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A WORKLOAD-ORIENTED MODEL OF THE CARRIER LANDING

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(Informal Paper)

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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.

This paper illustrates how task modeling can be used to examine a particularly crucial Navy mission flight phase, the carrier landing. The ultimate objective 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 same detail here although work is still ongoing 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 1 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. The purpose of this paper is to illustrate how the overall carrier landing task can be credibly cast in such terms and especially how this permits effective analysis. The full daytime VMC carrier landing task depicted in Figure 1 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

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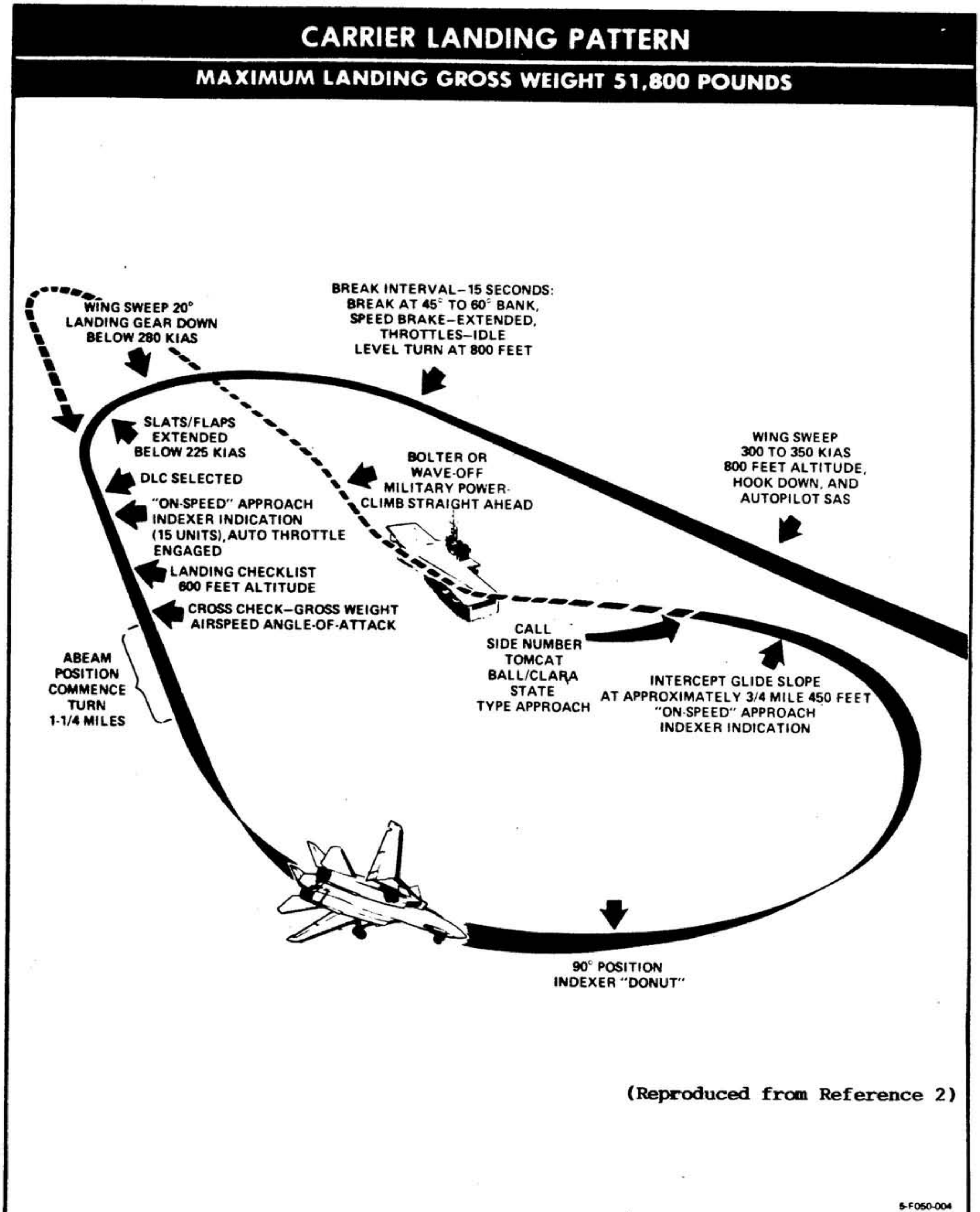


