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PILOT RE-ENTRY GUIDANCE AND CONTROL

by Albert B. Miller

Prepared under Contract No. NASw-869 *by*
THE BUNKER-RAMO CORPORATION
Canoga Park, Calif.
for

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FOREWORD

This report was supported in part under National Aeronautics and Space Administration Contract NASw-869, Office of Advanced Research and Technology, Electronics and Control, Control and Stabilization Division. Mr. Robert W. Taylor was the NASA Technical Monitor until March 1965, and Mr. Roger L. Winblade was the NASA Technical Monitor thereafter.

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SUMMARY

The present paper considers some of the problems confronting the pilot during a manually controlled re-entry, and some of the areas where additional research could most profitably contribute to a more complete knowledge of manual control. The relationship between re-entry vehicle configuration and the nature and severity of the manual control maneuvers is discussed in terms of the energy available to control the vehicle, and the display-control relationship as they relate to the functions performed by the human operator. The importance of training through simulation is stressed and some of the areas where additional simulation studies are needed is pointed out. It is shown that the problem of escape continues to be a critical problem which requires considerable effort if a solution is to be attained. With regard to future needs, it is pointed out that simulation studies will continue to be one of the most important vehicles for research into manual control problems and that many more studies of the basic behavioral components of manual control are needed in order to develop more complete models of the human control process. In conclusion, several articles are summarized in the annotated bibliography which are representative of the research now being carried out concerning manual control during re-entry.

INTRODUCTION

One of the most critical aspects of man's flight into space is his safe return through the atmosphere. As the missions of manned flights become broader in scope and vehicles more flexible in their ability to manuever the demands on the control system, either manual or automatic, also become more stringent. Re-entry represents the final phase of space flight where the problem of control is most critical and the cost of error high. For vehicles entering the atmosphere the major problems arise, out of the necessity, to control aerodynamic heating, deceleration loads and the requirement to control the time and location of landing. The nature of the control problem ultimately rests with the nature and scope of the mission. As Lesko (Ref. 12) points out "an all inclusive operational capability of a piloted re-entry vehicle would encompass its safe return to earth in a reusable manner, at any arbitrary site, from any random orbit, at any arbitrary time, under any weather condition, in daylight or at night". It is obvious that within the current state of the art that the above capability requires a large number of compromises, and a cost which at this time is prohibitive. At this time, also, the role of man is best determined for the specific re-entry and mission.

Probably the most critical problem regarding man's role in the re-entry phase of space flight is the development of procedures for the allocation of functions to man or machine. The problem is not simply one of determining those functions that man can perform, but one of determining the tradeoffs which exist within the mission context between those control functions which must be accomplished with respect to those which man is able to perform as they affect the total success of the mission. It is in this area that simulation will play an important role, not only in determining the abilities of the human in specific situations but also in setting up the parameters of the system within which the man must perform. There are then, at least two areas which must be investigated and two types of information which must be available in order to set up rational procedures for the allocation of functions:

1. Knowledge of the performance of man and machine in specific control situations, and

2. Knowledge of the specific system mission in order to assess the nature of the required tradeoffs.

An example is the low L/D lifting vehicles designed for orbital missions. It has been pointed out (Ref. 12) that such vehicles have high touchdown speeds, high approach speeds and steep glide angles which demand a great deal of concentration and precision from the pilot during the landing maneuver. In studies by Matranga and Armstrong (Ref. 76), and Bray, Drinkwater and White (Ref. 67) emphasis was placed on the importance of minimizing the pilot's tasks during the landing maneuver at low lift-drag ratios. The point here is that man is not eliminated because he is totally unable to perform the task but because of the task loading and the critical nature of the maneuver during this phase. Another indication of the effort to reduce the amount of manual participation in certain re-entry vehicles is found in a paper by Johnston and Gaines (Ref. 12) describing the piloting techniques used in the X-15 research airplane. They point out that because of the limitation imposed by aerodynamic structures and propulsion technology the determination of optimum approach and landing techniques becomes a critical re-entry problem. Their approach, which is applicable to vehicles such as Dyna-Soar and Apollo, is to use an optimization technique that selects that approach and flare or pullout, which minimizes the pilot task by virtue of the nature of the technique. Here again knowledge of the mission objective and the vehicle must be obtained in order to reasonably allocate functions since it is the vehicle's external geometry that affects the functional control system design.

Before proceeding further it might be valuable in terms of the overall approach of this paper to make some general orienting comments about the adopted view of the role of man in space systems. A great deal has been written about the role of man in space and the justification for his being there. With this has also come the statements concerning the usefulness of man in space in terms of those things which he can do best or which are supposedly peculiar to man. A listing of the desirable characteristics attributed to man and assumed to be useful in space missions would point out that man is:

1. adaptable to a broad range of flight control systems

2. a good decision maker

3. able to deal with unknown or unexpected occurrences

4. a good observer, reporter and communication link

5. capable of serving as a backup control for important subsystems

6. useful as a filter for unimportant or incorrect information

7. valuable in maintenance and repair, and the correction of malfunction

8. valuable in space rescue operations

9. capable of good servo element characteristics in the guidance and control system.

This list is representative, but not exhaustive of the abilities often cited in favor of man in the system. These are no doubt true statements about certain aspects of man's capability, but the position taken here is that any specific ability is only important and useful when considered in terms of the specific mission requirements and the utilities attached to certain aspects of the mission which may or may not be related to the "facts" of the relative abilities of man or machine. Our purpose then is not to justify the role of our usefulness of man during re-entry maneuvers but to try and focus on the kind of information that would be needed in order to make a reasonable allocation of function to man or machine, in terms of the mission requirements.

