Knowledge-Based System of Supermaneuver Selection for Pilot Aiding

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This paper describes the creation of a knowledge-based system, MASAS (MAneuver Selection Aiding System), which utilizes fuzzy logic, tactical planning, and knowledge-base techniques to select supermaneuver strategies for aiding pilots during defined missions. Supermaneuver strategy selections are based largely on experts' qualitative assessments to rank flight strategies. Because of ranking uncertainties, fuzzy max-min computation is introduced. MASAS consists of a supermaneuverable selector, a tactical planner, and an executive planner. Each of these planners interfaces with a knowledge base and an exception handler. The selector uses max-min operator on the fuzzy relation matrix to select suitable strategies. The tactical planner takes supermaneuver strategies and formulates a regional plan. Regional planning qualifies regional threats effects and identifies potential safe supermaneuvers among threats and within geometry constraints. Validation and integration of these regional plans are the functions of the executive planner. The exception handler is a feedback loop for reselecting and/or replanning supermaneuvers. The flight trajectory, an output from the executive planner, consists of a dynamic sequence of supermaneuvers.

I. Introduction

A KNOWLEDGE-BASED system, MASAS (MAneuver Selection Aiding System), is described. MASAS applies artificial intelligence technology for aircraft supermaneuver (super-M) selection to assist pilots in dealing with the extended flight envelope in air-to-air engagements. For this effort, the pilot must function both as a system manager and tactical decisionmaker. His task workload assignment will be reduced immensely. A super-M concept implies very high levels of agility and controllability. Agility is the aircraft ability to make a transition rapidly from one energy state to another. Controllability is its ability to change rapidly the velocity vector and nose attitude under any condition.

Interest in super-M technology is evidenced by the enthusiasm of government agencies, industries, and universities. Highlights of super-M are identification and testing of aircraft instability and controllability. Using super-M technology, a Grumman experimental aircraft was successfully flight tested in late 1983. It served as a "proof of concept" demonstrating the gains of the unstable aircraft design configuration. Rockwell and Germany's Messerschmit-Boelkow-Elohm experimental aircraft currently under development[1] will be flight tested. This aircraft, designed to exhibit extremely high agility, will test the supermaneuverable concepts by considering maneuvers with angles of attack (AOA) of up to 70 deg. It will be able to perform tactical small-radii turns and point its nose in a new direction to fire a quick shot. NASA is ready to start a 5-yr, $60 million program to study aircraft flight at high angles of attack. NASA Langley Research Center has selected a McDonnell Douglas aircraft for preliminary design of an advanced control system.[2]

A current survey of United States Air Force (USAF), United States Navy (USN), and United States Marine Corps (USMC) fighter pilots resulted in a consensus that the super-M utilization is a promising and desirable capability.[3] Given that these super-Ms are technically possible, pilots can enjoy the realization of accomplishing their missions. The results of extrinsic flying qualifiers such as pilot opinion and combat effectiveness show that in order for a pilot to perform super-M with an acceptable level of mental and physical workload, he is required to use an aiding system. The MASAS is designed to be the system for future needs.

Elements of MASAS discussed herein are super-M selector, tactical planner, executive planner, exception handler, and knowledge base. According to experts' preference, a fuzzy relation matrix is constructed. The super-M selector searches the fuzzy relation matrix based on the current criteria. The max-min operator is used for computing potential candidates listed in the matrix. The chosen candidate presents a flight path. A regional plan consists of two segments of a flight path necessary to obtain positional advantage in each sample time. SRI's GEMPLAN[4] (Group Element Model Planner) is a constraint-satisfaction tool for the tactical planner to generate regional plans. The executive planner smooths regional plans to form a trajectory based upon the essential constraints of fighter's survivability and combat effectiveness.

II. System Descriptions

The approach of system design of the MASAS has two steps: The first step is to create a system library of super-M strategies ranked by expert assessments for tactical air-to-air engagements. The second is to develop system components of MASAS by using the techniques of fuzzy logic, tactical planning, and plan integration. The system library contains super-M candidates, selection criteria, and three look-up tables: fuzzy relation matrices, regional constraint tables, and global constraint tables. The overall system architecture, shown in Fig. 1, consists of super-M selector, tactical planner, and executive planner plus two support modules which are the exception handler and knowledge base. The function of PVI (Pilot Vehicle Interface) is to present selection strategy information to the pilot. The goal is to keep the pilot fully aware of the current tactical maneuver strategy in a user-friendly environment. Information presentation can be achieved visually or orally.

