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A PILOTED SIMULATION STUDY OF ADVANCED CONTROLS AND DISPLAYS FOR GENERAL AVIATION AIRPLANES

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Abstract

A decoupled, fly-by-wire control system combined with a pictorial head-up display has been developed and evaluated on a piloted simulator. The test subjects used in the evaluation were primarily non-pilots who were given no training or practice before the data runs. Despite their lack of experience and training, all of the test subjects were able to complete a complex piloting task on their very first run. The piloting task was performed in reduced visibility conditions and consisted of a continuous series of common maneuvers beginning with a takeoff and ending with a landing. Severe upsets from turbulence and emergency situations such as engine failure were not simulated. Quantitative and qualitative data are presented to illustrate the large improvements in subject performance when using the advanced controls and displays compared to the conventional ones.

Introduction

The time and cost of becoming a private pilot has always been a deterrent to more widespread use of general aviation airplanes for personal transportation.(1) The majority of people who begin flying lessons drop out of the process before they get their certificate because of the time and costs involved. In addition, a majority of those who do get their certificate quit flying in a few years after they get their certificate due to the recurring proficiency requirements. Unfortunately, these training and proficiency requirements are well justified by the complexity of safely operating an airplane. What is needed is new technology that would reduce that complexity. This new technology could drastically reduce the need for extensive pilot training for normal operations. If the reliability of the systems can be made high enough, additional training for degraded modes of operation could be very limited or even eliminated.

Such new technology is currently being developed and used in other fields of aviation; however, it could be of even greater benefit to beginning general aviation pilots. For example, the fly-by-wire technology which has been developed for military and commercial aviation probably would be of much greater benefit to a novice pilot than it is to full-time pilots. The full-time pilot who regularly accumulates many hours of flying time is very familiar with the control characteristics of an airplane and has relatively little need for an airplane which is easier to control. The beginning pilot, on the other hand, often finds the control characteristics of an airplane strange and hard to understand and, therefore, needs the tailored control characteristics which can be provided by a fly-by-wire control system. The same comments can be made for other technologies such as microprocessors, glass cockpits, the Global Positioning System, and data link.

Over the years, the National Aeronautics and Space Administration (NASA) has developed technology aimed at increasing the efficiency and safety of general aviation airplanes. For example, NASA has explored ways to reduce the possibility of stalls and spins,(2) which historically have been responsible for many accidents. Such accidents have reinforced the continued requirement for rigorous pilot training and proficiency. The present work grew out of these stall/spin studies when the program began to expand from single-engine airplanes to twin-engine airplanes. A simulation study of the engine-out characteristics of light twins,(3) highlighted the need for improved control. Although a simple automatic trim system was developed which could aid the pilot in coping with an engine failure; however, the pilot still had to make the same basic control inputs.(4)

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It soon became apparent that the only way to eliminate many of the pilot mistakes was to use digital fly-by-wire control systems such as those in many military fighter designs. However, once these control systems are installed on an airplane for safety purposes, relatively simple software could tailor them to provide benign, intuitive control characteristics which were not previously possible.(5) Although these control characteristics were very easy for a novice to learn to fly, the problems of navigation and situational awareness in low visibility conditions were still far beyond the capabilities of the novice using conventional cockpit instruments. Therefore, a head-up pictorial display was developed which was compatible with the intuitive fly-by-wire control system.(6) The control system developed in these studies is called the "Easy-to-Fly" (E-Z Fly) control system, and the pictorial display is called the "The Highway-in-the-Sky (HITS) display.

This present paper describes and presents the last iteration of the control system and display as well as certain refinements in the evaluation procedure. One objective of this last iteration to the controls and display was to improve the test subjects' performance in the turns. An automatic trimming feature was added to the lateral control axis, and the pictorial display was modified by providing (1) closer spacing of the pictorial elements in the turns, (2) fixed reference guides, and (3) a new horizon line to improve climb/descent awareness. In addition, the effects of turbulence and steady winds were investigated, and improved engine power control information was provided for the comparison of the E-Z Fly control system with the conventional controls/power system.

As in the previous studies, the system was evaluated using a combination of non-pilots and pilots. None of the test subjects was given any training or practice before the data runs were started. The piloting task was performed in reduced visibility conditions and consisted of a racetrack-shaped pattern beginning with a take-off and ending with a landing and lasting slightly less than 10 minutes.

Abbreviations

CGI	computer generated image
E-Z Fly	easy-to-fly, fly-by-wire, decoupled control system
HITS	highway-in-the-sky pictorial display
Hp	horsepower
k	thousand
ILS	instrument landing system
PI	proportional plus integral (control law)
RMS	root-mean-squared

Description of System

The total system consisted of two complementary major subsystems: the E-Z Fly decoupled control system and the pictorial, highway-in-the-sky (HITS) display. These subsystems are described in the following sections. In a real airplane the E-Z Fly system would probably require a fly-by-wire control system, and the the HITS display would require a data link with air traffic control information.

