Human Performance in Short Orbital Transfer

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THREE readily discernable differences exist between the flight characteristics of atmospheric vehicles and those of space vehicles orbiting a planetary mass. These differences, due both to the lack of air resistance in space and to the effects of a vehicle's orbital motion, may be stated briefly as follows:

(1) Space vehicle rotation and translation motions may be made independently of each other. A space vehicle may rotate about any of its axes without effecting its velocity or it may translate along any axis without prior rotation and without effecting its attitude.

(2) An orbiting space vehicle will maintain its orbital motion without the application of any thrust. Such a vehicle will remain in its original orbit until power application; after thrust is applied, the vehicle will travel in an altered orbit or will intercept or escape the body it was orbiting.

(3) The flight path resulting from the application of thrust to an orbiting vehicle will, when viewed from that vehicle, appear to be curved rather than a straight line.

These, and other less important differences, make the tasks of atmospheric and space flight significantly different from each other. The two tasks are sufficiently different to have prompted a great deal of research exploring pilot performance in simulated space flights. The aspect of performance that has been the focus of most laboratory investigation is the question of human capacity to accomplish rendezvous with an earth orbiting vehicle. Interest in orbital rendezvous is stimulated by anticipation that this nation's space program will will require rendezvous capability in future space vehicles.

There appears to be a growing acceptance of the concept that a human pilot can contribute reliability to the total mission and precision to the terminal phases of the rendezvous maneuver. To the extent that the human operator can indeed function effectively as a controller or a data processor, he can replace electromechanical equipment. To the extent that he can replace such equipment, he can reduce booster weight and cost and contribute to the overall reliability of the mission. To explore the possibility of attaining these goals, rendezvous simulation studies have attempted to define human rendezvous capabilities with varied initial conditions and with varied displays and controls provided for the operator.

Levin and Ward[3] concluded that a human operator was a highly capable element of a rendezvous system. In a coplanar rendezvous task these authors provided the subject with information that included an oscilloscope display of the positions of both the pilot's vehicle and his target. Controls provided for forward and reverse, and upward and downward thrust. Levin and Ward found that their subjects could perform terminal rendezvous maneuvers with great precision.

Freeman,[2] using a simulator with displays similar to Levin and Ward's and controls supplemented by pitch capability, found that subjects' ability to rendezvous was highly dependent upon training and set. A number of Freeman's subjects found the rendezvous task so difficult that they "appeared somewhat irritated with lack of accomplishment and requested that they be permitted to terminate the experiment."

In a six degree of freedom simulator that provided attitudes controls and forward thrust, Brissenden,[1] et al., abandoned oscilliscope displays in favor of an all dialed instrument display panel. Results of the study indicated that human pilots could accomplish rendezvous successfully under relatively adverse conditions if adequate displays and controls were provided.

In one section of their study Wolowicz, Drake, and Videan[4] used a direct-visual-observation presentation of the rendezvous target. They found that the display was adequate for rendezvous, particularly if supplemented by range rate information.

The variety of apparatus configurations and of experimental methods represented in available rendezvous reports is indicative of the relative newness of such research, and of the large number of pertinent questions that remain unanswered.

Purposes of the study. The present study was conducted as an attempt to determine whether a human pilot could successfully accomplish short, coplanar transfers between orbiting vehicles if he were provided with only minimal display and control equipment. This rendezvous simulation experiment assumed that the total weight of the pilot, his transfer vehicle, and his life support system was 250 pounds. Under this assumption the pilot's vehicle can be nothing more complex than a gyroscopic stabilization unit and an individual propulsion unit. It was assumed that the pilot would receive no more display information than he could obtain by visual observation of the target satellite. Vehicles or propulsion units of this nature are being proposed for use by personnel transfering between earth orbiting vehicles and by personnel performing maintenance or assembly tasks.

The subjects in the experiment were provided with two different types of simulated propulsion control systems. One purpose of the study was the comparison of the influence of the two systems upon human

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rendezvous capability. It was hoped that some data might also be obtained that would indicate whether rendezvous range, relative orbital position, or initial vehicle attitude had any effects on the pilot's ability to complete successful interception of his target.

The current experiment was also designed to provide the experimenter with experience and insight into the pilot problems of orbital rendezvous to facilitate future investigations.

The pitch and thrust values of the simulated control systems were based on the control parameters of research equipment tested on zero gravity aircraft flights.

METHOD

Apparatus. The orbital rendezvous simulator used in the study consisted of displays, controls, and analog computer equipment. The components were arranged in the normal simulator pattern (Fig. 1) with the subject included as part of the simulation loop.

