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HELICOPTER INTEGRATED CONTROL (GAT-2H)

John D. Waugh
John A. Stephens

December 1976
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U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

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Two experimental three-axis helicopter controls combining collective and cyclic functions into an optional one-handed controller were simulator flight tested and their performance, measured in energy-expended terms, was compared to conventional helicopter controls.

The nature of the results indicate further development through flight testing should be undertaken.

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Mr. John Rollins, electronic technician, as a high-time fixed-and-rotary-wing aviator, provided important conceptual inputs and was responsible for the electrical modifications and operation of the simulator and the instrumentation required.

Messrs. Elmer Dieter and Vincent Stricker, machinists, for the painstaking mechanical and machine shop work required to fabricate and install the control systems.

CONTENTS

HELICOPTER INTEGRATED CONTROL (GAT-2H)

INTRODUCTION

The series of experiments described in this report are part of a continuing effort at the U.S. Army Human Engineering Laboratory (HEL) to explore the feasibility of utilizing a simple, three-axis control mechanism for the primary flight control of helicopters.

SUMMARY OF THE PROBLEM

From the earliest successful attempt by Igor Sikorski to develop a practical helicopter until today, the aviator has had to use both hands and both feet operating separate controls to maintain control of the helicopter's various axes of motion, and thus achieve the desired flight path.

Although the basic task of a helicopter's directional control has not changed significantly since its invention, an evolution in the development of the gas turbine has reduced the manipulative skill required of the pilot's left hand. Now it is no longer necessary for the pilot to match his collective-input power demands with appropriate engine-throttle adjustments as he once had to with reciprocating-engine-powered ships.

Although the hand throttle's twist grip remains part of the collective control lever, it is essentially preset and is not used in the primary flight-control process. The power demands are met automatically through the gas turbine's fuel-control system.

This power-control evolution has essentially reduced the control requirements on the left hand to just one: selecting the collective pitch of the main rotor system or, in simpler terms, controlling the amount of lift.

In some modes of flight, considerable collective manipulation is required to maintain the desired position, as in a hover, or a velocity vector in nap-of-the-earth (N.O.E.) flight. By and large, however, it appears somewhat wasteful to commit 50 percent of a pilot's manual capability to this one primary-control function. This arrangement causes several severe penalties in cockpit design and subsystem control.

While carrying out studies of helicopter combat losses in Southeast Asia (SEA) in 1969, it became apparent that there was an opportunity to save airmen's lives if the control system could be improved so the pilot could continue in full control while using either hand by itself, or both of his hands, at his discretion.

Ultimately, after several false starts in studying how incapacitation affects a pilot's ability to fly, which are not germane to this report, it became obvious that the four primary control dimensions--power and lift (or vertical thrust component) in the left hand, and lateral and longitudinal cyclic control in the right hand--had been essentially reduced to three dimensions in gas-turbine ships. Thus, from 1973 on, the effort focused on investigating the feasibility of controlling a conventional helicopter with an integrated cyclic and collective control or a three-axis controller that could be used with either hand or both hands.

APPROACH

It must be understood that a blue-sky approach was not utilized in developing these test controls. The controls that emerged during the preliminary studies reported here are not freaks or lash-ups. The cost of developing, fabricating and testing these simulator prototypes necessitated an exhaustive screening process to eliminate potential dead-ends, while at the same time insuring that sound approaches were not overlooked.

Control concepts with all manner of kinematics were proposed and analyzed. The following ground rules were set forth:

1. The control must occupy a minimum amount of space—both statically and dynamically.

2. It must not incorporate input control axes that are in line with major "G" forces produced by maneuver, vibration, gusts, or buffet loads on the pilot.

3. It must use a direct mechanical linkage without any Automatic Flight Control System (AFCS) or fly-by-wire components.

4. It must be inherently reversible to allow for hard-coupled dual installations.

This report will not attempt to develop the complete rationale for the control designs tested in the simulator. It is a loosely drawn oversimplification of the complicated technology of controlling helicopter rotors, and only a few simple design constraints are discussed. However, the overriding consideration in selecting candidate approaches was that they must not depend on fly-by-wire or AFCS components. It was felt that, if a three-axis controller had any place in future helicopter cockpits, its final form would necessarily have to totally replace the conventional system, and therefore must be suitable for all classes of ships. This would have to be true regardless of what lay between the pilot's grips and the rotor blades. This approach does not preclude all kinds of input shaping and augmentation in large, sophisticated applications; but, likewise, it does not prevent using a three-axis control in light, inexpensive applications where the pilot pushes directly on the swashplate or a gyro-bar.

The design philosophy behind the basic kinematics developed for the experimental controls likewise stems from examining the basic nature of the helicopter itself and from a "keep it simple" approach.

The key component in applying control forces to a helicopter's rotor blade is the swashplate. This device is the vital interconnection between the "airframe-fixed" control elements and the rotating-rotor-blade control elements. As it is tilted about its gimbal axes, it "pumps" longitudinal and lateral cyclic commands to the rotating parts and, as it is displaced vertically up and down the mast, it changes the rotor blade's overall or collective pitch angle along with the cyclical pumping. Thus the swashplate is a point where the cyclic and collective commands to the rotor are integrated into a single control element. The approach employed in the HEL controls was simply to maintain this same kind of integration all the way back through the system to the pilot's input.

Thus the pilot's controls, much like the swashplate itself, are rotated about their longitudinal and lateral axes for cyclic or directional control, and displaced along a third axis for collective or "lift" control. If the control were to be a truly "reflex" type, this third axis would have to be vertical; that is, the pilot would have to raise or lower the grip assembly to raise or lower the helicopter. This approach, however, would be complex to achieve mechanically and, even more important, would directly violate the second rule above. Consequently, the generally fore-and-aft axis was selected as the collective displacement's axis of control, with a pull aft providing up, and a push forward providing down, collective commands. Figures 1 and 2 show the wheel and grip concepts in the GAT-2H simulator.

PURPOSE OF THE EXPERIMENTS

The purpose of these experiments was to examine the performance of trained rotary-wing aviators utilizing a three-axis controller in simulated flight.

APPARATUS

The following apparatus was assembled into a system providing a vehicle for testing the pilot subjects (Ss), and a means of assessing their performance with the different flight controls.

1. GAT-2H Helicopter Simulator—Singer-Link. Instrument flight simulator with pitch-and-roll motion (including washout), navigational and radio-navigational capability (not used in this investigation), ground-track plotter, and electrical analog signals for all flight, aerodynamic and position parameters (located in the simulator computer).

2. Electrical interface which combined pitch, roll, and vertical rates into a weighted sum of their absolute values.

3. Model 45.009 Analog computer—PACE -EA1. The output from the above interface was scaled and integrated in the analog computer during each trial, and the integrated score was displayed on a Fluke Model 8100A digital voltmeter to five significant digits.

4. Chart Recorder—Sanborn Model 322. Depicted a time-history of the signal from the electrical interface and the integrated signal from the analog computer.

5. Videotape recorder and closed-circuit television camera and monitor-Sony Model AVC-3400. Monitored and recorded instrument-panel indications during each trial.

Figure 3 shows a schematic drawing of the entire system. The main performance indicator was the integrated score read directly from the output of the analog computer at the end of each trial. The rms and motion-count scores were read from the Sanborn chart-recorder tapes (Figure 4).

PROCEDURE

Because the test simulator is an instrument trainer with no visual-display capability, the basic flight task selected was a demanding instrument-flight pattern referred to as the Bravo pattern (Figure 5). Each S, whether he was familiar with the GAT-2H or not, was given an initial warm-up period of 1/2 to 3/4 hour. After familiarization, the S started practicing the modified Bravo instrument pattern. He flew the first few Bravo patterns with one of the experimenters in