Control System

The relationships between the motions of the primary cockpit controls and the airplane responses for the advanced decoupled control system (designated the E-Z Fly control system) are shown in figure 1. The three main cockpit controls (longitudinal wheel, throttle, and lateral wheel) individually and uniquely determine the three primary response parameters (vertical speed, airspeed, and heading rate). The exception to this rule is when the test subject commands maximum values of the response parameters at the same time, see below. The rudder pedals control the sideslip angle, but this control is not a factor except in crosswind landings. These primary control-airplane response relationships are intuitive and contrast sharply with conventional airplane responses shown in figure 2. In a conventional airplane moving one cockpit control causes two or three of the primary response parameters to change. Through training, the pilot has to learn to suppress these responses by simultaneously moving the other controls to get the desired (single) response.(5)

The control laws were developed on the simulator and consisted of four major control paths. The longitudinal wheel commanded the vertical speed using proportional-plus-integral (PI) forward paths. Gain scheduling as a function of airspeed and dynamic pressure was used along with pitch attitude and pitch rate feedback to provide proper damping. The throttle levers commanded the airspeed using a PI control law combined with a feed-forward path to reduce engine transients after large changes in the commanded airspeed. It was possible for the test subject to command combinations of vertical

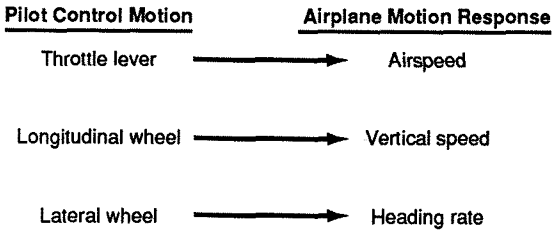

FIGURE 1. Relationships between pilot control motions and airplane responses for decoupled (E-Z Fly) control system.

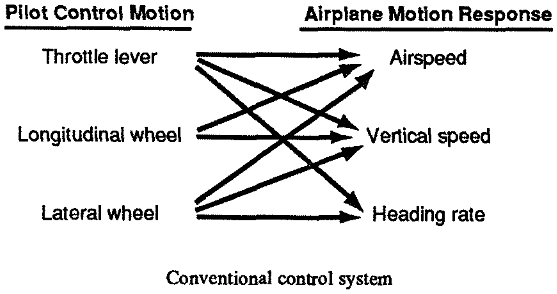

FIGURE 2. Relationships between pilot control motions and airplane responses for conventional control system.

speed and airspeed with the E-Z Fly control system which the airplane could not maintain indefinitely. In this case the vertical speed had the priority, but the airspeed was always maintained at a value above the stall speed. The lateral wheel commanded the roll attitude* through a simple gain with roll rate used to provide damping. The rudder pedals commanded the sideslip angle with yaw rate used to provide damping. All the control laws contained limits on the possible range of the commanded parameters to prevent unreasonable and/or dangerous commands such as commanding an airspeed below the stall airspeed. In addition, the gains of both the longitudinal and lateral wheel were reduced on final approach to reduce the responsiveness as the width of the HITS display narrowed to match the width of the runway. Finally, both the longitudinal and lateral cockpit controls had automatic control force trimming devices. These devices tended to reduce the control forces to zero whenever the controls were moved to a new position and held there for over a few seconds.

Display

The HITS pictorial display was refined and evaluated in these tests. The simulation runs were conducted with a wide-angle (36° by 20°) head-up color presentation superimposed on the simulator's normal real-world visual scene which is produced by a computer generated image (CGI) system.

The basic concept of the HITS display was to reproduce a highway which the test subject would follow through the sky. The display contained three different types of elements: earth-fixed, screen-fixed, and airplane trajectory-fixed, figure 3. The earth-fixed elements were designed to produce a "real-world" image of a highway which the test subject would follow through the sky. The screen-fixed elements had two different functions: (1) to provide an area on the display for additional information (alphanumeric and flight director arrows), or (2) to provide a fixed reference to align the airplane with the highway. The airplane trajectory-fixed elements provided information on the future path of the airplane relative to the highway.
The earth-fixed elements of the display were intended to represent a real-world view of the highway which the test subject was to follow. The highway was nominally 1000 feet wide and extended 6200 feet in front of the airplane. The flight director arrows, not shown in figure 3, were only on when the test subject flew completely off the highway or during takeoff and landing. The vertical trend marks presented the future intersection of the airplane trajectory with the boxes assuming the the pilot held his controls fixed. A more complete description of the display is given in.(7)