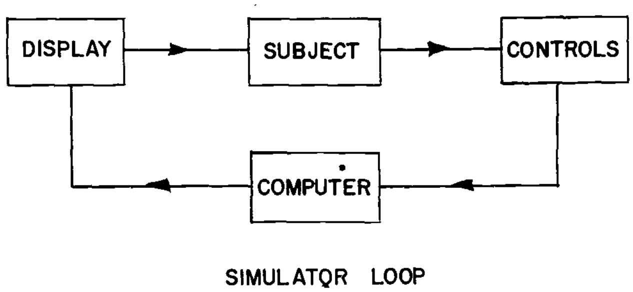

Fig. 1

Display. The target satellite, with which the subjects were required to rendezvous, was represented on the face of an oscilloscope. The oscilloscope was a 17 inch ITT Model 1735D. The target satellite was represented by a pair of concentric circles. The outer circle simulated the extreme dimensions of a 150 foot diameter spherical satellite. The inner circle represented a landing spot or dock centered on the surface of the target. The simulated landing spot was 4 feet in diameter. From the subjects' normal viewing distance of 24 inches, the oscilloscope circles subtended the same angles that an actual 150 foot satellite would subtend when viewed from the ranges simulated in the study. The full screen of the oscilloscope subtended a vertical viewing angle of 28 degrees.

The 28 degree angle was thought to be fairly representative of the field of view provided by a periscope in a small rendezvous vehicle. Even the rectangular coordinate grid with 1/10 inch graduations on the face of the oscilloscope could be duplicated on a vehicle periscope. The target display was an inside-out (fly-to) display with the moving element in the display representing the target rather than the operator, i.e., as the subject pitched or thrusted his vehicle downward the target moved upward in the display, as the subject pitched or thrusted his vehicle upward, the target moved downward on the screen; as the subjects' vehicle approached the target the circles grew in diameter, appropriate to the extent to which the subject had closed with the target. Since the study treated only rendezvous with the target and the vehicle in *coplanar* orbits, only fore and aft thrust and vertical motion were required of the rendezvous vehicle. The subjects were given the capability to induce those motions in their simulated vehicle.

Controls. Both of the control systems investigated in the study permitted the subject to maneuver his vehicle to a successful rendezvous with the target satellite. The subject's vehicle was presumed to be stabilized relative to the local vertical about the pitch, roll, and yaw axes.

One control system provided pitch and fore and aft thrust for the subject's vehicle; the other system provided fore and aft thrust and upward and downward thrust. The former system will hereinafter be referred to as the pitch-thrust system, and the latter will be called the orthogonal thrust system. Figure 2 illustrates the motion capabilities of the rendezvous vehicle under the two control systems.

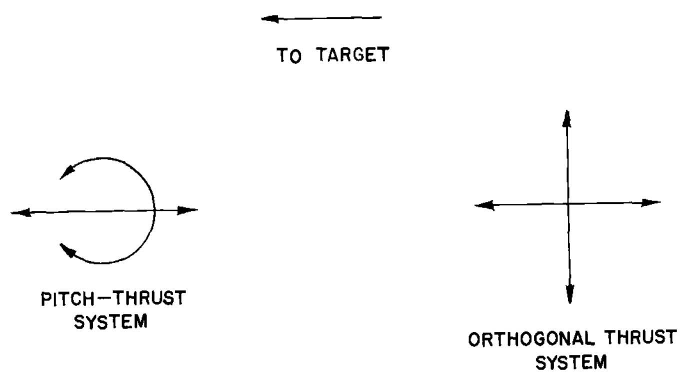

Fig. 2 MOTION CAPABILITIES PROVIDED BY TWO CONTROL SYSTEMS

In both systems the subject operated two control sticks to provide control inputs to his vehicle. The two control sticks were placed side by side between the seated operator and the oscilloscope display. In both systems the left hand stick controlled fore and aft thrust of the subject's vehicle. The control was a spring loaded, return-to-center, one dimension control stick.

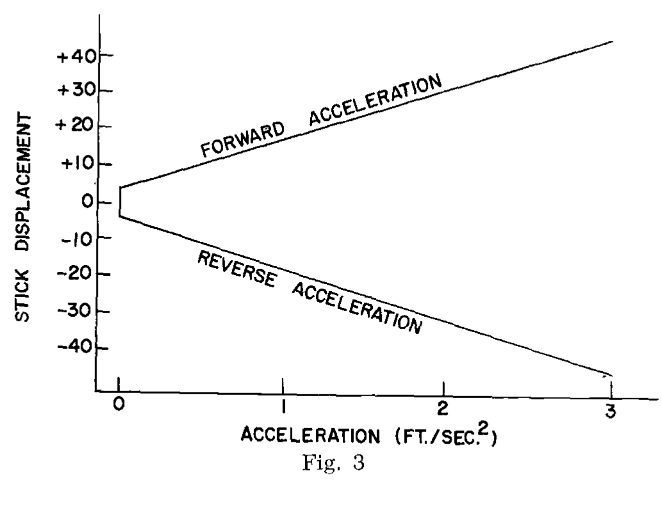

Fig. 3

The lever arm of the stick was 8 inches long, had a total travel of 45° forward of center and an equal travel backward from center. A force of one pound was required to produce a stick movement of 15°. In use, as the subject pushed the left hand stick forward he applied forward thrust to his vehicle; as he pulled the stick backward from the center position he applied reverse thrust to his vehicle; applied thrust was directly proportional to stick displacement as shown in Figure 3. A full displacement of the stick from its center position resulted in a vehicle acceleration of three feet per second per second. For example, if the stick were pulled fully backward and held fully back for 5 seconds, vehicle velocity would have been reduced by 15 feet per second, if the stick were held fully forward for 5 seconds, velocity would have been increased by 15 feet per second. Thrust always acted along the longitudinal axis of the subject's vehicle. After a subject had applied thrust and had released his thrust control stick, his vehicle would continue to move at a constant velocity in a trajectory acted upon only by the mechanics of his orbit, until he applied reverse thrust.

