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Extended Pilot-Vehicle-Task Models for Navy Missions

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EXTENDED PILOT-VEHICLE-TASK MODELS FOR NAVY MISSIONS

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Abstract

This paper presents the methodology for constructing comprehensive math models of the pilot-vehicle-task system in terms of perceptualmotor activity. Examples are given for a crucial Navy mission segment, the carrier landing. Modeling procedures are summarized along with techniques for extracting model parameters from pilot commentary and available flight data. Implications are drawn for time and mental effort aspects of pilot workload.

Nomenclature

BRC	base recovery course (ship's track)
FLOLS	Fresnel lens optical landing system
K_1	effective outer loop gain
K_η	effective deck lineup gain
LSO	landing signal officer
NAS	Naval Air Station
PVT	combined pilot-vehicle-task system
T_1	outer loop task duration
T_2	support loop command and sampling interval
$T_{()}$	duration of () loop
VMC	visual meteorological conditions
x	longitudinal axis of aircraft
y	lateral axis of aircraft
z	vertical axis of aircraft
δ_a	lateral control deflection
δ_{gear}	gear deflection
δ_{sb}	speed brake deflection
δ_Λ	wing sweep deflection
η	rotation of deck centerline perspective
π	3.1415...
ϕ	bank angle
ϕ_c	bank angle command
ϕ_{M_1}	uncompensated phase margin of outer loop
ω_{c_1}	outer loop bandwidth or crossover
ω_{c_2}	support loop bandwidth or crossover
$\omega_{c()}$	bandwidth or crossover of () loop
ψ	heading angle

I. Introduction

Math models of the task, pilot control strategy and controlled element can be instrumental in the analysis of such diverse topics as pilot workload, aircraft flying qualities, and even pilot skill development. However, the math modeling of the pilot-vehicle-task system must go beyond that of the conventional long-term continuous tracking task and address the time-bounded, deterministic, and discrete-control nature of many actual flight operations. In so doing it is also possible to appreciate more fully the role of the pursuit and precognitive-level pilot behavior which contributes to successful task execution.

From time to time, differences in pilot control strategy has been attributed to variations in pilot opinion ratings. In Reference 1 the prior exposure to the Navy "backside piloting technique" appeared to benefit in the operation of powered-lift STOL aircraft. Reference 2 suggests that pilot control strategy differences may have affected pilot ratings for certain helicopter displays being studied. Thus it can be instructive to quantify how a pilot operates an aircraft commensurate with other performance data which may be gathered. Such quantification of the pilot, of course, requires a basic model structure, hence, one purpose of this paper.

The following pages illustrate how task modeling can be used to examine a particularly crucial Navy mission flight phase, the carrier landing. The immediate objective of this model is to determine a means for drawing an explicit quantitative connection between pilot workload and aircraft flying qualities requirements.[**] The task model structure is given in some detail here although work and additional data are still needed to quantify model components.

The approach used to define the piloting task is based on the manual control theory point of view represented in Reference 3 but is augmented by recognition that the task itself is a major component in the overall system description. The closed-loop view of pilot performance is a major key to quantifying the task and pilot control strategy. Another purpose of this paper is to illustrate how a task such as the overall carrier landing task can be credibly cast in such terms and especially how this permits effective analysis. The entire daytime VMC carrier landing task depicted in Figure 1 (reproduced from Reference 4) can be stated in terms of a chronological series of perceptualmotor pilot-vehicle-task loop structures. Each component of the series is connected by cognitive procedural or decisional events. The result is a control-law program which provides an effective basis for exploring the sensitivity to any of the pilot-vehicle-task system parameters. This provides, a reasonably correct and complete operating context in which to examine the pilot workload as a function of aircraft flying qualities.

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[*] President
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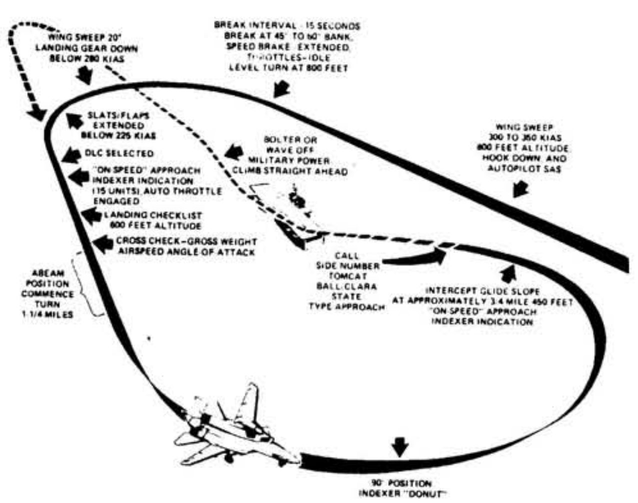