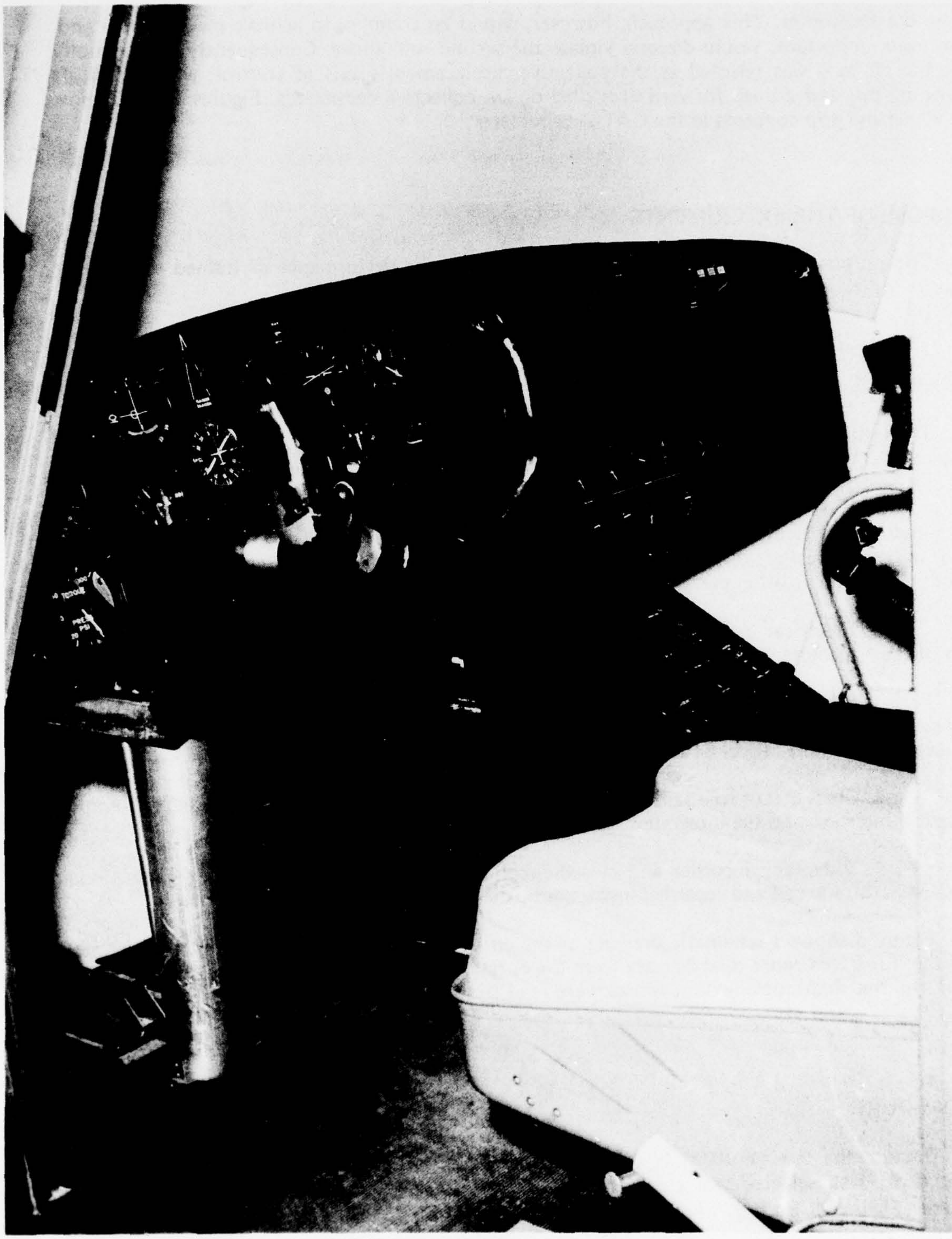


Figure 1. Wheel concept installed in GAT-2H simulator.

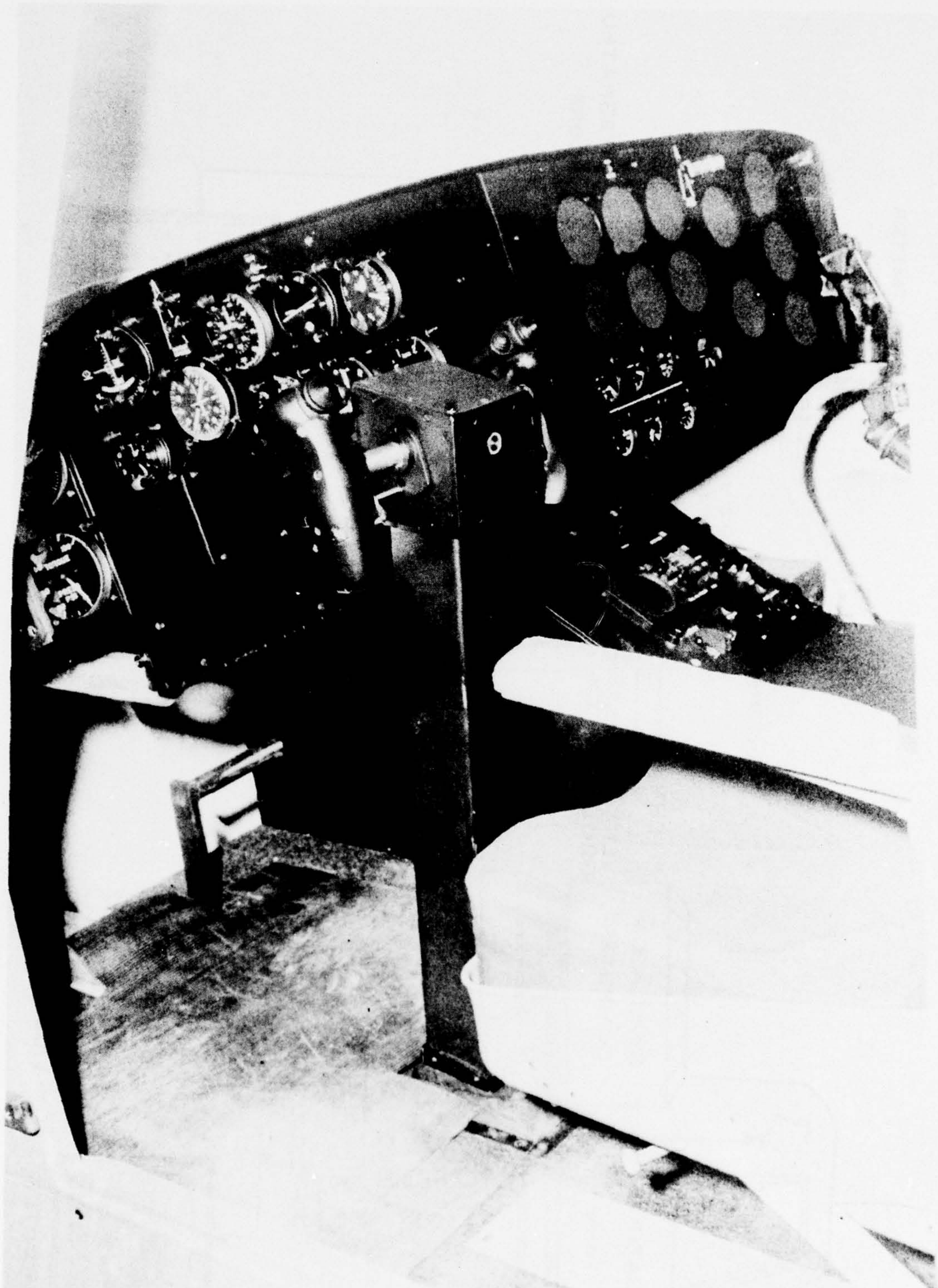


Figure 2. Grip concept installed in GAT-2H simulator.