In the pitch-thrust system, the right hand stick controlled vehicle attitude. This stick was mechanically the same as the thrust stick. With this stick the subject could control the pitch angle of his vehicle, and since he could alter the attitude of his vehicle, he could control the direction in which thrust was applied, relative to the earth and the target satellite. That is, the subject could alter his vehicle's attitude and by applying thrust along a non-horizontal line of sight, change his vehicle's altitude. If the right stick were pushed forward, the subject's vehicle pitched down (or forward), if the stick were pulled back, the vehicle would pitch up (or back). The rate of change of pitch angle was proportional to stick displacement, with full displacement providing a pitch change of three degrees per second. Thus, if the subject held the right hand control fully back for 4 seconds, his vehicle would have pitched up 12°. In the experimental situation this means, of course, that the target satellite would have moved downward 12° on the display. When the pitch stick was released, the subject's rendezvous vehicle was stabilized at its new attitude.

In the orthogonal thrust system the right hand control stick controlled vehicle altitude by providing upward or downward thrust. When the orthogonal thrust system was in use the right hand stick was rotated 90° on its base to place the control lever in a horizontal position. The subject could increase his vehicle's altitude by moving the stick upward, and could move his vehicle downward by moving the control downward. Such thrust applied to the vehicle was reflected by appropriate changes in the subject's display. Vertical acceleration was proportional to stick displacement, with maximum stick movement producing an acceleration of 3 feet per second per second. After a subject had applied vertical thrust and had released the control stick, his vehicle would continue to move vertically until the velocity attained was cancelled by a reverse thrust.

Computer. Control inputs were fed into analog computer equipment. The computer was programmed with the equations of orbital motion, and produced the display and display motion appropriate to the orbital motions of the vehicles and the subject's control inputs. The computer also produced the criterion-measure outputs. The analog equipment used consisted of the standard 16-31 series computer manufactured by Electronic Associates, Inc. The components included 60 amplifiers, 80 attenuators, 2 servo multipliers, 4 servo resolvers, 5 electronic multipliers, and 5 diode function generators.

Subjects. Five rated Air Force officers participated as subjects in the data collecting part of the study. A non-pilot civilian served as an additional subject and contributed data for one portion of the analysis as shall be noted later.

Procedure. Subjects were required to pilot a simulated interceptor vehicle to a rendezvous with a target satellite in a coplanar orbit. Both the vehicle and the target satellite were in circular orbits approximately 200 nautical miles above the earth's surface. At the beginning of each trial the subject's vehicle had velocity relative to the target satellite appropriate to the orbital conditions for that trial.

Training. Although all of the subjects had some appreciation of the nature of the orbital rendezvous task, an extensive instruction program was undertaken with each subject prior to the data-taking trials.

Each subject first read the "Orbital Rendezvous Study Instructions" (Appendix) which explained the general nature of the rendezvous task. Each subject was then introduced to either the pitch-thrust or the orthogonal thrust control system, and read the instructions appropriate to that system (Appendix). The subject was seated at the subject's station and observed the display and familiarized himself with the controls. Using the assigned control system, the subject then attempted to fly his vehicle to a rendezvous with the target satellite. The computer was programmed for a rendezvous trial with its starting point at T1 as seen in Figure 4. Figure 4 also indicates the orientation of the pilot's vehicle relative to the earth and the target. In some initial positions the pilot was upside down (simulated) relative to the earth. The subject repeated runs from T1 using the assigned control system until he completed two successive successful rendezvous. The criterion of success was simply landing or impact on the target. The subject was then introduced to the other control system and read the instructions appropriate to it. He then was required to practice with the new system, starting each trial from initial point T1, until he completed two successive successful runs. Then using the two control systems in the same order, the subject had to reach the same criterion of success with each system starting from point T2 as seen in Figure 4. This completed the training session. During the entire training period, the subject's questions were answered and the experimenter continued to make suggestions to improve the subject's technique. The duration of the average training period, held the day before the data trials, was approximately 6 hours.