Fig. 1 Carrier Landing Pattern

II. Features of the Task Model

The modeling procedure presented here is intended to address the three aspects of pilot workload suggested in Reference 5: (1) mental effort load, (2) time load, and (3) stress load. While "stress" is inherently difficult to express analytically, the mental effort and time loadings can be approached quantitatively. This can be done, in part, by using the relationship between excess control capacity and controlled-element form which is reflected in data from Reference 6, then augmenting it with the kind of discrete-maneuver pilot control strategy model described in Reference 7. The general idea is that time loading can be estimated by assessing the time available and time required for a limited-duration task or subtask. Mental effort can be estimated by representing some key feature of the uncompensated controlled element such as amplitude-response rolloff or phase angle at the effective operating point.

It is useful to break both the pilot control strategy and controlled element into units according to the control axis and support-loop roles. This at least allows some estimation of the degree of difficulty (mental effort) of each loop taken individually. Figure 2 shows the components which can be used to define basic pilot control strategy for a given control axis and loop.

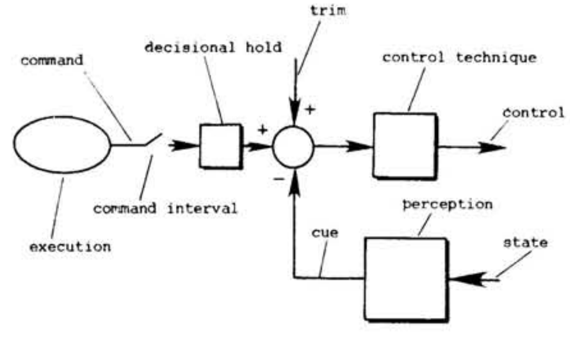


Fig. 2 Pilot Control Strategy Topology

When the above is combined with the respective controlled element, the pilot-vehicle-task system is formed. The main features which allow an analysis of time and mental effort workload include:

(i) Task duration

(ii) Outer loop bandwidth

(iii) Outer loop controlled element

(iv) Support loop command interval

(v) Support loop bandwidth

Time and mental effort aspects can be quantified for each control loop by evaluating the controlled element characteristics corresponding to the time required to complete a finite-duration task or subtask. In fact, a kind of closed-form time/mental effort tradeoff can be constructed if mental effort is expressed as, say, the uncompensated phase margin. Simply stated, the shorter the execution time for a discrete maneuver then the higher the bandwidth requirement and the lower the phase margin in both the outer and support loops.

Figure 3 shows generically how the components of the task model can be rated in terms of phase margin debits. Hence, one could express an explicit tradeoff, for example, between the phase margin, ϕ_{M_1}, (reflective of outer loop mental effort) and the time required to accomplish the task, T_1 (reflective of time load when compared to the time available for the task).

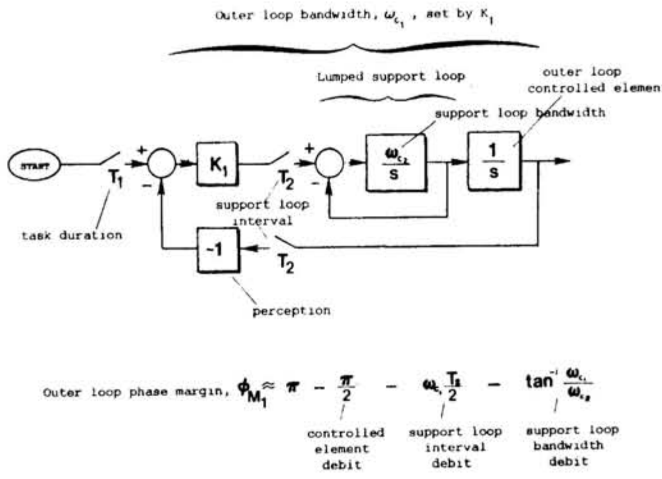


Fig. 3 Discrete Maneuver Factors for a k/s Loop

Note that the ϕ_1 and T_1 tradeoff can be adjusted by the inner loop duty cycle, T_2. But, at the same time, T_2 is limited by the inner loop bandwidth available, ω_{c_2}.