Combined System

The E-Z Fly control system and the HITS display, as described above, were designed to operate together. The overriding principle for the design of the total system was to have, as far as the test subject was concerned, one mode of operation which could be used for all phases of flight. This mode of operation required the test subject to continuously and actively "close the loop" on the control of airplane. The test subject was thus forced to be aware of the airplane's state at all times and was not merely a monitor for automatic systems which flew the airplane. It is believed that such an approach would produce a higher level of acceptance by the potential users because of the feeling of control over the situation. Complete automatic control would probably lead to anxiety in certain situations when the passenger-monitor would have to passively observe certain maneuvers. This pilot-

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* Since the rate of change of the heading is proportional to the roll angle, the lateral wheel was in essence commanding heading rate as shown in figure 1

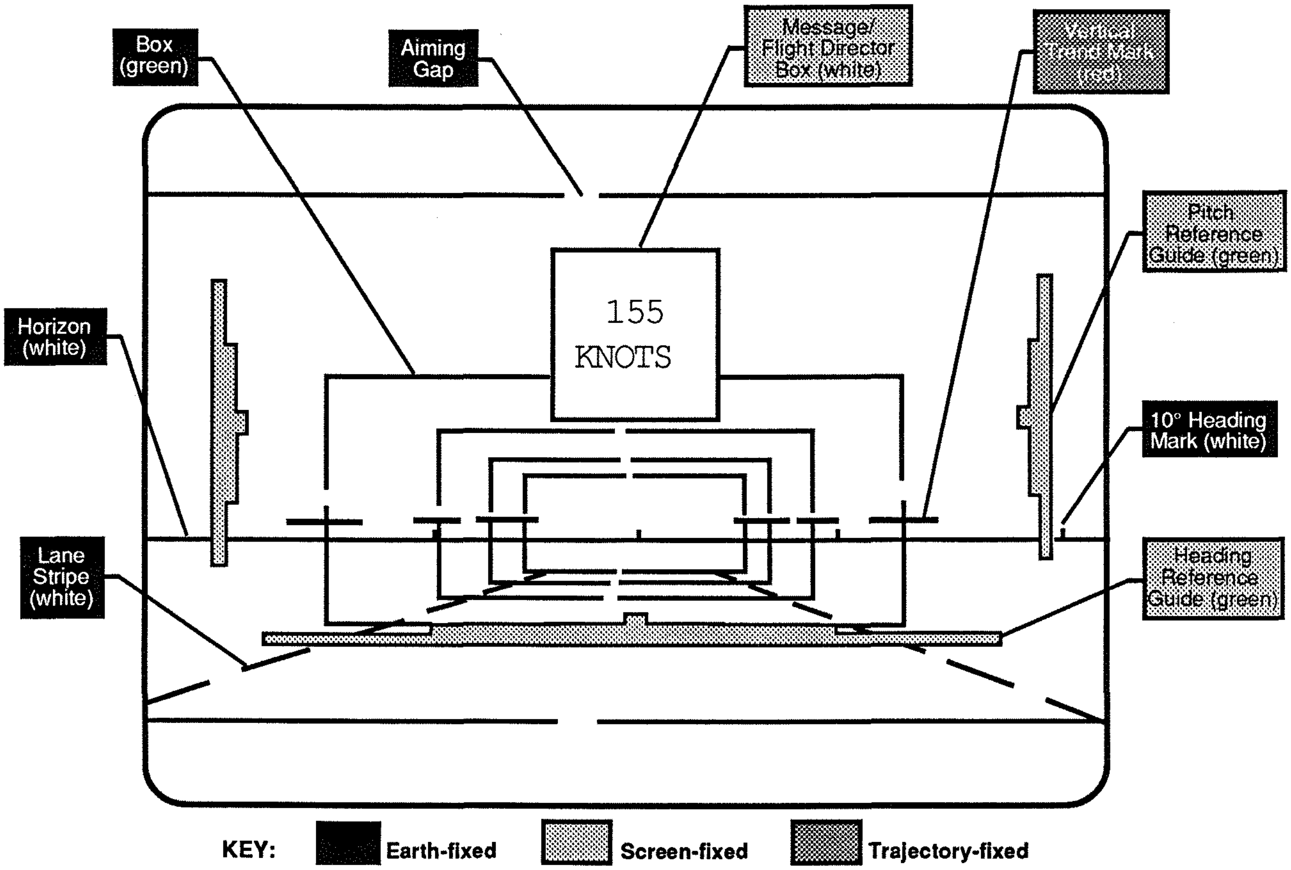


FIGURE 3. Format of pictorial, Highway In the Sky (HITS) color display.

in-the-loop mode of operation could be used in all phases of flight and ordinarily would be used everywhere except during long periods of cross-country flight when a completely automatic system could be used to track a desired path.