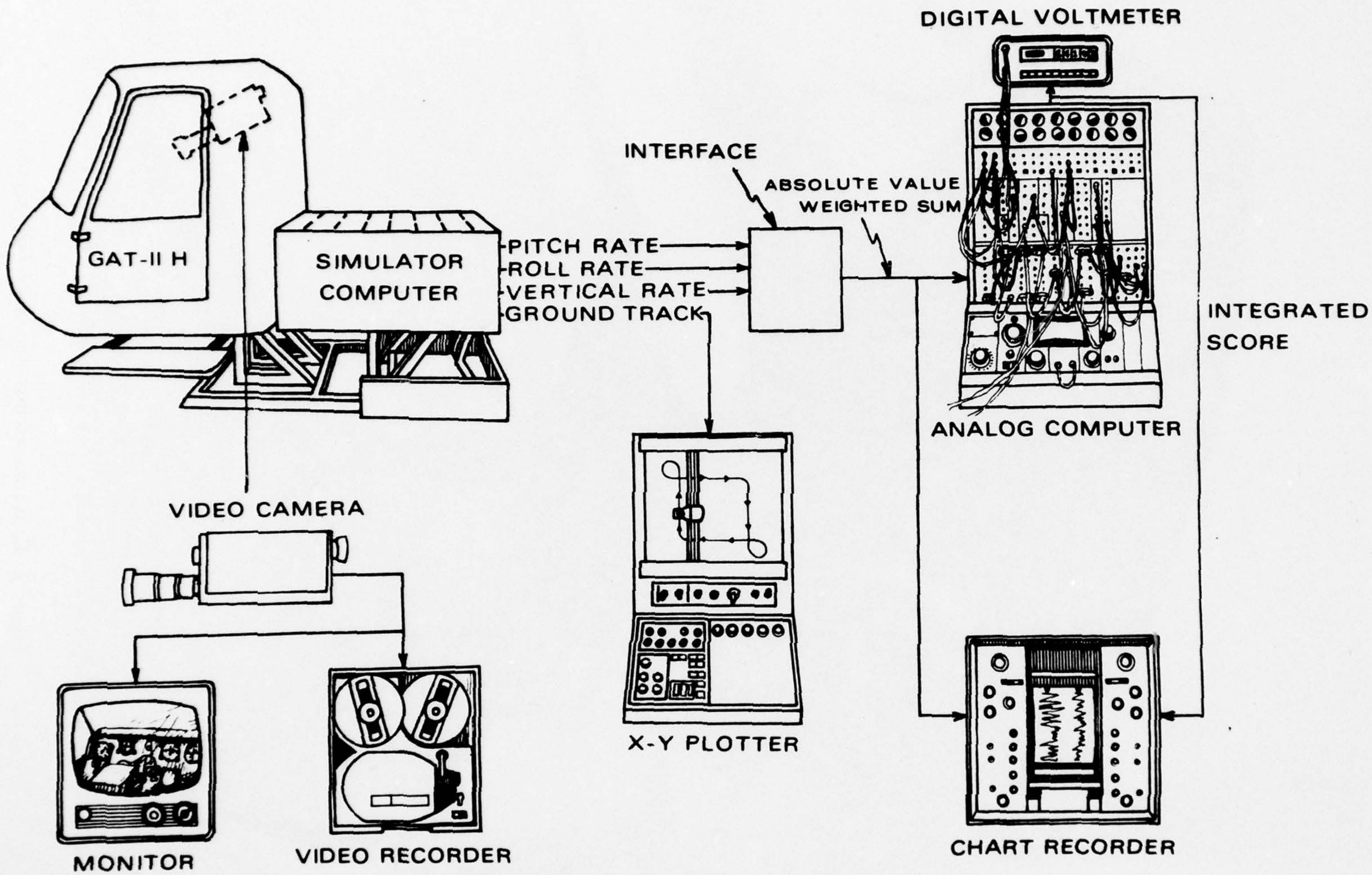


Figure 3. Simulator, monitoring, and scoring system.

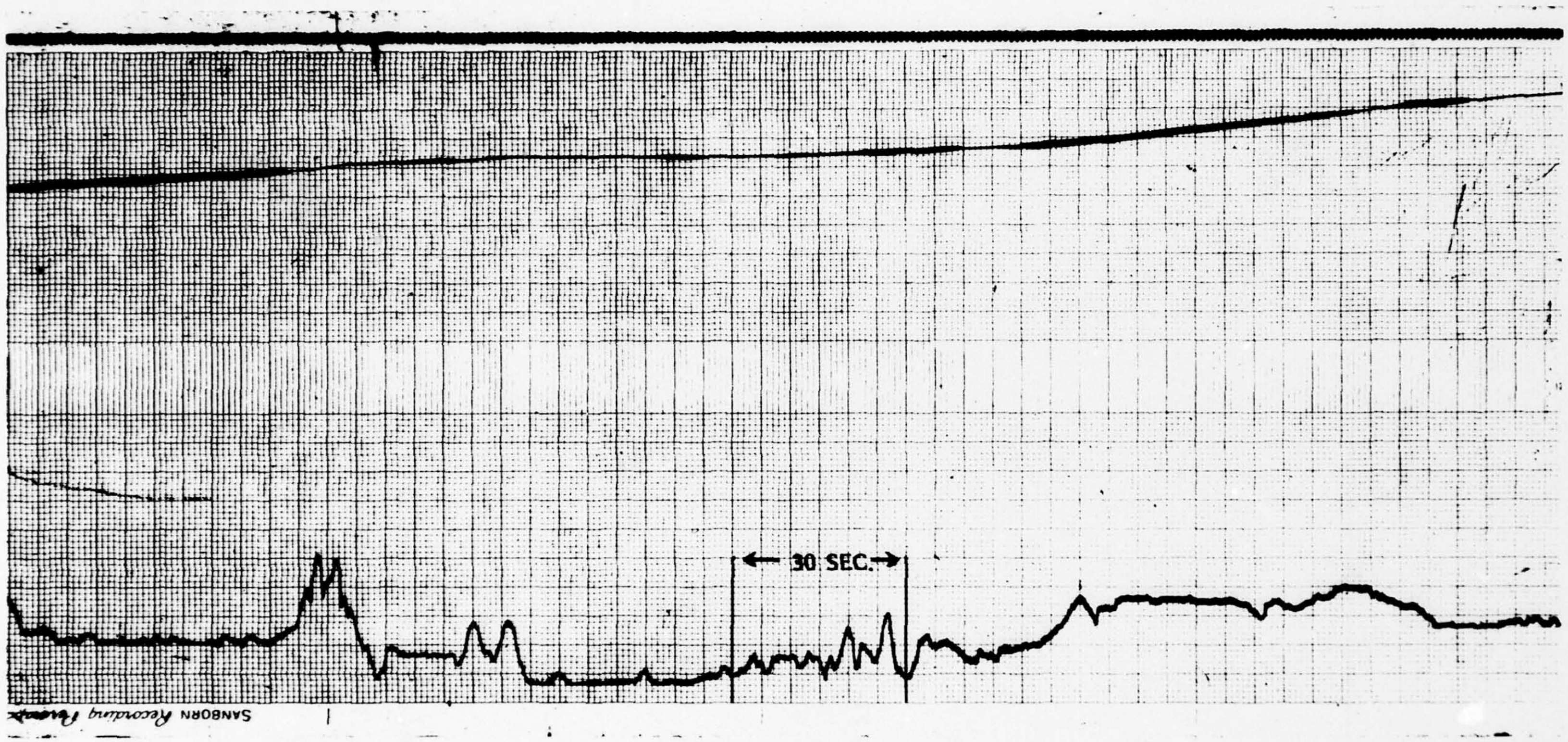
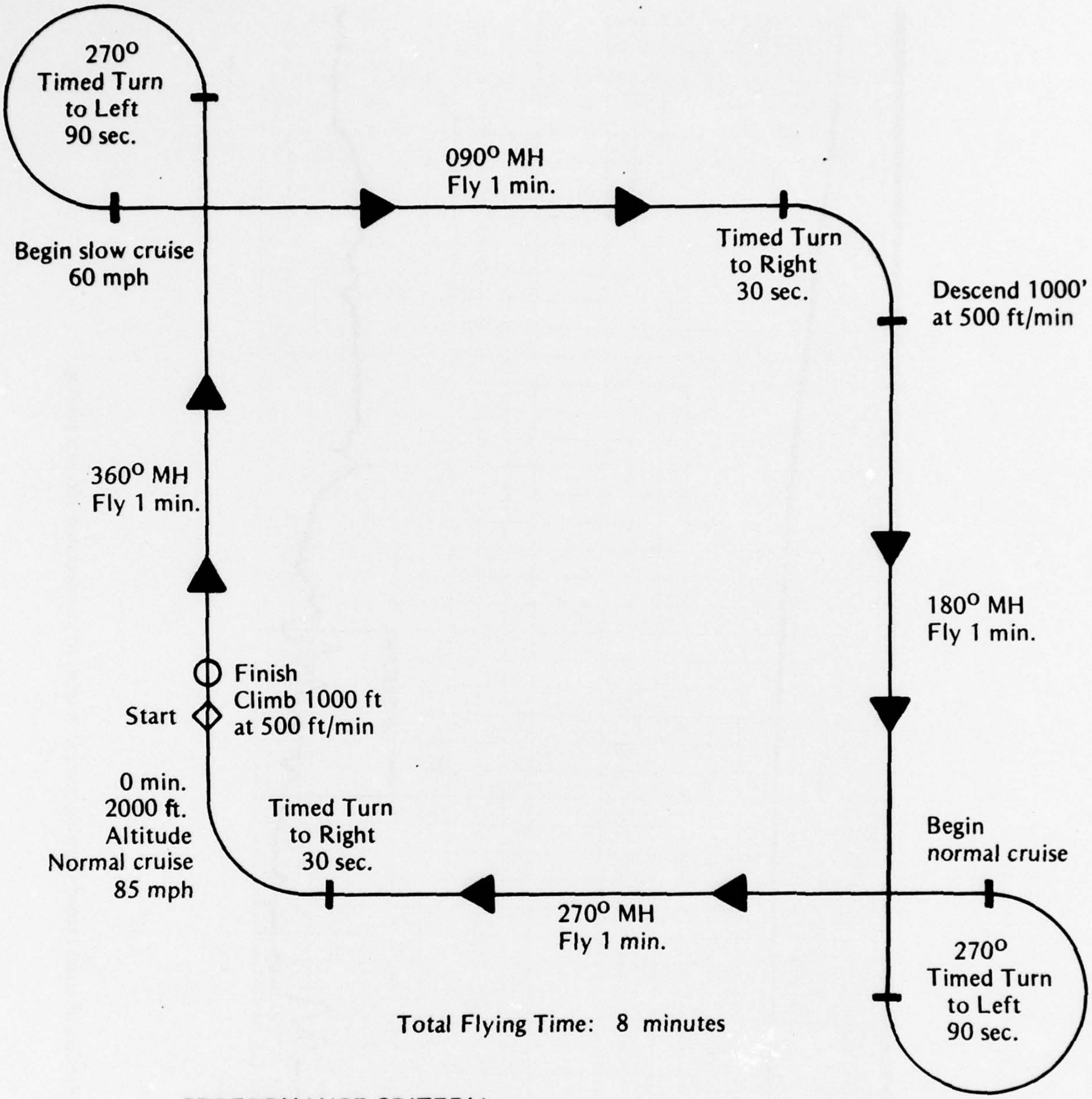


Figure 4. Portion of chart record showing portion employed in integrated and rms scoring.