It can be seen that the frequency of support loop commands and the support loop bandwidth could contribute substantial phase lag under certain conditions. To counter this, the support loop command interval needs to be short compared to task duration and the ratio of support loop bandwidth to outer loop bandwidth needs to be small (about 3). Opposing this is the time available for outer loop task execution and the allowable support loop bandwidth.

Finally, the two-loop structure shown in Figure 3 can be compounded depending upon the actual number of support loops within any control axis. For example, maintaining course could involve a heading support loop and, in turn, bank angle to support heading.

III. Summary of Modeling Procedure

While pilot-vehicle-task modeling is, to some degree, a matter of "style" or "art", at least part of the process can be formalized. The following represents one approach and involves an example from the carrier landing task, namely the final leg line-up task. Three main steps can be viewed: 1) Definition of the overall task scenario; 2) identification of control axes, support loop structure, and cueing; and 3) determination of discrete command timing and loop bandwidths.

Task Scenario Definition

The purpose of this step is to obtain an overview of the task, its objectives, and its constraints. All available sources should be consulted including pilots' oral descriptions and commentary, published flight manuals and training materials, and representative flight or simulator records. The important features to be noted for each segment are initial conditions, signals for starting the segment, environmental factors, vehicle conditions, and terminal objectives.

The final leg of the carrier landing segment begins in a descending turn with the aircraft already fully configured and trimmed. Several things can signal the start of the final leg including crossing the ship's wake, entering the visible region of the FLOLS, or observing the bearing to the ship. The main objective in the lateral axis is, of course, to achieve a course line-up on the canted-deck centerline. The need to catch an arresting wire on-center and the narrow confines of the landing area both dictate a lateral precision of only a few feet. Further requirements at touchdown are that sideward drift be nulled and roll attitude be essentially level. While crosswinds are not normally a problem in the carrier environment, some lateral disturbance from the carrier airwake can occur. Time loading, mental effort, and stress are all high during this segment.

Control Axes, Support-Loop Structure, and Cueing

This next step also requires listening to the pilot's conscious observations of how the task is executed, but other objective evidence must also be considered. The pilot simply may not be able to describe accurately the actual control strategy, especially when operating in a high-workload phase or when using outside visual cues.

For the final-leg example, the outer loop control is "lateral position" defined by the landing area centerline and the vertical drop line plus any auxiliary horizon information from the ship or the actual horizon, if visible. By deduction, the perspective view of the deck centerline rotation from vertical is a highly plausible candidate for the main outer loop guidance information. Likewise, an extreme inner loop consisting of visual roll attitude is likely. Not immediately apparent is whether an intermediate loop on heading or y-velocity may be involved.

The existence of intermediate loops can be probed by examination of the partitioning of loop bandwidths, controlled element dynamics, and command intervals. To illustrate this, consider the following example.

In the case of final leg lineup at least two plausible loop structures can be hypothesized, each suggested by pilot commentary and consideration of available cues. These are:

1) $\eta \longrightarrow \phi_c \; ; \; \phi \longrightarrow \delta_a$

2) $\eta \longrightarrow \psi_c \; ; \; \psi \longrightarrow \phi_c \; ; \; \phi \longrightarrow \delta_a$

The first contains only two loops--lineup angle, η, and bank, ϕ. The second structure contains in addition an intermediate loop around heading, ψ. The examination of loop bandwidths as outlined in the next subsection indicates that the apparent "aggressiveness" (as explained below) of heading and lineup angle is about equal, thus a series loop structure should not be possible. Preference would therefore have to be given to the likelihood of the first structure hypothesized above.

Discrete Command Timing and Loop Bandwidths

This step requires a detailed analysis of task performance. Time histories of any states likely to be used as cues are valuable along with corresponding phase plane portraits. The latter is an aid in identifying discrete commands and the level of aggressiveness in executing those commands. Time correlations then provide information about command intervals or task duration.

An example is given in Figure 4. Phase plane trajectories are shown for the lineup (two discrete lineup corrections) and for the bank angle response supporting the first lineup (three discrete bank commands). Finally a cross plot is given which relates the bank angle commands to the corresponding lineup angle.

