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DECISION AIDS FOR AIRBORNE INTERCEPT OPERATIONS IN ADVANCED AIRCRAFTS

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ABSTRACT

Rapid and prompt decision-making during the execution of an F-14 AWC-9 air-to-air intercept mission has been a continuing problem facing the aircrew over the years. The aircrew has had to rely on an inordinate amount of 'gut feel,' rule-of-thumb decisions invariably resulting in ad hoc tactic selection. Consequently, it is generally recognized in the air C³ community that realtime Tactical Decision Aids (TDAs) are needed by the aircrew in air intercept operations. Fortunately, the extended memory and improved processing capabilities of today's weapon systems computer have made it feasible to incorporate realtime decision aiding algorithms in the onboard software. This paper presents a TDA for the F-14 aircrew, i.e., the NFO (Naval Flight Officer) and pilot, in conducting a multi-target attack during the performance of a Combat Air Patrol (CAP) role. The TDA employs hierarchical multiattribute utility models for characterizing mission objectives in operationally measurable terms; rule-based AI-models for tactical posture selection; and fast-time simulation for maneuver consequence prediction. The TDA makes aspect maneuver recommendations, selects and displays the optimum mission posture, evaluates attackable and potentially attackable subsets, and recommends the 'best' attackable subset along with the required course perturbation.

INTRODUCTION

In a typical F-14 air-to-air mission, the aircrew (Naval Flight Officer and pilot) are called upon to make a multitude of decisions in a rapidly unfolding threat environment. A significant proportion of these decisions impact the overall outcome of the entire mission. Presently, the aircrew make these decisions based upon some combination of training, experience and a limited number of low-level decision aids provided by the F-14's AWC-9 tactical program. These aids, however, have had to be simple due to the limited memory allocation in the onboard computer. However, with the emergence of a large number of sophisticated, high performance threats, it is generally recognized in the air C³ community that onboard tactical decision aids are required in almost all phases of an air-to-air mission. Fortunately, realtime computer-based TDAs are possible today primarily because of the expanded memory and processing power of today's onboard computers. It is worth noting, however, that despite the evident need, decision aids if not designed from user's viewpoint and task loading can expect great "psychological" resistance from the user pool.

In this paper, a decision aid for assisting the F-14's aircrew in the CAP role of a fleet air defense mission is presented. The aid, based on proven methods from decision analysis, artificial intelligence and fast-time simulation assists the aircrew in the situation assessment and alternative selection functions.

Combat Air Patrol (CAP) Role

In performing its air-to-air missions, the F-14 in the general role of a Maritime Air Superiority Fighter acts as an element of the force Combat Air Patrol (CAP). A typical air-to-air fleet defense mission with the F-14 performing a Combat Air Patrol (CAP) role is given in Figure 1. The CAP objectives are early detection, interception, and attack of airborne threats that endanger the fleet elements. Within the overall CAP role, phases 5, 6, and 7 were selected for aircrew aiding because (1) during these phases the aircrew task loading is high and (2) feasibility of TDAs can be demonstrated in these phases.

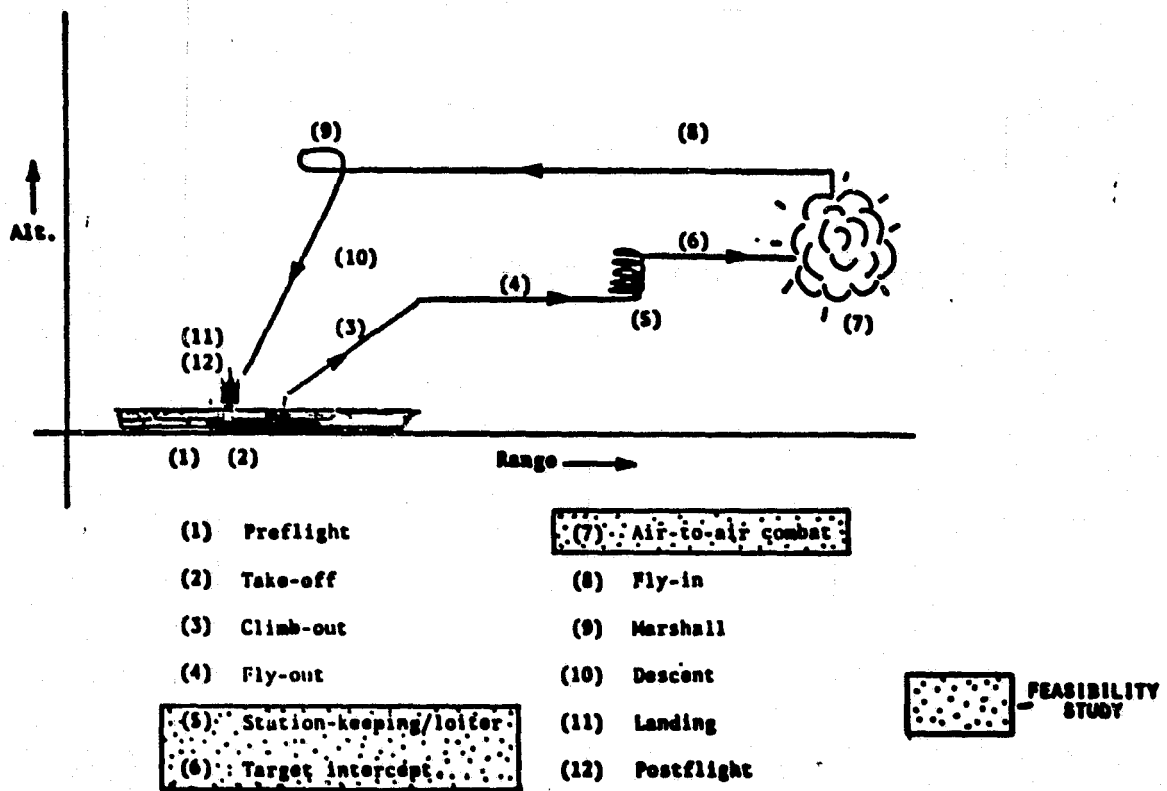


Figure 1. CAP Role Vertical Flight Profile

Phase 5 is station-keeping/loiter. In this phase, the F-14 adheres to a patterned flight at a designated position from the task force. This phase terminates when patterned flight ceases upon target detection.

Phase 6 is target intercept. In this phase, the aircraft pursues a flight path toward a relative position (target conversion) on a selected airborne target. This phase terminates when both the intent to launch a weapon and the capability to effectively launch a weapon exists.

Phase 7 is air-to-air combat. In this phase, the aircraft is flown within a selected weapon launch envelope against a specific target. This phase includes all beyond visual range (BVR) and within visual range (WVR) engagements. The air-to-air combat phase terminates when no further launch capabilities exist or are desired, and the desired return altitude and speed profile has been attained.

Decision Structuring for the F-14 CAP Role

The F-14 CAP role is comprised of a sequence of decisions leading to engagement with and launch on incoming threats. The typical scenario commences with detection and identification of the set of threats. The NFO must quickly switch radar modes, monitor fuel and weapon system status, decide on the subset of the threats to prosecute, select an intercept trajectory, determine the missile launch points, and assess the results.