The super-M selection function decides which candidate permits judicious maneuvering to a tactical advantage position. Criteria for selection are expert's experience and aircraft performance measurements. The objective of the tactical planner is to construct regional plans for improving aircraft surviv-

Presented as Paper 88-4442 at the AIAA/AHS/ASEE Aircraft Design, Systems and Operations Meeting, Atlanta, GA, Sept. 7–9, 1988; received Feb. 22, 1989; revision received June 30, 1989.

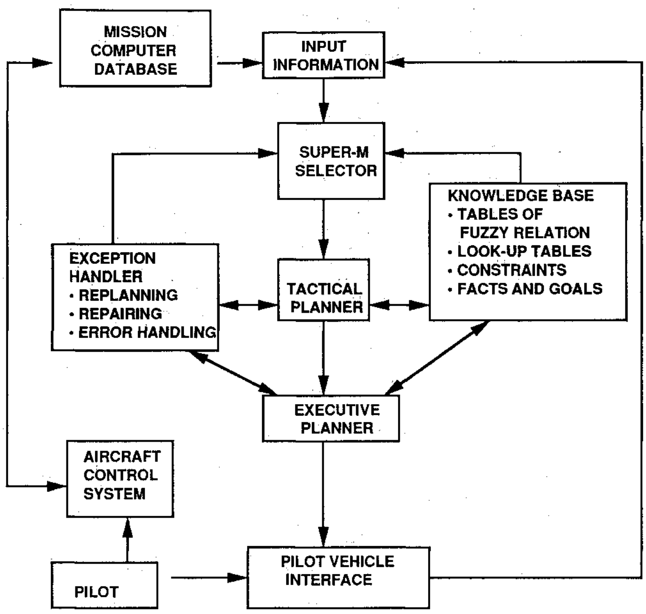

Fig. 1 System structure of MASAS.

ability in a multithreat environment using all-aspect weapons. It is not just a matter of planning current aircraft flight paths, but also of planning concurrent defensive, offensive, and neutral strategies. The function of the tactical planner is to generate all regional plans for the executive planner. The executive planner checks and validates constraints of regional plans to generate a trajectory. If there are any inconsistencies between plans, the exception handler will invoke the tactical planner for replanning or repairing. Otherwise, the executive planner will generate trajectories by smoothing and monitoring all consecutive regional plans.

A. System Library

The intention of the system library is twofold: 1) knowledge acquisition, and 2) knowledge base. The technique for knowledge acquisition is to define selection criteria and to set up well-defined tables for experts to assign memberships of all potential super-M candidates. Uncertainties of human assessment are sometimes conveniently expressed in linguistic labels by subjective fuzziness and the physical meaning is similar to the membership assignment of a fuzzy set.[5] The idea is to construct a homomorphism from a qualitative preference system into a quantitative preference system thereby constructing a fuzzy matrix. It was emphasized by Bellman and Zadeh[6] that the membership of an element is not a statistical quantity assigned by some individual. A membership assignment preserves some basic properties of the individual's qualitative preference structure on a numerical scale.

The universe of discourse is defined as the fuzzy set of all linguistic labels to describe its quantized levels. Knowledge-criteria experts are responsible for giving grade of memberships for all super-M candidates. The grade-of-membership values are assigned subjectively to define a cubic fuzzy matrix. During the maneuver selection phase, given input criteria labels are compared with cubic fuzzy matrix entries. The measurements of each super-M candidate will be computed by using fuzzy relations and max-min composition.

Contents of the system knowledge base consist of super-M candidates, selection criteria, fuzzy relation matrix, regional constraint table, and global constraint table, which are described in the following paragraphs.

1. Super-M Candidates

The most critical segments in air combat are associated with weapons employment and evasive maneuvers,[7] which will increase the complexity of multiple aircraft engagements and threats. MASAS is designed to reduce difficulty in choosing candidates. These candidates are required to be tested in the real-time simulation and evaluated by experienced pilots, tacticians, and engineers. The candidates of super-M are represented as a combination of maneuver strategies, fighter agilities, and tactical objectives. A list of potential candidates is shown in Table 1.