Experimental Task. The task of the subject during the data gathering period was to fly his vehicle to a rendezvous with the target satellite. Each subject made five runs with each control system from each of four different initial positions. The order in which starting points were assigned was randomized. The initial points are identified as D1, D2, D3, and D4 in Figure 4. The

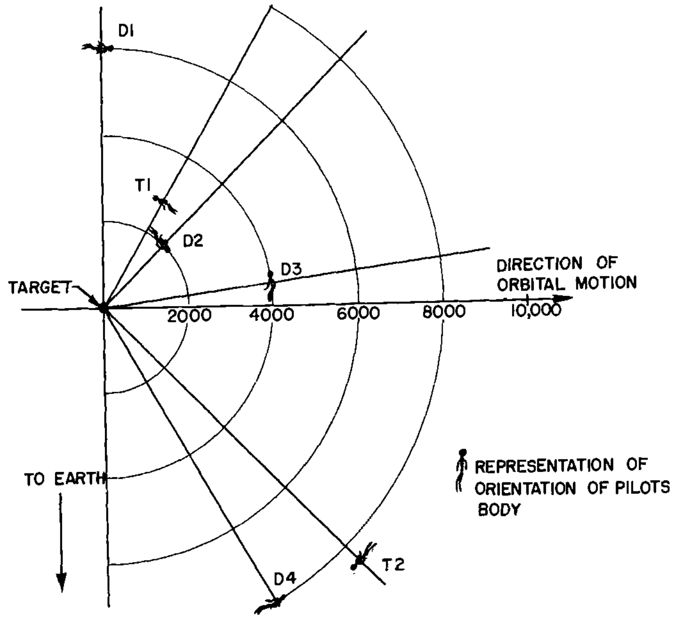

Fig. 4

first two of each set of five runs were considered orientation runs that served to familiarize the subject with the peculiarities of flying a rendezvous from that particular initial position and orientation. Data were recorded on the final three trials of each set of five for each position-control combination. Approximately 2 minutes elapsed between the runs from any particular starting position; approximately five minutes were allowed between the final trial from one position and the first trial from the next position. During the inter-trial interval the experimenter reported results to the subject. After successful trials the experimenter reported the elapsed time and the impact velocity of the subject's vehicle on the target. After unsuccessful runs the experimenter reported whether the subject had overshot or undershot the target, and the distance by which the target was missed.

During each trial the computer traced, on an x-y plotter not visible to the subject, the path followed by the subject's vehicle. After each trial the experimenter recorded the velocity of impact of the vehicle upon the target, the time required to effect the rendezvous, and the amount of fuel consumed by the subject's vehicle. Runs were terminated if the subject passed by the target at such a distance or with such a velocity that the experimenter judged that it would be improbable that the subject would be able to effect a successful rendezvous.

Experimental Design. The subject's primary task, as emphasized in the instructions, was to intercept the target satellite. Secondarily, he was to try to conserve both fuel and time while achieving the rendezvous, and land on the target with a low velocity. The interception data were recorded as a success-failure dichotomy for each data run. With the inclusion of criterion data from a sixth subject, a Wilcoxon Matched-Pairs Signed-Ranks test could be conducted to determine whether the two control systems in the study differed significantly from each other in permitting the subjects to land on the target. Data from the sixth subject were used in the Wilcoxon test only, and have been neither used nor reported in any other part of this report.

Target interception data from the five principal simulator pilots were subjected to a Friedman two-way analysis of variance to determine whether the degree of interception success is dependent upon the starting point of the rendezvous.

Impact velocity, elapsed time, and fuel consumption data are presented graphically, as are the results of combining time and fuel data.

The 95 per cent confidence level was selected for conducting tests of significance on the data.

RESULTS

All subjects were, after the training period, able to rendezvous with the target satellite using either the pitch-thrust or the orthogonal thrust control system. The subjects did not, however, attain equal degrees of success with the two systems. Each subject piloted three data trials or runs from each of four different starting points with each control system. The six subjects who contributed data to the first part of the analysis, therefore, provided data from 72 trials with each control system. Of the 72 trials with the pitch-thrust system, 46 resulted in rendezvous with, or impact on, the target. With the orthogonal thrust system the subjects were able to intercept the target on all 72 trials. The orthogonal thrust system thus yielded 100 per cent "hits" or successes while the subjects were able to achieve rendezvous only 64 per cent of the time with the pitch-thrust system. The Wilcoxon Matched-Pairs Signed-Ranks test applied to the data permits us to conclude that a significant difference exists between the two systems compared on the criterion of frequency of hits attained with each. Details of the Wilcoxon test are shown in Table I.

TABLE I.

Source	N	T	P
Control Systems	6	0	.05

If the data contributed by the sixth subject are removed from consideration, the success of the five military pilot subjects with the two systems may be considered. Such procedures show that the Air Force subjects achieved impact with the target 100 per cent of the time when using the orthogonal thrust system but only 58 per cent of the time with the pitch-thrust controls.