Figure 1. Carrier Landing Pattern

parameters. This provides a reasonably correct and complete operating context in which to examine the pilot workload as a function of aircraft flying qualities.

FEATURES OF THE TASK MODEL

The model presented here is intended to address three aspects of pilot workload suggested in Reference 3: (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 4, then augmenting it with the kind of discrete-maneuver pilot control strategy model described in Reference 5. 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 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 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. When combined with the respective controlled element, this forms the pilot-vehicle-task system. The main system features which allow an analysis of time and mental effort workload include:

- Task Duration
- Outer Loop Bandwidth
- Outer Loop Controlled Element
- Support Loop Interval
- Support Loop Bandwidth

Time and mental effort aspects can be quantified for each control loop by evaluating the controlled element characteristics for the operating point corresponding to the time required to complete a finite-duration task or sub-task. 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, the higher the bandwidth requirement and the lower the phase margin in both the outer and supporting loops.

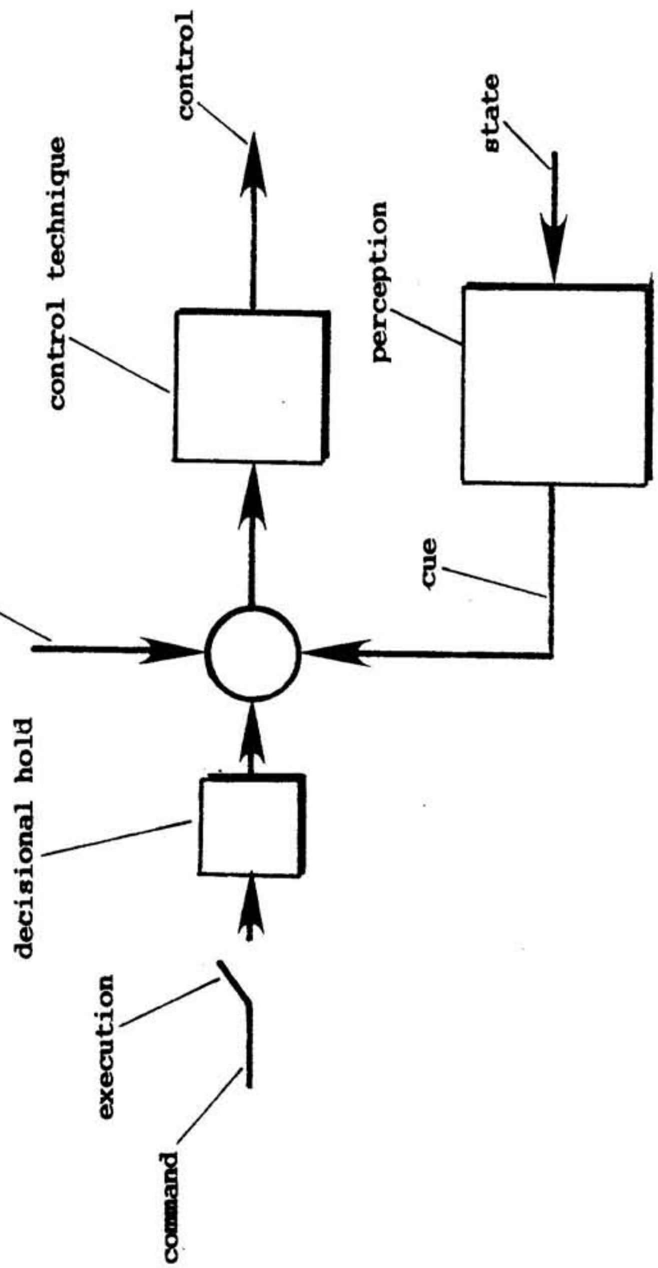


Figure 2. Pilot Control Strategy Topology

Figure 3 shows generically how the components of the task model can be divided into phase margin debits. Hence, we can express an explicit tradeoff 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).