Because the system had only one mode of operation, so-called "mode errors" (errors in which the pilot makes an inappropriate input because he forgot which mode the airplane was operating in) were eliminated. Mode errors are probably more likely in highly automated systems than in simpler systems, and they are usually more serious than other types of errors.

Description of Simulation and Tests

Simulation Model and Equipment

An existing math model,(3) of a twin-engine, light airplane was used in these studies. The simulated airplane had a weight of 6200 lbs and a wing span of 40 feet. The simulated propulsion system consisted of two 300 Hp turbo-charged engines with constant-speed propeller systems. Although the simulated airplane had two engines, asymmetric power conditions were not investigated.

The simulation cockpit was mounted on hydraulic actuators to provide a limited amount of motion cues, figure 4. This motion-base system was capable of small pitch, roll, and heave motions: (+16° to -10°), (±16°), (+4.75 inches to -4.5 inches), respectively. The interior of the simulation cockpit was similar to that of a typical twin-engine light airplane with side by side seating for two, figure 5. Conventional mechanical instruments were simulated, but rarely used, especially by the novice test subjects. The forces on the longitudinal wheel, lateral wheel, and rudder pedals were simulated with hydraulic loaders driven by the main computer. A visual scene from a color monitor was projected through a virtual image system to produce a visual scene with a field of view of about 36° horizontally by 20° vertically. The visual scene was a computer generated image (CGI) of a typical airport runway (10,000 feet long and 150 feet wide) at a major city.

The equations of motion and all other calculations, except those associated with the

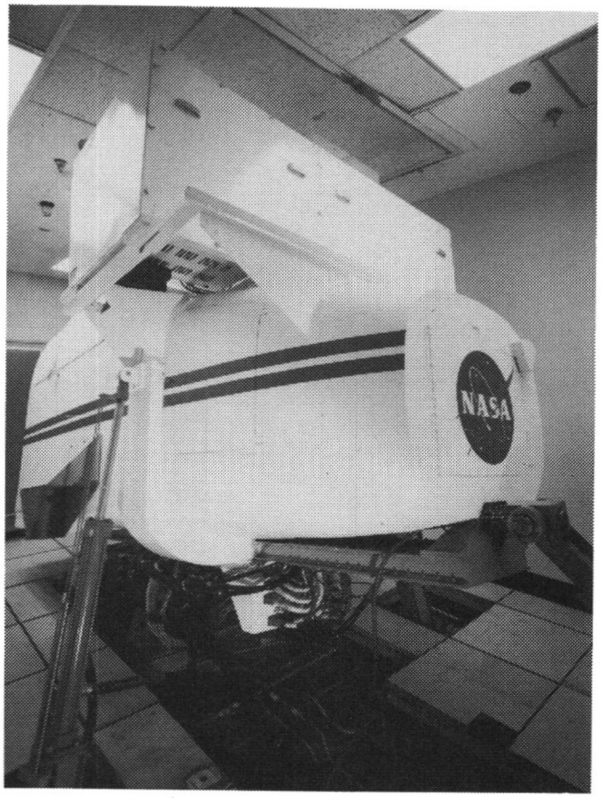


FIGURE 4. Exterior of Langley General Aviation Simulator showing motion-base hydraulic actuator.

FIGURE 5. Interior of Langley General Aviation Simulator.

pictorial display, were solved on a mainframe computer every .03 seconds. The pictorial display was generated on a graphics computer running at a variable rate which was generally larger than that of the mainframe computer. Data for analysis of test subject control activity and performance were calculated on the mainframe computer.

Piloting Task

The task given to the test subjects was intended to exercise the skills necessary to execute a typical trip from takeoff to a landing with a 200-foot ceiling. However, in order to limit the time required to complete the maneuver, a racetrack pattern was flown about a single runway, see figure 6. The maneuver included a takeoff, straight climbs, a climbing turn, a level downwind section, a descending turn, and a two-segment straight-in approach to a flare and landing. A total of seven different segments were included, each with a different target airspeed from the previous segment. The retractable landing gear and flap systems were also exercised at the appropriate places. No severe upsets from turbulence or other sources were imposed on the maneuver, and no failures of either the E-Z Fly or HITS systems were simulated.