From the fact that the subjects achieved a perfect rendezvous record with the orthogonal thrust system it is evident that the starting point of a trial had no influence on a subject's ability to intercept the target while using the orthogonal controls. Successes with the pitch-thrust system were not, however, evenly divided between starting points. Figure 5 shows the relative

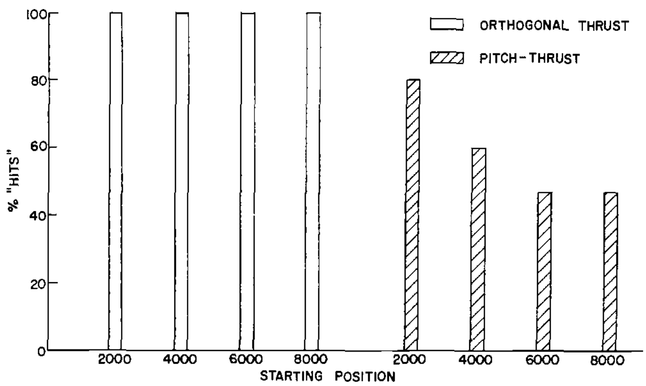

Fig. 5

number of hits scored from each starting position with each control system. It should be noted that approach angle and initial range are completely confounded in the present design. Hereinafter, the starting points shall be referred to by the range associated with each.

Using the pitch-thrust system the five subjects achieved rendezvous on 80 per cent, 60 per cent, 47 per cent, and 47 per cent of the trials from, respectively, the 2000, 4000, 6000, and 8000 foot starting positions. These relative success data for the pitch-thrust system were subjected to a Friedman Two-Way Analysis of Variance by Ranks. In spite of the differences in the data, the Friedman test failed to indicate the existence of a statistically significant difference between the different starting positions.

Interception of the target satellite was the subject's primary task, but consideration was also given to secondary criteria of success. The subjects were instructed to fly the rendezvous maneuvers in such a way that their velocity at the moment of impact with the target satellite was as low as possible. The subjects were told that terminal velocities below ten feet per second were desired. A comparison of data for the two control systems reveals that the orthogonal thrust system yielded a lower landing velocity than did the pitch-thrust system. The mean impact velocity for the 60 successful trials with the orthogonal thrust controls was 4.61 feet per second. The average terminal velocity for the 35 successful runs with the pitch-thrust controls was 7.86 feet per second. The impact velocity ranges for the two systems were 12.75 and 24.50 feet per second respectively.

The mean impact velocity data for runs from each position with each control system are plotted in Figure 6. Average terminal velocities for the different starting positions with the orthogonal thrust system were, in order of increasing range of the starting point, 6.65, 3.82, 4.57, and 3.42 feet per second. Impact rates, in the same order for the pitch-thrust system were 5.19, 9.00, 6.21, and 12.64 feet per second.

Another secondary criterion of rendezvous success was speed of interception. The subjects were instructed to accomplish the interception of the target satellite as rapidly as possible consistent with the other criteria. Total time to rendezvous was recorded for all successful trials. However, since rendezvous range varied, total time to impact was, for all trials, divided by range to make comparisons meaningful. The resulting measure was seconds per foot; high scores indicating relatively long rendezvous times and low scores indicating relatively rapid runs. The mean time score for the 60 orthogonal thrust trials was .045 seconds per foot. The mean time score for the 35 successful pitch-thrust runs was .070 seconds per foot. Thus, the orthogonal thrust rendezvous runs were made in less time than the pitch-thrust runs. The time scores ranged from .024 to .085 seconds per foot with the orthogonal thrust controls, and from .038 to .140 seconds per foot for the successful runs with the pitch-thrust controls.

Mean time scores with the orthogonal thrust system for trials from each starting position were, in order of increasing range of the initial position, .059, .044, .035, and .041 seconds per foot. Time scores for the successful pitch-thrust system trials given in the same order, were .106, .070, .055, and .047 seconds per foot. These data,

