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DYNA-SOAR PILOT FUNCTIONS, UTILIZATION, INFORMATION, AND DISPLAY

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SUMMARY

Considerations of crew utilization and crew station design are placed in the context of total system development. A model of the development process is presented in which the relations ideally existing between the different phases are clarified. Special attention is given to the functions, design, and crew performance phases as they relate to the development of cockpit indicator displays.

The objective of the functions phase is to define the functional requirements of man and machine. The functions allocated to the pilot constitute the information output which is required of him. The parameters of those functions are his input information requirements, and their indication in cockpit displays is a functional requirement of the machine.

The definition of these functional requirements is accomplished through analysis of the system's mission, within the constraints of the technological and human resources which are available for the accomplishment of that mission. The resulting performance specifications must also be taken into account as they become available. Functions are defined on each of the system's output variables. These functions are then allocated between man and machine, subsidiary functions being defined where necessary. Requirements are established separately for each longitudinal segment of the mission which exhibits a distinct functional organization.

The objective of design is to specify equipment (e.g., indicator displays) which will satisfy the machine-allocated functional requirements developed in the functions phase. The design specifications are constrained in the first instance by the available human and technological resources, and subsequently by the feedback of performance specifications.

In the crew performance phase there is a synthesis of equipment design specifications with the pilot-allocated functional requirements.

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The resulting specification of pilot performance is fed back to the design and functions phases, where account must be taken of the task's difficulty level. Excessive task difficulty necessitates redesign of equipment and/or reallocation of functions between man and machine. The development process is thus seen to be an iterative one, continuing until functional requirements and design specifications combine to specify performance whose realization is feasible.

Two general approaches to crew task definition are possible: simulation and rational synthesis. Simulation is particularly attractive
because of the increase in confidence which must attend a demonstration L
of feasibility in simulated operation. Rational synthesis must also be 1
employed, however, because of the impossibility of fully simulating 1
operational conditions. 2
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INTRODUCTION

In designing an aircraft cockpit, it used to be possible to rely upon a vast background of successful experience in the operational environment. Instrument systems which had proved themselves in earlier vehicles were simply taken over, with their indicator displays intact. Minor adaptations may have been necessitated by the somewhat more exacting requirements of the new vehicle. But little or no deliberate attention was paid to the pilot's role in the man-machine system, or to the implications of that role for equipment design.

This approach to cockpit design was not systematic in the sense of proceeding from a clearcut statement of requirements to a system which would satisfy those requirements. But it worked. Whatever the requirements were, they could usually be solved by minor adaptations of established techniques. This was true because the problems were but minor variations on familiar problems.

But this casual approach to crew station design is not possible in the case of Dyna-Soar. The experience which served so well in the past simply does not apply to the problems of boost, orbit, reentry, and hypersonic glide. A systematic approach to the pilot's role and to cockpit design is indispensable if we are to deal competently with these problems. It is the purpose of this paper to describe such a systematic approach and to illustrate its application to Dyna-Soar.

The diagram in figure 1 is an idealized model of the development process. It will serve to place considerations of crew utilization and crew station design within the context of total system development. The boxes in the diagram represent phases which would ideally occur in the development of any complex man-machine system. The arrows connecting

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them represent the relations which would ideally exist between the phases. Three of these developmental phases lie within the scope of the present paper. They are the functions, design, and crew performance phases.

In the functions phase of system development, an analysis of the system's mission is carried out. The mission has previously been defined, as the diagram indicates, through operations research. The output of the functions phase is a set of functional requirements, allocated between the system's crew and the residual system. These requirements, represented in the diagram by hollow arrows, are defined and allocated subject to constraints imposed by the resources, both human and technological, which are available for mission accomplishment.

The functional requirements which are allocated to the residual system constitute the input to the design phase. The design output consists of specifications for equipment. These are represented in the diagram by solid black arrows. The use of solid arrows to symbolize the output of design, in contrast with the use of hollow arrows for its input, signifies that abstract functional requirements are given a concrete interpretation in the design phase. As the diagram indicates, this interpretation is constrained by the available human and technological resources.

Finally, in the crew performance phase, there is a synthesis of equipment design with the crew-allocated functional requirements. The result is a specification of the tasks to be performed by the crew. The performance specifications are represented in the diagram by striped arrows, since they are determined jointly by functional requirements and equipment specifications. As the diagram indicates, they are fed back to the functions and design phases, where their feasibility is evaluated.