Test Subjects

A total of 16 test subjects were used in the evaluation of the various combinations of configurations and conditions. Three test subjects had some pilot training and the other 13 test subjects had no previous piloting experience. Both male and female test subjects were used. Although most of the test subjects were either engineers or engineering students, there were 5 non-technical professionals in the group of test subjects. Ten of the test subjects were designated as primary test subjects, and only their data are presented herein. This group flew a complete set of at least 10 maneuvers to evaluate variations of the display, controls, and wind conditions. The other six test subjects flew fewer maneuvers and evaluated other configuration variations. All the configuration variations and their test results are presented in.(7)

Research Variables and Procedure

The first two runs for each test subject were made to evaluate and demonstrate the effectiveness of the E-Z Fly control system when used with the HITS display. The test subjects received no training or practice before these runs. They were given a short explanation of the cockpit controls and the display they would be using. After the first run with the E-Z Fly control system, the non-pilot test subjects were given a few minutes of additional instruction on the control characteristics of the conventional control system (E-Z Fly off) before they flew that configuration. No further instruction was given for the remaining eight runs. All runs used the HITS display or variations of the HITS display.

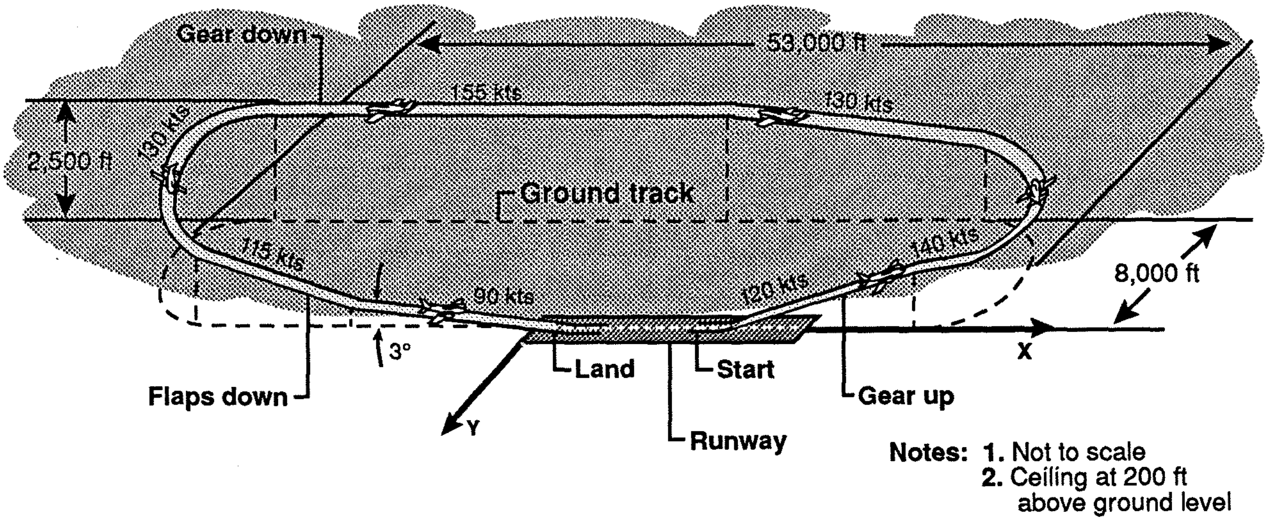


FIGURE 6. Test maneuver.

The quantitative data are presented in terms of averages of RMS errors and averages of the absolute values of errors. Although the sample sizes are relatively small, the standard deviations are also calculated to give a measure of the variability from test subject to test subject. Since the RMS and absolute errors are always positive, an error bar which extends into negative values indicates a distribution skewed to high values.

Results

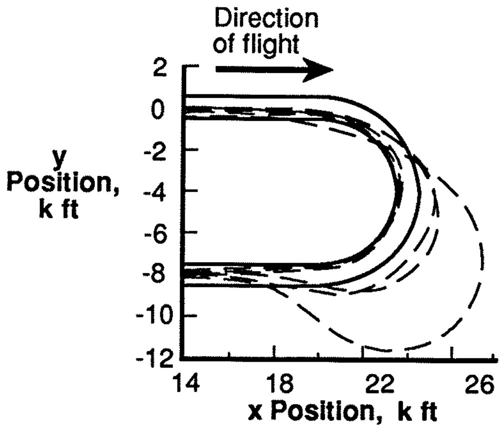
General Observations

There were large differences in the performance of individual test subjects. There was a wide variation in the background of the test subjects, and among the non-pilot test subjects there were obviously large variations in inherent capabilities and aptitude for flying. A poor-performing test subject tended to perform poorly with all configurations. For example, a test subject who performed relatively poorly with the E-Z Fly control system on was almost certain to crash with E-Z Fly off.