PERFORMANCE CRITERIA:

1. Hold Heading within $\pm 5^{\circ}$
2. Hold Altitude within ± 50 ft.
3. Hold Airspeed within ± 5 knots.
4. Fly Precision Timed Turns of 3° per/sec. within ± 2 seconds accuracy.

Workload was held high by calling for changes in altitude, headings and airspeed throughout the 8-minute pattern. The largest amount of elapsed time between changes was 60 seconds, and the smallest, 30 seconds. Sometimes two changes occurred simultaneously; e.g., roll out of the first turn on a heading of 90° and begin to reduce airspeed to the slow-cruise (60 mph) range.

Figure 5. Modified Bravo instrument pattern.

the other seat to "talk" him through the pattern. Once the S was able to fly the routine without close guidance, he received further practice alone in the cockpit; however, communication was maintained through the simulated radio equipment in the GAT-2H. At this point scoring (uncorrected integrated scores) began. Practice trials with scoring were continued until it was apparent that the S's learning was essentially complete; that is, the numerical variation in successive scores was less than 10 percent, and the scores had stopped decreasing, or improving. Once the Ss had learned their task, they completed five additional trials for the record.

The ground-track plot and the instrument-panel indications were monitored and recorded by closed-circuit television to verify that each trial adhered to the prescribed flight path.

Each S's progress was monitored throughout his trial by closed-circuit television and by the ground-track plot to insure that he was within the limits of the pattern. If a trial for record ran outside of these limits, it was eliminated and a replacement trial was given. Invalid trials actually occurred less than half a dozen times throughout the entire experiment, and they were primarily timing errors in the sequence of maneuvers making up the Bravo pattern. Each S logged from three to five hours of simulator time for each control configuration that he flew. Naturally, the Ss tended to take less time to relearn the routine the second or third time around. Throughout the familiarization and trials, there was a break of 5 to 10 minutes after every three or four trials. Also, the Ss had immediate knowledge of their own results. This appeared to motivate them to achieve the best possible scores.

Subjects

A total of 16 Ss were used in the experiment: 13 Army aviators and 3 civilians of mixed experience and capabilities. The military Ss were all current, instrument-rated rotary-wing pilots, six of whom were also rated in fixed-wing, and one of the five was an instrument examiner. Their ages ranged from 26 to 36, rank from WO-2 to Major, and their total logged flying hours ranged from 350 to 3,900.

Of the 3 civilian Ss, one was a former military aviator—dual rated. Another was a private pilot—airplane, single-engine, land— with approximately 120 flying hours. The third was not a rated pilot at all, but has 11 years of work experience (including flying experience) in aviation-related areas, and is familiar with both rotary-wing and fixed-wing flight and their principles. As an afterthought, we wished to see how the latter two relatively naive Ss compared to the highly experienced ones.

It will be seen in other portions of this report that not all the Ss participated with all of the control configurations. This was, for the military Ss, due to both scheduling difficulties and, in some cases, temporary duty and permanent change of station.

PERFORMANCE MEASUREMENT

The performance of piloting an aircraft on a critical course can be measured by how much system energy the aircraft expends over and above steady-state flight. This concept is not new but, to our knowledge, it has not been utilized or developed to any extent.

It was desirable to develop such a performance-related measure, which would record the excess energy expended by the aircraft/pilot system. This energy can be attributed directly to the pilot's accuracy and the manner in which he manipulates the controls to achieve the desired (criterion) flight path. Energy expended, in terms of actual fuel-rate consumption of the simulator's engine, would have been a most desirable measure. However, the feedback from aircraft motions due to noise in the pilot's control, and consequently increased fuel demand, resulted in such miniscule voltage deviations (roughly one part in 2,000 to 4,000) that such a measure became impractical.

The next best approach to excess energy expended was examining the minute changes in the flying aircraft's attitude and altitude rates. The rationale is that, in perfect steady-state flight, neither pitch, roll, or yaw angles, nor altitude, longitudinal or lateral velocities, change; therefore the pitch, roll, yaw, and vertical, longitudinal, and lateral rates are all zero. Put another way, the rates of change in all six degrees of freedom are zero for ideal flight in the steady state when there are no disturbances from within and outside the aircraft. On the other hand, whenever any of these six rates is more than zero, the energy expenditure must be more than the steady-state requirement.

Lateral velocities and yaw rates were not important enough to measure, because both of them have relatively small values in forward flight at cruise airspeeds. Even so, their influence would be the same for all control configurations, because the yaw pedals which cause these fluctuations were a constant during the investigation. Longitudinal velocity or airspeed was also dropped from the scheme, since it is primarily a function of pitch angle, which was measured, and which changes slowly with respect to the other rates. Rate of longitudinal angular change (pitch rate), rate of lateral angular change (roll rate), and rate of altitude change (vertical speed) were the three parameters chosen to best describe how the expenditure of energy differs from the energy required for perfect steady-state flight. These variables change instantaneously as the airframe reacts, and their values are available as scaled, recordable, analog voltages in the computer section of the GAT-2H Simulator.

These rate terms deserve discussion as energy terms. To move the airframe in any of six degrees of freedom requires applying a force to the airframe, equal and opposite to the restorative force—usually a drag force, whether the movement is translational or rotational. The force on the airframe must move through a distance to accomplish the change, and force times distance gives the energy expended. The classical laws of motion, however, say that the force diminishes to zero as the rate becomes a constant. We are safe in saying, then, that the control forces acting on an airframe are small, at least with respect to the primary forces of lift and thrust. If the forces in our excess-energy approach are relatively small, perhaps it would be better to measure the distances moved. Here is where the rates come in: by integrating a measured rate over time, we can express the total distance (or angle for rotational rates) traveled during that time period for the degree of freedom whose rate was measured. Integrating the rate's excess beyond what was required for the perfect flight yields the excess distance (or angle) through which the airframe traveled.

Therefore the score's value comprises the absolute values (always positive) of pitch rate, roll rate, and vertical rate. These rates are weighted and summed—primarily to assure that vertical rate makes the same contribution as the two angular rates–scaled to the analog integrator's capacity, and integrated over the 8 minutes of the trial. Specifically, the score follows equation (1):

$$S = \frac{1}{40} \int_0^t (2|P| + 2|q| + .5|H|)\, dt \qquad (1)$$

Where	P =	rate of roll	$\pm$ 10v = $\pm$ 180°/sec
	q =	rate of pitch	$\pm$ 10v = $\pm$ 40°/sec
	H =	rate of altitude change	$\pm$ 10v = $\pm$ 60 ft/sec

Because the flight trials call for specific changes in heading, airspeed, and altitude, affecting roll, pitch, and altitude rates respectively, every S will accumulate some minimum score by the end of the trial, even if the S flies the pattern perfectly. This minimum score was determined empirically so it would eliminate minute anomalies and electrical biases which were observed, probably due to otherwise undetectable errors in reference voltages and electrical-component values. The empirical value was established by observing the integrated scores for long-period, steady-state climbs, turns, etc., then averaging several trials for speed changes, and averaging roll-ins and roll-outs for the turns. The minimum score is 4.1084 (Appendix), which was subtracted from each individual S's score according to equation (2):

$$S = \frac{1}{40} \int_0^t (2|P| + 2|q| + .5|H|)\, dt - 4.1084 \qquad (2)$$

A second performance-related measure was devised when it was observed that the time history of the weighted sum of the rates showed more oscillation when the Ss changed speed to slow cruise in each trial (Figure 4). That portion of the flight was digitized from the graphic records, and a relative root-mean-square (rms) value was computed for the period of the oscillations only, following equation (3):

$$\text{rms} = \frac{\Sigma(X^2)}{N} = \frac{\Sigma\left[(2|P| + 2|q| + .5|H|)^2\right]}{N} \qquad (3)$$

where X was digitized at each trace reversal

and N = the number of reversals encountered during the maneuver.

A third performance-related measure was the number of rate reversals each S made during the same speed-change maneuver, which is simply N from equation (3).

The maneuver to reduce airspeed from normal cruise (85 mph) to slow cruise (60 mph) is done by lowering collective (power) and raising the nose to kill airspeed, while maintaining heading and altitude. The oscillations on the record stem primarily from the changes in pitch attitude. The vertical-rate and roll-rate terms can also contribute to the score, however, if the S was not attentive in maintaining altitude by adjusting power and roll trim.

