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PILOT WORKLOAD FACTORS IN THE TOTAL PILOT-VEHICLE-TASK SYSTEM

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ABSTRACT

This paper is based on a current study of pilot workload models for crucial Navy flight tasks such as the carrier landing and high-speed, low-level navigation. The objective is to construct a more rigorous and complete view of the overall pilot-vehicle-task system in order to describe how facets of pilot workload can be associated with elements of the system. The purpose of the paper is to discuss workload features in a system context as a first step to developing a more thorough workload prediction process for the design and operation of aircraft.

INTRODUCTION

The following represents part of a recent study to develop a pilot workload model which lends itself to analyzing aircraft handling qualities.* This work began with a review of pilot workload literature in order to identify and to develop quantitative connections with aircraft handling qualities. While the many sources described in various surveys such as those of Clement, 1978; Wierwille, 1980; and Soulsby, 1983; have tended to emphasize workload assessment, the aim of this study has been decidedly on workload prediction or modification. In particular, how does one design or alter the stability and control features of the aircraft to ensure suitable mission performance within the capabilities of the pilot?

This paper discusses pilot workload in terms of the total pilot-vehicle-task system, that is, pilot workload factors associated with 1) vehicle dynamics, 2) pilot dynamics and pilot control strategy, and 3) task dynamics. While the first item is the focus for forming the handling qualities connection, the other two play key roles in the combined relationships.

Another feature of the approach to examining workload is the consideration of actual Navy flight tasks and aircraft. The tasks studied include the carrier landing, low-level navigation, and in-flight refueling. Each is viewed in terms of F-14 aircraft operations. One result of studying specific Navy tasks and aircraft has been a revision of how to model the pilot-vehicle-task system and thereby estimate workload demands.

The following sections include discussions of task modeling, workload-related features, consideration of a specific task--the carrier landing, and a summary of workload factors for that task.

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TASK MODELING FEATURES

Task modeling is seen as a fundamental step in the successful modeling of pilot workload. Detailed task analysis and interviews of Navy pilots have revealed that workload demands can vary greatly depending upon how the pilot actually executes the task (e.g., Craig, 1972). Further, many crucial high-workload tasks appear to involve a series of short-term discrete maneuvers and task segments, not the long-term continuous tracking tasks frequently associated with pilot-in-the-loop models. Recognizing these features, in fact, aids the pilot-vehicle-task analysis and facilitates in the quantification of some of the workload aspects which will be discussed shortly.

It is useful to break both the pilot control strategy and controlled element into units according to the control axis and support-loop roles. Figure 1 shows the components which can be used to define basic pilot control strategy for a given control axis and loop.

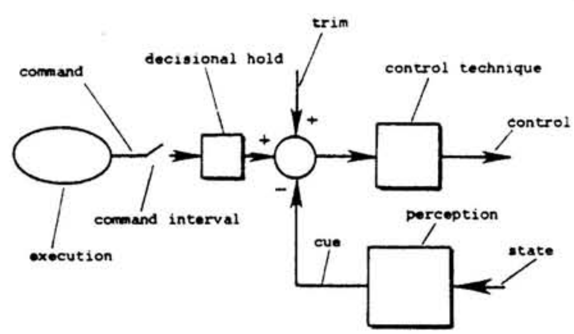


Figure 1. Pilot control strategy topology.

When the above is combined with the respective controlled element, the pilot-vehicle-task system is formed. The main features which can be related to workload include: (i) Task duration, (ii) outer loop bandwidth, (iii) outer loop controlled element, (iv) support loop command interval, and (v) support loop bandwidth.

PILOT WORKLOAD FEATURES

Pilot workload demands can be associated with pilot-vehicle-task model structure in various ways. Considering the three aspects of pilot workload suggested by Reid et al, i.e., (1) mental effort load, (2) time load, and (3) stress load, at least the mental effort and time loadings can be approached quantitatively.

Mental Effort Load

This element of workload is seen as the effort or attention required in applying a "piloting technique" and in the perception of associated aircraft states. A key aspect is organization of pilot actions. One need is to catagorize and quantify degrees of mental effort required for execution of specific flight tasks.

It can be shown that complexity of loop structure alone does not set mental effort load, however. More important is the kind of compensation and coordination required of the pilot. Even the simple single loop critical task can involve very high workload if substantial lead-compensation is required for coping with marginal system dynamics.

At least three dimensions are involved in mental effort load: 1) Axis of control (parallel loop structure); 2) support loop structure (series structure within each axis); and 3) compensation, coordination, and stage of successive organization of perception (SOP--see McRuer, 1978). One present quantitative basis of mental effort workload is the set of interactive critical task measurements for the various controlled element types studied by McDonnell, 1966 and repeated below in Figure 2.