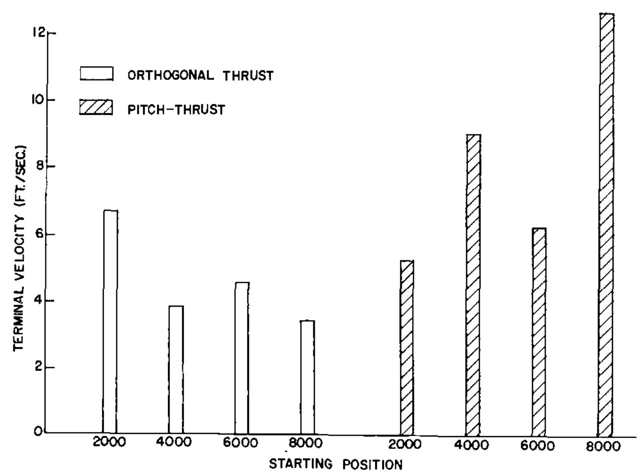

Fig. 6

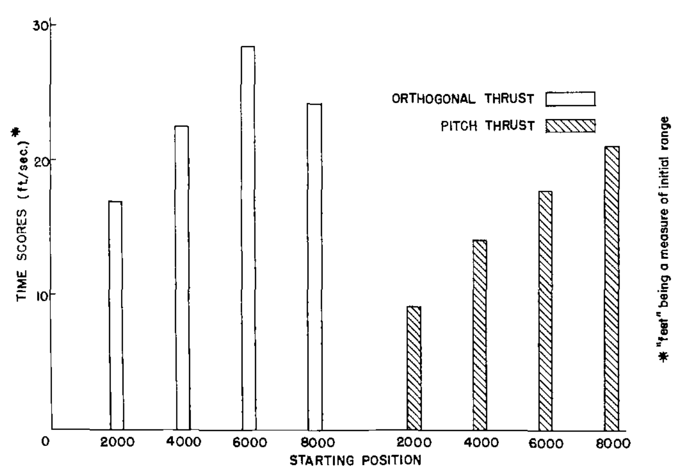

Fig. 7

converted to average velocity in feet per second, are plotted in Figure 7.

The amount of fuel consumed during each rendezvous attempt was recorded by the experimenter at the end of each successful trial. Subjects had been instructed to try to conserve fuel by maintaining moderate interception velocities and by carefully planning all course corrections. Since fuel consumption, as well as rendezvous time, could be a function of initial range under the conditions of the experiment, fuel consumption for each successful trial was divided by range to make comparisons between initial conditions more meaningful. The resulting data were expressed in terms of fuel units expended per foot of initial range; a low fuel score, therefore, indicates good fuel management, and a high fuel score suggests the expenditure of relatively large amounts of fuel. Since no specific fuel was assumed, fuel units are unlabeled. If a specific impulse value is assumed, fuel units could be converted to pounds.

The mean fuel score for the 60 successful orthogonal thrust trials was .00435 units per foot. The 35 successful pitch-thrust trials were flown with an average fuel score of .0050 units per foot, indicating slightly poorer fuel economy than that achieved with the orthogonal thrust control system. Ranges of fuel scores on individual successful trials were .0023 to .0128 units per foot and .0016 to .0215 units per foot for the orthogonal thrust and pitch-thrust systems respectively.

Orthogonal thrust system mean fuel scores for trials from each initial position were, in order of increasing range, .0058, .0045, .0034, and .0037 units per foot. Fuel consumption scores on the successful runs with the pitch-thrust controls were, in the same order, .0099, .0039, .0038, and .0024 units per second. The fuel consumption data, converted to feet of initial distance closed per unit of fuel consumed, are presented in Figure 8.

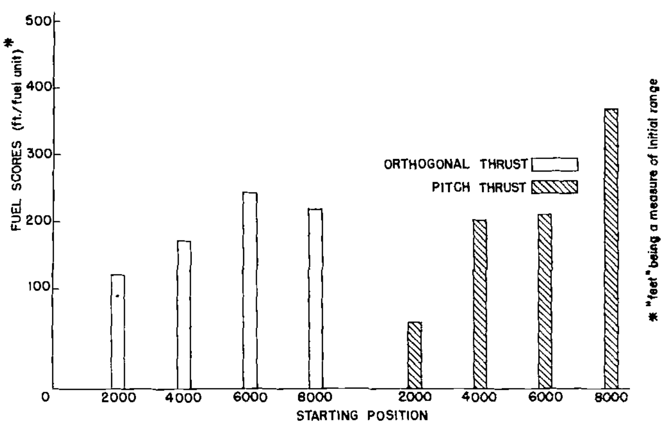

Fig. 8

Though the subjects were instructed both to fly the rendezvous maneuver in a short time and also to rendezvous with a small expenditure of fuel, it was realized that each subject had to reach some compromise between fuel economy and time economy. To some extent the two requirements were incompatible. The rendezvous could be accomplished quickly if it were done with accuracy and a high rate of speed; but high speeds required large expenditures of fuel. Fuel consumption could be minimized by maneuvering accurately and by maintaining low speeds; but low speeds necessarily resulted in large time costs. In order to take both time and fuel factors into account when making data comparisons, the two criterion measures were combined. The resulting measure was the product of feet per second and feet per unit of fuel, or range squared divided by the product of time and fuel. This combined measure, which is indicative of the economy of both fuel and time, was called the index of operating efficiency. A high index indicates economy of operation; a low index indicates relative inefficiency.

The mean index of operating efficiency for the 60 trials with the orthogonal thrust system was 5760; the index yielded by the 35 successful pitch-thrust trials was 4458. Indices of individual orthogonal thrust trials ranged from 1348 to 13514. The range of indices for the successful pitch-thrust trials was 332 to 10526. Operating efficiency means for the orthogonal thrust system, in order of increasing range of the starting point, were 2950, 5000, 8333, and 6757. Mean indices of operating efficiency of the pitch-thrust system, in the same order, were 875, 3597, 4587, and 8772. These data are plotted in Figure 9.