RE-ENTRY, APPROACH AND LANDING

As previously pointed out, aerodynamic heating, deceleration, and the control of the time and location of landing characterize the problems of the re-entry maneuver up to the approach and landing phase. The severity of the re-entry and landing is directly related to the type of vehicle used. When the vehicle encounters the atmosphere the shock wave at the nose of the vehicle causes high temperatures. With ballistic or steep angle entry the vehicle reaches the lower and denser atmosphere in a very short time while a shallower lifting entry into the atmosphere takes longer to reach the lower and denser atmosphere. The problem of control during re-entry becomes more complex as the vehicle L/D increases from zero to 2 or 3 and the configuration changes from that of a blunt body of revolution, to that of a winged, airplane-like shape. The nature and complexity of the control problem of lifting re-entry vehicles has thus far only been available for study through simulation. The ballistic flights of Project Mercury provide only limited insight into the problem of manned lifting re-entry vehicle control. Glenn demonstrated, however, the ability to manually orient the Mercury vehicle for the proper re-entry attitude, but once the retro-rockets were fired the vehicle had no control over its trajectory, loads or landing point. Where roll attitude control is not necessarily required for a non-lifting body, it must be controlled or modulated on a lifting body if the landing area is to be predicted even approximately. Also, the pitch and yaw attitude control requirements of a non-lifting body are less stringent. Several experiments have shown the critical control situations which may develop during re-entry. (Refs. 67, 76). Using stationary and moving flight simulators and aerodynamic configurations representing a boost-glide vehicle, the X-15 and a blunt-body-type vehicle, it was found that critical control situations developed at high angles of attack and involved coupling between the lateral control and the aircraft directional response. With accelerations greater than about 4g when the pilot was controlling a lightly damped vehicle, his tracking performance deteriorated markedly. In another study

(Ref. 61) of fixed base and in-flight simulations of longitudinal and lateral-directional handling qualities for piloted re-entry vehicles, the ability of the pilot to control a wide range of conditions was demonstrated.

The rôle of the pilot in re-entry begins just prior to entering the atmosphere or the application of de-orbit thrust if entering from an orbit rather than directly as from a lunar or a deep space mission. With respect to entries from near-earth orbits the main problems are concerned with limiting deceleration and heating, and range control to a successful landing. For direct re-entry from deep space, variations in re-entry point, re-entry angle, and re-entry plane must be considered, therefore, the vehicle must have the ability to control its range after re-entry in order to achieve the desired touchdown point. An additional restriction is placed on re-entry calculations when entering at supercircular speeds because of the tendency of the vehicle to skip or be thrown out of the atmosphere by the centrifugal forces which overcome the earth's attraction. This results in an overshoot limit in the re-entry angle, and when combined with the undershoot limit, forms the corridor through which a successful re-entry can be made.

A valuable role of simulation as illustrated by the above studies is in specifying the boundary conditions within which certain levels of performance are required and assessing man's effectiveness within these bounds. In terms of allocation of function and determining the point in the control loop where man may make his greatest contribution, the use of simulators is invaluable. An area of extreme importance and one where the simulator could be used to specify boundary conditions is in that portion of the trajectory from entry to pull up, since this phase determines the peak heat rates, the peak loads, both of which constitute conditions of stress for man, and the entry corridor which is used as a measure of the necessary guidance requirements to achieve a satisfactory entry. It is almost impossible to make any reasonable specific suggestions in terms of manual control modes during this phase unless we consider the mission and the vehicle configuration. The difficulty of allocating functions under these conditions can readily be seen. We can, however, as previously pointed out, establish boundary conditions which may be used to determine performance limits of either man or machine thus minimizing to some extent the problem of function allocation.

The approach and landing consists of four phases, a positioning phase, final approach, the landing flare or pullout and the deceleration to touchdown. During the positioning phase, the vehicle flies a pre-planned path so the final approach can be made at the desired airspeed, altitude and position above the ground. During this time the pilot can check his position and make whatever corrections are necessary to land at the desired point.

In the final approach the vehicle maintains a constant airspeed and steady state glide aligned with the runway and aimed at a point near the runway threshold. At a predetermined altitude in the final approach the pullout is made which is continued until the rate of descent is arrested and acceleration is reduced to 1g. During this time the pilot tries to make the flare as close to the ground as possible without actual contact. The final phase of deceleration and touchdown is essentially 1g flight path glide during which the pilot controls the sink rate until ground contact is made. The landing technique described above was developed at NASA Ames for low L/D vehicles. It has been used in the simulation of X-15 characteristics using an F-104A (Ref. 12) and at the Martin Company in their Lifting Re-Entry Vehicle Simulation Program (Ref. 249).

There are many studies which suggest a useful role for man during re-entry and landing, and there is considerable evidence that the success and certainly the reliability of the mission would be enhanced by having man aboard. Justification for man has largely been a matter of simply stating those things that man does well or which characterize man (e.g., adaptability, decision making, etc.) as valuable in the system. It would seem more profitable not only in terms of justifying the use of man but in terms of designing better systems to demonstrate within the context of a particular mission and type of vehicle the specific ways in which man can contribute. Herein lies the tremendous importance and necessity for simulation studies.

RE-ENTRY VEHICLES

The severity of the re-entry problem is to a large extent determined by the design of the vehicle. A clear distinction can be made between ballistic and lifting body type vehicles, and it is the lifting vehicle which provides the most challenging control problems. A number of lifting body re-entry configurations have been proposed with varying degrees of aerodynamic control. At least three types are distinguishable:

1. A configuration representing a boost-glide vehicle such as the original Dyna-Soar (generally vehicles with the delta wing style)

2. The X-15 type vehicle

3. Blunt body type vehicles with varying degrees of lift.

It is clear that the design of the vehicle itself will have a significant effect on the role and effectiveness of the human operator, lifting versus non-lifting vehicles being an obvious example. With the advent of lifting re-entry vehicles with moderate values of hypersonic L/D, the problem of deceleration loads will be less critical. With wider re-entry corridors and better ranging capability, the overall control problem will be alleviated. However, the higher L/D vehicles generally make re-entry more complex, especially in respect to the control actions required by the human operator. Attitude control is especially critical in lifting body type vehicles. Re-entry complexity also increases as vehicle configuration changes from that of a blunt body of revolution to that of a winged, airplane-type shape. Thus, the particular type of re-entry vehicle will be a major consideration in the allocation of functions to manual or automatic control modes.