Note that the ϕ_{M_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}. Such tradeoffs can be illustrated and explored in the analysis of the carrier landing.

DESCRIPTION OF TASK SEGMENTS

Based mainly on Navy F-14 fighter pilot interviews conducted at fighter squadron VF-111, NAS Miramar, detailed multiloop block diagrams of the pilot-vehicle-task system have been constructed for each segment of the carrier landing. These have been refined using F-14 flight data from the Naval Air Test Center, Patuxent River, MD (Reference 6). Training manual descriptions (Reference 7) were also consulted. The four major segments of the daytime racetrack pattern include:

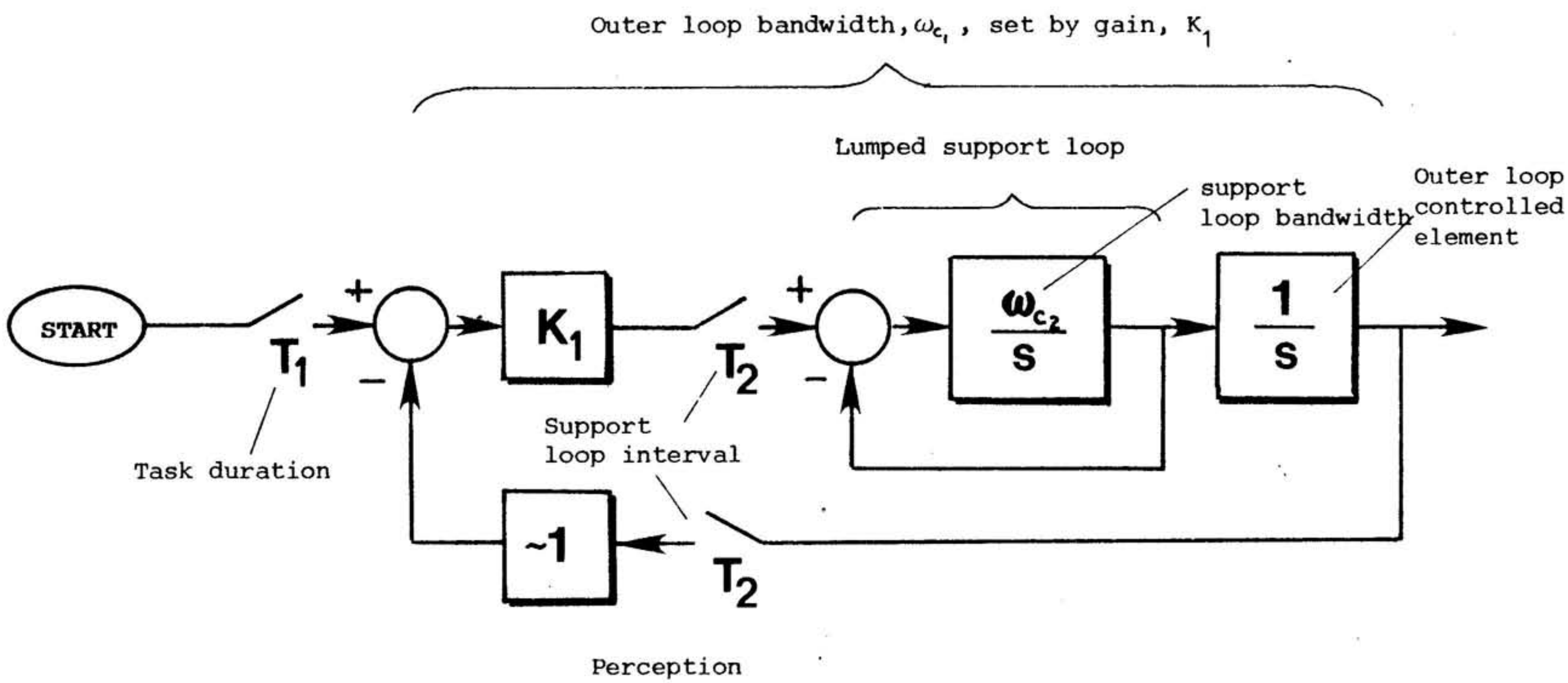
- Initial approach from astern
- Break (turn to downwind leg)
- Turn from downwind to final leg
- Final approach leg (using optical guidance)