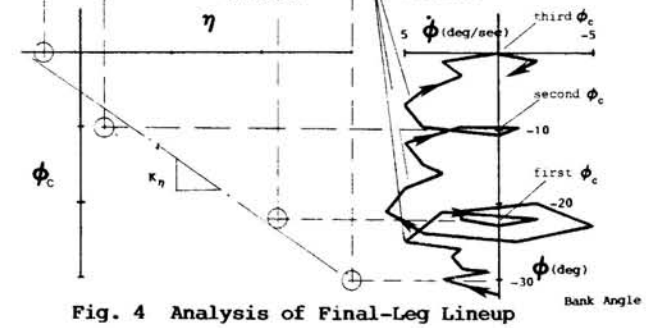


Fig. 4 Analysis of Final-Leg Lineup

Control strategy parameters are thereby computed using the following features:

1) Outer loop gain, K_η, is the slope of ϕ_c versus η.

2) Outer loop bandwidth, ω_{c_η}, (task aggressiveness) is estimated by the relative size of peak $\dot{\eta}$ to the magnitude of the η correction (as described in Reference 7).

3) Support loop bandwidth, ω_{c_ϕ}, is similarly estimated.

4) Outer loop task duration, T_η, is observed from the time between commands.

5) Support loop command intervals, T_ϕ, are similarly measured.

These values are summarized in the lineup control strategy shown in Figure 5.

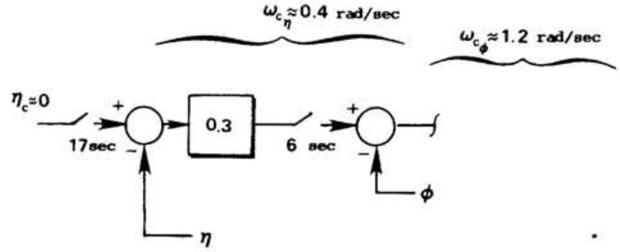


Fig. 5 Quantified Lineup Control Strategy

According to this diagram, a discrete lineup command occurs about every 17 seconds (i.e., two lineup corrections are made in the 40 seconds of the final leg). Further, for every lineup command, there are about three bank commands at the rate of one every 6 seconds. The closed-loop bandwidths supporting these "almost-periodic" commands are fairly generous. Approximately two full duty cyle corrections could be made within the command interval (e.g., $\pi/1.2 = 2.6$ sec for a bank angle correction, 44 percent of the 6 sec command interval). The ratio of inner loop to outer loop bandwidths is also three. This factor of three represents a favorable tradeoff between mental effort and time load (referring back to Figure 3). The high bandwidths relative to the command intervals may indicate a control axis time sharing capacity. General knowledge of such quantities for various crucial task segments would provide an improved basis for flying qualities estimates.

IV. Description of the Carrier Landing

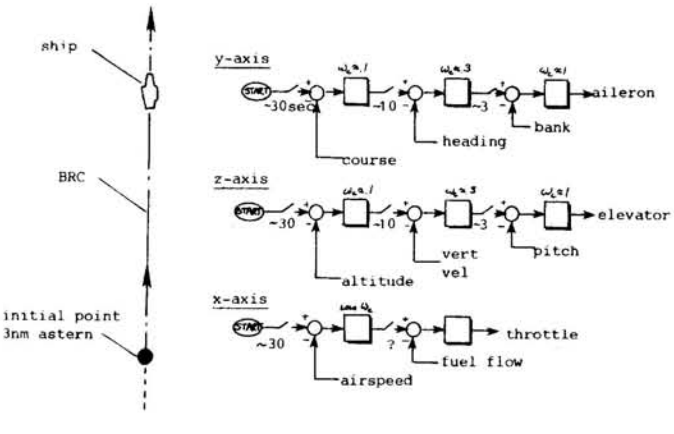
The following is an overall description of the carrier landing which illustrates the modeling concepts described previously. Detailed multiloop block diagrams of the pilot-vehicle-task system have been constructed based mainly on Navy F-14 fighter pilot interviews conducted at Fighter Squadron VF-111, NAS Miramar. These have been refined using F-14 flight data from the Naval Air Test Center (Reference 8). Training manual descriptions (Reference 9) have also been consulted. The four major segments of the daytime racetrack pattern include:

- 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 below.