The sequence of actions in this scenario can be efficiently represented using a decision tree format, as shown in Figure 2. Action decisions, in which the possible choices open to the NFO are listed, are represented by a square box. The decision maker is free to choose only one of the actions. Event nodes, shown as circles, have as branches all the outcomes that may occur at that

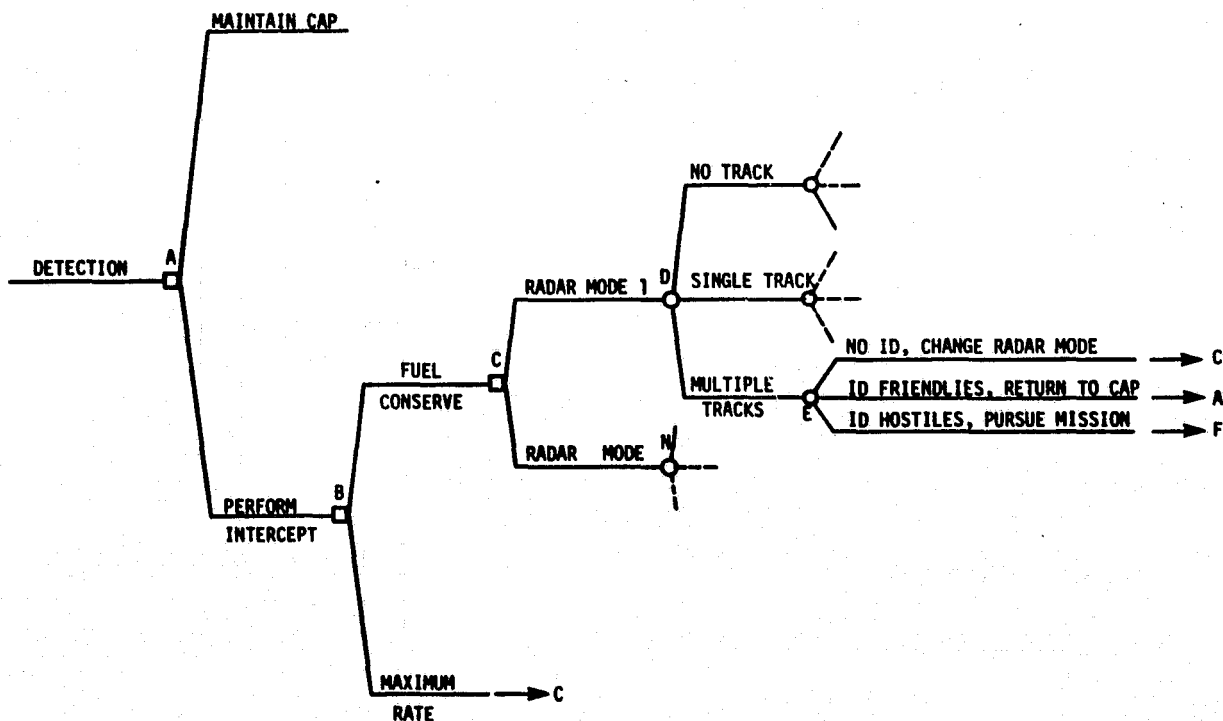


Figure 2. CAP Role Decision Sequence

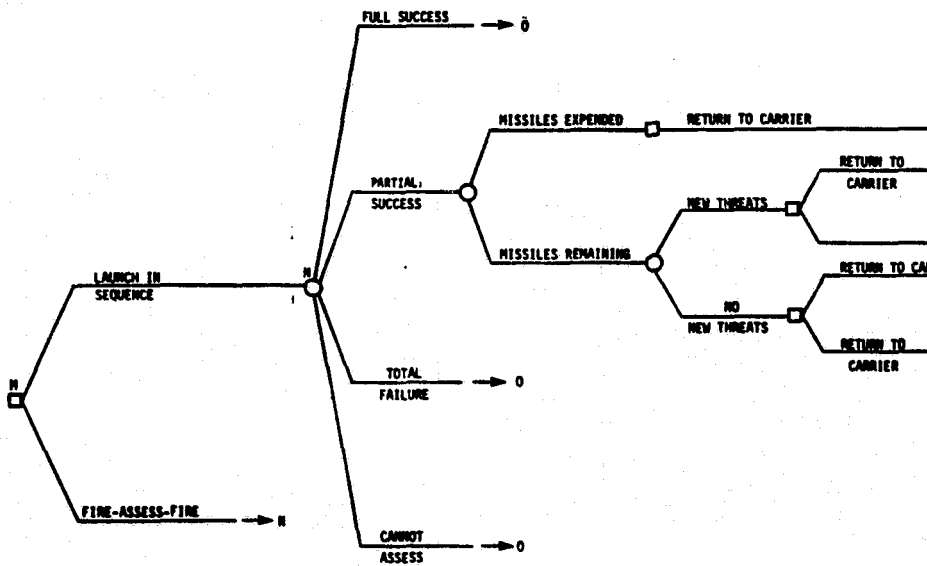
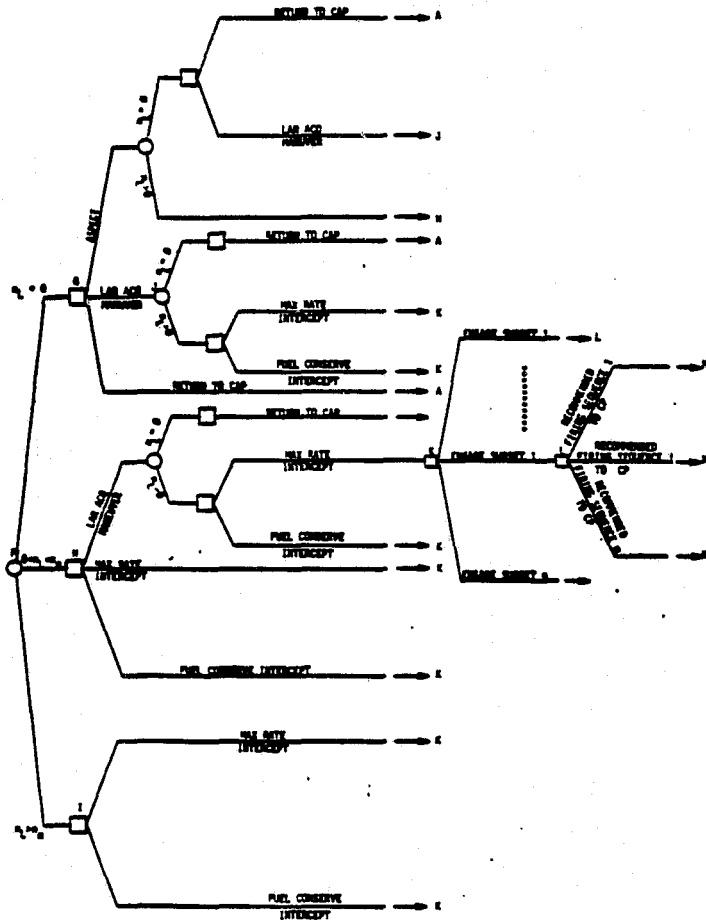


Figure 2. CAP Role Decision Sequence (Cont'd)

point in the tree. The events are characterized by their probability of occurrence and by the value of the outcome. If one path from the beginning of the tree is followed to the end, it describes a possible "scenario." The most effective sequence of actions can be determined by taking the expectation (probability weighting) of utilities over each alternative. The recommended course of action is the one with the highest expected utility.

In order to perform this type of analysis, values and likelihoods must be assigned to each possible outcome. Since there is not enough time to elicit such judgments from the NFO during prosecution of an engagement, results from off-line prior analyses must be loaded into the TDA as routines.

Value estimation in this complex, dynamic environment is best performed using multi-attribute utility (MAU) analysis. MAU methods decompose the complex multi-criterion evaluation problem into more manageable subproblems of scaling, weighting and combining criteria. The MAU evaluation can be expressed as a simple aggregate of constituent factors.

$$\text{Value (Option } j) = \sum_k p(z_k) \sum_i \alpha_i U(x_{ijk})$$

where $p(z_k)$ is the probability of occurrence of event k ; α_i is the importance weight of attribute i ; and $U(x_{ijk})$ is the utility of attribute i associated with option j and event k . This divide and conquer approach of MAU analysis involves defining the problem, identifying relevant dimensions of value, scaling and weighting the dimensions, and finally aggregating the dimensions into a single figure of merit for evaluation. The specific attribute set for evaluation in the F-14 scenario is presented in a later section.