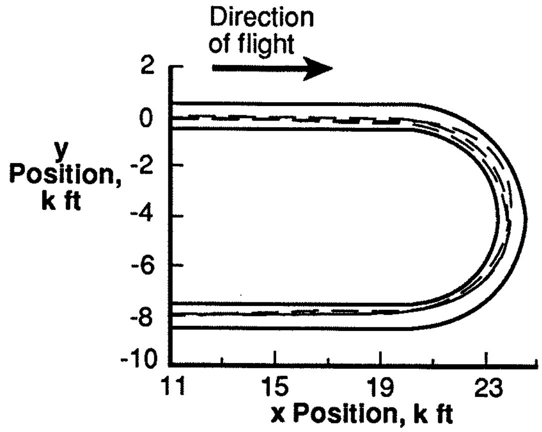
Despite the enhancements to the control system and display compared to the earlier studies, the turns were still more difficult than the straight segments. All the tasks associated with the straight segments were present, but there were additional complications. First, the airplane had to be banked 20° to 30° to follow the turning radius of 4000'. There was no positive reference as to the exact bank angle needed because the boxes, etc remained oriented vertically. A second complication was that the test subjects could not "see around the corner" while in the turns. They could only see two or three boxes ahead while on the straight segments they could see 5 or 6 boxes ahead. This was in spite of the fact that the boxes were spaced more closely in the turns than in the straight segments.

The relative difficulty of negotiating the turns is illustrated in figures 7 and 8. In the first turn, the non-pilots often "flew off" the highway on their first maneuver. (Their performance improved rapidly on subsequent runs). Once off the "highway" the boxes and lane stripes were out of view, and the test subjects had to use the flight director arrows to guide them back to the point they could re-intersect the correct path. One of the reasons some of the non-pilot test subjects gave for running off the highway was that they were "afraid" of making "large" inputs to the wheel even though they recognized they needed to turn more sharply. Evidently they were not comfortable with bank angles of over 10° or so on their first maneuver. The pilot test subjects were, of course, comfortable with large bank angles and had much better performance, figure 7b.

The performance by the non-pilots in the second turn of their first maneuver was much better than that in the first turn, see figure 8a reflecting the steep learning curve for novice test subjects during a given run. Although the pilot test subjects were generally able to stay within the bounds of the turn, their performance



(a) Non-pilots

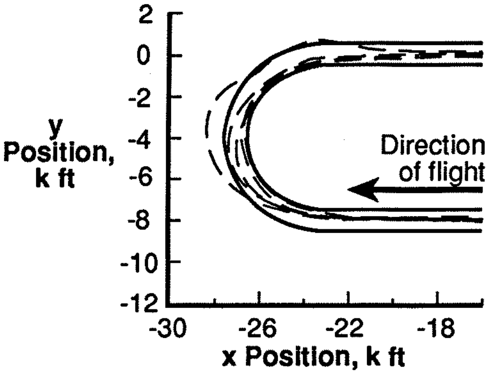


(b) Pilots

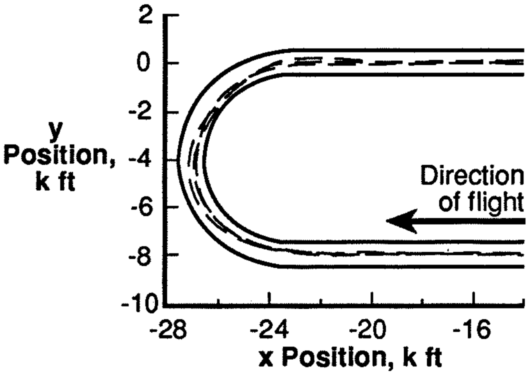
FIGURE 7. Lateral tracking performance in turn one. Solid lines are lane boundaries.

in the turns was also less precise than that in the straight segments.

The test subjects' glide path performance on final approach for each primary test subject's first maneuver is shown in figure 9. It should be remembered that there was a simulated solid cloud cover for altitudes above 200-250 feet so that the test subjects were flying exclusively by the guidance provided from the HITS display at altitudes above that level. In spite of their inexperience and lack of training and practice, all the non-pilot test subjects (and pilot test subjects) were usually able to stay within ±.35° of the the desired glideslope which corresponds to ±1 dot on an ILS glideslope indicator. With this good control on final approach, all seven of the non-pilot test subjects (and all three pilot test subjects) were able to make controlled touchdowns on the runway as will be shown later.



(a) Non-pilots



(b) Pilots

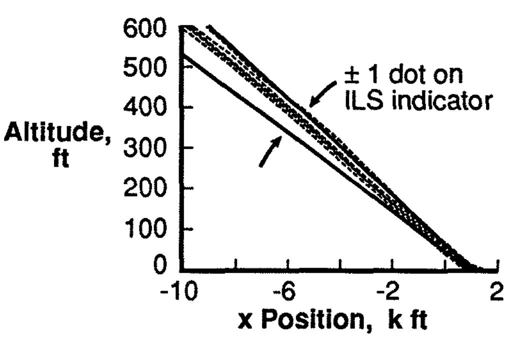
FIGURE 8. Lateral tracking performance in turn two. Solid lines are lane boundaries.