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 4a, 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.

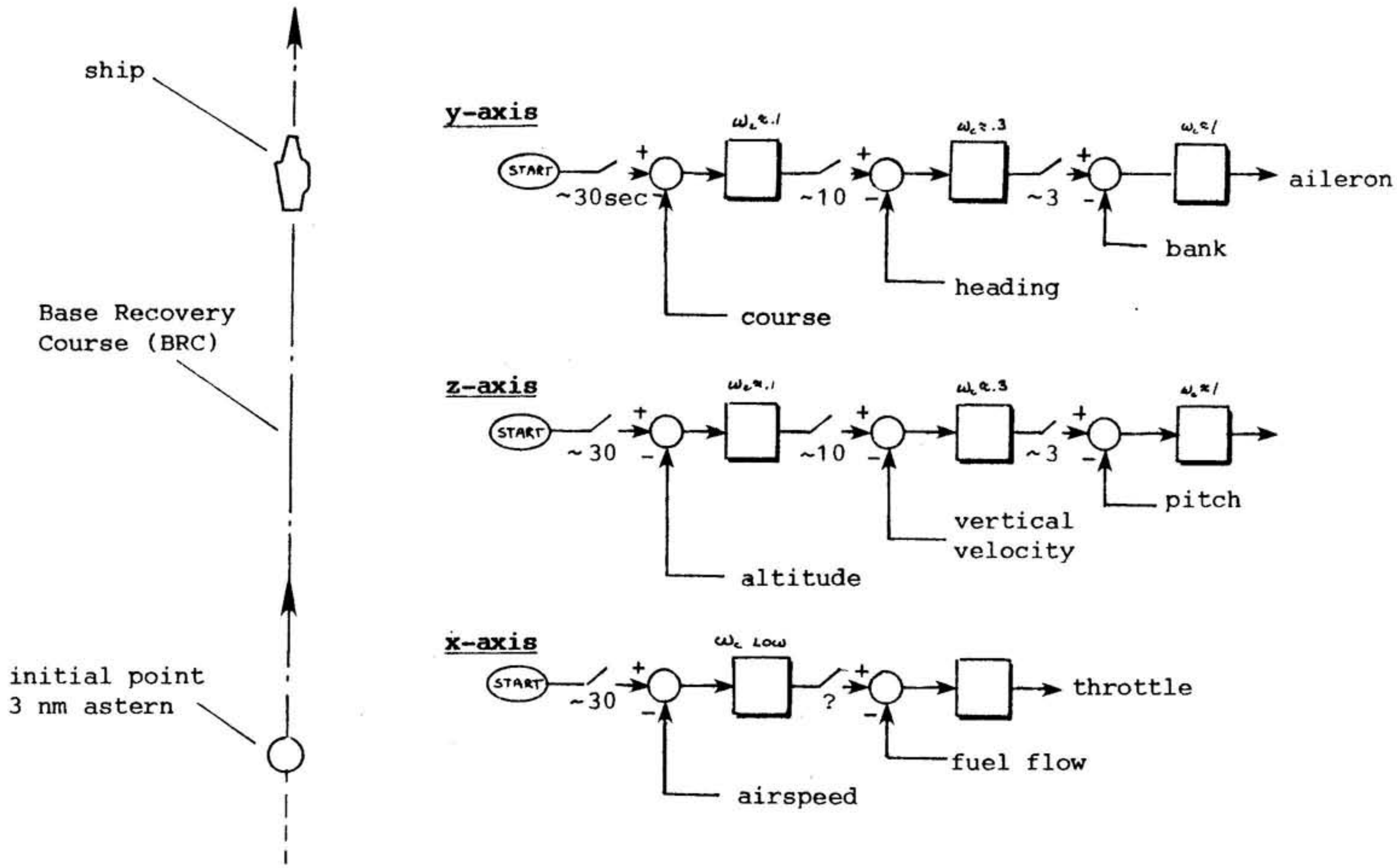
The pilot control strategy of Figure 4b, based on pilot descriptions, involves a compensatory management of course and altitude with