If the tasks to be performed by the crew are found upon evaluation to be excessively difficult, the functional requirements may be reallocated between crew and residual system, or the equipment may be redesigned, or both. In any case, new crew performance specifications are defined and fed back to the functions and design phases for evaluation. This iterative process continues until all crew performance specifications are found to be feasible.

While this process is going on, a similar process leading to a feasible set of machine performance specifications is simultaneously going to completion. This complementary process is indicated at the top of the diagram. When both processes are complete, equipment specifications are released to production and crew performance specifications to training and organization. The ensuing events, which are indicated in the diagram, are beyond the scope of this paper.

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THE FUNCTIONS PHASE

In considering the functions phase of system development, one point is worthy of emphasis. Functional requirements are abstract. They are not specifications of crew performance, nor do they specify equipment. Functional requirements allocated to the machine may be interpreted in a variety of designs. Similarly, there are various ways to interpret crew-allocated functions as crew performance.

The mission which is analyzed in the functions phase is a general L
statement of what the system must be to achieve its operational objec- 1
tives in its operational environment. The functional requirements which 1
are defined in this phase are the detailed logical consequences of the 2
mission and of the available resources. The mission which has been 3
assumed as a point of departure for our studies was defined in Phase I. As development proceeds, changes in this mission will be fed into the functions phase. The functional requirements which have been defined will then be modified appropriately.

The definition and allocation of functional requirements, as previously mentioned, are subject to certain constraints. These constraints are imposed by the resources which are available, or expected to be available, for the accomplishment of the system's mission. The major part of this symposium has been concerned with the resources of inanimate technology. But there is a different class of resources - the potential utility of the pilot. Just what is this potential utility? The pilot's contribution to mission accomplishment consists, in general, of satisfying certain of the system's functional requirements which may be allocated to him.

Two steps are involved in the functions phase of system development: First, the required performance of the system must be specified and, second, the responsibility for realizing the required performance must be allocated between man and machine.

Specification of Required Performance

In order to specify the required performance of the system, a set of variables must be chosen. These variables are termed "outputs." The required value of each output can then be defined as a function of one or more parameters. The functions so defined, called "output functions," are the required performance of the system. The parameters, called "input parameters," constitute the system's requirement for input information.

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In order for the required value of an output to be realized, two things are necessary. First, the output must be programed - i.e., a series of decisions must be made as to its required value. And second, the decisions must be implemented - the values decided upon must be brought about. These things are represented diagrammatically in figure 2. In that figure, output functions are represented by double vertical lines. Since the required value of an output is a function of one or more parameters, programing may be conceived as a functional linkage between parameter and function. Such a linkage is diagramed on the left-hand side of each function symbol. Thus, if required velocity is a function of actual position, the programing of velocity is symbolized by the arrow linking actual position to required velocity. The implementation of a decision respecting the required value of an output is diagramed as a functional linkage on the right-hand side of the function symbol. In this case, a decision as to required velocity is implemented through an acceleration program. The implementation of decisions respecting required acceleration is not represented in this figure.

It will be noticed that in the figure required acceleration is linked on the left to both required and actual velocity. This implies that required acceleration is a function of both parameters. Decisions respecting required acceleration must be based on information as to both actual and required velocity.

The pattern of functional linkages between the various output functions of the system and their input parameters is the basis of the system's functional organization. Diagrams such as these are of great utility in defining functional requirements and in allocating them between man and machine. Their useful interpretation, however, demands that they be supplemented by a more detailed statement of the functions involved. The range and domain of each function, the form of each function's dependence upon its parameters, and the allowable variation of each output about its required value must all be explicitly defined.

In the analytical work which has been completed to date, the required performance of the system has been specified with respect to 15 outputs (fig. 3). Of these, two define the vehicle's position in space, three define its velocity vector, five are the factors which control its acceleration vector, and five are the changes or rates of change of those factors. The required value of each of these outputs has been expressed as a function of one or more input parameters. This has been done only for normal, or nonemergency, conditions. The analysis is presently being extended to the case in which one or more of the outputs of the system or of its subsystems is out of tolerance.