Baseline E-Z Fly and HITS Systems

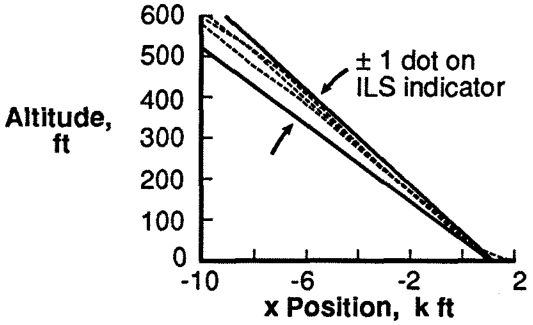
Success rate: The effectiveness of both the E-Z Fly control system and the head-up HITS display is illustrated by the following table for all of the primary test subjects:

Table I. Effect of control system on success rate

	Control System			
	E-Z Fly On		E-Z Fly Off	
	Runs	Ldgs	Runs	Ldgs
Non-Pilots	7	7	7	2
Pilots	3	3	3	3



(a) Non-pilots



(b) Pilots

FIGURE 9. Glideslope performance on final approach.

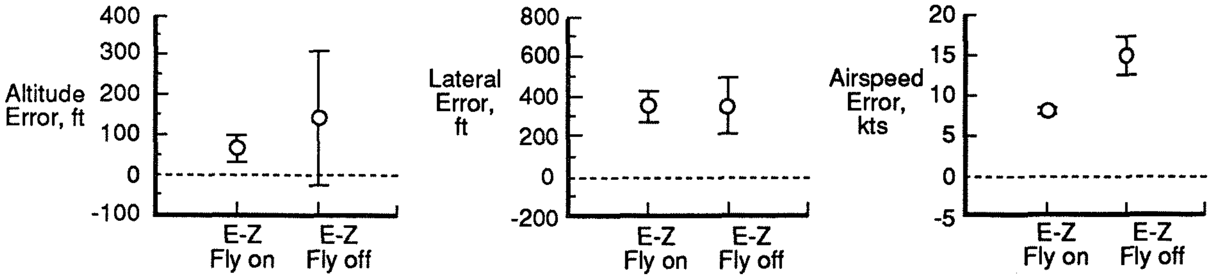
For the seven non-pilots the piloting task was always completed successfully when the E-Z Fly decoupled control system was used. This result is very significant considering the fact that no training or practice was allowed before the E-Z Fly runs and that most of task was flown in reduced visibility without reference to any ground features. This success rate was a slight improvement over the results of references 6 and 8 which had success rates of 50% and 92% respectively. In fact, there were zero crashes for all 122 maneuvers flown by all 16 test subjects with the E-Z fly control system on. Of course, in the latter 106 maneuvers the test subjects had the benefit of the experience in the immediately preceding runs and were less likely to make mistakes.

For the three test subjects who had some pilot training, all runs were successfully completed to a landing as can be seen in the table.

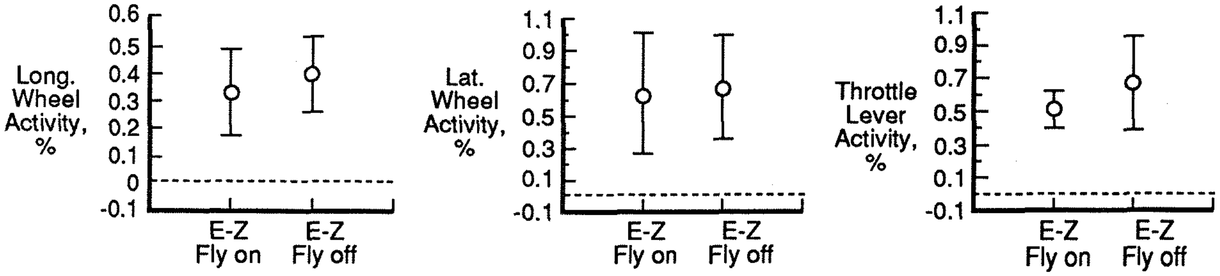
The effectiveness of the HITS display by itself (with E-Z Fly Off) is also demonstrated by the data in the table. That is, for this piloting task (which would be nearly impossible with conventional displays), 2 out of 7 of the runs flown by the non-pilots were successful. And of the other 5 runs, the HITS display enabled some of non-pilots to successfully fly for an extended period of time before they crashed.