Interpreting the integrated score is straightforward: the larger the score, the poorer the performance. Interpretations of the rms and N scores are not clear cut. If the S changed his airspeed in a few oscillations of the record (and some did), rather than many oscillations, his performance might appear good. The rms score would be relatively high, and the number of reversals low. The S who "nibbled" at the change with more corrections, but smaller ones, would score a lower rms and higher N, and certainly could not be faulted for poorer performance. The reader is reminded at this point that reversals or oscillations on the graphic record must not be equated or confused with control reversals on the part of the pilot. Because the integrated-control concepts investigated have generally greater sensitivity than the conventional controls–i.e., integrated controls require less movement than conventional controls–it appears that a higher rms score, and a lower N score, signified poorer performance. This is discussed further in the discussion portion of the report, following data analysis.

EXPERIMENTAL DESIGN

This investigation was intended to be straightforward, since all Ss were exposed to all of the experimental conditions (i.e., all control configurations. Therefore the design is a complete Treatment X Subjects design, as described by Lindquist (2). Each cell mean was generated by five trials flown by each S, after a series of learning trials had stabilized his scores.

It was necessary, at the expense of proper experimental method, to expose each S to the same order of presentation treatments. This order of treatment was: (a) Integrated-Control Wheel Concept, (b) Integrated-Control Grips Concept, and (c) Conventional Helicopter Controls. Order could not be varied because it took up to 2 weeks to remove one system and install the next control system in the simulator. Typically, a month would elapse between a S's trials on one control system and his trials on another. As mentioned before, not all of the Ss were able to fly all of the controls. However, 7 of the 13 military Ss did complete the full set.

In addition to the military Ss, some civilian employees at HEL served as Ss. These Ss were tested under four treatments: the same three above, plus a condition of no trim function/no control-centering-force gradient for cyclic inputs while flying the No. 2 concept, the Integrated Control Grips Concept. During the course of the study, it became desirable to perform a short assessment of possible differences between flight with and without a centering-force gradient. The primary interest, however, remains the military Ss.

RESULTS

Mean scores for each S, by control system, appear in Table 1. Table 1 shows that not all Ss were able to participate with all of the controls. Ignoring the no-trim trials for the moment, Ss one through seven completed trials on all of the controls. Figures 6, 7 and 8 summarize the mean scores for Ss one through seven as a group for integrated score, root-mean-square score, and motion-count score. Note that, for the integrated and root-mean-square measures, the integrated wheel control yielded the highest (least favorable) scores, followed by the integrated grip control, and the conventional control gave most favorable performance. On the other hand, the motion-count scores (Figure 8) have just the opposite trend, indicating that the Ss moved the conventional controls more often, but with less excursion of the airframe as measured by the integrated and rms scores. The following sections will discuss this effect further.

The low-time, private-license civilian S was not available when the Integrated Wheel Control was installed in the simulator, leaving only two civilian Ss who flew all three control systems. Of these, one was the former Army aviator, and the other the non-pilot. The civilians as a group are anything but homogeneous, so their flight scores can have only limited value.

TABLE 1

Mean Scores, by Subjects and Controls

Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17
									Integrated Score							
Integrated Wheel	2.023	1.908	1.700	1.579	1.129	1.304	1.341	1.460			1.735			1.592		0.929
Integrated Grip	1.984	1.525	1.054	1.130	1.177	1.238	1.051		1.000	1.595		1.663	1.869	1.136	0.859	1.528
Integrated Grip (No Trim)														1.913	1.910	1.222
Conventional	1.364	1.269	0.835	1.067	1.207	0.896	1.017		0.906	1.057		1.284	1.640	1.126	1.163	0.699
									Root Mean Square Score							
Integrated Wheel	63.52	65.54	77.96	51.06	54.37	59.12	43.96	49.88			53.07			37.25		37.38
Integrated Grip	80.77	50.26	30.09	25.08	49.49	57.20	38.08		37.37	49.05		74.55	59.73	56.15	62.95	40.16
Integrated Grip (No Trim)														46.97	77.47	56.34
Conventional	32.50	27.25	14.04	25.52	32.93	23.59	26.72		15.40	31.51		33.55	22.52	31.09	58.09	56.74
									Motion Count Score							
Integrated Wheel	12	16	24	16	13	9	16	15			9			13		10
Integrated Grip	17	16	18	14	18	16	13		17	22		19	13	15	17	13
Integrated Grip (No Trim)														19	19	10
Conventional	29	22	16	12	24	17	15		15	17		14	13	15	14	9

Subjects 1- 13 - Military
Subject 14 - Civilian, Former Army Pilot, Dual Rated
Subject 15 - Civilian, Low-Time Private Pilot, Single-Engine Fixed-Wing
Subject 17 - Civilian, Non-Pilot

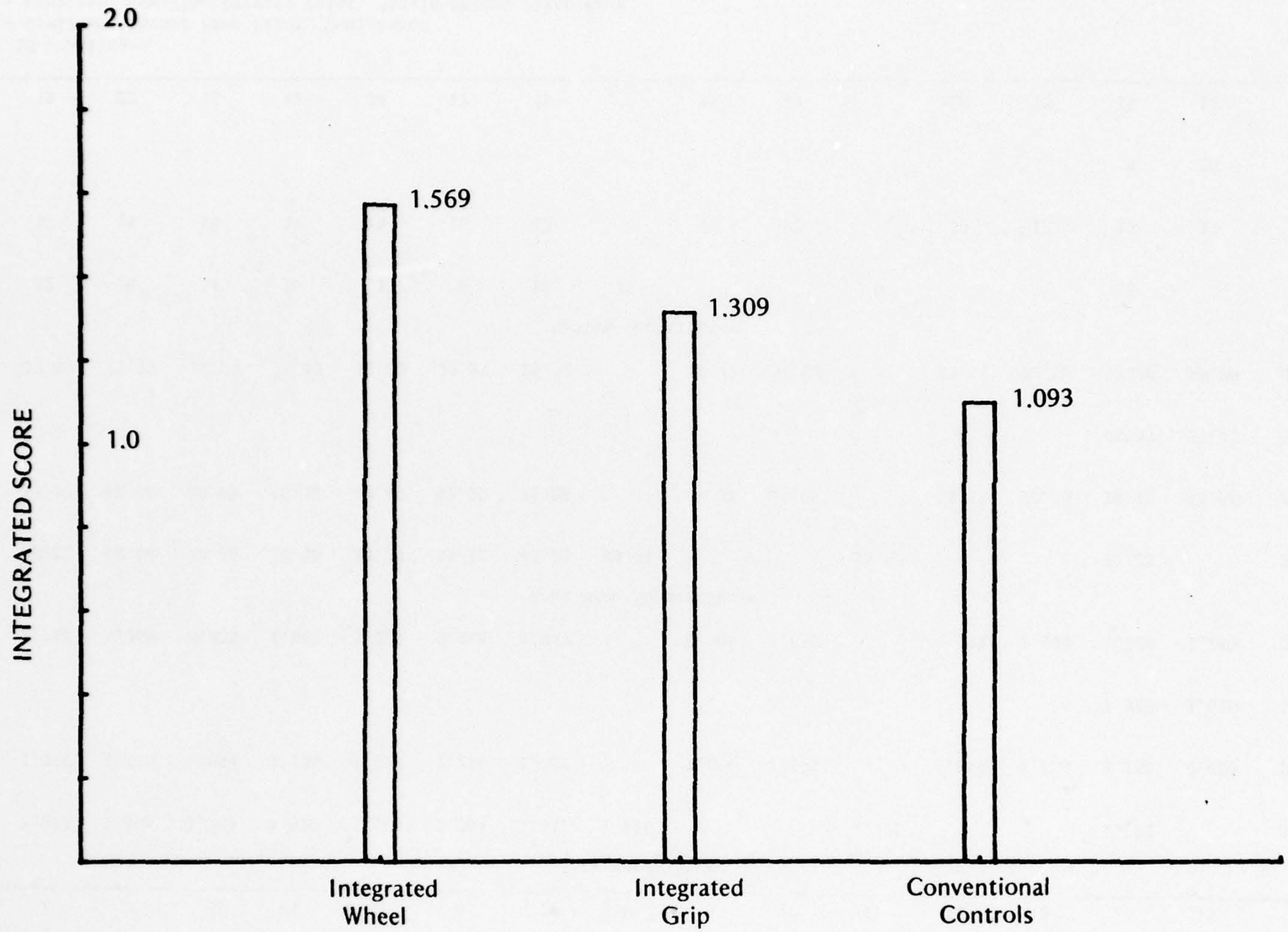


Figure 6. Mean integrated scores – Subjects 1 through 7 (military).