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Allocation of Functional Requirements

A pattern of relations such as are diagramed in figure 2 is the basis of the system's functional organization. A complete diagram of that organization, however, must also represent the allocation between the man and machine of the responsibility for realizing the required outputs. It is a simple matter to incorporate this additional information. Functional linkages allocated to the pilot for realization are represented in figure 4 by broken arrows, while solid arrows symbolize those whose realization is allocated to the machine. In this figure there appear a number of single vertical lines. These symbolize the outputs required of various subsystems in support of the system's output functions. Such required subsystem outputs are referred to as subsidiary functions, or simply subfunctions. Subfunction symbols lying between solid and broken arrows represent man-machine interfaces. An interface is a display indication if the solid arrow lies on the left of its symbol, and a control action if the solid arrow is to the right. Besides the interfaces, another kind of subfunction is represented in figure 4. This is the interpretation which the pilot must make of his sensory input. Such subfunctions as these are implicit responses required of the pilot.

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Now what does this diagram tell us? Briefly, it makes six statements:

(1) Actual position is indicated to the pilot in a display.

(2) The pilot determines required velocity on the basis of that display indication.

(3) Actual velocity is indicated to the pilot in a display.

(4) The pilot reads that display indication and interprets it as a sign of actual velocity.

(5) The pilot correlates actual and required velocity and transmits the result as a control action.

(6) The machine determines the required acceleration on the basis of the pilot's control action.

This diagram is a comprehensive way of presenting the functional organization of the man-machine system. Once again, however, its useful interpretation requires supplementary information. Besides the detailed statements of the output functions there must be similar statements of the subsidiary functions. Over what range must a parameter be indicated, with what precision, and with what rates of change? With what precision must the

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pilot read and interpret the indication, and as a sign of what? What must the pilot correlate, how often, and what is the form of the correlation?

An initial allocation has been made of the responsibility for realizing our fifteen output functions under nonemergency conditions. This trial allocation was guided by a policy of maximum pilot utilization. Under this policy, any functional requirement which is not clearly beyond human capability is allocated to the pilot. The resulting functional organization represents the maximum work load which can be imposed upon the pilot insofar as the normal guidance and control of the vehicle is concerned. Emergency operations and the management of subsystems can of course increase his workload above this level. This policy was adopted to establish a baseline from which pilot utilization can be reduced as may appear desirable and feasible in the ensuing studies.

Segmentation of Mission

In this discussion of the system's functional organization, there is one question which must have occurred to all of you. Doesn't the functional organization change during the course of the mission? It certainly does. For this reason it has been necessary to divide the mission into a series of longitudinal segments, each characterized by a particular functional organization.

The process of segmentation is an iterative one. It begins with a set of trial segments. An attempt is made to define the system's functional organization in each. If analysis discloses a change in organization during any of these, it is immediately divided into two or more new trial segments. Analysis may also show two or more trial segments to have the same organization. Such trial segments are combined. This process continues until a set of mission segments is defined whose elements taken serially constitute a restatement of the system's mission.

Like the overall mission, each segment is characterized by certain objectives. The initial conditions necessary for the accomplishment of each segment must be among the objectives of the segment which precedes it. To insure that this would be the case, the initial trial segments were defined in reverse order. The process began with the vehicle safely at rest, its mission completed, and worked backward to launch.

The mission segments which finally resulted are presented in figure 5. Their objectives are not given for reasons of security. Time does not permit any detailed consideration of these segments and their functional organizations. However, a quick look at a typical organization diagram may be of interest. Figure 6 is presented to illustrate the general

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appearance of these diagrams. The functions represented there are defined in detail in the report from which this figure was taken.

The Functional Requirements

The mission has been divided into seven longitudinal segments, and the functional organization characterizing each segment has been diagramed. In these diagrams are indicated the allocation of functional requirements between man and machine. Just what are these requirements? In a word, they are for information. An information output is required of the pilot, and he in turn requires input information of the machine.

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In figure 4 the pilot's information output is shown to be transmitted as a control action. In order to determine the required control action under the functional organization shown here, he must do two kinds of things. He must interpret display indications, and he must correlate the interpretations. One display indication is interpreted as a sign of required velocity, the other as a sign of actual velocity. The correlation of these interpretations, transmitted to the machine as a control action, selects an acceleration which will tend to reduce their discrepancy. Correlation and interpretation, then, are the functional requirements allocated to the pilot. A full definition of these functional requirements would, as we have said, include a statement as to the form of the relations between the required responses and their parameters, or independent variables, and the allowable variation of the responses about their required values.

If the pilot is not able to determine the parameters of his required responses with sufficient precision, they must be indicated to him by the machine. Twenty-two functional requirements for display indication are symbolized in figure 6. These are the requirements for input information which must be satisfied by the machine under the functional organization diagramed here. Once again, their full definition must include a statement as to the range of the required display indications and the allowable error of indication.