Arriving at estimates of the probability of occurrence of each outcome is also difficult. Two approaches are possible: (1) exhaustively list and estimate off-line the likelihood of each consequence in the CAP scenario or (2) perform fast-time on-line simulations of the maneuver options to analytically determine the major consequences. The first approach, using subjective probability estimates, is expected to be somewhat unreliable and difficult to implement. Even experienced NFOs may be hard-pressed to agree on the probability of acquiring a LAR or encountering a given threat penetration given a specific situation and maneuver. Accordingly, the objectively derived, fast-time simulations were used as much as possible in the TDA operation.

Time Line of the F-14 CAP Role and Aiding Requirements

The current minimally aided F-14 CAP role will be discussed in the following paragraphs with the specific objectives of demonstrating where and when the NFO performance can be enhanced via tactical decision aiding.

The scenario, summarized earlier in Figure 2, commences with the F-14 in a CAP role on the verge of a potential new engagement. The F-14 aircrew are informed of new detections and moments later observe target tracks on the Tactical Information Display (TID). The NFO at this time has to decide if he want to perform intercept or stay on CAP. This decision depends on whether the tracks are identified as 'friendlies' or 'hostiles' and if a successful intercept trajectory to the

oncoming targets is feasible. Currently, target identification once completed, is displayed to him on the TID. However, he has no indication if a successful intercept is possible or not. He draws upon his past experience to make this assessment. If the targets are identified as friendlies, then he stays on CAP. If the targets are identified as hostiles and he decides to embark on an intercept course he has to decide if the intercept should be performed at maximum rate or in fuel conservation fashion. This decision depends on the projected mission profile, and availability of in-flight refueling. Also, he has to determine the details of executing his intercept, i.e., should he "swing" an aspect prior to pursuing an intercept, should he try to acquire Launch Acquisition Regions (LARS) on additional targets or stay with the ones he currently expects to have. Since currently he has no way of knowing what the LAR configuration would be if he executed specific LAR acquisition maneuvers, he makes this determination on his present state of knowledge and 'gut feel.' With regard to performing an aspect he takes into consideration the number of targets he has on the TID, and the number of targets with LARS against his current missile load. Not always will he make the same decision because his perception of secondary factors like time to encounter, and intercept geometry may differ from case to case. However, it is safe to say that if the number of LARS and targets are less than his missile load, he may try to acquire additional LARS. In any case, his next major decision is which subset of targets to go after if there are more targets than missiles and in what sequence to attack them. Currently, the intercept trajectory is usually head collision based on target centroid, emphasizing instantaneous heading and altitude. The firing sequence depends on the order of increasing time until optimum range, nominally fifteen percent into LARS. The current mechanization has manifest drawbacks. There is no objective criteria for attackable target subset selection. The NFO determines who he can go after, generally one at a time, and performs the intercept on that basis. The lead collision intercept trajectory is also suboptimal across the entire spectrum of intercept geometries while the choice of firing sequence is totally ad hoc.

After having "completed" an engagement, i.e., no further attackable threats, the NFO may decide to return to CAP or to the carrier depending on his remaining missile and fuel resources. If he has adequate missile and fuel supply, he prepares for evaluating a reattack if a new wave of threats is detected.

THE TACTICAL DECISION AID (TDA)

Overview

Several key stages of the CAP role immediately present themselves as candidates for aiding. The choice of whether to make an aspect maneuver to gain additional information, what course perturbation to perform to acquire additional LARS, and which subset of threat to engage are all complex decisions well-suited for computer-based aiding. Each of these tasks have well-defined options (turn 15° left, continue on course, etc.) and discrete outcomes (acquire new track, acquire LAR, etc.). Also, the same mission objectives apply to each task.

The portions of the CAP role dealt with by the TDA are summarized in Figures 3 and 4. This tree is roughly equivalent to nodes f through k in the original decision tree (Figure 2). The TDA-assisted decision tree begins with the situation assessment state. After a number of targets are detected and identified, LARS may or not be present on the targets. If no LARS are present, the NFO may elect to stay on the CAP role, prosecute the attack immediately, or perform an aspect

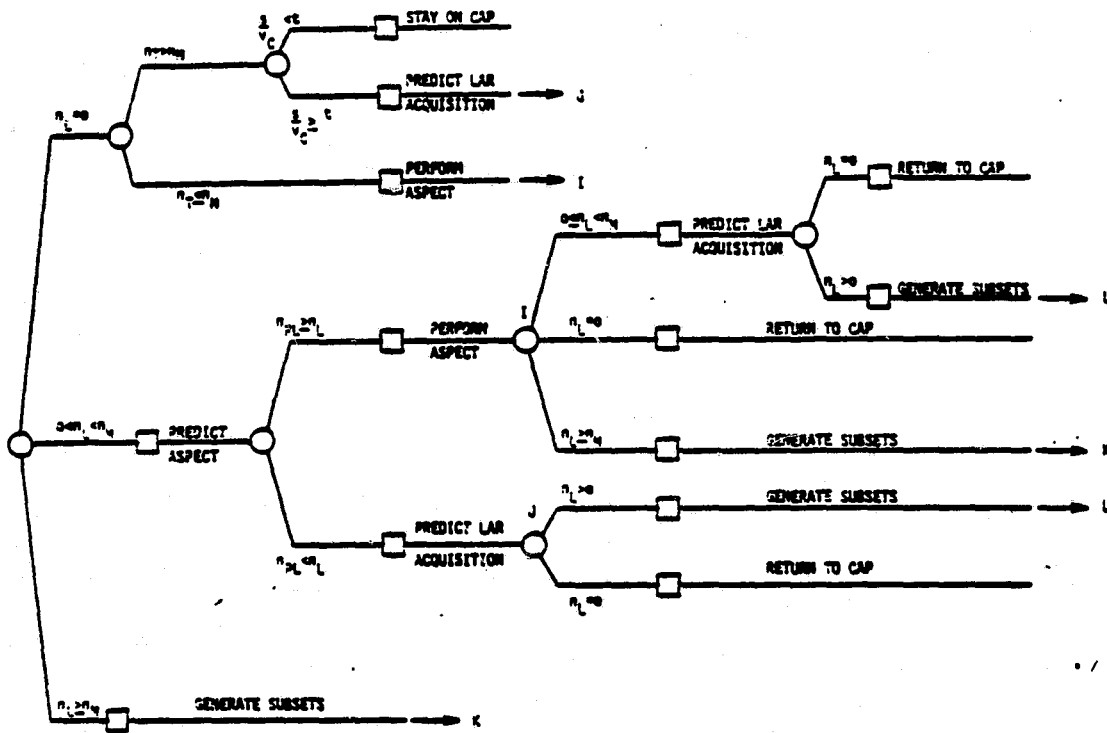
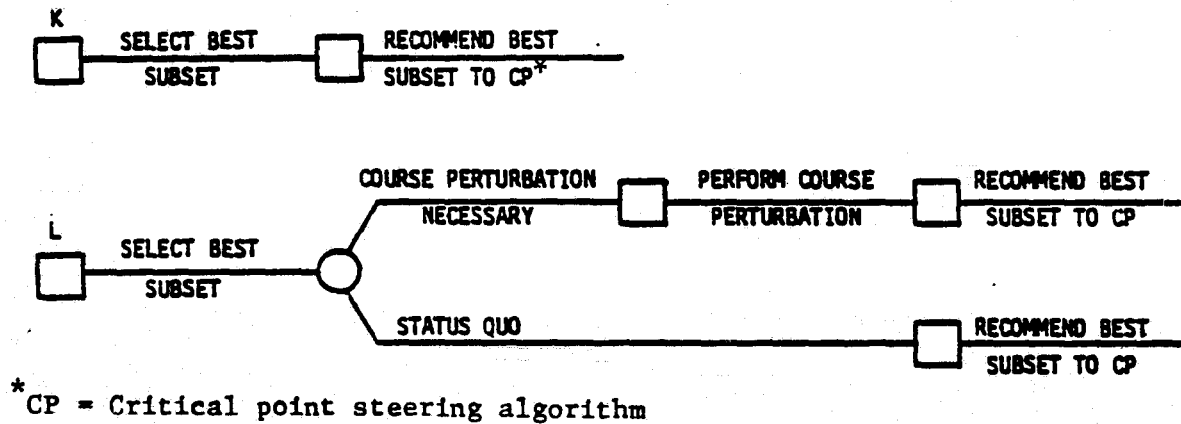