A blunt body has less variation in static stability than a winged vehicle and requires a less complicated control system. It has been pointed out (Ref. 250) that a blunt body could probably re-enter with nothing but a rate damping system. From the point of view of handling qualities, high L/D vehicles need more stability augmentation than blunt bodies. High L/D vehicles generate an increasing amount of lift during re-entry which means that roll and angle of attack and possibly pitch attitude must be closely controlled if the flight path is to be followed. A comparison of the control system of the Mercury and X-20 vehicles illustrates the relative complexity of the lift versus non-lift vehicle. The Mercury re-entry followed a ballistic and almost uncontrolled path whereas the X-20 entered by gliding through the atmosphere as a winged vehicle and was thus subject to all the stabilization and control problems of a vehicle with low aspect ratio and high speed. As described by Secord (Ref. 250) the X-20 pilot had a choice of four modes of flight control operation.

1. Manual Direct Mode-used stick for changing control surface position, rocket thrust vector, or reaction control operation - no augmentation in this mode.

2. Pilot-Selectable Gain Mode - a three axis stability augmentation system was activated in place of the manual-direct system. The augmentation system controlled aerodynamic surfaces, rocket nozzles, and reaction jets in response to gyro and accelerometer commands. The pilot commanded the vehicle rate for stick displacement and selected the system loop gains for the MACH number range through which he was flying.

3. The Manual-Augment Mode - was identical with the pilot-selectable gain mode except that the system loop gains were computed automatically by the flight control electronics.

4. The Automatic Mode - was identical with the manual-augment mode except that outer loop signals were accepted from the guidance system to control angle of attack, sideslip angle, and roll angle. These three angles were programmed for automatic re-entry, and the flight control electronics automatically directed the vehicle to follow the programmed guidance commands.

These four modes of the X-20 are indicative of the modes of control which characterize lifting vehicles which must operate under a wide range of flight conditions. A non-lifting vehicle of low L/D requires a relatively simple control system, probably with fixed gain damping and low precision attitude control, usually supplied by on-off reaction jets. A high L/D re-entry vehicle must have variable-gain damping and precise three-axis attitude control. Secord (Ref. 250) has pointed out that the vehicle might have been uncontrollable without automatic control. Thus a natural limit is placed on the role of the human operator, at least at this time.

Another interaction of the type of vehicle and the resultant problems of manual control is in controlling the rate of deceleration. When the amount of deceleration becomes intolerable, aerodynamic lift must be used, which reduces the rate of descent and lengthens the path to the ground thus decreasing the maximum deceleration. As previously pointed out the performance of the lifting vehicle depends on its L/D, the more slender the shape, the higher the L/D. For a given shape, the L/D is determined by its angle of attack. It has been pointed out (Ref. 12) that vehicles with an L/D of no more than 2 can be landed anywhere in an area extending thousands of miles, both forward and laterally, from a given entry point. Variable lift maneuvers can also reduce the peak deceleration below that achieved with a constant L/D. These advantages however are not without their costs. One penalty is the greater heat load at slender low drag shapes which themselves take up a large portion of the heat produced in deceleration. Another penalty for the use of lift is increased weight. Another important factor which arises out of the characteristics of the vehicle are the allowable entry paths. A problem which is of considerable importance for entry from orbits, is the guidance accuracy required in order to accomplish the desired entry maneuver, as for example completing entry on a single pass without excessive deceleration or heating. Loh (Ref. 7) expresses this problem in the following way: "Terrestrial flight is tolerant of guidance errors accompanying a landing approach, since an undershoot is readily corrected by a brief application of power, and an overshoot by a return approach. Space flight in contradistinction, is unforgiving of guidance error, since undershoot may cause destruction of the vehicle during entry, and, in a hyperbolic approach, overshoot may result in a homeless exit into space." The critical nature of the control problem during this phase is obvious and the necessity for a high degree of automatic control is apparent.

The design of vehicles which can successfully operate in the hypersonic to subsonic range naturally leads to performance in the subsonic range that is considerably degraded when compared with conventional airplanes. This requirement also imposes severe constraints on the potential use of manual control. Lesko (Ref. 12) points out that for the flight regime extending from orbital speeds to subsonic speeds, it is essential that the vehicle have good handling qualities over all range of intended operation and acceptable handling qualities beyond the range of intended operation.

In conclusion, the particular type and design of the re-entry vehicle is of tremendous importance insofar as it determines the nature of the problems to be encountered during re-entry. Of prime importance are the limits of deceleration and heating, and range control to a successful landing. The effectiveness of using lifting vehicles to overcome some of these problems represents a major goal of future re-entry vehicles. Lifting vehicles also provide the opportunity to refine present re-entry techniques. The problems for the human operator are indeed more complex going from simple attitude control in a vehicle like Mercury to 3-axis control necessary in a winged vehicle.

DISPLAY-CONTROL PROBLEMS

The pilot's interface with the vehicle displays and controls during the re-entry maneuver represents an area of great potential in terms of enhancement of the contribution of the human operator. An important function for man will be as a backup to critical controls and the task-loading in terms of monitoring and decision making will be high. The human operator can make a number of contributions such as: (1) selecting alternate modes of control in the event of failure of the on-going system, (2) selective monitoring of sensing devices which may provide critical control information, and (3) in some cases overriding the automatic system and taking manual control. These are some areas where man can contribute to overall system reliability. There are many events, which could occur during the re-entry and landing phase of a mission which could seriously affect the success of the mission. The sensing and prediction of corrective or alternative action can be effectively accomplished by the human operator.

Display Criteria

One of the critical requirements of the re-entry phase is the extreme accuracy and timing required to insure re-entry of the vehicle without excessive heating as it enters the atmosphere. This re-entry phase ends when a safe velocity is attained at which aerodynamic flight can be achieved or where drag mechanisms can be deployed. Critical displays for manual control of attitude will be displays of attitude, attitude rate, or angular acceleration commands. By making reference to the appropriate displays and controls it will be necessary to establish or verify re-entry conditions, such as position, velocity and trajectory, verifying the re-entry corridor, initiating the countdown and monitoring the critical navigation parameters. In terms of attitude stabilization and control it will be necessary to establish and maintain close attitude tolerances during re-entry thrust and following burnout, attitude must be varied to achieve the desired landing point.

In order to set up reasonable criteria for the display of the necessary information for re-entry, the determination of the information requirements must be related to the particular mission and operating modes of the navigation system. One of the important functions during re-entry and one which the human operator could play a significant role is attitude control, and at least three types of display are desirable for manual control of attitude:

1. Quantitative attitude indicators showing vehicle orientation in each axis with reference to the desired coordinate system,

2. Quantitative display of rate information for each of the three axes,

3. An integrated pictorial display of vehicle orientation in all three axes with reference to some coordinate system, providing in a single source continuous information regarding vehicle orientation.