Outer Loop Phase Margin, $\phi_{M_1} \approx \pi - \frac{\pi}{2} - \omega_{c_1}\frac{T_2}{2} - \tan^{-1}\frac{\omega_{c_1}}{\omega_{c_2}}$

- $\frac{\pi}{2}$: controlled element debit
- $\omega_{c_1}\frac{T_2}{2}$: support loop interval debit
- $\tan^{-1}\frac{\omega_{c_1}}{\omega_{c_2}}$: support loop bandwidth debit

Figure 3. Discrete Maneuver Factors for a K/s Outer Loop



a. **Nominal Trajectory**

b. **Likely Pilot Control Strategy**

Figure 4. Features of the Initial Leg Segment

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.

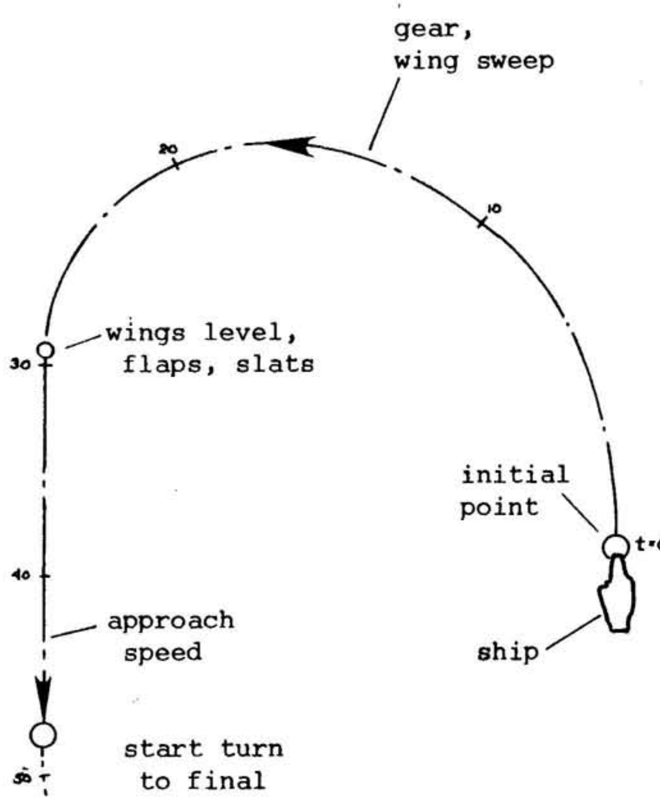
Break Maneuver

As shown in Figure 5a, 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.