Figure 3. Situation Assessment and Alternative Generation



* CP = Critical point steering algorithm

Figure 4. Alternative Selection

maneuver. The TDA evaluates the options on the basis of the number of targets present (n_T), the number of missiles onboard the F-14 (n_M), and the time to engagement (t_E): and make a recommendation to the NFO. Similar situation assessments are made if there are targets with LARS at the initiation of the engagement. Of course, the criteria of evaluation employed in the actual TDA evaluation are more complex than that described above. The TDA considers the impact of each choice and outcome on the threat to the carrier, on the damage inflicted on the enemy, and on the F-14's own vulnerability. The specific criteria are developed in detail in subsequent sections. The next stage in the decision tree leads to alternative generation (nodes I and J in Figure 3).

If an aspect maneuver is recommended, on the basis that the predicted number of LARS following the maneuver (n_{PL}) is greater than the original number of LARS (n_L), then following the maneuver, the NFO must choose to continue prosecution of the threats or return to CAP. A return to CAP would only be called for if following the maneuver no LARS were present.

The above sequence illustrates an important characteristic of the TDA. Instead of requiring subjective estimates of the likelihood of LAR acquisition in each situation, the LAR tests are made by calling a fast-time simulation. In this way, the decision aiding is based on hard data of position, course and speed of the F-14 and the threats.

Once the aspect maneuver is complete, course perturbation checks and subset generation are performed by the TDA (Nodes K and L). Here changes in heading, altitude and speed are tested to see if additional LARS result. Then the "best" threat subset is recommended for attack. The specifics of what is "best" will be covered in the next section.

In the following paragraphs, the structure and operation of the TDA will be presented in terms of: the mission objectives hierarchy which "drives" the aid, the automated programs for mission posture specification, aspect maneuver recommendation, course perturbation, target subset selection, and display requirements.

Objective Structuring and Mission Success Hierarchy

The overall mission objective for the F-14 CAP role starting with target detection and culminating with target reattack can be summarized in three key tradeoff objectives: (1) maximize carrier safety; (2) maximize tactical gains; (3) minimize resource expenditure. Each of these objectives can be embedded in a linear multi-attribute representation framework and can be further decomposed into explicit sub-objectives that themselves constitute measurable attributes or have measurable attributes associated with them. Each of these attributes provide a scale for measuring the degree of attainment of the associated sub-objective. The weighted combination of these attribute levels provide an indication of the attainment of each parent key objective. The weighted combination of the level of attainment of each key objective then provides a measure of the overall mission success objective. The mission success hierarchy is shown in Figure 5. The actual choice of the attribute set is extremely important. Dawes (1974) states that the choice of factors to include is probably of greater impact than the determination of the model form. Desirable characteristics are

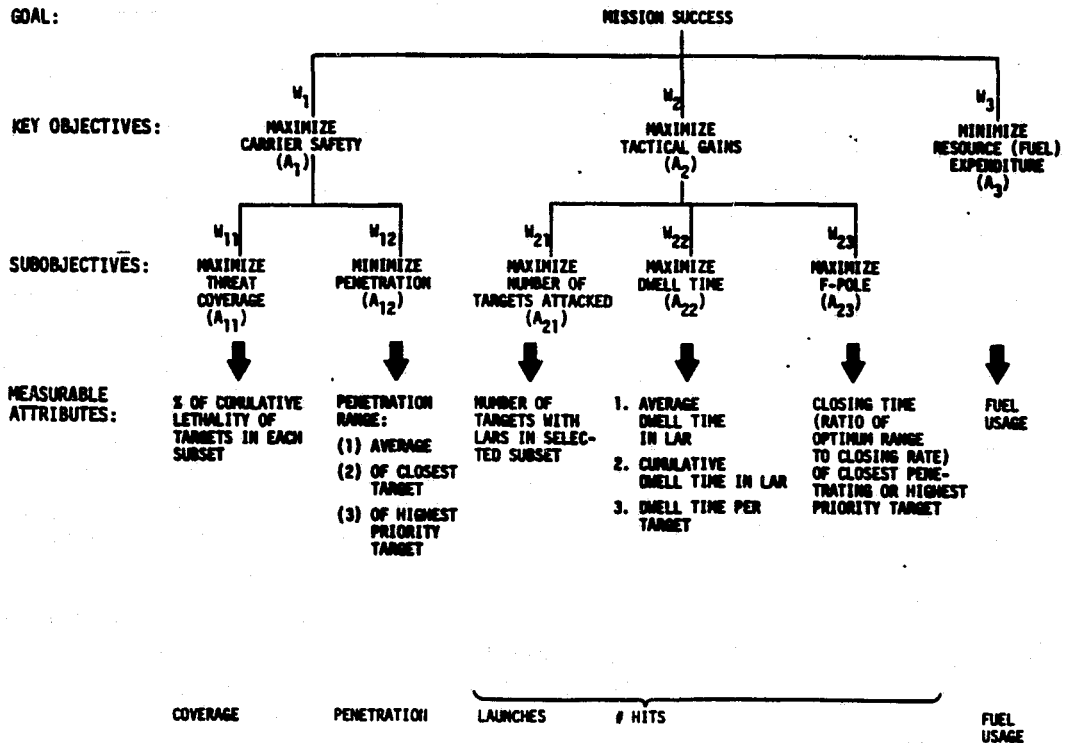


Figure 5. Mission Success Hierarchy

accessibility for measurement, independence, monotonicity with preference, completeness of the set, and meaningfulness for feedback. Monotonicity, in this content, implies that an increase in the attribute level always results in an increase in preference. If the attribute levels are monotonic, a simplification is possible. Fisher (1972) and Gardiner (1974) note that a straight line approximation to the utility function results in minor losses of model accuracy. The attributes selected within the framework of the three key tradeoff objectives that characterize the F-14 CAP role mission phase possess the desired characteristics described above. These attributes were elicited from Naval Flight officers and pilots who jointly agreed upon the selected attribute set.

The first key objective, maximizing carrier safety, can be decomposed into maximizing threat coverage and minimizing target penetration. Threat coverage is measured in terms of the threat associated with the engaged subset of targets. The greater the threat engaged the higher the threat coverage. Target penetration range is defined as (1) the range from Task Force Center (TFC) of either the closest penetrating target attacked or the highest priority target attacked (whichever is chosen due to situation). Minimizing target penetration range is equivalent to maximizing the range from the TFC of either the closest penetrating or highest priority target while ensuring that the average range of the remaining targets from the TFC is above a predetermined range threshold.