Much development can be expected to occur with regard to the latter type of display used, however, the critical problem is whether or not the necessary information is presented in usable form. In a study by Wingrove and Coate (Ref. 49) a predictor type display was used in a problem at guiding maneuverable vehicles through a planetary atmosphere to a desired touchdown point without exceeding temperature and acceleration limits. In this study, destination was presented on the pilot's display in relation to the predicted range capabilities of the vehicle rather than in geocentric latitude and longitude. The target is presented as a pip on the display, which appears to the pilot as though he were looking through a window in the vehicle as it approaches its destination. The fixed face of the display indicates the locus of end points, with respect to the destination, at which the vehicle would land if a given combination of roll angle and trim angle of attack (L/D) were held constant for the rest of the flight. When the destination pip is in the center of the maneuver capability, the pilot has 50% of the control capability available to make corrections. In addition, two limits were also presented on the display related to the two L/D's which would cause excessive deceleration (above 10g) or cause the vehicle to skip back out of the atmosphere. In a simulated re-entry task, pilots used this guidance display in conjunction with trim and bank angle indicators. The pilots considered the system satisfactory. The only pilot function was a simple one of closing the control loop between the bank and trim angle indicators and the navigation display which meant occasionally changing trim conditions during the trajectory.

A brief description of the major displays and controls applicable to re-entry and their use by the operator follows. The display will be described only in terms of its general function (e.g., attitude indication) rather than its specific type (e.g., sphere with 3 axes freedom, vertical needle displaying roll error, horizontal needle displaying pitch error, etc.).

<u>Attitude Indicator and Control</u> - used to control attitude manually or in automatic mode.

<u>Body Rate Indicator</u> - used to limit rates to conserve fuel and provide a means of emergency control of vehicle in case of manual maneuvers.

<u>Accelerometer</u> - used to monitor acceleration during re-entry and as a means to manually control re-entry in event of failure of primary inertial guidance system.

<u>Mode Sequence Display</u> - used to monitor time course of automatically sequenced events.

<u>Altimeter</u> - displays altitude and used to verify nominal altitude profile.

<u>Velocity Indicators</u> - used to check if nominal rates are being followed.

<u>Angle of Attack Indicator</u> - provides a reading of angle of attack.

<u>Cross Range Position and Velocity Indicator</u> - provides a means to continuously check the operation of the inertial guidance system.

This list of displays and associated controls is by no means exhaustive but represents those used for the primay control of the vehicle. In all cases considerable monitoring, checking and adjustment are required. The performance of the human operator must be assessed not only in terms of isolated specific control actions required for successful re-entry but also in terms of the total task loading occurring at the time the re-entry must be performed. There are many auxiliary status displays that must also be monitored concurrently.

Monitoring and Decision Making

A primary factor determining the level of man's participation during re-entry are the control requirements. The relationship between control requirements and particular types of re-entry vehicles has already been discussed. However the general control requirements in terms of the potential need for monitoring and decision-making or in direct control action by the human operator can be described in terms of the mode of control; i.e., automatic, manual or re-programming. In automatic control man's function will be solely that of a monitor and backup in case of failure of the automatic system. His role will be to detect deviations of certain prescribed functions of the automatic system; e.g., normal trajectories, abort conditions (very difficult during re-entry) and possibly a class of propulsion programs. Some systems might include a manual override. Reprogramming control consists of those functions where the human operator may contribute to updating the automatic system by inserting new information into the computer. This information in turn is gleaned primarily by human operator generated information about the on-going conditions of the flight. However, it is apparent that during the re-entry phase even the reprogramming functions may have to be built in to the extent that certain programs are inserted merely by pressing a button or some combination of automatic or semi-automatic functions. This is necessary because of the time-critical nature of re-entry. This fact intensifies even more the critical nature of human monitoring and decision making during re-entry. Thus much of the reprogramming inputs will be obtained automatically from other sources and transferred manually for computer entry. The unique ability which man brings naturally to this situation is his ability to correlate new data and relate it to past information in a very short time. What makes this capability unique in man is that it has already been programmed with a long stored history of correlative and integrative behavior.

The third control requirement is that of manual control. The exact range of functions that man will be able to perform manually is yet to be determined, however, available data do suggest some fruitful manual functions. Manual control within the context of the re-entry mission refers to those functions that allow the human operator to take over the function of, or override, the automatic system. One of the major manual control functions, especially with the re-entry and landing of lifting vehicles is in control of attitude stabilization and thrust programming of the propulsion systems. Another important factor regarding the amount and kind of manual control concerns the operating mode of the navigation and guidance system. The question here concerns the particular sequence or procedures used in performing a particular function with a certain piece of equipment. For example, when the automatic control system is operating as it should, the role of the human operator is as a monitor, however, if it fails or malfunctions in some way the human operator must be ready to take over.

The precision and speed of response requirements during re-entry and landing make the question of what constitutes the most useful form of display an important consideration. The pilot requires body-rate and attitude information of high accuracy and presented so as to minimize perceptual motor problems. The use of integrated display systems, quickened, and command display devices should aid in the performance of the attitude control task by the crew. It seems clear that the efficiency with which the pilot performs will be determined by the quality of the displays and controls at his disposal. The use of a window to provide a means of external visibility has been shown to be important; for example, John Glenn used a window to aid in maintenance of attitude. This should prove to be even more important when the pilot is confronted with the task of landing a vehicle entering from space. Other studies have made similar conclusions concerning the use of a window (c.f. Ref. 237). The number and types of interfaces with the vehicle displays determines the nature of and the efficiency with which monitoring and decision making functions are carried out. One study has shown (Ref. 237), for example, that when body rate information is displayed the manual control of attitude maneuvers is significantly better than without the aid of body-rate information. An important function of simulation in future research should be to determine the type of information required by the operator to successfully control the vehicle during re-entry.