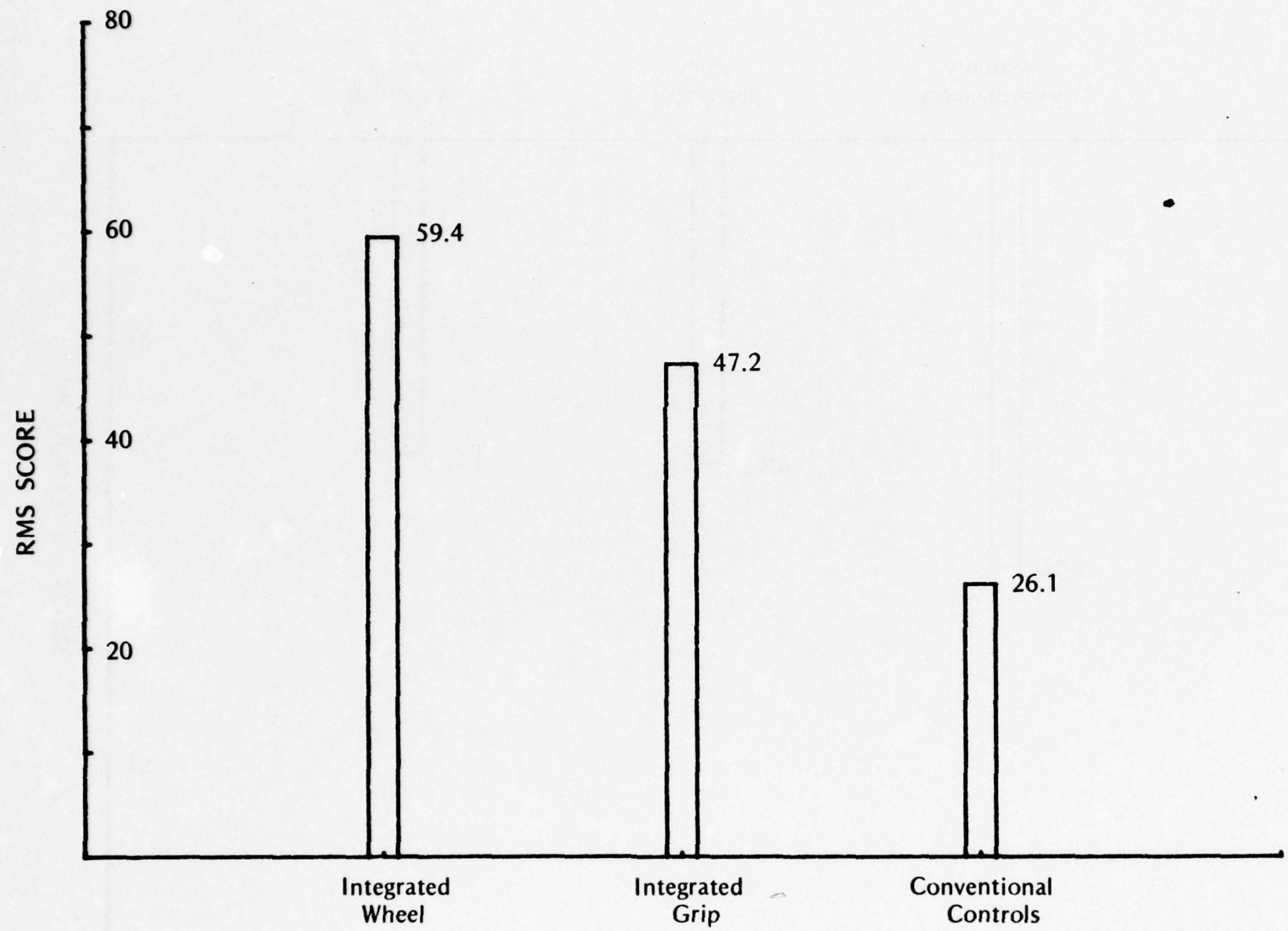


Figure 7. Mean root-mean-square scores — Subjects 1 through 7 (military).

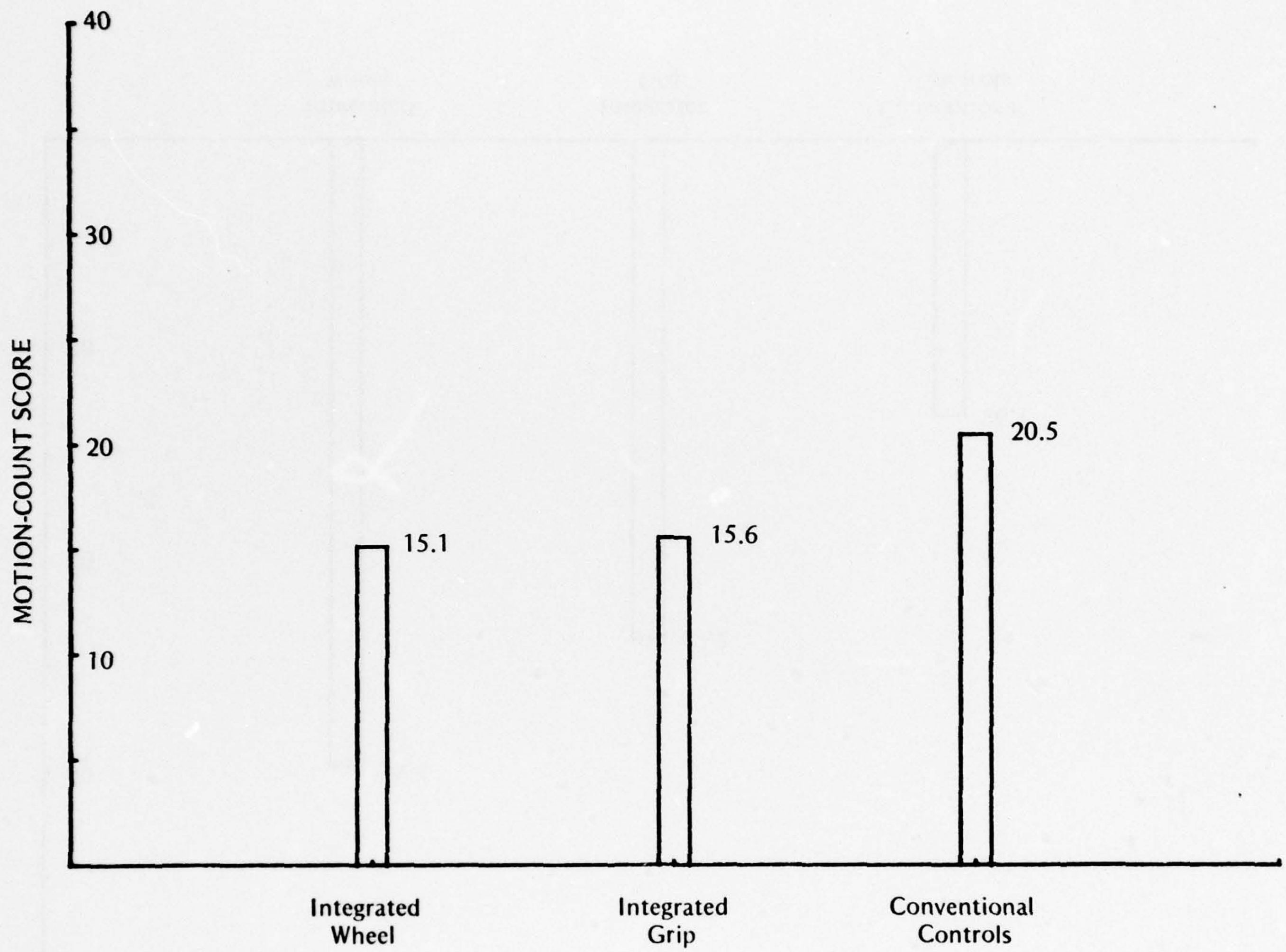


Figure 8. Mean motion-count scores – Subjects 1 through 7 (military).

It is, however, most interesting to note how the non-pilot S's scores compare to the other Ss' scores. Figure 9 compares his mean integrated scores to the mean of the seven military Ss; he was among the lowest scorers of the entire study.

Analysis of Results

Before comparing the merits of the three controls, product-moment correlations coefficients were computed (Table 2) (1).

TABLE 2

Intercorrelation of Scores

	Integrated Score	rms Score	Motion-Count Score
Integrated Score	-		
rms Score	.337	-	
Motion-Count Score	.097	-.020	-

According to Table A11 in Reference (3), only the correlation coefficient between the Integrated and rms Scores, .377, is significant ($p > .01$). However, this correlation accounts for only $(.377)^2$ or 14.2 percent of the variance. It is safe to conclude, then, that there is little correlation among the three measures and, for practical purposes, they are almost independent. Had a high correlation been present, it would not have been useful to analyze the related scores separately.

Analyzing the military S's scores has primary importance. Table 3 contains analyses of variance for the three scores, for military Ss one through seven.