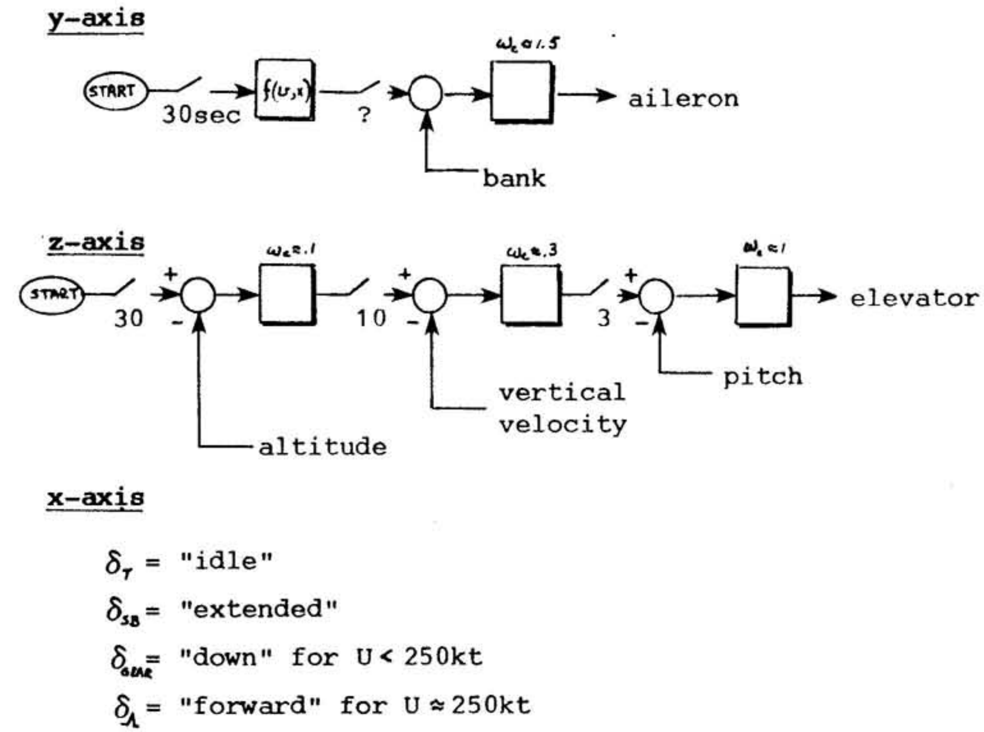
A dramatic change in pilot control strategy accompanies the break. Figure 5b shows that trajectory control is essentially precognitive as is airspeed. Only altitude retains the same compensatory character seen in the initial leg.

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.



a. **Nominal Trajectory**



b. **Likely Pilot Control Strategy**

Figure 5. Features of the Break Maneuver Segment

Altitude control strategy in the break is similar to that of the initial leg although a pursuit technique involving pitch/throttle co-ordination 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 6a). 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.

Shown in Figure 6b, lateral axis pilot control strategy is pre-cognitive 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.