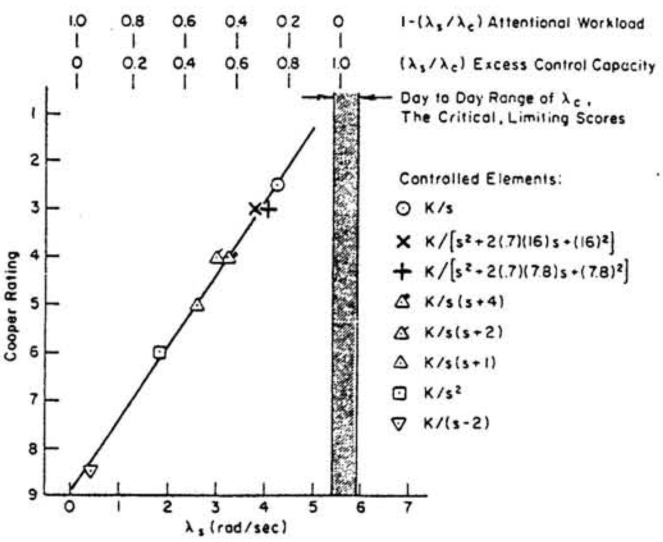


Figure 2. Cross-adaptive measure of excess control capacity for several examples of primary controlled elements (McDonnell, 1968).

It is possible to interpret these data in a more general way if we first note the linear correlation of "attentional workload" (assumed to be akin to "mental effort") and "pilot rating." Figure 3 shows a mapping of these data as a function of phase angle and slope of amplitude rolloff. Phase angle may be preferable because it more easily embodies the effects of delays and non-linearities.

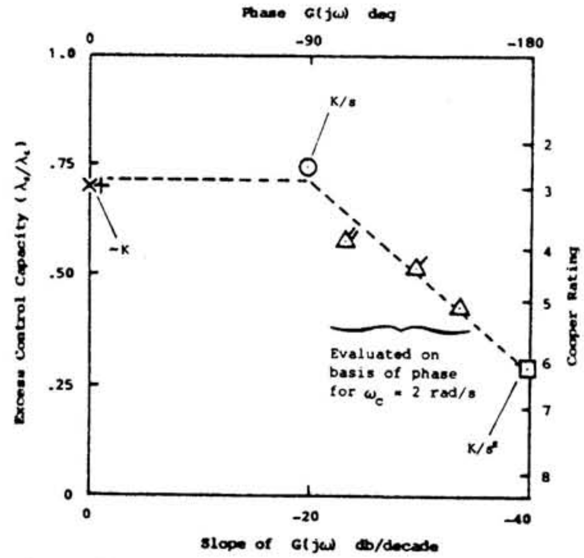


Figure 3. Mental effort load as a function of controlled-element characteristics. (Data mapped from Figure 2.)

Yet to be answered satisfactorily is how the above relationships, based on single-loop experiments, can be extrapolated to multi-loop/multi-axis systems. This has been variously treated by Dander, 1962 and Ashkenas, 1972. However, it still appears necessary to study how multi-loop/multi-axis workload compounds for actual, finite-duration, discrete-maneuver flight tasks.

Time Load

This element of workload represents the ability to meet time constraints. It is the amount of time required to execute a task compared to the time available.

One observation is that tasks are usually carried out in fairly discrete lumps rather than a strictly continuous fashion. In effect, the pilot works as a multi-rate, sampled-data system switching among axes. Also there are time intervals for executing each individual part of the task loop structure. This ranges from the short time intervals involved in making discrete attitude corrections in the inner-loop to the relatively long overall task execution time.

There is a fundamental interaction between 1) the time load and how it is handled and 2) the mental effort load as set by the basic control strategy organization. For example, insufficient time available might force a radical reorganization of control strategy by the pilot dropping outer control loops, regressing to lower stages of SOP, or reducing loop gains and compensation. Such behavior represents extreme workload sensitivity, and the responsible vehicle or task fea;tures are of prime interest to the aircraft handling qualitites.

One way of approaching time load involves looking at the elemental corrections made within a given loop and controlled element. This can be viewed in the phase-plane domain as a discrete correction in a state as illustrated by Heffley, 1982.

Time load can be evaluated explicitly by comparing the time required for a discrete correction to the time available either to support an outer loop or to meet a task terminal condition. Consider an example. If a carrier aircraft on final approach has an excessive lateral offset 5 sec from touchdown and the pilot's lateral position bandwidth is .3 rad/sec, then the correction simply can't be made. (A half-cycle lateral correction would require $\pi/0.3 \cong 10$ sec.) Either the pilot would have to find another control strategy capable of doubling the y-loop crossover or take a waveoff. If the time load is only marginally excessive then a slight increase in crossover might be feasible but probably with some penalty in mental effort.