It can be seen that subjects differ significantly on at least the integrated and rms scores. It is natural to expect individual differences from S to S. Note that the controls produced significant differences for each type of score, demonstrating that at least one control configuration had a different influence on scores than another configuration for all three scoring variables. The significant interaction term for the motion-count scores means that the Ss who tended to have high motion-count scores also scored significantly higher with the conventional control than with the two integrated controls. For example, Figure 10 plots the mean motion-count scores, grouping Ss 1, 2, 3, and 5 as high scorers (average scores higher than the group's mean), and grouping Ss 4, 6, and 7 as low scorers (average scores below the mean). Note the divergence that occurred with the conventional controls; if there were no interaction, the lines would have been more or less parallel.

Since at least one of the control configurations is different from at least one other, a multiple-range test was performed. Table 4 summarizes the results.

For the integrated and rms scores, each control differed significantly from each other control, with the conventional control faring what must be considered best, and the Integrated Wheel at the other end of the scale. For the motion-count score, the two concept controls did not differ from each other, but each differed from the conventional control. Note that the rank

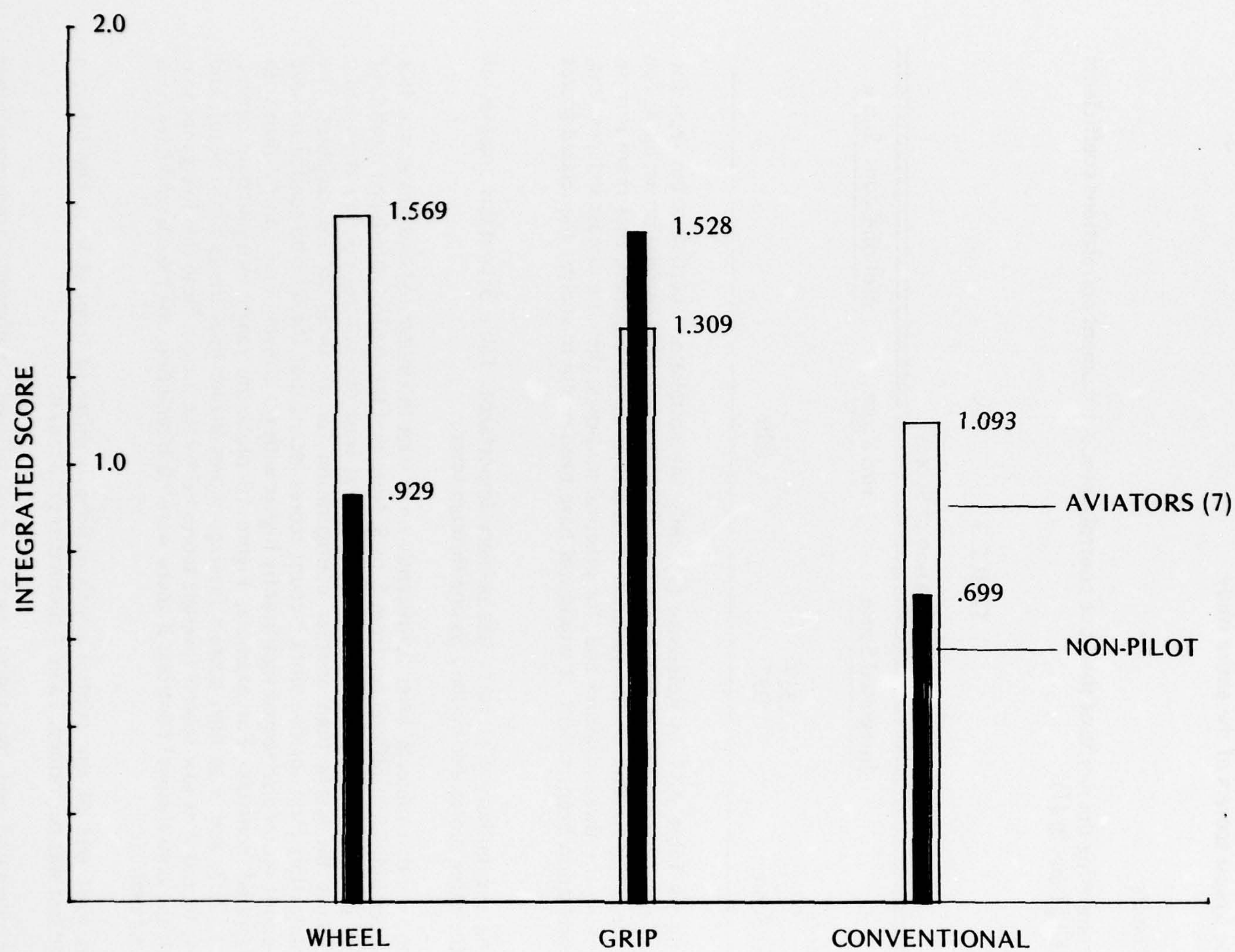


Figure 9. Non-pilots' mean integrated scores, compared with mean for Subjects 1 through 7 (military).

TABLE 3

Analysis of Variance, Subjects 1 Through 7

Source	SS	df	MS	F	
Integrated Score					
Subjects	5.812	6	.969	9.386	sig. P<.001
Controls	3.976	2	1.988	9.262	sig. P<.001
Interaction	2.042	12	.170	1.649	no sig. P>.05
Within	8.669	84	.103		
Total	20.499	104			
rms Score					
Source	SS	df	MS	F	
Subjects	6277.99	6	1046.33	2.485	sig. P<.05
Controls	19864.67	2	9932.34	23.593	sig. P<.001
Interaction	9118.56	12	759.88	1.805	no sig. P>.05
Within	35363.33	84	420.99		
Total	70624.55	104			
Motion Count Score					
Source	SS	df	MS	F	
Subjects	472.51	6	78.75	1.634	no sig. P>.05
Controls	616.13	2	308.07	6.393	sig. P<.005
Interaction	1587.60	12	132.30	2.746	sig. P<.005
Within	4047.60	84	48.19		
Total	6723.84	104			

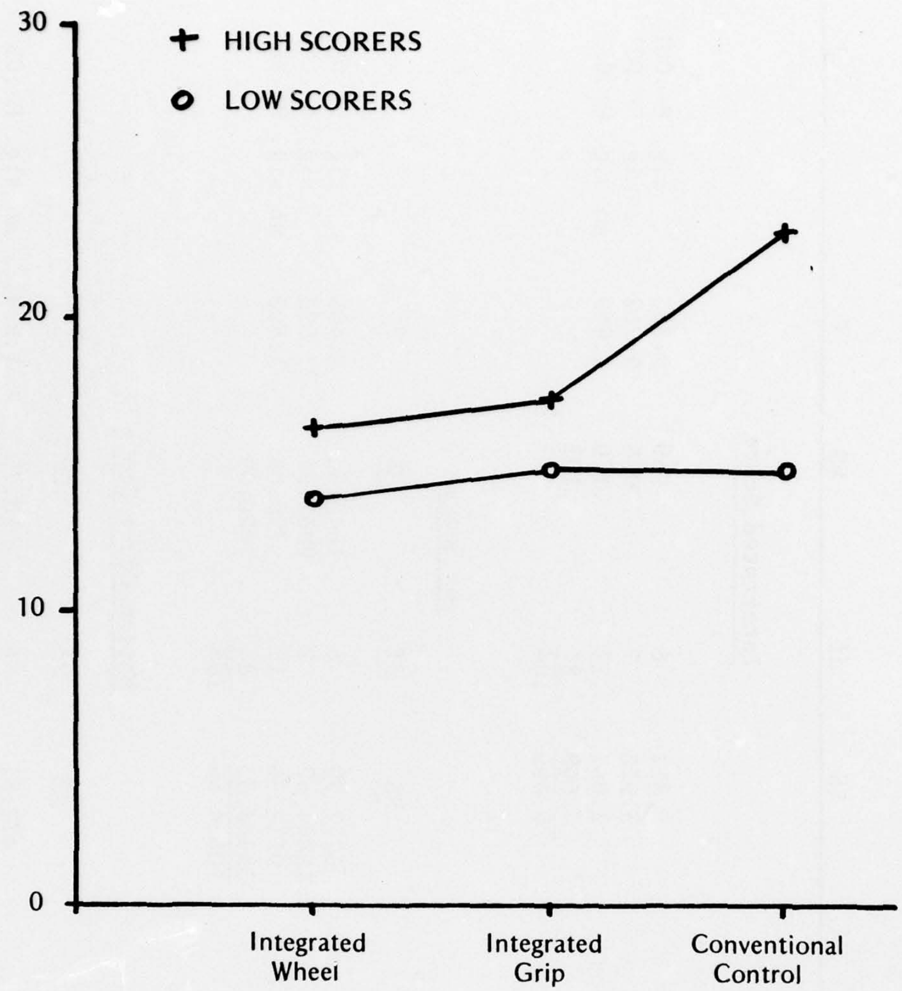


Figure 10. Average mean motion-count scores for high- and low-scoring subjects, $\underline{S}$s 1 through 7 (military).