THE DESIGN PHASE

The functional requirements for display indication are among the inputs to the design phase. They are the only such inputs which will be considered in this paper.

The design phase, like the functions phase, is constrained by the available resources. The sensing, computing, and indicating technologies impose practical limits on the displays which can be specified. Further

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limits are imposed by the ability of a man to read a display indication within given tolerances of time and error. Subject to these constraints, displays are designed so as to facilitate the pilot's required responses of interpreting and correlating.

The outputs of the design phase, as far as this paper is concerned, are specifications for indicator displays. Displays are designed to satisfy the given functional requirements subject to the given constraints. The concern of this paper, let it be noted, is with indicator displays, not with indicators. By this is meant that these specifications are for what the pilot actually sees, and not for the mechanism of the indicator, which is hidden from him.

In the design phase, display specifications were developed in three steps. First, the functional requirements were summarized. Second, a panel concept was defined to integrate the functional requirements. And third, the panel concept was elaborated in concrete detail.

In the seven functional organization diagrams to emerge from the functions phase, there are denoted no less than 95 different requirements for display indication. For each of these a summary sheet was prepared. On that sheet was entered the parameter to be indicated, its maximum expected rate of change, and the required range of indication. This information was then supplemented on each summary sheet with data respecting the responses required of the pilot - viz., his interpretations and correlations. Error tolerances were associated with each required response. (The reading tolerances are implicit in the allowable error of interpretation.) These summary sheets contain a complete statement of the functional requirements for display indication; but although there were 95 distinct requirements, many of them were so nearly identical that they could be considered the same requirement. Accordingly, the summary sheets were collected into essentially homogeneous clusters. In this way, the number of functional requirements was reduced to some twenty, a much more manageable number.

The integration of these requirements into an organic panel concept came next. In the definition of that concept these things were considered:

(1) The presentation to the pilot of his required input information. This, of course, is the functional requirement to be satisfied.

(2) The facilitation of the pilot's required responses of interpretation and correlation. The demands upon the pilot for these responses must not exceed his ability to make them within the given error tolerances. The difficulty of his task is importantly influenced by the organization of the instrument panel.

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(3) The state of the instrumentation art. This consideration is recognizable as the technological resources which constrain the design phase of development.

The general concept which was defined and adopted for further elaboration is depicted in figure 7. The information needed by the pilot can be acquired from the displays denoted in that figure.

It is interesting that so complex a welter of requirements for display indication can be satisfied by an instrument panel so simple in conception. The design of such a panel is possible only on the basis of the exact functional requirements for display indication. Such a basis allows the conception of an uncluttered, starkly functional panel.

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The individual displays were designed and arranged so as to facilitate the required interpretations and correlations. And the demands imposed by the display specifications upon the state of the art have been held to a minimum.

The third and final step was elaboration of the panel concept. In this step exact specifications were defined for the panel and for the individual displays. The dimensions and operating characteristics of the displays were specified. The scales and indices were designed in detail, and the use of color to facilitate interpretation, particularly in check reading, was explored.

In presenting these specifications, great attention is being given to their rationale. The method by which they were developed lends itself to such documentation. The indication of any parameter on this instrument panel is justified by reference to the functional requirements which are thereby satisfied. The particular form of the display in which it is indicated and the relation between that display and the rest of the panel are justified as attempts to facilitate the responses required of the pilot. Along with the specifications for indicator displays, suggestions for the instrumentation of those displays are being prepared. These suggestions include possible data sources and possible indicator mechanisms.

THE CREW PERFORMANCE PHASE

As noted in figure 1, it is in the crew performance phase that functional requirements join with equipment design to define the pilot's task. It will be clear from what has been said that both inputs are required to specify the performance required of the pilot. For given functional requirements his task will vary with the design of the

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indicator displays with which he is provided. And a given instrument panel may be used to satisfy a variety of functional requirements.

Since both inputs are needed to specify the pilot's task, it is also clear that a definitive statement that the task is feasible cannot be made on the basis of either input alone. Just as the pilot's task changes with variation in either his functional requirements or his displays, so does the difficulty of that task. It is for this reason that his performance specifications are fed back to the functions and design phases.

These specifications provide the basis for modifying the original design specifications and the functional requirements originally allocated to the pilot. If the initial performance specifications are not feasible - i.e., if their demands exceed the available human resources - they must be modified. And the performance required of the pilot can be modified only by modifying either his functional requirements or the design of his equipment.