TRAINING THROUGH SIMULATION

The problem of training of the human operator and of assessing his performance characteristics and capabilities is approached mainly through flight simulation. The task of specifying what the nature of the training will be and the method to be used brings in not only the nature of the control process itself, but also the problem of performance measurement and evaluation. The immediate and specific need in the area of re-entry simulation is a more complete definition of what is to be simulated. One of the areas which appears most important in re-entry simulation is that of energy management functions and attitude control during re-entry of lifting vehicles. The simulator can aid in determining what displays and controls the operator will need and whether or not a given function is best accomplished by an automatic system, a pilot, or a combination of both. In many instances it will be necessary to use simulators which simulate the specific conditions of a given mission although this is always not necessary for valid solutions to re-entry manual control problems. Entry simulators for different atmospheres and environmental conditions, for example, will considerably increase the complexity of the simulation problem. In addition, the simulation requirements of zero-lift vehicles are quite different from those of lifting vehicles, however, future research must consider more and more the problems of lifting re-entry vehicles. Ballistic re-entry does not provide us with much information about pilot abilities since after the retro-rockets are fired, the vehicle and the operator have no control over trajectory or landing point.

A simulator that is adequate for the simulation of manual control problems during re-entry will incorporate all those interfaces that exist between man and machine during the re-entry maneuver. The conditions which must be simulated for training purposes must consider speeds which range from Mach 26 at initial entry down into the subsonic range. The flight history would include de-orbit and re-entry down to an altitude of about 300,000 feet, glide which ranges between 300,000 and 150,000 feet to touchdown. Probably the only training the pilot will get will come from simulators designed to reproduce the conditions existing during these phases. The prospect of obtaining generalized criteria for re-entry simulation seems remote because of the complexity of the data required for the simulation of a complete mission and the fact that conditions vary for various types of systems. Thus the use of part-task simulators will be of value in simulating portions of the mission. A major problem in re-entry simulation is in the visual simulation of the conditions relevant to re-entry.

Much of the training for re-entry manual control will continue to be done on ground based simulators, as was much of the training for X-15 flights. In-flight training will consist of flying vehicles like the X-15 since many of the problems are similar to those faced by a pilot of a winged re-entry vehicle. Mercury training was also done largely in ground based simulators. In-flight training such as that obtained from X-15 flights will be extremely important to future research with regard to manual control and training of pilots flying lifting re-entry vehicles. Especially important in these type of flights will be the simulation of emergency conditions, task loadings and environmental stresses of re-entry. The use of complete mission simulators to achieve high fidelity mission conditions with the relevant contingencies operating in real time will be an important aspect of simulation training. A factor to be investigated here is the decision-making skills necessary within the context of the space mission, and the conditions necessary for optimal decision making. Judging from the severity of the control problems to be expected during re-entry it appears that one of the major functions of the human operator will be to monitor vehicle flight conditions, select various automatic modes of operation and assess and make decisions about the state of the system.

Important for future training requirements for re-entry will be: (1) the simulation of those activities associated with controlling and spatially positioning the vehicle, (2) selection of the appropriate subsystem function, (3) maintenance, and (4) those activities associated with specific mission requirements. A separate problem to be investigated in this regard is how much of the actual events and conditions of re-entry must be simulated in order to have an effective vehicle for training. It appears that a considerable amount of dynamic simulation will be needed in order to gain a representative measure of the nature of the control problem. Also important for training will be appropriate simulation of problems of multi-man crews in order to determine the extent of interaction necessary between the crew members in terms of monitoring, decision making and control functions.

An indication of current research in re-entry is given in the annotated bibliography which summarizes some of the representative problem areas.

ESCAPE

Each phase of a space flight mission has its own hazards in terms of both equipment failure and human error, re-entry being one of the most critical phases. Task loading during re-entry, even under normal conditions is heavy which makes an emergency condition during this phase especially critical, and manual reaction is likely to be slow while the effect of failure is likely to be very rapid. It is very likely that a system similar to the ASIS (Abort Sensing and Implementation System) used in the Mercury system will be required. In the event of a malfunction it is doubtful that the astronaut could detect it in time to take abort action, and if he were able to abort his response times would not be short enough to separate safely from an exploding booster.

Some of the hazards involved in escape at high altitude from very high velocity aircraft include tumbling and spinning, low atmospheric pressure, wind blast, deceleration and low temperature. It is felt (Ref. 205) that the effects of tumbling and spinning may present problems which are difficult to resolve. Some sort of stabilization of the man in descent from high altitudes may be required even when enclosed in a capsule, in order to prevent the man from reaching rotational speeds beyond his physiological tolerance. An analysis by Haber (Ref. 204) indicates the magnitude of the problem of escape and survival. He states that "In falling from an altitude over 100,000 feet a body attains a speed greater than that of sound but arrives at sea level with a final speed around 100 mph. Also, where does the body lose all its speed? For a closer investigation of this problem, take for example a fall from 300,000 feet and direct attention to the deceleration encountered during the fall. In the beginning of the fall, the body is weightless because there is no force supporting it. Speed is picked up, rapidly attaining a maximum in order of Mach 3, and is then decelerated to terminal velocity. The cause for the change in velocity is the air drag which rises as the body gains speed and loses altitude. The air resistance soon exceeds the weight of the body, and the acceleration turns into deceleration which, in this case, reaches a value as high as 3g to 4g. Deceleration then falls back close to 1g. Deceleration of 3g to 4g lasting for 1 to 2 minutes are tolerable. Considering again the case of man arriving at the top of the atmosphere with escape velocity, the maximum deceleration is found to be in the order of 300g. Nobody could withstand this. It can no doubt be considered just a braking effect of the atmosphere but it must be considered a crash. Such a collision with the atmosphere would give rise to all the detrimental consequences. Thus, it is an astonishing fact that a man falling from outer space back to earth would have a speed at sea level, safe for parachute landing, but he would not survive to this point because he is first subjected to the fatal impact of encountering the atmosphere."

Haber also makes a very important point concerning escape capsules within the vehicle. Because a capsule has a greater drag area loading than a human body, the capsule will experience higher g forces during deceleration in free fall. Therefore, the design of the capsule or other escape device becomes extremely important. It should not be made too sleek, but should have air brakes or a small parachute in order to increase the air resistance from the beginning of the fall. In the event a manually operated escape device is used, considerable attention must be given to the pilot's ability to manually operate it. It should be readily accessible for use and should not involve an unusual effort for the man to free himself from restraint systems. It is obvious that a means is necessary for protecting the body from the forces induced by re-entry.