Maximizing tactical gains is analogous to maximizing expected kill (E_K). This objective is not amenable to direct measurement but can be decomposed into related operationally measurable objectives, the attainment of which implies the attainment of the related parent objective. Thus, E_K is expressed in terms of maximizing (1) the number of Phoenix launch opportunities or the number of targets attacked, (2) the dwell time in LAR, and (3) F-pole. The number of Phoenix launch opportunities is the number of LARS the F-14 obtains on the threat subset plus the number of second shot opportunities. A second shot opportunity is predicted if a target previously acquired is expected to have a LAR at a time $t > k$ later. The second attribute, number of targets attacked, is the number of distinct targets in the subset upon which LARS are predicted. The dwell time in LAR is the predicted time in seconds between the entry and exit points summed across all LARS in the subset. The final attribute, F-pole is not directly predictable. However, it is proportional to R_{OPT} and inversely proportional to the closing rate, V_C . Thus, R_{OPT}/V_C is employed as an indicator of F-Pole.

The final key objective, minimizing resource expenditure, implies minimizing fuel expenditure. The predictable attribute corresponding to fuel expenditure is the fuel remaining after each of the perturbation maneuvers. The prediction of each of the operationally measurable attributes is discussed below.

Predicted Attribute Level Computation. Predictive computation of the various attributes that define mission success hierarchy are defined on normalized 0 to 1 scales.

1. Threat Coverage. Threat coverage is defined as the weighted sum of the total number of attackable targets (with LARS) in the subset of targets selected for engagement. The weighting factor associated with target i is its lethality index, i.e., the lethality of target i . Lethality, in general, is primarily a function of the onboard weapon load and the EW capability of that target. These two parameters can usually be determined once the target has been identified. There are also some generic tactical doctrines that drive the lethality computation. For instance, it is generally agreed upon by the operational community that platforms should be attacked first, so that they cannot return another day and pose a recurring threat to the NFO. Additionally, attacking platforms first provides a tactical advantage in that the platforms are denied midcourse guidance correction. A second doctrine is that manned aircrafts should be attacked/engaged prior to attacking any missiles. However, since such detailed lethality indices were not available during the study, a priori lethality values were assigned to the different targets modeled in the multi-target KIWI simulation environment. The initial implementation was in the form of a table look-up of lethality index versus target type for the candidate threats that were simulated. With this simplification, threat coverage can be computed as:

$$\text{Threat Coverage} = \sum_{i=1}^k l_i$$

where λ_i , $i=1, \dots, k$, is the lethality of target i ; k is the total number of targets in the subset selected for attack.

The above computation is normalized relative to the product of the number of missiles currently onboard and the lethality index associated with the most lethal target. Thus,

$$a_{11} = \sum_{i=1}^k \lambda_i / N_{\text{miss}} \cdot \max_i (\lambda_i)$$

2. Penetration Range. Penetration range is defined as a weighted combination of the distance from the Task Force Center (TFC) of either the closest penetrating target attack or the highest priority target attacked, and the average range from TFC of the remaining targets on the TID. Penetration range as defined here should be maximized for the successful attainment of mission objectives. If \underline{r}_T is the location (position vector) of the closest penetrating target or highest priority target (depending on the context), $\underline{r}_{\text{TFC}}$ is the position vector of the Task Force Center and \underline{r}_C is the position vector of the centroid of the remaining targets, then maximizing penetration range implies maximizing

$$a'_{12} = (1-\epsilon) \underbrace{|\underline{r}_T - \underline{r}_{\text{TFC}}|}_{\text{primary objective}} + \epsilon \underbrace{|\underline{r}_C - \underline{r}_{\text{TFC}}|}_{\text{secondary objective}}$$

$1-\epsilon$ and ϵ are the weights associated with the primary and secondary objectives, respectively.

\underline{r}_C is defined by

$$\underline{r}_C = \frac{1}{n-1} \sum_{i=1}^{n-1} \underline{r}_i$$

where n is the total number of targets on the TID and \underline{r}_i is the location of target i . Normalizing, attribute

$$a_{12} = a'_{12} / |\underline{r}_{\text{max}} - \underline{r}_{\text{TFC}}|$$

where $\underline{r}_{\text{max}} (= \max_i \underline{r}_i)$ is the position of vector of the farthest target in the threat cloud.

3. Number of Phoenix Launch Opportunities or Number of Targets Attacked. The number of Phoenix launch opportunities can be predicted conservatively on the basis of the number of targets (i.e., LARS) in the selected subset. This definition, of course, assumes that no existing LARS will be lost nor new ones acquired during the course of the impending engagement. Thus, the number of Phoenix launches, n , is given by

$$\begin{aligned} n &= n_T, \text{ if } n_T \leq n_M \\ n &= n_M, \text{ if } n_M > n_T \end{aligned}$$

where n_T is the number of targets in the subset and n_M is the onboard missile load.

The normalized attribute is then given by

$$a_{21} = \frac{n}{n_M}$$

4. Cumulative Dwell Time. Dwell time, t_D , is defined as the time spent in the LAR of a given target. Thus, dwell time in LAR of target i , t_D^i , is given by

$$t_D^i = \frac{|R_{\max}^i - R_{\min}^i|}{V_C^i}, \quad i=1, 2, 3, \dots, k$$

Cumulative dwell time, T_D , is the sum of the dwell times in the launch zone of each individual target.

$$T_D = \sum_{\text{target } i} \frac{|R_{\max}^i - R_{\min}^i|}{V_C^i}, \quad i=1, 2, \dots, k$$

The normalized attribute dwell time (a_{22}) is given by

$$a_{22} = \frac{T_D}{K\alpha}$$

where $\alpha = \max_i [t_D^i]$

5. F-Pole Range. F-Pole range is the fighter to target range at the end of the predicted missile TOF. Maximizing F-Pole range is equivalent to maximizing closing time for that target. The closest penetrating target i in each subset k is found from the closing time to the TFC, $t_{c_i}^k$.

$$t_{c_i}^k = \frac{|\underline{r}_i^k - \underline{r}_{TFC}|}{v_{c_i}^k} = \min_j t_{c_j}^k$$

where $v_{c_i}^k$ = closing rate of target i in subset k on TFC = $\underline{U}_{LOS}^T |\underline{v}_i - \underline{v}_{TFC}| \approx \underline{U}_{LOS}^T \underline{v}_i$
 \underline{r}_{TFC} = position of vector of TFC
 \underline{r}_i^k = position vector of target i in subset k
 $\underline{v}_i, \underline{v}_{TFC}$ = velocities of target and TFC, respectively

For each closest penetrating target i in each of the subsets k , compute

$$\alpha_k = \left(\frac{R_{opt_i}}{v_{c_i}} \right)_k ; \quad \alpha_{max} = \max_k \alpha_k ; \quad k = 1, 2, \dots ;$$

$R_{opt_i} \approx 85 R_{max_i}$ = optimum range; v_c = closing rate between fighter and target
 $= \underline{U}_{LOS}^T |\underline{v}_i - \underline{v}_F|$

The normalized attribute level, a_{23} for each subset k is given by

$$a_{23} = \alpha_k / \alpha_{max}$$

6. Fuel Usage. The last attribute that has to be predicted is the fuel remaining following a perturbation maneuver. Each perturbation maneuver requiring a change in altitude, speed or heading can be ranked in terms of fuel requirements from the most fuel intensive to the least. The ranking along with the fuel requirements on a scale of 0 to 1 is given in Table 1. The attribute level derives directly from the table.