Stress Load

The stress element of workload includes both psychological and physiological factors. Its role is on a par with mental effort and time loadings, but stress presents a problem in how to find direct cause-and-effect ties with the vehicle and flight task. At this stage only an empirical approach to quantification of stress appears feasible.

Some of the flight-related factors which need to be associated with stress load include: 1) Risk perception; 2) urgency of performing the task; 3) skill or lack thereof; and 4) embarrassment potential. Based on pilot interviews, each of these factors appears to be the basis of sometimes large levels of stress.

There may be at least empirical ways to imbed "stress load" in a math model. The most tempting is to apply a magnification coefficient to either time or mental effort or both. The time estimation technique of workload assessment (e.g., Hart, 1978) seems to suggest that stress may distort time perception. In effect, the time available is mis-estimated by the pilot. A sample portrayal of mental effort, time, and stress for a task segment is proposed in Figure 4. While time and mental effort scales would be quantified in terms of the parameters mentioned above, the stress scale is undefined.

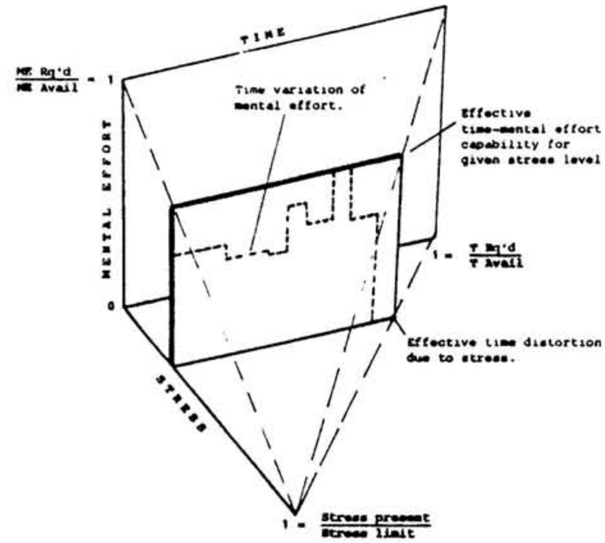


Figure 4. Possible portrayal of workload during a task segment.

Stress acting on the mental effort load might be considered to affect the baseline workload as well as the individual incremental effects. The basis of this hypothesis is that stress, where it affects the organizational ability, reduces workload capacity. However, it is really necessary to explore any such effects in the laboratory. To do so requires strict attention to how the pilot is executing the task and an assessment of specific sources of stress.

THE CARRIER LANDING AS AN EXAMPLE

The following is a task description of the carrier landing, abridged from Heffley, 1983, which permits a quantitative treatment of time and mental effort loading. The detailed multiloop block diagrams of the pilot-vehicle-task system have been constructed based mainly on Navy F-14 fighter pilot interviews conducted at Fighter Squadron VF-111, NAS Miramar. These have been refined using F-14 flight data from the Naval Air Test Center. Training manual descriptions have also been consulted. The four major segments of the daytime racetrack pattern illustrated in Figure 5 are:

- Initial approach from astern
- Break (turn to downwind leg)
- Turn from downwind to final leg
- Final approach leg

Each of these segments is characterized by a fundamental shift in pilot control strategy and is described in detail by Heffley, 1983. A synopsis of the final segment is given below.

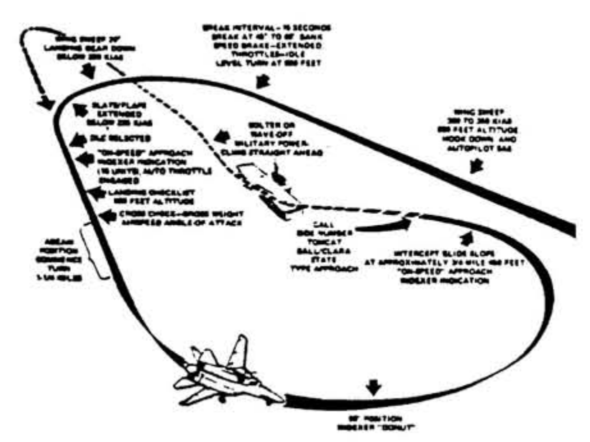
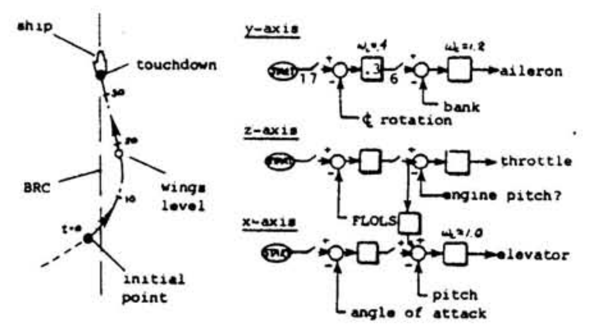


Figure 5. Carrier landing pattern (reproduced from F-14 NATOPS).