The success of escape during re-entry at this time remains slim and considerable research and testing of various concepts and systems must be accomplished. This area is indeed one of the most important in terms of future research needs.

FUTURE RESEARCH NEEDS

As previously pointed out, a logical extension of our present manned space flight programs will be the use of lifting body type vehicles where the landing site can be chosen with a great deal more flexibility than ballistic type vehicles. The increased complexity and criticality of the overall control problem -- especially those functions where many might play a role -- makes it necessary to undertake research programs which will lead the development of the specific vehicle, so that the information necessary for the rational allocation of functions will be available before the actual vehicle is designed and constructed. The need for basic design information, whether of a human factors nature or engineering information, to be available at the beginning of the system development cycle has long been recognized, however, the fact that there will probably be no flight tests of actual vehicles in space makes it even more critical that all necessary information be available as early in the development of the vehicle and training programs as possible.

The information which must be developed from future research with respect to the role of man during re-entry or space flight in general, will be related to a large degree to the progress made by engineers and physical scientists concerned with such problems as: the nature and structure of planetary atmosphere, aerodynamic plasmas formed by the shock wave heating of gas, the thermochemical state of the gas which envelopes the vehicle in the shock layer, aerothermoelastic effects on vehicle structural response and aerodynamic performance, and low speed aerodynamics important during the landing and re-entry phase. All of these areas are important in determining the controllability of the vehicle and indirectly the role of man. As an example we may consider the differential effects of various planetary atmospheres. It has been estimated (Ref. 12) that the touchdown speed for Mars would be 2.2 times that of earth, while that of Venus is 26% of that for earth. The rate of change of velocity in the deceleration phase would be reduced to 40% of the value of Earth at Mars and 90% at Venus.

For the purpose of discussing the future research areas of importance to manual control during re-entry, four major topic areas will be used; they are: Manual Control Studies, Training Research, Simulation Studies and Behavioral Studies of Basic Processes.

Manual Control Studies

The future research in this area should move in two general directions. First, studies should be undertaken to isolate the specific behaviors involved in manual control under the conditions relevant to re-entry; for example, various degrees of deceleration and vehicle configurations and other environmental stresses such as heat and speed and precision requirements associated with re-entry. This first class of studies is concerned not directly with the system output but rather with the specific behavioral requirements under these conditions. The emphasis is placed on modifying the behavior of the human operator rather than the vehicle subsystem in order to achieve the desired results. The purpose of these studies is not to make general statements about manual control but to bracket the range of behaviors which might be expected from the specific conditions imposed. In this respect the studies are referenced to particular types of missions and vehicles. Also needed, however, are studies which investigate what Muckler (Ref. 248) calls the "Microstructure" of control behavior. It may be that the greatest potential long-term gain will come from studies designed to isolate the basic behavioral components involved in manual control. The second class of studies should be concerned with the manual control problems associated with a specific mission using a specific vehicle operating in a particular atmosphere, etc. The objective here is not to establish a range of conditions but to delineate specific problem areas and determine the manual control problems for a given mission and vehicle configuration. Whereas the first class of studies might be concerned with the attitude control problem as a function of varying L/D the second class is concerned with a vehicle with a given L/D.

It is clear that these studies, with the possible exception of those dealing with the microstructure of control behavior, do not represent new areas in manual control research. The objective is to extend those principles and practices, which we have already found to be effective, to the conditions to be expected in the future. In some cases, however, this may involve generating new data, procedures and principles.

Training Research

A problem which exists in many areas of research, manual control research in particular, concerns the behavioral state of the subject with regard to the behaviors that are assumed to be important to the problem under study. Stated simply the question is: Should we use naive subjects or should we use trained subjects, (e.g., trained pilots versus college freshmen)? Part of the problem is a result of a misunderstanding of the research objective. If, for example, we are interested in the microstructure of control behavior it would be perfectly valid to use subjects who had no experience with the control task or other relevant control behaviors since one of the objectives would be developing procedures whereby the specific behavior required to perform the task efficiently would be isolated. This does not mean, however, that the same statements could be generalized to conditions other than those under which the behaviors were exhibited. This distinction is analogous to testing the validity of a statement by prediction or control. Using the basic functional statement $y = f(X)$ under c (under certain specified conditions), testing by prediction would state that for new conditions, N, then when c, and $X = X_N$, then $y_N = f(X_N)$. In testing by control we would state that $y = f(x)$ under c. If for new condition, N, we wish to have $y = y'_n$, then set c and $X = X_N$ and $y_N = f(X_N)$ should result. It is clear that the control method is stronger since if you know X you can know y but if you know y you cannot specify X. Thus, if we know the basic behavioral components of control behavior; i.e., its microstructure, we can set up the conditions necessary to get a certain type of behavior. This does not mean, however, that use of trained subjects in manual control research is not profitable, in fact, the inherent complexity of the behavior might necessitate using subjects who already have the appropriate behavior and then trying to isolate the critical behaviors for more intensive study.

The purpose of the above discussion is to indicate the kind of research problem involved in specifying the training requirements necessary for a specific control task versus the requirements necessary to be effective as a pilot of a spacecraft. Research with naive subjects would seem permissible in determining the first set of requirements, however, it would seem to be of limited value to use naive subjects in the second case. It is here that trained and experienced pilots must be used. It is necessary, however, in terms of future requirements to pursue both avenues of research in order to establish training requirements for the manual control problems of future lifting re-entry vehicles.

Simulation Studies

It is apparent that simulation studies are presently an extremely valuable source of information on manual control and will continue to be in the future. In going through the re-entry literature with respect to manual control there seems to be at least three areas toward which future simulation studies should be directed. The first is in the real time physical simulation of representative re-entry conditions. These studies are necessary because of the time and precision requirements imposed by re-entry and the fact that much of the empirical data developed here should be extremely valuable in terms of working back to the studies of the microstructure of control behavior as previously described. The second area is concerned with attaining simulations which control the conditions closely enough to generate data of laboratory quality. The third area to which future simulations should be directed is in determining the level of automation and the allocation of function. This could be one of the most fruitful results of future simulation studies.