Table 1. Fuel Requirements of Perturbation Maneuvers

PERTURBATION MANEUVER	FUEL REQUIREMENT
1. CLIMB (+ 2000 Feet)	1.0
2. INCREASE SPEED (+ .1 MACH)	.8
3. CHANGE HEADING (+ 10 ⁰)	.2
4. DESCEND (- 2000 FEET)	0
5. DECREASE SPEED (- .1 MACH)	0

Situation Assessment Aid

Situation assessment in a tactical environment is the process of determining the values or levels of the salient attributes or dimensions that characterize the tactical problem confronting a decision maker. In the F-14 CAP role aiding context, the situation assessment aid provides the NFO with prompt and timely estimates of the tactical situation confronting him. This "sensed" information enables the NFO to maintain intimate contact with the time-varying data that characterizes the relevant dimensions of the tactical environment. This aid recommends a suitable mission posture to the NFO based on a combination of internal and external "sensed" conditions. It, further, evaluates if an aspect maneuver is warranted given the prevailing tactical configuration and recommends an aspect if it is indicated. In the following paragraphs, the key mission postures will be identified along with a set of conditions that exhaustively span the transitions from one posture to the other. Included also is the rationale and criteria for performing an aspect maneuver.

Tactical Mission Postures. The relative weighting on the various attributes in the mission success hierarchy varies according to the tactical situation. A total of six postures have been identified, each with a distinct set of attribute weights:

- (1) Offensive -- maximize number of enemy downed, with secondary goals of maximizing carrier safety and resource conservation. ($W_2 \gg W_1, W_3$) where W_1, W_2, W_3 are shown in Figure 5.
- (2) Defensive -- maximize carrier safety, with secondary goals of maximizing E_k and resource conservation. ($W_1 \gg W_2, W_3$)
- (3) Conservative/Offensive -- maximize E_k and resource conservation. Virtually ignore carrier safety. ($W_2, W_3 \gg W_1$)
- (4) Conservative/Defensive -- maximize carrier safety and resource conservation. Virtually ignore E_k . ($W_1, W_3 \gg W_2$)
- (5) Carrier Safety -- maximize carrier safety alone. ($W_1 = 1; W_2 = W_3 = 0$)
- (6) E_k -- maximize E_k alone. ($W_2 = 1; W_1 = W_3 = 0$)

The first four postures, Offensive (O), Defensive (D), Conservative/Offensive (C/O), and Conservative/Defensive (C/D), are "trade-off" strategies. Different combinations of attributes are emphasized in each. In the offensive posture, for

instance, E_k is emphasized at the expense of carrier safety and resources. The final two postures, Carrier Safety and E_k are "pure" strategies. Carrier safety puts zero weighting on E_k and resources. E_k only weights the E_k attributes.

The six postures correspond to distinct tactical situations. These can be classified by conditions associated with the following tactical variables:

- (1) Threat penetration range. The threat distance from (a) the task force center or (b) the weapon release line around the carrier.
- (2) Fuel remaining. The amount of fuel left to return to the carrier.
- (3) Numerical advantage. The numbers of missiles compared to the number of targets.
- (4) Lethality. Phoenix missile-equivalents of the threats.

Posture Transition Criteria. An exhaustive set of relations between the postures and the conditions are given in Table 2. For example, defensive posture (P_2) is called for if high threat level is present, sufficient fuel remains, either a numerical advantage or disadvantage exists, and low lethality is present. Similar descriptions for the choice of the other postures can be given (see Table 2).

Table 2. Posture Transition Logic

	Meaning	C_1	C_2	C_3	C_4	Transition Logic
P_1	Offensive	0	0	1	1	If $(P_1 \wedge (E_1 \wedge E_2) \wedge ((C_3 \wedge C_4) \vee \bar{C}_3))$ Then P_1
P_2	Defensive	1	0	-	0	If $(P_2 \wedge (C_1 \wedge E_2 \wedge \bar{E}_4))$ Then P_2
P_3	Conservative/ Offensive	0	1	1	-	If $(P_3 \wedge (C_1 \wedge C_2 \wedge C_3))$ Then P_3
P_4	Conservative/ Defensive	0	1	0	-	If $(P_4 \wedge C_2 \wedge ((E_1 \wedge E_3) \vee C_1))$ Then P_4
P_5	Carrier Def. Only	1	0	-	1	If $(P_5 \wedge (C_1 \wedge E_2 \wedge C_4))$ Then P_5
P_6	E_k	0	0	1	0	If $(P_6 \wedge (C_1 \wedge E_2 \wedge C_3 \wedge \bar{E}_4))$ Then P_6

CONDITIONS:

- C_1 : Enemy poses high threat, i.e., at least one target close to WRL; \bar{C}_1 = low threat
- C_2 : Fuel critical, i.e., insufficient fuel to complete engagement and return to carrier; \bar{C}_2 : fuel critical
- C_3 : Numerical advantage, i.e., onboard missile load \geq number of targets; \bar{C}_3 = numerical disadvantage
- C_4 : Cumulative lethality, L , of subset high, i.e., $L \geq L_{min}$; \bar{C}_4 = low lethality

Transition-Conditions. There are four conditions which are monitored to determine posture transitions. These conditions are: C_1 - threat level, C_2 - fuel status, C_3 - numerical advantage status, and C_4 - cumulative lethality.

There are two values necessary to compute the C_1 's. These are LMIN and FUEL-THRESH. LMIN is the threat cloud lethality threshold (based on a critical missile load).¹ This value is contingent on the scaling of the lethality values that reside in a table look-up. Since lethality values associated with different targets were unavailable, each target in KIWI was assigned a lethality value. This information was contained in a table look-up. More sophisticated lethality computation scheme based on target identification and missile carrying capacity can replace this table look-up in a straightforward manner. FUEL-THRESH is the amount of fuel required on the average to fire all missiles onboard the F-14 and return to the carrier. THRESH2 is the minimum time threshold for the closing time between threat cloud centroid and weapon release time. With FUEL-THRESH calculated for the current situation, the C_1 's can be computed as follows:

- (1) If the closing time for the centroid of the threat cloud to weapon release time is less than some threshold THRESH2, set C_1 to high; otherwise, set C_1 to low.
- (2) If the fuel remaining is less than FUEL-THRESH, the critical fuel threshold, set C_2 to high; otherwise, set C_2 to low.
- (3) If the onboard missile load is less than the number of targets, C_3 is set to low; otherwise C_3 is set to high.
- (4) If the cumulative lethality of the current threat cloud is less than LMIN, C_4 is set to low; otherwise, C_4 is set to high.

The mapping of the tactical conditions to postures allows the automated transition from one posture to another as the sensed situation changes. The TDA has access to all of the condition levels and contains the logic for transitioning between postures.

Aspect Maneuver Recommendation. The first point at which the TDA aids the NFO is in the initial aspect maneuver. Here a set of threats has been detected, and a decision is needed on whether to perform a horizontal aspect maneuver to resolve additional threats behind those currently being tracked. The disadvantage of an aspect maneuver is that the F-14 may end up with an inferior tactical position, i.e., have less LARS than currently predicted. What the NFO needs is some means of predicting what the resultant LAR configuration would be if he performed an aspect maneuver. The TDA performs this predictive computation. If the number of LARS is strictly less than the number of missiles but greater than zero, the TDA predicts the consequences of a canned aspect maneuver. If the number of LARS expected after performing aspect is greater than or equal to the number currently expected, the TDA displays the aspect recommendation on the TID, by changing the steering dot and displaying "ASPECT" just below the TID buffer readout. If the number of LARS is zero and number of targets is less than or equal to the number of missiles then aspect is predicted and recommendation displayed. On the other hand, if $n_t > N_m$, the F-14 either stays on CAP or tries to acquire LARS depending on the duration of time to encounter.

¹I.e., $LMIN = \sum_i \text{lethality } i$, for all i , where the summation is for each target in the threat cloud.