Initial Leg

The purpose of the initial leg is to arrive overhead the carrier on a standard course, heading, and altitude in preparation for executing the racetrack pattern. As shown in Figure 6a, this leg formally begins three miles astern the ship at 1200 ft and ends above or slightly beyond the bow. For the lead aircraft the main flight tasks during the initial leg are to arrive over the bow, on the base recovery course (BRC), and at 800 ft. altitude. (For aircraft flying formation on the lead aircraft, their task is limited only to maintaining formation and not to navigation.) Airspeed is set at the prerogative of the lead aircraft between 300 and 400 kt with the F-14's wings fully swept.



a. Nominal Trajectory b. Likely Pilot Control Strategy

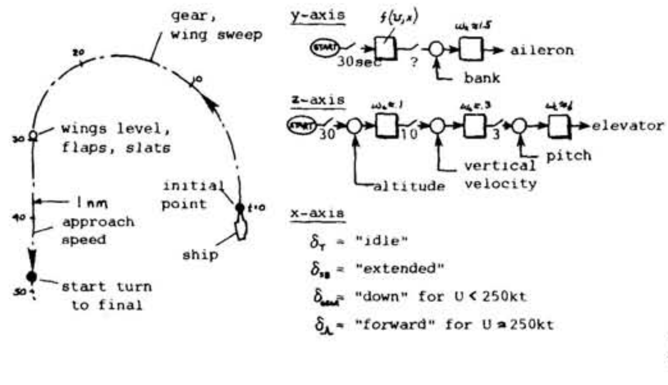
Fig. 6 Features of the Initial Leg Segment

The pilot control strategy of Figure 6b, based on pilot descriptions, involves a compensatory management of course and altitude with timing and loop gains set mainly by the 30 second duration of the leg. Both axes are similarly characterized by supporting middle and inner loops. That is, course is supported by a middle heading loop which, in turn, is supported by an inner bank angle loop. Altitude is supported by vertical velocity, and it in turn by pitch attitude. The third axis, airspeed, appears not to involve any substantial active regulation. Throttle or fuel flow rate is set at a nominal position and left there.

The controlled-element dynamics during the initial leg are benign. The 300 to 400 kt speed range ensures minimal effective lag in pitch, roll, and vertical flight path. Thus the controlled element is essentially either "k" or "k/s" for each of the three series loops in the two main control axes. The resulting mental effort required for these perceptualmotor tasks is therefore low. However, the large excess control capacity can be used up by decisional tasks connected with deck spotting and planning for a minimum-interval approach.

Break Maneuver

As shown in Figure 7a, this phase of the approach starts the 360 degree racetrack course and includes crucial deceleration and reconfiguration events. In addition a new course and altitude must be attained toward the end of the break on the downwind leg.



δ_T = "idle"

δ_{SB} = "extended"

δ_{gear} = "down" for U < 250kt

δ_Λ = "forward" for U ≈ 250kt

a. Nominal Trajectory **b. Likely Pilot Control Strategy**

Fig. 7 Features of the Break Maneuver

A dramatic change in pilot control strategy accompanies the break. Figure 7b shows that trajectory control is essentially precognitive as is airspeed. Only altitude retains the same compensatory character seen in the initial leg.

The desired horizontal-plane trajectory in the break a downwind course about 1.1 miles abeam the ship. This is achieved by an open-loop bank angle command at the start of the break. This bank can range from 45 to 70 deg depending upon initial airspeed and the pilot's judgement of the resulting nonuniform turn radius. No visual position cues relative to the ship are really available until well around the 180 degree turn. At this point a minor heading change might be used to adjust the distance from the ship.

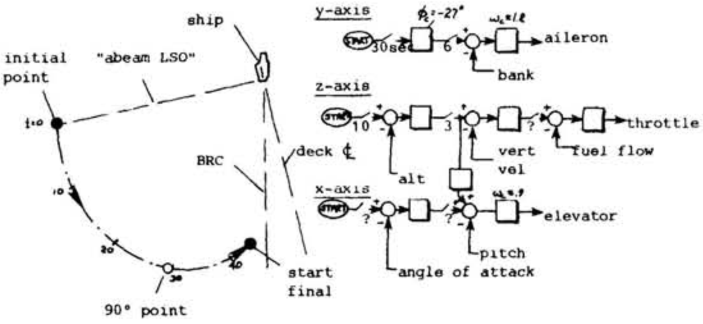
Airspeed is a procedural matter determined by the reconfiguration sequence. Simultaneous with the break the speed brakes are deployed. A few seconds later the wings are unswept but not so early as to compromise the benefit of high induced drag. Then, as quickly as airframe limits allow, the gear is lowered and flaps extended to help the deceleration. Timely execution of each discrete step in the break can be crucial to the pilot arriving at the subsequent flight phase, prepared for the next set of tasks. It should be noted that the break maneuver involves several discrete actions which depend on airspeed and is therefore closed-loop in nature.