TABLE 4

Multiple Range Tests, Ss 1-7, P < .05

Rank	1	2	3
Control	Conv.	Grip	Wheel
Mean Score (Integrated)	1.093	1.309	1.569
	(1)	.216	.476
	(2)		.260

df = 102 $S\bar{x}$ = .0438
Q2 = 2.81 D2 = 0.123
Q3 = 3.37 D3 = 0.1476

Conv. Grip Wheel
All controls are sig. diff. from each other.

Rank	1	2	3
Control	Conv.	Grip	Wheel
Mean Score (RMS)	26.08	47.24	59.36
	(1)	21.16	33.28
	(2)		12.12

df = 102 $S\bar{x}$ = 2.5431
Q2 = 2.81 D2 = 7.146
Q3 = 3.37 D3 = 8.570

Conv. Grip Wheel
All controls are sig. diff. from each other.

Rank	1	2	3
Control	Wheel	Grip	Conv.
Mean Score (Motion Count)	15.14	15.51	20.46
	(1)	.37	5.32
	(2)		4.95

df = 102 $S\bar{x}$ = .6625
Q2 = 2.81 D2 = 1.862
Q3 = 3.37 D3 = 2.233

<u>Wheel Grip</u> Conv.

Controls <u>not</u> underscored by the same line are sig. diff.
Controls <u>underscored</u> by the same line are not sig. diff.

order of the control systems is just the opposite of the rank order for the other two scores. This suggests that the higher the motion-count score, the more favorable the control system. The implication is that more fine adjustments or corrections were made with the conventional controls, yet the aircraft's excursions and level of activity were smaller than with the integrated-concept controls. Several explanations might be offered, but they would only be conjectures.

Two civilian Ss, numbers 14 and 17, were measured on all three control systems. Table 5 summarizes the analyses of variance for these two Ss. While these Ss have vastly different backgrounds–a former Army pilot versus a non-pilot–the analysis of rms scores did not show any statistically significant difference between them. Even more interesting, only the integrated-score analysis showed differences between the control systems. In view of the military results, this lack of differences is most likely due to the much smaller size of this group. The multiple-range test for the integrated scores in Table 6 shows that the conventional controls stand alone with a lower score than the two concept controls, which were equivalent in performance. Recall, however, that this result is based upon a two-S group, with five data points per S, which is hardly an optimum sample size.

These same two Ss also flew the GAT-2H simulator with all control-centering forces and force gradients removed from the Integrated-Grip concept. This brief exercise attempted to determine whether a no-trim condition would change flying behavior. Table 7 is an abbreviated summary of the statistical test results. The integrated score was the only measurement which yielded a significant F ratio. The attendant multiple-range test revealed that, in the no-trim condition, the integrated grip was significantly poorer than the grip with trimmable force gradients, as well as Wheel and Conventional controls. This finding may arise because the grip has higher sensitivity than the conventional control, and because the control was not damped by the trim springs, thus allowing the Ss to exhibit more dither when they attempt to make fine adjustments. Again, while the small sample size reduces the power of the analysis, the outcome was easily predicted.

CONCLUSIONS

With respect to the maneuvers performed, the conventional controls fared best, with the Integrated Grip poorer, and the Integrated Wheel the poorest. This report constitutes the first formal analysis of a pair of control concepts which have not enjoyed the years of refinement embodied in conventional helicopter controls. Control sensitivity appears to be the most important determinant of the resulting scores. While the nature of the Integrated-Control concepts implies a smaller envelope of motion at the pilot's hands, and consequent higher control sensitivity, it is entirely feasible to refine the design and expand this envelope.

Subjective reactions of the pilots who flew the test controls in the simulator were totally positive in nature. However, hovering flight is the most demanding regime in evaluating the man/machine characteristics of helicopter control; since this portion of the flight envelope cannot be evaluated in our simulator, we concluded that further concept work in the present simulator could very well prove misleading.

TABLE 5

Analysis of Variance, Civilian Ss 14 and 17

Source	SS	df	MS	F	
Integrated Score					
Subjects	.405	1	.405	6.318	sig. P<.025
Controls	1.008	2	.504	7.861	sig. P<.005
Interaction	1.531	2	.766	11.947	sig. P<.001
Within	1.538	24	.064		
Total	4.482	29			

rms Score

Source	SS	df	MS	F	
Subjects	80.07	1	80.07	.610	no sig.
Controls	597.00	2	298.50	2.276	no sig. P>.10
Interaction	2203.51	2	1101.75	8.400	sig. P<.005
Within	3148.04	24	131.17		
Total	6028.62	29			

Motion-Count Score

Source	SS	df	MS	F	
Subjects	104.53	1	104.53	6.788	sig. P<.025
Controls	46.87	2	23.43	1.522	no sig. P>.10
Interaction	16.47	2	8.23	.535	no sig.
Within	369.60	24	15.40		
Total	537.47	29			

TABLE 6

Multiple Range Tests, Civilian Pilots 14 and 17

		1	2	3
Rank		1	2	3
Control		Conv.	Wheel	Grip
Mean Score (Integrated)		0.912	1.260	1.332
	(1)		.348	.420
	(2)			.072

df = 27 $S\bar{x} = 0.0718$
Q2 = 2.905 D2 = .2085
Q3 = 3.505 D3 = .2517

Conv. <u>Wheel Grip</u>

Controls underscored by the same line are not significantly different.

TABLE 7

Abbreviated Summary of the Statistical Test Results

Analysis of Variance - Integrated Score:

Subjects	$F\alpha$ 1,32 = 7.771	sig. $P<.01$
Controls	$F\alpha$ 3,32 = 6.304	sig. $P<.005$
Interaction	$F\alpha$ 3,32 = 4.429	sig. $P<.025$

Multiple-Range Test - Integrated Score:

	Conv.	Wheel	Grip	Grip (No Trim)
Mean Scores	0.912	<u>1.260</u>	<u>1.332</u>	1.618

Scores underlined by the same line are not significantly different.

Analysis of Variance - rms Score:

Subjects	$F\alpha$ 1,32 = 1.356	no sig.
Controls	$F\alpha$ 3,32 = 2.247	no sig.
Interaction	$F\alpha$ 3,32 = 4.474	sig. $P<.01$

Analysis of Variance - Motion-Count Score:

Subjects	$F\alpha$ 1,32 = 11.450	sig. $P<.005$
Controls	$F\alpha$ 3,32 = 1.122	no sig.
Interaction	$F\alpha$ 3,32 = 0.948	no sig.

It was also obvious that experienced rotary-wing aviators were forced to do a considerable amount of "unlearning" to adjust to a three-axis control. Since experienced aviators would necessarily be the first to actually fly such a control, it appeared that the sooner we met this problem face-to-face in actual flight, the better it would be.

It was, therefore, concluded that we could continue to develop and refine the three-axis control in the simulator–but that this course, though of scientific interest, would probably lead only to developing a highly refined laboratory model for up-and-away simulator flight. Instead, we chose to drop further simulator work at this stage and start developing a three-axis controller that can be installed in an aircraft for actual flight testing.

As a result of the effort described here, the integrated-grip controller was reengineered for flight and installed in an OH-58 helicopter. This control was flight tested by the Aviation Engineering Flight Activity early in 1976, and a limited safety-of-flight release was subsequently issued by the U.S. Army Aviation Systems Command. Flight tests are continuing, and an improved flight version is being developed for further testing in 1977.

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APPENDIX

MODIFIED BRAVO PATTERN - IDEAL MINIMUM INTEGRATED SCORE

	Alt.	A/S	R/C	Turn	Time	Segments	Volts/Min.	Volts
1.	2250	85	+500	N/A	1:00	1	.8556	.8556
2.	2750	85	+500	STD-L	1:00	2	1.2100	1.2100
3.	3000	85	0	STD-L	0:30	3	.4340	.2170
4.	3000	60	0	N/A	1:00	4	-.0666	-.0666
5.	3000	60	0	STD-R	0:30	5	.3733	.1866
6.	2750	60	-500	N/A	1:00	6	.7763	.7763
7.	2250	60	-500	STD-L	1:00	7	1.1420	1.1420
8.	2000	60	0	STD-L	0:30	8	.3640	.1820
9.	2000	85	0	N/A	1:00	9	.0000	.0000
10.	2000	85	0	STD-R	0:30	10	.5070	.2535
11.	3000	60	0	Roll In		5 (2X)	.0100	.0200
12.	3000	60	0	Roll Out		5 (2X)	.0126	.0252
13.	2000	85	0	Roll In		10 (2X)	.0220	.0440
14.	2000	85	0	Roll Out		10 (2X)	.0143	.0286
15.	3000	85→60	0	Slow Down		4	.0176	.0176
16.	2000	60→85	0	Speed Up		9	.1266	.1266
								4.0184

Items 1-10 - 3-minute sample
Items 11-16 - 3-sample average