The NFO may override the aspect recommendation if he acquires external knowledge of the raid structure or if he spots a high priority target in the process. If such information is available, he overrides the aspect recommendation by pressing the "OVERRIDE" button on the TDA-dedicated portion of the CAP panel. This action results in returning the steering dot to the original position and blanking the readout. If the NFO decides to go along with the recommendation, the aspect maneuver is performed. (The actual number of resultant LARS may or may not be the same as the number predicted.) The aspect maneuver itself is set to be a 20-30 degree heading change in the horizontal plane in the direction of increasing aspect. The time to complete the maneuver is established in a look-up table.

The new coordinates are calculated by the TDA and fed to the steering dot program. If the aspect maneuver is recommended, aspect is shown on the TID drum and the steering dot is moved to the new course.

During the time required for the aspect maneuver, the TDA programs are suppressed. This is because a sequence of targets with or without LARS may come into view during the maneuver, requiring continuous updating. Instead, a prediction of time to aspect completion is computed and all processing halted until that time has elapsed.

If performing the aspect maneuver results in total loss of LARS and time to encounter is less than time to perform LAR acquisition, the NFO may wish to return to the CAP role; otherwise, he tries to acquire LARS. In any case, the next major decision is one of acquiring additional LARS and generating attackable subsets versus generating attackable subsets directly.

A special situation is present if more than nine targets appear initially. Because of computational constraints, large target sets are pruned down to the nine most important targets and these targets are then considered by the TDA. The measure of selection is the lethality (missile carrying capacity) divided by the closing time (distance/closing velocity). The threats are ranked in decreasing order of this measure and the top nine selected for TDA processing.

Aspect Prediction. Aspect Prediction calculation is called for prior to making an aspect recommendation. Typically, an aspect maneuver is made in order to resolve the individual targets in a multiple target raid. As aspect maneuver is culminated when the aspect angle is about 30° . Where exactly the fighter ends up at the end of an aspect is a function of the F-14 and target heading angles, the current F-14 and target velocities, the nominal g-forces employed in a turn and the basic assumptions associated with the turn. For instance, a constant velocity, fixed radius turn assures minimum fuel usage while a move to the desired aspect in minimum time assures the performance of the maneuver in an acceptable amount of time. In this instance, each of the considerations are warranted because fuel should be conserved when possible and the maneuver should be done as fast as possible to allow the NFO adequate time to evaluate TDA recommendations en route to actual engagement. The aspect prediction equations are derived in Madni, et al (1980).

Alternative Generation and Selection Aid

Attackable Target Subsets Generation. An attackable subset is defined as a group of targets in which all targets have LARS for a specific location of the F-14. Incremental changes in the F-14 location can result in a totally different attackable subset. An attackable subset can be no smaller than the onboard missile load if the number of targets is greater than the on-board missile load. Thus, if the onboard missile load is four, say, then the attackable subset can have no less than four targets.

If the number of LARS is greater than or equal to the number of missiles, the attackable subsets are generated directly by forming all feasible combinations of targets with LARS corresponding to the current state vector. If the number of LARS is less than the remaining number of missiles onboard and time to encounter is greater than or equal to time to LAR acquisition, then LAR acquisition maneuvers are predicted. All possible attackable subsets are generated by forming all feasible combinations of targets with LARS corresponding to the current and perturbed F-14 state vectors. If in this process, a priority target is selected by the NFO by pressing PRIORITY function button on the CAP panel followed by manually hooking the target on the TID, then all possible attackable target subsets are scanned to determine if they contain the priority target. Only those subsets that contain the priority target are viable candidates for subsequent evaluation.

Attackable Subset Selection. The subset evaluation is accomplished by first forming all feasible combinations of targets with LARS. Feasibility demands that the number of targets in the subset is less than or equal to the number of missiles onboard and that all geometric constraints are satisfied. Then each subset is assigned a vector of attribute levels according to projected performance. The attributes are defined as before in Figure 5. In this mission success hierarchy all measurements are normalized to 0 to 1 scales, where zero corresponds to the worst case possible (max lethality coverage). The attributes are weighted by importance. The weighting is also normalized so that an overall zero implies zero on all attributes and an overall one implies a one on all attributes. The relative weighting itself differs according to tactical situation (the postures in Table 2) and is estimated through expert elicitation.

Course perturbation takes the form of positive and negative changes in heading, speed and altitude. The step size is defined at +10 degrees in heading, +1 Mach, and +2000 feet in altitude. All perturbations are checked to determine the number of LARS present. Target subsets for each perturbation are evaluated according to the above process (Figure 6). In the end, a maneuver and subset is recommended which has the highest overall utility, according to the mission posture and conditions. This recommendation is displayed by showing "subset recommendation" just below the TID buffer readout, and moving the steering dot on the TID display.

If the "Priority" button is pressed, the priority target can be manually hooked by the NFO on the TID. All subsets containing the priority target are evaluated as before with the subset with the highest overall utility under the prevailing posture being recommended. The manual subset select button allows the NFO to disengage the TDA and hook the desired target set manually. The selected targets are output directly to the steering algorithm.

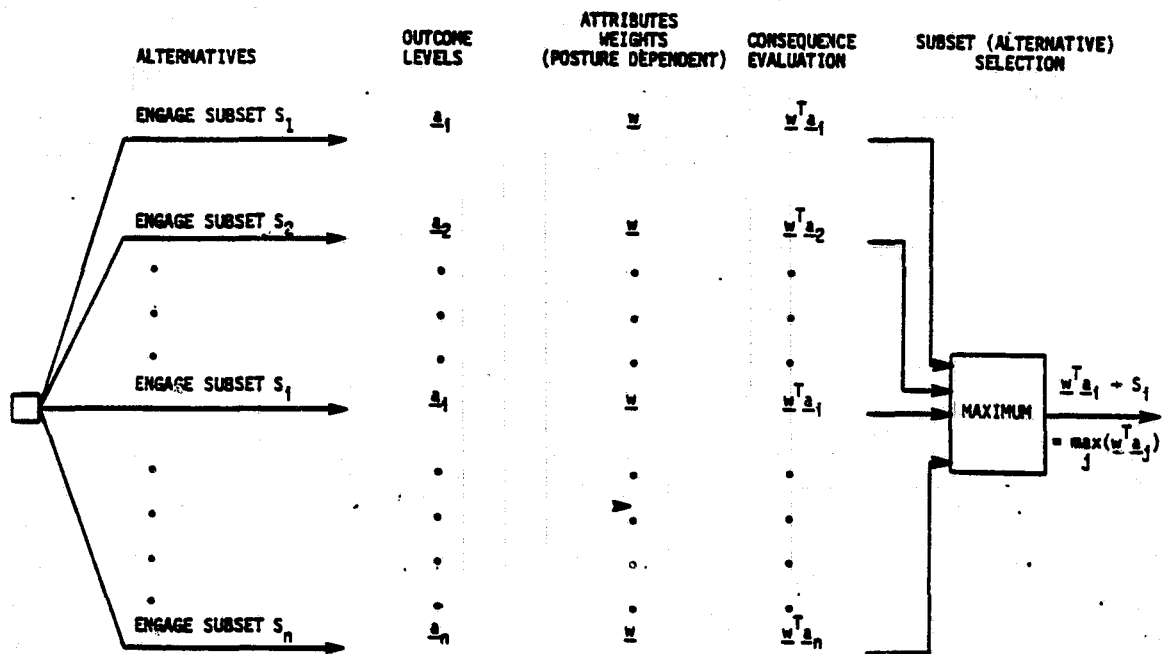


Figure 6. Subset Selection

NFO-TDA Interface

CAP Panel Modification. At the very outset of this project, it was established that the Computer Access Panel (CAP) was going to be used by the NFO to communicate his inputs to the TDA software and that TDA-related information was going to be displayed to the NFO on the Tactical Information Display (TID). Consequently, the NFO-TDA interface was configured to fit within the space and configurational constraints of the aforementioned devices.