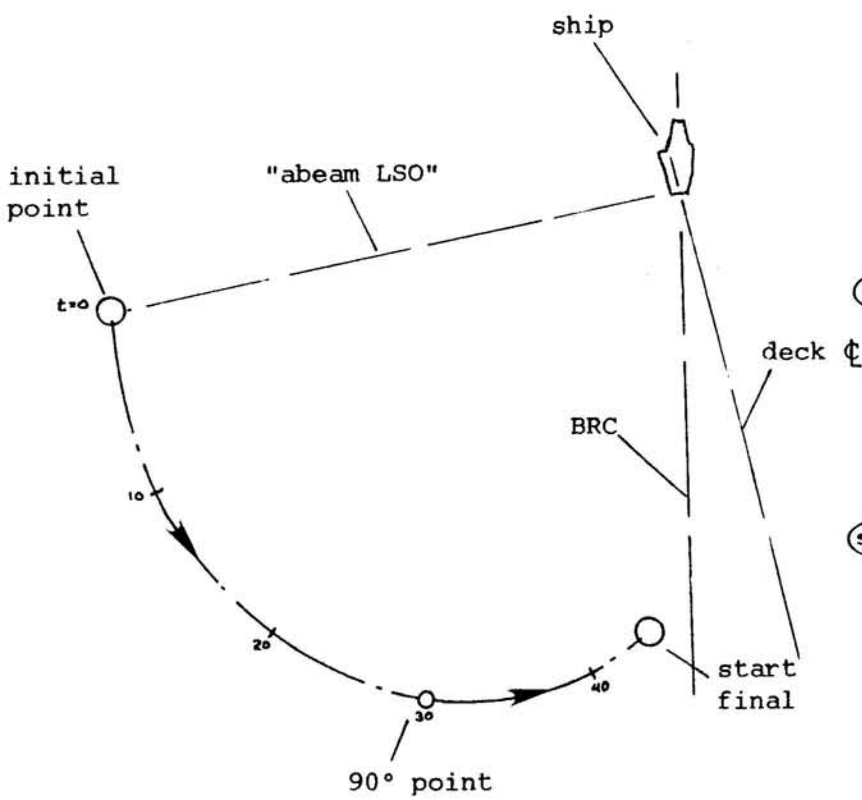
The x-axis involves a loose compensatory regulation of angle of attack by varying pitch attitude. Upsets to this axis are minimized by effective thrust/pitch coordination in flight path.

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.

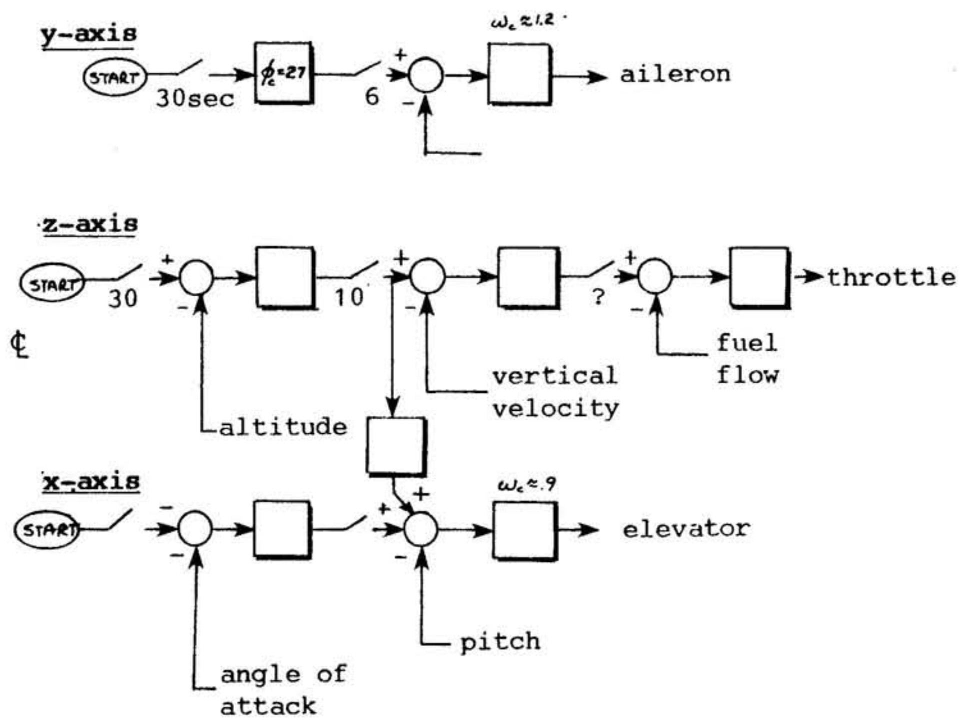
Final Approach Leg

The final leg really begins while the aircraft is still in the turn to final (Figure 7a). 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.