Table 1 Potential candidates

A. Offensive
1. Horizontally initiated pointing
2. Vertically initiated pointing
3. Decelerating climb pointing
4. Loading roll pointing
5. High angle-of-attack shooting
6. High angle-of-attack tracking
7. Yo-yo attacking
8. Lag roll attacking
9. Overshoot reattacking
B. Defensive
1. Decelerate separating
2. Accelerate separating
3. Roll orthogonal breaking
4. Low-speed high AOA breaking
5. Orthogonal snapshot breaking
6. High-speed break turning
7. Descend break turning
8. Transition overshooting
9. Transient overshooting
C. Neutral
1. Load horizontal separating
2. High-energy vertical separating
3. Low-energy session separating
4. Death spiral maneuvering
5. F-pole maneuvering
6. Transition pursuing
7. Transient turn pursuing

2. Selection Criteria

Criteria for choosing candidates are determined by the pilot's physical abilities, tactical geometry, and super-M characteristics. The pilot's ability to withstand high-*g* maneuvers depends upon his reaction to the maneuver types and duration. The criteria imposed here should avoid undesirable stress on pilots. Tactical geometry considers initial aircraft and threat conditions, and their relative positions.

The characteristics of super-M provides an exciting new air-combat envelope expansion into the poststall speed, high angle-of-attack, and sideslip flight.[8,9] The air-combat arena is also allowed to expand in all directions, because of the aircraft ability to change rapidly its translation and rotation. The high levels of supersonic thrust-to-weight with minimum fuel consumption will be utilized in beyond-visual-range combat where a sustained supersonic escape turn follows target detection, identification, and missile launch during a head-on pass.[10] The minimum turning time and the velocity recovering time with heading position can be exactly used to represent the best firing position. The super-M can quickly point at an adversary and utilize snap shooting guns and missiles for first shot and multiple target opportunities.

The selection criteria of super-M should be able to utilize the safe limits of fly-by-wire flight control to obtain better performance by pilots. The selection criterion domain should be sufficiently generic to necessitate minimal modification. A sample of selection domain is described in the following six criteria.

a) Ownship Information. The selection of a super-M candidate depends on the specific values of the following parameters:

1) Aircraft parameters: aircraft state vector consisting of initial altitudes, initial airspeeds, initial heading angles, AOA, and bank angle.

2) Aerodynamic characteristics: roll rate, load factor rate, load factor, available and normal acceleration, and tangential deceleration.

3) Field of view: boresight method which consists of the preferred method in the interest of improved sensitivity, better discrimination, and safety.

4) Firing, launch, and intercept envelopes: locus of points that represent the current position of a target when a missile can be fired or launched with the expectation of achieving an intercept with the target. The intercept envelope is similar to the launching and firing envelope, except that the focus of points now represents the location of target at the time of missile intercept.

b) Engagement envelopes. In developing engagement envelopes for choosing candidates, it is useful to partition the air-combat flight envelope into four phases. They are the beyond-visual-range (BVR) phase, the transition phase, the within-visual-range (WVR) phase, and transient phase.

1) BVR: high airspeed at high altitude. The maneuvering advantage is to position the weapons and pointing to a firing position.

2) Transition: thrust reversing. The maneuvering advantage is to achieve first nose position and firing solution. In offensive strategy, the nose-on position offers more initial advantage against all-aspect missiles.

3) WVR: high rate of turn. In offensive strategy, the agility offers more advantage to achieve final tracking in the end game. The advantage is to decrease extraction time in defensive or neutral situations.

4) Transient: tight turn radius. It offers positional advantage.

c) Engagement maneuver duration. Engagement maneuver duration consists of the *g*-level duration limits, maneuver initiation, and maneuver transition time. The limitation to a maximum duration is necessary.

1) Maneuver initial time: the elapsed time following missile launch.

2) Maneuver transition time: "time-to-go," which is determined by ratio of relative distance and relative speed between aircraft and missile.

d) Engagement parameters. During engagement, a successful choice of maneuver type is influenced by its associated parameter values. Some of the important parameters are the aircraft initial reaction time slew rate, target detection range, acquisition time, and tracking rate. The criteria are described as below.

1) Initial reaction time: time interval that elapses between the time a threat is made aware of a need to be fully operational and the time the threat is ready to begin its normal operational mode against the target aircraft.

2) Slew rate: angular velocity in both azimuth and elevation at which the tracking carriage of the threat can be rotated in order to begin tracking and engaging an aircraft that is in a different sector of the sky than the carriage had been initially pointing.