Quantitative data: Summaries of the primary test subjects' performance with and without the E-Z Fly control system show the superiority of the E-Z Fly control system, figure 10a. The plots show an average RMS error from a perfect trajectory. Two of the performance measures with E-Z fly on were less than one-half that with E-Z Fly off. The variability, as shown by the error bars, was also much less. The average lateral error is about the same with E-Z Fly on or E-Z Fly off, but the variability is much larger with E-Z Fly off. This indicates less consistent lateral control for the conventional control system (E-Z Fly off). The average altitude and lateral errors appear to be relatively large (50 and 400 ft, respectively) because most of the maneuver was at altitude where the highway-in-the-sky was 1000 feet wide and great precision was not required. But it is also true that a few of the non-pilot test subjects flew completely off the "highway" in the turns (error > 500 ft) as shown earlier, figures 7 and 8. Although the average airspeed error with the E-Z Fly control system is only one-half that of the conventional control system, it also appears to be large. The reason for the large value was the seven different airspeed changes made during the maneuver. The engines were just not powerful enough to make the airspeed changes quickly. Once the airspeed was achieved, the E-Z Fly control system generally maintained the airspeed within 1 or 2 knots of the commanded airspeed which is reflected in the small standard deviation. The large airspeed errors with E-Z Fly off are due in large part to the fact that the manifold pressures presented in the HITS message box were only approximate. Even if the test subjects had set the manifold pressures exactly, the airspeed errors would have been much larger than with E-Z Fly system on because it continuously closed the loop on airspeed. In previous studies,(5,6,8) the desired airspeeds (and not the manifold pressures) were presented with E-Z Fly off. This resulted in a very high workload because the test subjects had to actively monitor the airspeed to keep from losing control of airspeed and possibly stalling, especially on final approach. The new manifold pressure presentation helped reduce the workload and the possibility of stalling.

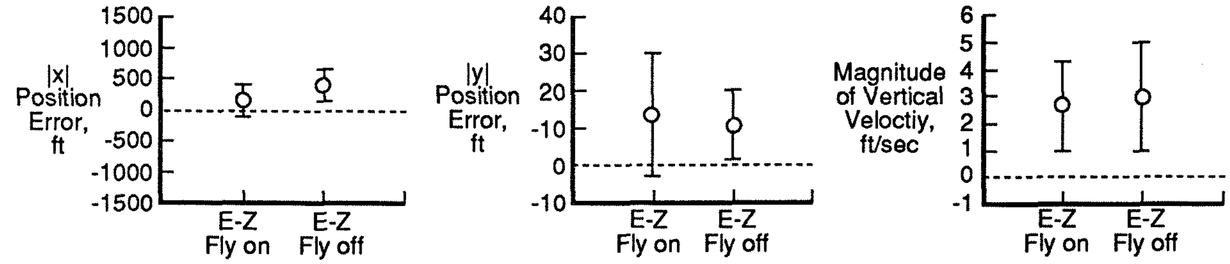
Summaries of the test subjects' control activity indicate a slight possible improvement for the E-Z Fly control system, figure 9b. The average control activity of all three of the primary cockpit controls was slightly less than that of the conventional control system (E-Z Fly off), but the



a. Tracking performance



b. Control activity



c. Landing performance

FIGURE 10. Effect of E-Z Fly decoupled control system. (Nine runs per category).

relatively large error bars indicate the differences are probably not statistically significant.

Summaries of the test subjects' landing performance are presented in figure 10c. The five maneuvers for the test subjects who crashed (with E-Z Fly off) were excluded so that only the data for the successful maneuvers are shown. Excluding the unsuccessful maneuvers with E-Z Fly off caused the landing performance to be practically the same with perhaps a slight improvement with E-Z Fly on. Including all the data for E-Z off would result in such large position errors and touchdown velocities that they could not be plotted on the same scale as figure 10c.

Concluding Remarks

A fly-by-wire, decoupled control system (E-Z Fly) and a pictorial, head-up display (Highway-in-the-Sky or HITS) have been evaluated on the Langley General Aviation Simulator using test subjects who were predominantly untrained non-pilots. The piloting task was performed in reduced visibility conditions and consisted of a continuous series of common maneuvers beginning with a takeoff and ending with a landing. Severe upsets from turbulence and emergency situations such as engine failure were not simulated. Quantitative and qualitative evaluations of performance and task difficulty were made.

The results showed that with this advanced control system and display, 100% of the novice test subjects successfully completed the entire piloting task without prior training or practice. In addition, a few of the novice test subjects were able to successfully complete the piloting task using the advanced pictorial display and a conventional mechanical control system.

The E-Z Fly control system was clearly superior to the conventional mechanical control system. All the test subjects preferred the E-Z Fly control system and practically every quantitative measure of test subject performance and control activity was better with the E-Z Fly control system. Without the E-Z Fly control system, the novice test subjects often lost control especially in the first turn. Loss of control of airspeed in the final approach was not as much a problem in this study as in earlier studies. This improvement was attributed mainly to the new engine manifold pressure commands provided the test subject by the HITS display.

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