The TDA's implementation on the CAP panel was determined after extensive discussions with Naval Flight Officers (NFOs). The implementation impacts the CATEGORY switch and the message selection pushbuttons. The CATEGORY switch is a six position switch which permits sharing the message selection pushbuttons. When the CATEGORY switch is rotated, a matrix of labels next to the MESSAGE pushbuttons is changed. When the CATEGORY switch is set to TDA, the legend associated with the ten multi-purpose MESSAGE pushbuttons correspond to the posture, target and override controls (Figure 7). This mechanization was selected on two counts: (1) in the opinion of the NFO's, it fit naturally within their task structure and user interface, and (2) it resulted in minimal hardware changes to the existing controls and display configuration.

E _K	CD
OFF	DEF
COFF	CDEF
PRIORITY	MANUAL SUBSET SELECT
OVERRIDE	RESET

POSTURE
CONTROLS

TARGET
CONTROLS

OVERRIDE
CONTROLS

LEGEND: E_K: Expected Kill
 CD: Carrier Defense
 OFF: Offensive
 COFF: Conservative Offensive
 DEF: Defensive
 CDEF: Conservative Defensive

CATEGORY

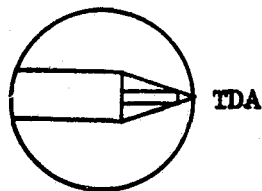


Figure 7. TDA Controls

Posture Selection Controls. The top six set of buttons correspond to the six postures that can be manually selected by the NFO. A button press results in the button being backlit signalling selection of the associated posture. This feature allows the NFO to keep track of the prevailing posture at all times. The postures are automatically selected by the transition program if no NFO posture-selection is indicated. If the NFO presses a posture button to select the posture of his choice, then this selection disengages the TDA posture transition logic and his selection posture will then be "frozen" regardless of conditions (and displayed just below the TID buffer readouts) until the NFO decides to reset the automatic posture selection logic of the TDA.

Target Selection Controls. The target selection section of the panel consists of two buttons: (a) priority target, (b) manual subset select. The "priority" target button allows the NFO to manually hook one target on the TID. This target is then included in all target subsets considered for subsequent evaluation. Priority target selection is accomplished by first pressing the priority target button and then hooking the target on the TID. The "priority" target button responds to button press by flashing and continues to flash until the target is hooked. The "manual subset select" button allows the NFO to manually designate the entire subset. When first pressed, this button starts to flash. The NFO then hooks each target in turn, until all targets have been hooked. The NFO indicates completion of subset selection to the system by pressing the manual subset select button once again. When the button is pressed for the second time, the flashing light goes off.

Override Controls and Maneuver Displays. The two basic override controls are available in the form of "reset" and "override" buttons, shown in Figure 7. The "reset" button allows the NFO to re-engage the automatic posture transition logic portion of the TDA. Once this software is invoked, target subset recommendation consistent with the prevailing posture is made automatically by the TDA and displayed on the TID along with the necessary course perturbation, if any, being indicated by a shift of the steering dot on the TID. There are at least three distinctively different occasions when the NFO might wish to use the "reset" button: (1) after selecting a posture manually, he decides against the selection; (2) after pressing the priority target button, he decides he does not want to hook a priority target or hooks a target and decides against it; (3) after pressing manual subset select he decides against it or after hooking a subset of targets he decides that one or more of them are inappropriate. For case (2) or (3), if the posture was selected manually, pressing reset puts the TDA in automatic posture select. If the NFO prefers to stay with his original manual selection of posture, he must reselect the posture manually after pressing "reset." The "reset" button requires two presses. The reason for this is that if accidentally bumped once it will not "erase" the target subset selected thus far by the NFO and/or deselect his manual posture selection. Consequently, when pressed once, the "reset" button causes a warning to be displayed on the DD, when pressed a second time it disengages the targets selected thus far and turns off the priority or manual subset select button backlighting. It also deselects the posture if it were manually selected by the NFO and turns off the backlit posture button. The "override" button allows the NFO to reject (1) a recommended aspect maneuver and/or (2) a recommended perturbation maneuver with associated subset.

When an aspect maneuver is recommended, the steering dot is moved on the TID and the aspect recommended is displayed as "ASPECT MAN" just below the TID buffer readout. When the override button is pressed following an aspect recommendation, the steering dot is returned to its previous position, the display area assigned to display "ASPECT MAN" is erased, and the TDA program branches immediately to subset select rather than waiting for the aspect maneuver to be performed. The other recommendation provided by the TDA is that of optimum target subset selection with associated perturbation. When this recommendation occurs, the subset is brightened, the steering dot is moved on the TID and "LAR ACQ MAN" is displayed just below the TID buffer readout. If "override" is pressed during a subset recommendation, the "next best" subset with associated perturbation is presented, the TID steering dot is moved, "LAR ACQ MAN" is displayed as before, and subset display on the TID modified accordingly. If reject is exercised again, the "LAR ACQ MAN" display is erased but the "next best" subset remains the same (i.e., does not change from the previous display). In this case, since the NFO finds the TDA's recommendation unsatisfactory, he can select the targets manually by "hooking" them on the TID after pressing manual subset select.

TDA Override and Restart Options

There are three TDA-related KIWI activities that were found to be logical abort points for establishing new parameters and re-directing TDA processing. These are:

- (1) Aspect maneuver.
- (2) Perturbation maneuver.
- (3) Steering to encounter.

Aspect Maneuver Override. The "override" button may be pressed by the NFO at any time during the aspect maneuver sequence. When this happens, only the aspect maneuver is aborted, thus, as far as the decision logic is concerned, the aspect maneuver is assumed to be completed and the subsequent TDA activities remain unaltered.

Perturbation Maneuver Override. The "override" button may once again be pressed by the NFO anytime during the perturbation maneuver. This action causes control to be immediately passed to the steering algorithm rather than wait for completion of the perturbation maneuver before passing control to the steering algorithm.

The restart options that can be exercised during any of the three logical abort points include manual posture selection, target selection, and TDA reset

Manual Posture Selection. Selecting a posture manually by pressing the intended key on the CAP panel will discontinue TDA or KIWI activity at any of the three abort points and pass control to the subset optimization procedure. If posture is altered prior to target detection, the TDA decision sequence is unaffected.

Target Selection. Pressing "manual subset select" or "priority target" disengages the TDA or KIWI at any of the three abort points. After manually selecting targets with "manual subset select," control is passed immediately to the steering algorithm. When a priority target is selected, control is passed to the subset optimization procedure in the TDA. Optimization is performed with the constraint that the priority target must be contained in the "optimum subset."

TDA Reset. When this button is pressed, the TDA or KIWI is disabled at any of the three abort points and control is passed to the initial target acquisition phase of KIWI with automatic posture updating.

CONCLUDING REMARKS

This paper has presented a realtime Tactical Decision Aid (TDA) for the F-14 aircrew in air intercept operations associated with the Combat Air Patrol (CAP) role. The aid has been designed with special emphasis on ensuring that (1) its operation fits naturally within the task structure of the aircrew; and (2) it in no way appears to usurp any of the aircrews' traditional activities. While it was recognized that there is strong preference among the user community for the display of options rather than the optimum (Mackie, 1980), the short time horizons associated with air intercept tactics preclude the aircrew from scanning and cogitating the various alternatives. Consequently, the aid allows the aircrew to exercise manual override over any recommendation it makes. The aid is currently being implemented in the multiple target environment of the KIWI simulator, a realtime AWG-9 simulation at Naval Air Development Center, Warminster, Pennsylvania.

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