the exception of Task 2A, where separate ratings for the transition to and from the hover were required.

Table 1. Task details for the first experiment.

Task #	Title	Content
1	Manoeuvring at Hover	1.1 Hover into and across wind 1.2 360° turn left and right 1.3 Lateral translation, *moderate rate* 1.4 Accelerate and rapid stop
2A	Circuit from and to Hover	2.1 *Transition from hover* 2.2 Transition to hover
2B	Landing	2.3 Zero speed landing from hover to terminate in marked zone
3	High Speed Flight	3.1 Summetrical pull-ups 3.2 Steep turns 3.3 *Roll reversals* 3.4 Partial power descents 3.5 Sideslips 3.6 High power climb
4	Operational *Manoeuvres*	4.1 Pop-up and point 4.2 *NOE course* 4.3 Downwind take-off and turn

Second Experiment

Figure 1 represents the ground course marked out for the second experiment. The boxes contain instructions to the subject, while the circled numbers indicate radio transmissions required for data correlation. Table 2 gives the dimensions of the various linear segments.

Table 2. Ground course dimensions.

From	To	Distance (ft.)
A	B	670
B	C	445
C	D	450
D	E	500

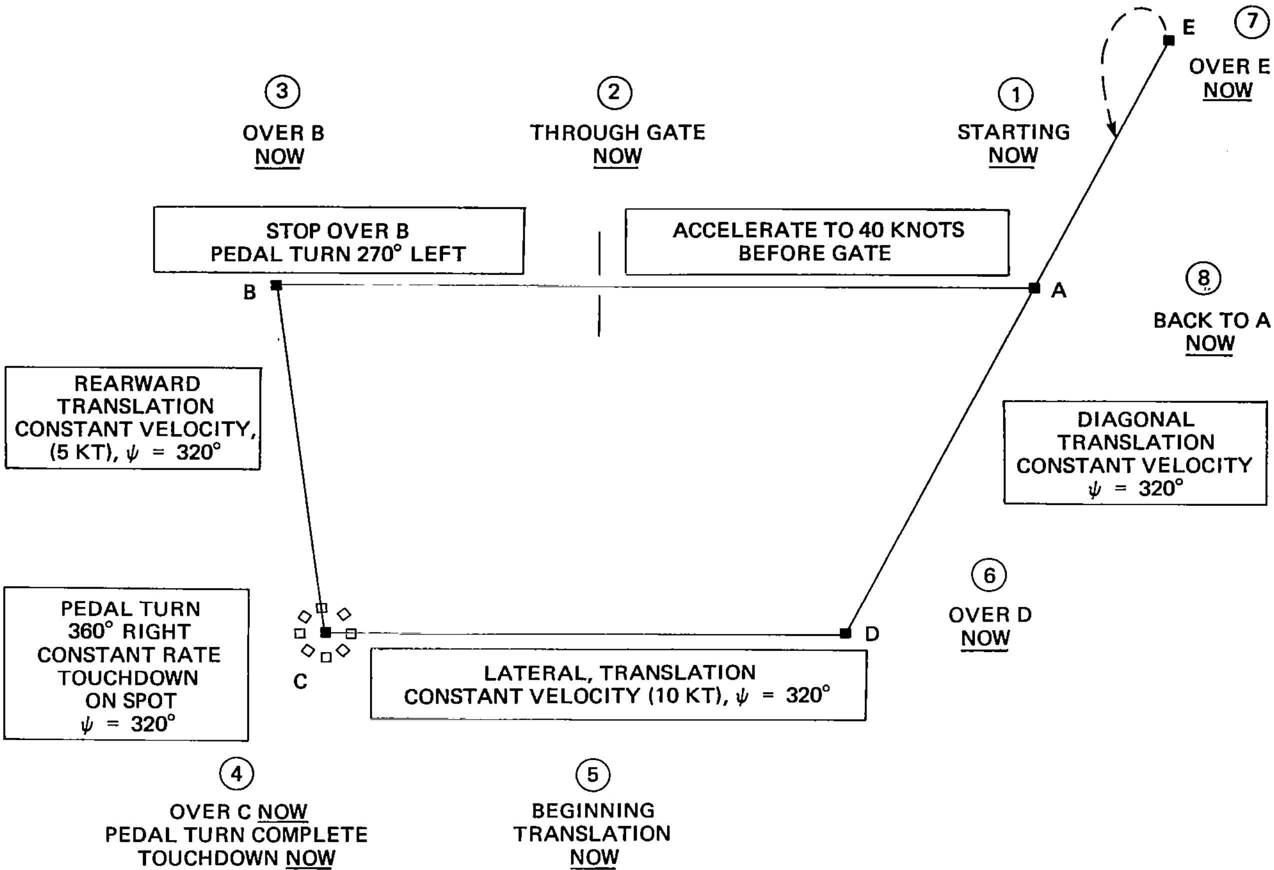

FIG. 1: COURSE FOR INTEGRATED SIDE ARM CONTROLLER EVALUATIONS