Behavioral Studies of Performance and Perceptual Processes

The future need in this area is not so much concerned with the specific behavior involved in, for example, vision, size and shape constancy, etc., as it is with the problems which will come up in specific missions. There is a large amount of material already available in these areas, however, there is little that is directly applicable to the problems to be encountered during re-entry or space flight in general. The visual abilities of man in the space environment, for example, are very important, and have been little investigated. An important effort should be devoted to the development of techniques, procedures, and equipment for the visual simulation of the space environment. Another area of importance for which simulation facilities should be developed is motion and distance perception. These factors will be especially important in the re-entry and landing phase of lifting vehicles. Areas of performance needing further development concern performance, especially manual control, after long-term missions and the effects of isolation and confinement, performance studies under high task loads and the environmental stresses of re-entry.

Conclusion

It can be seen that the areas for future research are not substantively different from areas already being investigated. In fact, the point is that future research must be directed toward extending our knowledge in these areas and further delimiting the problems specific to pilot re-entry guidance and control.

REPRESENTATIVE SIMULATION STUDIES

This section presents summaries of a few of the representative studies concerned with the problems of re-entry. Included are purely analytical studies done mainly with computer simulation, and studies of a more empirical nature with the human operator performing manual control functions. The purpose is not to illustrate all of the aspects of the re-entry problems that have been studied but only to present studies which are representative of the kinds of problems which the human operator might experience in the manual control of a re-entry vehicle.

Fixed-Base and In-Flight Simulations of Longitudinal and Lateral-Directional Handling Qualities for Piloted Re-Entry Vehicles - ASD-TDR 61-362, Feb. 1964

This study utilized a high-fidelity fixed-base ground simulation with evaluations made by three pilots of longitudinal and lateral-directional flying qualities for the re-entry mission. In-flight evaluations were also made using a three-axis variable stability airplane flown with a two-axis side controller and conventional rudder pedals. The purpose of the study was to determine minimum-acceptable and minimum-flyable boundaries as a function of the individual handling quality parameters. The three-axis variable stability airplane was especially modified for use as a fixed-base ground simulator. The plane, a T-33, was modified in such a way that the system manager, or rear seat pilot could vary the handling characteristics about all three axes by simply changing the setting of gain controls located on the console. The evaluation pilot was unaware of the changes that had been made. The cockpit instrument displays and controls operated in the fixed-base simulator just as they would in flight except that an analog computer was used to solve modified linear six-degree of freedom equations of motion of the normal T-33 to replace the aerodynamic and mass effects of flight.

The mission was described to the pilots as the re-entry, descent and landing of a re-entry vehicle. The maneuvers selected as representative of the piloting task were as follows:

1. Straight flight, including small turns, pitch corrections, and pilot induced disturbances about level flight.

2. Turning flight. Shallow and steeply banked turns involving heading changes of at least 90° and bank angles up to 60°, with particular attention to the control of pitch angle, bank angle, and sideslip angle as required.

3. Tracking task. Track roll and sideslip random inputs and minimize pitch disturbances (two minutes).

Summary of Major Results

1. For the particular two-axis side controls used, the pilot-selected control sensitivities in terms of applied aileron and elevator stick force agree closely to values previously obtained during in-flight evaluations with a center stick. The pilots were quite tolerant of a wide range of rudder pedal control sensitivities. Sensitivities higher than optimum evoked a sharper reduction in rating than did insensitive rudder pedals.

2. The pilot is quite tolerant of off-optimum control sensitivities for the re-entry mission, but the desired control sensitivities agree well with those selected in other experiments for the fighter mission.

3. The pilot requirements of longitudinal short period dynamics for re-entry are less stringent than for the fighter mission.

4. In the evaluation of short period dynamics for the re-entry mission, the pilot tended to rate similar handling characteristics the same or better in flight than in the fixed-base ground simulator. In some regions, however, the opposite was true.

5. Evaluation and rating of minimum longitudinal handling characteristics are strongly dependent upon:

    a. The conditions under which the pilot encounters the poor characteristics a configuration encountered without initial transients presents less difficulty.

b. The amount of training the pilot has had in the subject characteristics; i.e., his preparedness for them.

c. The external disturbances which are present to excite the configuration.

d. The amount of concentration required for other piloting or management tasks.

e. The length of time which the condition must be controlled.

f. The task which must be performed, including the control precision required.

g. The state of anxiety of the pilot.

6. Pilot comment data suggested that proprioceptive cues of flight may not account for all differences between flight and ground simulator results. Some difference may be due to the acute awareness in flight of the structural limitations of the aircraft, and the resultant changes in control characteristics of the pilot.

7. A high-fidelity fixed base ground simulator is a useful device in handling qualities research for defining the problem through preliminary examination of handling qualities under consideration for bounding the areas of principal interest, and for generation of pilot comment and rating data to aid in the design of subsequent flight verification experiments.

Flight Control Study of a Manned Re-Entry Vehicle, WADD TR 60-695, vol. II, July 1960

This study investigated by way of an analog computer some of the variables concerned with the operation of the energy management system concept. The objective was to determine the requirements for energy management. The vehicle used was a glide vehicle with an L/D of 1.5. Only one representative glide vehicle was used since the energy management system requires a great deal of programmed information relating to the vehicle's nominal maneuvering capability, but it was felt that the vehicle is representative of the vehicles of interest.

The studies were separated into four phases. The first phase dealt with the open loop characteristics of the vehicle to determine the consequences of varying certain parameters. The second phase investigated the operation of the range control loop or angle of attack control loop with a non-rotating earth. The third phase concerned range and cross range maneuvering with a non-rotating earth. The fourth phase included the effects of the earth's rotation and east-west wind velocities representing the motion of the atmosphere, were introduced.

The flight of the vehicle was divided into four simulation modes which defined the phase the vehicle was in as well as to indicate what set of control equations were applicable. The modes were:

Mode 1 - that portion of the flight when the inertial velocity is greater than 25,000 fps. which includes the initial re-entry and transition to equilibrium glide.

Mode 2 - is in effect when the inertial velocity is less than 25,000 fps. and the velocity relative to the target is greater than 10,000 fps. It defines the condition that the vehicle is banked 30° due to a large cross range error.