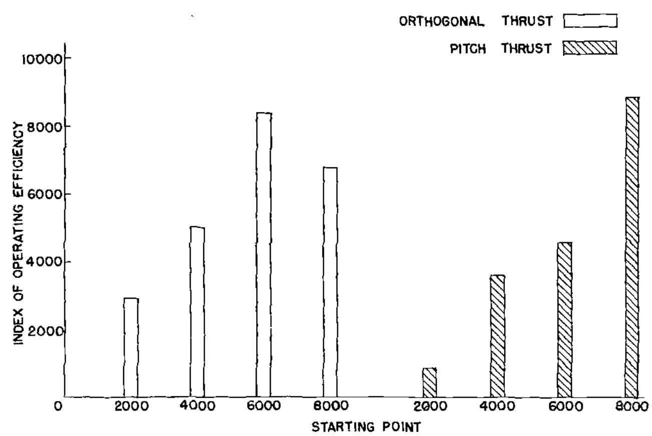

Fig. 9

DISCUSSION

Any conclusions drawn from the results of this study must take into account the limitations of the study. The apparatus presented an imperfect simulation of coplanar orbital rendezvous. The simulation was imperfect to the extent that the display included neither earth horizon nor star field; in addition, the image of the target satellite was obviously an oscilloscope display rather than an optical view of a space vehicle. The simulator was of the fixed-base variety that provides no sensory motion cues other than the visual cues of the display. Furthermore, it would have been desirable to have had a larger subject population than that which was used.

Within the limitations of the experiment, it may be concluded that the orthogonal thrust control system which provided both vertical and fore-aft thrust capability, was superior to the pitch-thrust system which offered fore-aft thrust and pitch control. The Wilcoxon test results permit this conclusion, and the secondary criteria results support it. Not only did subjects rendezvous on 100 per cent of the orthogonal thrust trials as opposed to 58 per cent of the pitch-thrust trials, but the use of the orthogonal thrust system resulted in lower landing velocities, less time expenditure, and lower fuel consumption. In addition to the support lent to the orthogonal system by the objective data, the subjects reported unanimous preference for that system.

The subjects achieved 100 per cent rendezvous success with the orthogonal thrust system; the degree of success of interception was entirely independent of the starting position of the subject's vehicle relative to the target satellite. The Friedman test indicates that, in this experiment, rendezvous capability was also independent of starting position with the pitch-thrust system. A more sensitive experimental design might reveal differences in degree of rendezvous success attributable to differences of initial range, approach angle, or interceptor orientation. Such a conclusion is supported by the data presented in Figure 5. Target interception with the pitch-thrust system was 80 per cent successful when subjects started from the 2000 foot point, but only 47 per cent successful from the 6000 and 8000 foot starting points. There appears to be a definite trend suggesting that successful rendezvous becomes less certain as range increases when subjects are using the pitch-thrust controls. When rendezvous from different initial positions are compared on the basis of impact velocity, time requirements, and fuel consumption, positional differences again appear to exist. Future experiments could be designed specifically to test for the existence of such differences.

Mean impact velocities with the orthogonal thrust and pitch-thrust systems were 4.61 and 7.86 feet per second respectively. Both means are below the 10 feet per second figure suggested to the subjects, and both are certainly low enough to be absorbed safely by a human landing on his feet or protected against shock. The orthogonal system landing speeds might have been even lower than they were if the subjects had had less confidence of succeeding while using that system. Some subjects appeared to be so confident that they could intercept the target with the orthogonal system that they used less caution in making course corrections or in programming deceleration thrusts than they did with the pitch-thrust system. It should be noted that with the pitch-thrust system, there again appears to be a deterioration of performance as range increases.

The fact that interceptions were generally made in shorter time with the orthogonal thrust system than with the pitch-thrust system was probably also due, in part, to the subject's greater confidence in their ability to achieve rendezvous with the former system. The subjects' confidence apparently resulted in their programming higher speeds from each starting position when using orthogonal thrust than when using pitch-thrust controls. In general, it appears that temporal efficiency of rendezvous increases with increasing range of the starting point from the target.

A similar trend of efficiency is suggested by the fuel consumption data plotted in Figure 10. For both control systems there appears to be an increase in efficiency of fuel expenditure as range increases. Slightly better fuel consumption records were made with the orthogonal thrust system, but the differences were relatively small compared to the differences measured by other criteria.

In view of the efficiency trends suggested by the time and fuel records, it is reasonable that such trends should also be reflected in the index of operating efficiency data which were developed from the time and fuel scores. Such is the case. The higher efficiency of operation attained on the long range trials is most striking in the data for the pitch-thrust system. It must be remembered, however, that only successful trials contributed data to the means plotted in Figure 9, and that fewer successful runs were flown from the distant starting positions. The average efficiency of operation was again higher for the orthogonal thrust system than for the pitch-thrust system.

In general, and within the limitations of the simulation, it may be concluded that evidence has been presented suggesting that subjects *can* successfully accomplish short, coplanar orbital transfers to a target satellite. Successful rendezvous can be made repeatedly and reliably even with minimum display and control equipment, if both vertical and fore-aft thrust are provided by the pilot's control system. Finally, impressions gained during this experiment strongly support the use of training simulators. Situation understanding and rendezvous technique can be strengthened intensely through training with realistic simulators.