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

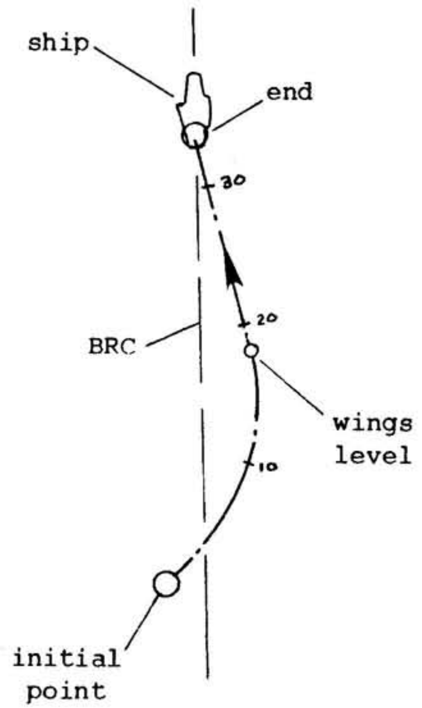


a. Nominal Trajectory

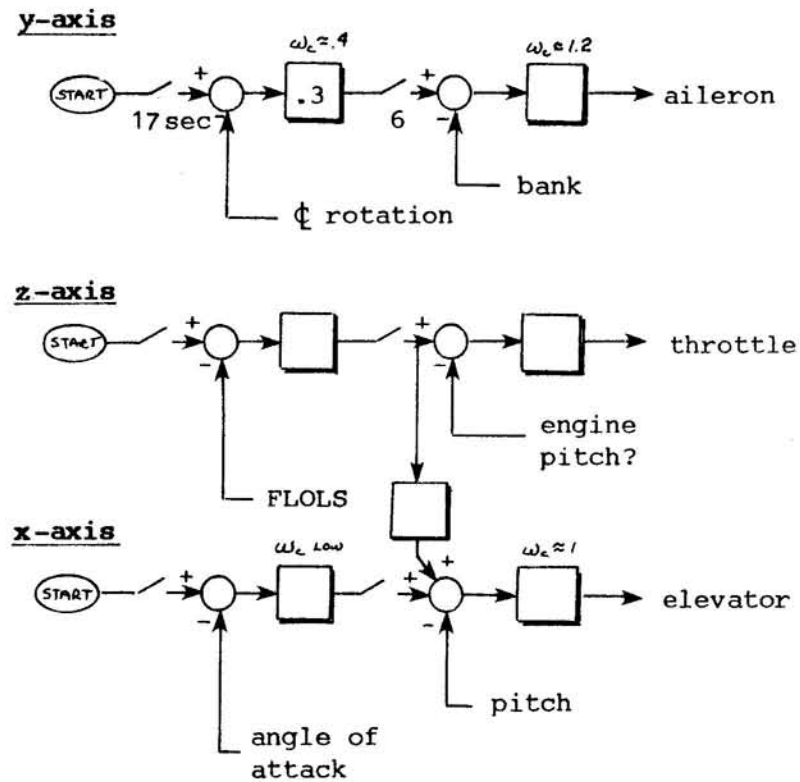


b. Likely Pilot Control Strategy

Figure 6. Features of the Turn-to-Final Segment



a. Nominal Trajectory



b. Likely Pilot Control Strategy

Figure 7. Features of the Final Approach Segment

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.

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 4 through 7, 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 will the reconfiguration tasks 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. Analyis 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 8, a pursuit strategy is essential in the vertical axis in order to excute 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.

CONTINUING TOPICS OF STUDY

The model described herein is continuing to be refined and better quantified using all available flight data. The culmination will be a workload model (distinct from the task model) containing the factors of time, mental effort, and stress--structured to permit analysis of aircraft flying qualities. The carrier landing task model forms the operational context for applying the workload model.

Many of the numerical values given here are estimates, of course. Still needed are a comprehensive set of in-flight measurements to fill out the math model quantification. However, the form of the task models accomodates simple and direct parameter identification techniques such as suggested in Reference 5.

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 demands, these aspects need to be evaluated in a time-bounded and realistic flight task context.

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