Two general approaches to the definition of performance requirements are available: rational synthesis and simulation. There are advantages and disadvantages to each method.

The method of rational synthesis may also be called the armchair method. It assumes various forms. For example, a detailed series of concrete interactions of man and machine may be specified. These consist chiefly of the actuation of controls and the discrimination of display indications. The equipment and operational conditions are examined to determine whether these interactions are feasible, given the nature of the crew member. In this form the armchair method has been called "task analysis." Being independent of the laboratory, it can be carried out quickly and is useful for rough estimates of a task's feasibility. It does not often lend itself to exact statements, however, and does not inspire great confidence when applied to complex systems of any novelty.

Simulation of the man-machine system, on the other hand, permits the study of a concrete analog of the system to which inference is made. Although this method is comparatively slow, being dependent on apparatus, it does lend itself to exact measurements. In this method the performance required of the pilot is demonstrated physically as the behavior of the experimental subject in a successful simulated operation. And the confidence in the feasibility of the pilot's task which is inspired by such a demonstration is limited only by the fidelity of simulation. This fidelity is of course not perfect. Indeed, there is no practical way of simulating certain of the stresses which the operational system must be expected to encounter. About the only way of dealing with this problem is to supplement the method of simulation with rational synthesis. The feasibility of the pilot's task is demonstrated in operations simulated under favorable conditions. Estimates are then made of the extent to which his performance will be degraded under operational stress. The paper by Euclid C. Holleman deals with some of the empirical bases upon which estimates of this kind may be made.

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DEVELOPMENT OF A MAN-MACHINE SYSTEM