APPENDIX
ORBITAL RENDEZVOUS STUDY INSTRUCTIONS

This study is one of a series of studies designed to investigate human performance in piloting a small orbiting space vehicle to a landing on a large manned satellite. In these studies you, the pilot, will have no tasks other than that of making a soft landing on a target spot on the side of the satellite. We are trying to find out how well people can do this job with only very simple controls and displays.

In this particular experiment your ship is orbiting the earth in the same plane (not necessarily the same altitude) as the target satellite but you may be above or below, ahead of or behind your destination, or some combination of these. Your starting position will be within two miles of the satellite; you will have essentially no motion relative to your target and you will always face the target at the beginning of the run. Your vehicle is inertially stabilized about all three axes but you will have sufficient control over your ship to rendezvous successfully.

Your task in this study is a rather difficult one since, owing to the nature of orbital mechanics, your flight path will not always correspond to your line of sight. With practice, however, the task can be performed very reliably. There are, in fact, several different ways of successfully making the transfer to the target. We will illustrate the methods we want you to use. Your display will consist of an oscilloscope mounted in front of you. The face of the oscilloscope represents an optical window in your vehicle. This window permits a total viewing angle of about 28° in the vertical direction. The target satellite is seen in the center of the screen. The outer circle of the target represents the satellite's 150 foot diameter; the small spot in the center of the circle represents a 4 foot diameter landing spot on which you will try to land.

Your only clue to your distance from the target is the target's size in the window, as you approach, the target and the landing spot will appear to grow larger, but the landing spot will not appear to grow larger until you are within 375 feet of the target. When you have travelled half the distance from your starting point to the satellite, the target will have grown to twice its original size. Your cue to your line of sight (the direction you are facing relative to the satellite) is the displacement of the target from the center of your window. If the target is above the center of the window, you are pointed below the target; if the target is below the center of the window, your line of sight is above the target.

In each part of this study we would like you to land on the satellite at a low velocity using as little time and fuel as possible; however, in view of the serious consequences of missing the target, your primary task will be to land on the satellite as near the target spot as possible, regardless of fuel, time, or velocity.

PITCH-THRUST SYSTEM INSTRUCTIONS

You have two control sticks in front of you, the left stick controls forward and reverse thrust, thrust always acts along your line of sight, that is, toward the center of your window. Push the left stick forward and you will accelerate toward the center of the screen until you release the stick. When you release the stick, you will coast forward until you reverse the thrust by pulling back on the stick. This stick is a proportional control. A stick displacement of approximately one inch will yield an acceleration of one foot per second per second. A full displacement of the stick from its center position will result in an acceleration of three feet per second per second. For example, if the stick is held fully forward for ten seconds, you will have reached a velocity of thirty feet per second.

The right hand stick controls the pitch angle of the vehicle. With this stick you can change your line of sight and therefore, your line of thrust as well. That is, if you have applied thrust along your original line of sight and you then change your line of sight, by adjusting the right hand stick, and finally apply thrust along your new line of sight, your resultant velocity will be the vector sum of your original thrust and the added thrust along the new line of sight. If you push the right hand stick forward, the vehicle will pitch down (or forward) at rates up to three degrees per second (full forward on control) and will continue to pitch until the stick is released. Now you will remain stabilized in the new position. When you pitch down the satellite image will move upward in the window. If the pitch stick is pulled back you will pitch up (or back) at rates up to three degrees per second. When the stick is released you will be stabilized in the new position. When you pitch up your target image will move downward in the window. One inch on the screen represents two and one-half degrees of angle. You must remember that in a space vehicle merely changing your pitch angle will not change the direction in which you are travelling. To change your direction of travel you must pitch to some desired angle and apply thrust with the left hand stick.

ORTHOGONAL THRUST SYSTEM INSTRUCTIONS

You have two control sticks in front of you. The left stick controls forward and reverse thrust. Thrust always acts along your line of sight, that is, toward the center of your window. Push the left stick forward and you will accelerate toward the center of your screen until you release the stick. When you release the stick, you will coast forward until you reverse the thrust by pulling back the stick. This stick is a proportional control. A stick displacement of approximately one inch will yield an acceleration of one foot per second per second. A full displacement of the stick from its center position will result in an acceleration of three feet per second per second. For example, if the stick is held fully forward for ten seconds, you will have reached a velocity of thirty feet per second.

The right hand stick controls vertical or up-and-down thrust of your vehicle. With this stick you can move above or below your original line of sight. If you pull the stick back or down, you will move downward and the target will therefore move upward in your window. If you push the stick forward or up, you will move upward and consequently, the target will move downward in your window. If you have pushed the stick forward to move upward, and have then released the stick, you will continue to coast upward until you reverse the thrust by pulling back on the stick. This stick is also a proportional control yielding accelerations from one foot per second per second to three feet per second per second. One inch on the screen represents two and one-half degrees of visual angle.

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