Altitude control strategy in the break is similar to that of the initial leg although a pursuit technique involving pitch/throttle coordination is beneficial as the approach speed is reached.

Controlled-element features during the break are highly dynamic owing to the changing airspeed and high normal acceleration, but the pilot control strategy is fundamentally tolerant to this change. For example, an intermediate sink rate loop minimizes the effects of varying heave damping on flight path.

Turn-to-Final

This portion of the approach sets up the final leg (Figure 8a). Precise execution is essential for success since, as in the break, another open-loop lateral trajectory is involved. The controlled-element dynamics have now reached a relatively sluggish level compared to earlier phases, but they remain steady because speed is constant.



a. Nominal Trajectory **b. Likely Pilot Control Strategy**

Fig. 8 Features of the Turn to Final

Shown in Figure 8b, lateral axis pilot control strategy is precognitive just as in the early part of the break. When precisely "abeam the LSO platform," the pilot executes a 27 deg banked turn toward the ship which is again necessary because of the absence of explicit lateral guidance cues. In effect, this segment is performed "on instruments".

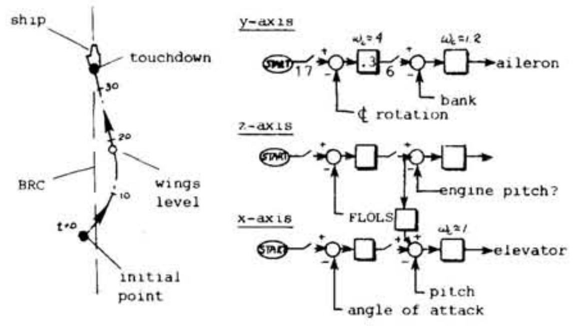
Altitude continues to involve about the same control strategy as previous segments. Starting downwind at 600 ft the next target is 450 ft at the 90 deg point in the turn. A middle vertical velocity loop supports altitude. However, because of the low airspeed, a coordinated use of thrust and pitch must be used to support vertical velocity.

The x-axis involves a loose compensatory regulation of angle of attack by varying pitch attitude. Upsets to this axis are minimized by effective thrust/pitch coordination in flight path.

The controlled-element characteristics are typically "low-speed." Heave damping is low, speed damping high, adverse yaw a factor, and loss of lift due to lateral spoilers a problem. The last feature induces pilots to use lateral control sparingly in order to avoid upsetting sink rate, especially on the final leg.

Final Approach Leg

The final leg really begins while the aircraft is still in the turn to final (Figure 9a). 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**

Fig. 9 Features of the Final Leg

Pilot control strategy in the outer loops now adapts to a pursuit level. 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.

V. Discussion of Workload Factors

Analysis of the task segment trajectories and pilot control strategy diagrams given 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.

One important step in the perceptualmotor workload analysis is to examine the controlled *element dynamics in the context of pilot control* strategy. The effective controlled element response, say, for flight path, can vary significantly depending upon how the pilot chooses to manage it. As shown earlier in Figures 6 through 9, strategy is varied depending upon the demands of each task segment.

For the initial leg the controlled element lags are all minimal because of the high speed and the ability to partition the y-and z-axes into three loop structures. The x-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 x- and z-axes with the y-axis being mainly a precognitive banked turn. Here procedural tasks must be performed as quickly as airspeed reduction permits. This loading is not a fuction of time but rather of flight condition and will vary depending upon where and how fast 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 pre-determined 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. These include crossing the ship's wake and 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). It appears that the pilot has time for no more than two lateral corrections and about the same for the vertical. As discussed in Reference 10, 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 flying qualities, therefore, needs to be judged according to how well they support these rather deterministic demands as well as in countering random disturbances.

VI. Conclusions

In general there is a need for dealing with complex 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. The techniques illustrated above suggest how a complex task such as the carrier landing can be handled both on a global scale and in terms of control strategy details.

One feature of this modeling approach is the ability to deal with some of the deterministic aspects of perceptualmotor task performance. Many crucial piloting tasks found in actual flight operations involve fairly deterministic maneuvers where anticipation and higher level control strategies are essential. Features such as finite-duration task execution, multi-rate sampling and command, and control strategy switching aid in the analysis of such maneuvers.

The models described herein can be better and more completely defined as additional flight data become available. The collection of such data should be pursued when possible.

Many of the numerical values given here are estimates. While in-flight measurements are needed to fill out the math model quantification, the form of the task models accomodates simple and direct parameter identification techniques such as those suggested in Reference 7.

Construction and analysis of the 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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