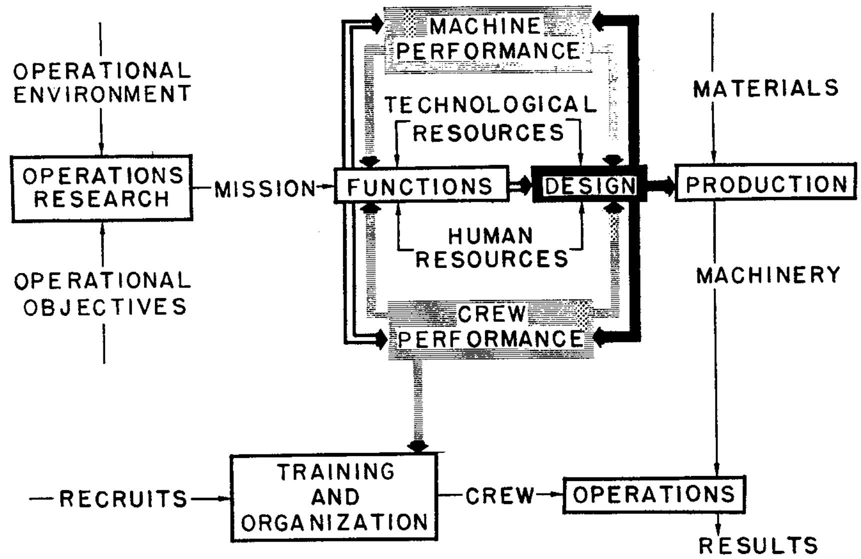

Figure 1

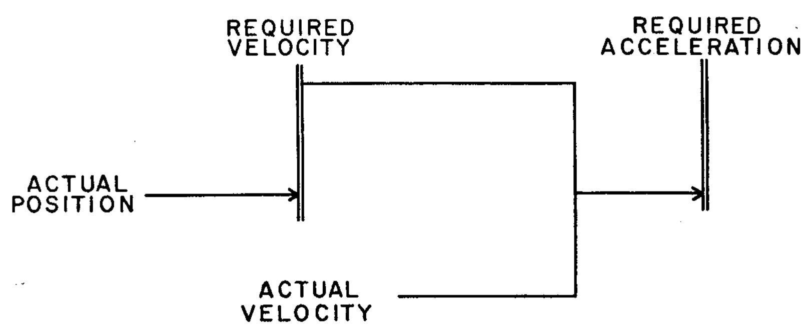

Figure 2

OUTPUTS

POSITION
- GROUND POSITION
- ALTITUDE

VELOCITY
- TRACK
- VELOCITY
- FLIGHT-PATH ANGLE

ACCELERATION
- ROLL
- ANGLE OF ATTACK
- DRAG CONFIGURATION
- THRUST
- SIDESLIP

ACCELERATION CHANGE
- ROLL RATE
- PITCH RATE
- CHANGE OF DRAG CONFIGURATION
- THRUST CUTOFF
- SIDESLIP ANGULAR RATE

Figure 3

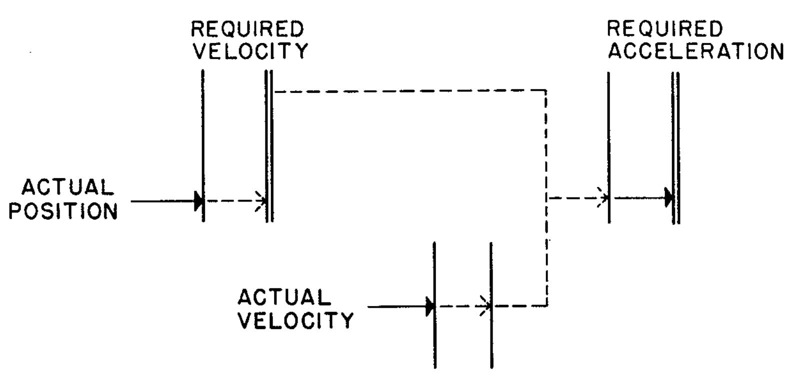

Figure 4

MISSION SEGMENTS

- TERMINATION
- SUPERSONIC GLIDE
- HYPERSONIC GLIDE
- REENTRY
- ORBIT
- COAST
- BOOST

Figure 5

FUNCTIONAL ORGANIZATION OF THE SYSTEM IN HYPERSONIC GLIDE

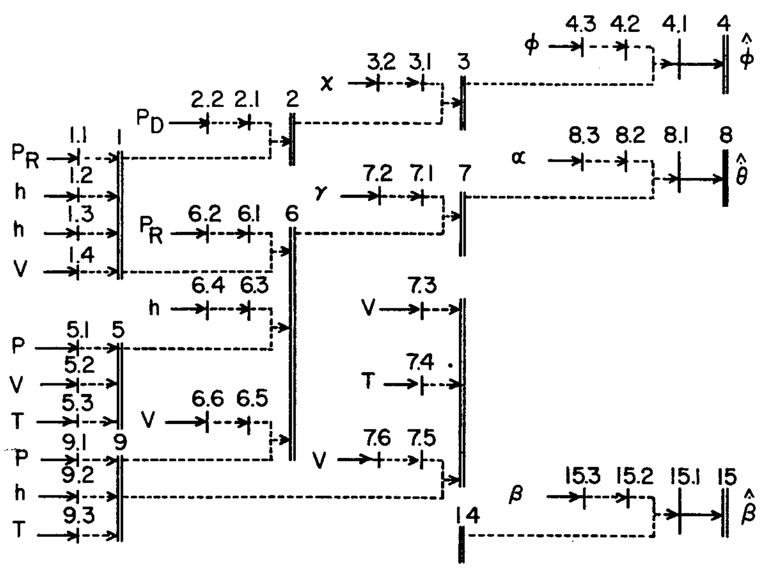

Figure 6

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PANEL

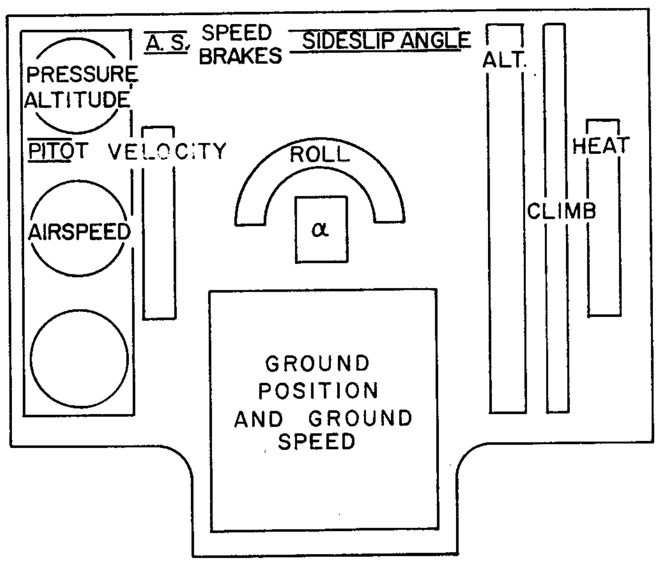

Figure 7

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