The final leg really begins while the aircraft is still in the turn to final (Figure 6a). This corresponds to the acquisition of final approach visual guidance -- the carrier Fresnel Lens Optical Landing System (FLOLS). The objective of this leg is to land precisely within the narrow confines of the deck arresting gear.



a. Nominal Trajectory   b. Likely Pilot Control Strategy

Figure 6. Features of the final leg.

Pilot control strategy is shown in Figure 6b. The vertical axis strategy is to null and stabilize the FLOLS, and for the lateral axis, to line up with the deck center line. Inner loop strategy must operate at a pursuit level in order to maximize outer loop bandwidth and minimize perceptualmotor mental effort. This is dictated by the short time-to-go (15 to 25 sec) and slow pitch, roll, and heave response. A pursuit crossfeed of pitch and thrust is needed to maximize path response and minimize angle of attack upset.

One additional aspect of the final leg is the pilot's interaction with the Landing Signal Officer (LSO). This is another source of flight path, position, and angle of attack information. The LSO assures the pilot of a clear deck or the need to wave off via light signals.

DISCUSSION OF CARRIER LANDING WORKLOAD FACTORS

Analysis of the task segment trajectories and pilot control strategy diagrams such as above provide a basis for estimating mental effort and time loadings during the carrier landing. Also the crucial cognitive events can be itemized. The following is a brief recap of some of the workload factors for each of the segments.

For the initial leg the controlled element lags are all minimal because of the high speed and the ability to partition the lateral and vertical axes into three-loop structures. The speed axis requires little or no active regulation. A substantial excess control capacity in the initial segment permits deck spotting and planning for executing the racetrack pattern.

In the break the pilot's mental effort shifts to the speed and vertical axes with the lateral involving mainly a precognitive banked turn. Here procedural tasks must be performed as quickly as airspeed reduction permits. This loading is not a function of time but rather of flight condition and will vary depending upon where and from what airspeed the break was initiated. The closer to the ship and the higher the airspeed at the break, the more the reconfiguration tasks will pile up toward the end of the break maneuver. If not completed before the turn to final, they will begin to intrude on execution of the next task segment.

The turn to final marks the beginning of higher perceptualmotor loading and less cognitive. The pilot must hold a steady turn toward the ship, increase sink rate, and stabilize angle of attack in order to arrive on final in a steady, well-managed condition. Substantial precognitive behavior is evident such as holding a steady roll attitude, making a predetermined fuel flow adjustment to set sink rate, and altering the nominal angle of attack to compensate for the effects of the turn. In this segment it appears that the pilot operates at high levels of control organization in order to maximize performance, while keeping mental effort and time loading manageable. Subjective assessment of workload is high at this point according to pilot commentary.

The final approach leg begins with various indications of lateral position relative to deck centerline such as crossing the ship's wake or acquiring the FLOLS beam visually. Analysis of the rollout onto final has revealed an economical two-loop lateral axis structure involving the rotation of the centerline perspective as the outer loop and bank angle as the inner loop. This strategy permits quick lateral adjustments (about 17 seconds) and moderate bank angle bandwidth (about 1.2 rad/sec). Flight data show that the pilot has time for no more than two lateral corrections and about the same for the vertical. As discussed by Heffley, et al, 1980, a pursuit strategy is essential in the vertical axis in order to execute path corrections with acceptable mental effort in such a short period. In addition, an experienced pilot will apply subtle precognitive vertical path corrections just prior to landing in order to counter peculiarities of the carrier's air wake.

Carrier pilots emphasize that effective management of workload depends upon performing tasks on schedule and upon the degree of anticipation applied to making corrections. The adequacy of aircraft handling qualities, therefore, needs to be judged according to how well they support these rather deterministic demands as well as in countering random disturbances.

CONCLUSIONS

An understanding of pilot workload requires consideration of flight phases or mission segments on a macro-scale as well as the micro-scale of individual pilot loops. The latter is still important for analyzing cause and effect, especially in the controlled element, but it is just as important to establish the overall operating context of a task in order to understand the total demands on the pilot.

Task modeling offers the hope of predicting workload components. Existing single-axis perceptualmotor data suggest connections between the controlled element and mental effort, and time loading can be associated with discrete maneuver models.

Construction and analysis of the above carrier landing model has helped to identify some of the more crucial factors missing in the pilot workload data base. These include an understanding of how perceptualmotor elements build pilot workload in terms of multiple axes of control and multiple support loops. Also, as the model suggests, these aspects need to be evaluated in a time-bounded and realistic flight task context.

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