Mode 3 - same as Mode 2 except that only small cross range errors exist, the bank angle is limited to plus and minus ten degrees.

Mode 4 - is that part of the flight when the velocity of the vehicle relative to the target is less than 10,000 fps.

Summary of the Major Results

1. The attitude rate damping command after having accomplished the task of bringing the vehicle into equilibrium glide, becomes essentially zero and has little effect on angle of attack command thereafter.

2. As the range error is reduced to a small value, the transition from a boundary equilibrium glide path to the nominal path is done smoothly with very little overshoot. Once reduced to zero the range errors stay at zero although there may be some small oscillations of the angle of attack command about zero.

3. A lack of altitude rate damping will cause skipping but it will not affect the range. This indicates the gain in the damping loop could be lowered without severe penalties; although it would cause small oscillation about the boundaries of the safe flight corridor.

4. Errors in measurement of the altitude rate will cause errors in the command of angle of attack during the initial re-entry when the altitude rate damping is based on the actual altitude rate of the vehicle. Any resultant errors in range are not due to the energy management system since it is not in effect at this time. Instead, these errors in range become initial range errors to be removed by the energy management system.

5. The desired altitude rate can be computed using the nominal L/D instead of the L/D generated by the particular angle of attack command. The resultant errors in altitude rate are small and can be tolerated.

6. Excessive gain in the range loop will cause the vehicle to oscillate around the nominal angle of attack after the range error has been reduced. This is due to the total angle of attack command changing faster than the vehicle's ability to gain or lose altitude. The range change capability remains the same.

7. It is shown that there is no need to predict the forces on the vehicle that will be generated by the velocity of the atmosphere. The vehicle

can counteract these forces by banking. The only prediction necessary is in predicting the future position of the target.

8. The effectiveness of the energy management system is independent of the direction the vehicle re-enters the atmosphere, and independent of the location of the target on the surface of the earth.

9. It is necessary that the range correction be based on the future position of the target while the vehicle azimuth is on the present position of the target during that period of flight when only small bank angles are commanded. Once the velocity becomes less than 10,000 fps., both range and direction are based on the present position of the target.

Dynamic Analysis of a Simple Re-Entry Maneuver by F. C. Grant, Langley Research Center, NASA TN D-47, 1959

This study presents the dynamic properties of a simple re-entry maneuver designed to put the vehicle on a smooth glide trajectory after a single skip.

Summary of Major Results

It was found that the single skip maneuver was possible over a wide range of conditions, but was easiest at low L/D's. Effects of wing loading were small and the high L/D maneuvers were possible only at high re-entry angles.

Modulated Entry by F. C. Grant, Langley Research Center, NASA TN D-452, 1960

This study investigates the use of modulation or variable coefficients for lifting and non-lifting vehicles as it affects peak acceleration, entry corridors and heat absorption.

Summary of Major Results

The use of modulation serves to reduce peak loadings at steep entry angles. It was found in this study that coefficient modulation on vehicles with good lifting capability attains loading reductions and wider entry corridors making steep entry angles practical.

The Effect of Lateral and Longitudinal-Range Control on Allowable Entry Conditions for a Point Return From Space by A. G. Boissevan, Ames Res. Center, NASA TN D-1067

This study is an attempt to specify allowable tolerances in entry conditions resulting from longitudinal and lateral range control of the entry vehicle. The problem here which represents the basic re-entry problem; i.e., to return to a specified landing point on earth. It is pointed out that manned vehicles entering the atmosphere from space will likely perform aerodynamic maneuvers in order to land at certain preselected sites. Deviations from intended entry result from imperfect control of the trajectory in space which must be corrected by some form of aerodynamic maneuvering.

Summary of Major Results

By studying the interaction of an assumed control over the lateral and longitudinal range and the initial conditions of approach to earth it was found that a lateral-range capability of ± 500 miles from the centerline of an entry trajectory can allow a variation in the time of arrival of over $3\frac{1}{2}$ hours.

Flight Simulation of Orbital and Re-Entry Vehicles, Part III, Aerodynamics Information Required for Six Degrees of Freedom Simulation by H. Buning, Univ. of Mich.
ASD TR 61-171

This study presents the aerodynamic information required for a glide re-entry vehicle simulator in terms of the phases of flight. The aerodynamic parameters are defined for hypersonic re-entry, hypersonic-supersonic glide, and supersonic-transonic-subsonic approach and landing. It presents computational techniques and sample calculations for generating functions of two or three independent variables. It is pointed out that at the supersonic, transonic, and subsonic flight velocities, conventional linearized equations may be satisfactory for training-type simulators.

Dynamic Stability and Control Problems of Piloted Re-Entry From Lunar Missions by M. T. Moul, A. A. Schy, and J. L. Williams, Langley Research Center, NASA
TN D-986

This study utilizes a fixed based simulator to study the stability and control problems of piloted re-entry from lunar missions. Pilots were given simulated navigation tasks of altitude and heading angle commands made within the constraints imposed by acceleration and skipping. The analog simulation used two vehicles; both simple bodies of revolution, but one a low-drag cone and the other a blunt-face, high-drag capsule. The simulator included a two-axis hand controller; foot pedals; a display of trajectory, dynamic, and acceleration parameters.

Summary of Major Results

It was found that after a brief pilot-training period both vehicles were easily controlled with the provision of three-axis automatic damping. It was felt that more extensive simulator programs should be undertaken using angular motion simulators and centrifuges to study the types of control problems considered. Further conclusions reached were:

1. Both vehicles could be controlled to some degree with all dampers out and were rated satisfactory for emergency operation.

2. The existence of excessive dihedral effect makes the precise control of bank angle a difficult task for dampers out.

3. In damper-failure conditions, lifting cone vehicles may encounter appreciable oscillatory accelerations which required investigation in a human-centrifuge program.

4. Performance of rolling maneuvers at low dynamic pressures with vehicles of unstable pitching moment curves at high angles of attack may result in a divergence and loss of control.

5. Required re-entry maneuvers can be performed without any aerodynamic controls by using vertical center-of-gravity offset to trim at required L/D and roll reaction controls to make rolling maneuvers.

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