3) Target detection range: threat range. It is often expressed numerically with respect to a target signature of a standard size.

4) Acquisition time: elapsed time from the time of alert to the time the tracker has acquired the target.

5) Tracking rates: rates in azimuth and in elevation for measuring the aircraft's position vs. time.

e) Environmental factors. These factors include the threat mobility, threat environmental adaptability, and super-M weather capability.

1) Threat mobility: ease with which a threat can be moved. Criteria involved are the effort required for attack, re-attack, and setting up a new location so that effective firing or launching can be achieved.

2) Threat environmental adaptability: ability of a threat to adapt to its target environment and to take tactical advantage. Criteria must be considered in the threat's future position, intercept point, and platform direction.

3) Super-M weather capability: capability of super-M during variations in visibility, cloud cover, or light conditions. The criteria must be considered as follows: a) clear day with no intervening clouds and with required visibility; b) clear night with no cloud or visibility constraints, but with reduced light level; and c) extremely low light levels, complete cloud cover or minimal visibility.

f) Threat information. The threats to fighter are defined as those elements of a man-made environment designed to reduce the ability of a fighter to perform mission-related functions by inflicting damage effects, forcing undesirable maneuvers, or degrading aircraft effectiveness. The hostile environment can be made up of numerous threat elements, each having a distinct set of characteristics and capabilities.

1) Threat features: identification, tracking, detection, early warning, electronic counter countermeasures, and firing platform.

2) Threat propagators: projectiles, guided missiles, and radiation sources.

3) Threat lethality: collection of factors relating to the fire control, the propagator trajectory, and the terminal effects parameters. Threat lethality is independent of the target aircraft. It only depends upon the inherent capabilities of the threat in directing or projecting the propagator in the direction of the aircraft and on the size of the damage mechanisms.

3. *Fuzzy Relation Matrix*

The fuzzy relation matrix is formed by selection criteria and candidates as the rows and columns respectively. Since there were 25 super-M candidates considered, each candidate can be characterized by selection criteria. Within each criterion, there are seven levels to describe the classification of candidate's qualities. Thus, the seven possible quantized levels are described by linguistic labels as follows:

PB = positive big
PM = positive medium
PS = positive small
ZO = zero
NS = negative small
NM = negative medium
NB = negative big

The universe of discourse is defined as a set of super-M candidates that are mapped into the interval of [0,1] as a degree of preference. The measure scores indicate the preference membership of candidates in each selection criteria. A sample of the fuzzy relation matrix used for assigning membership is shown in Table 2.

An element of the relation matrix is represented as $a(i,j,k)$, where the index value of i is a selection criterion, j is one of the fuzzy levels, and k is a candidate of super-M. The entries $a(i,j,k)$ are assigned and evaluated by the pilots, tacticians, and system designer. It is the state of mind of the experts involved in the qualitative preference structure. Thus, $a(i,j,k)$ is a numerical score to transfer from qualitative measure to quantitative measure. A fuzzy cubic measure matrix is constructed in lieu of all potential selection criteria. This would be a novel approach in handling measurement for the super-M selection problem.

Table 2 Selection criterion[a]

	M_1	M_2	M_3 ...	M_{24}	M_{25}
PB	$a(1,1,1)$	$a(1,1,2)$	$a(1,1,3)$ ...	$a(1,1,24)$	$a(1,1,25)$
PM	$a(1,2,1)$	$a(1,2,2)$	$a(1,2,3)$ ...	$a(1,2,24)$	$a(1,2,25)$
PS	$a(1,3,1)$	$a(1,3,2)$	$a(1,3,3)$ ...	$a(1,3,24)$	$a(1,3,25)$
ZO	$a(1,4,1)$	$a(1,4,2)$	$a(1,4,3)$ ...	$a(1,4,24)$	$a(1,4,25)$
NS	$a(1,5,1)$	$a(1,5,2)$	$a(1,5,3)$ ...	$a(1,5,24)$	$a(1,5,25)$
NM	$a(1,6,1)$	$a(1,6,2)$	$a(1,6,3)$ ...	$a(1,6,24)$	$a(1,6,25)$
NB	$a(1,7,1)$	$a(1,7,2)$	$a(1,7,3)$ ...	$a(1,7,24)$	$a(1,7,25)$

[a] M_1, M_2, M_3, ..., M_{24}, M_{25} are super-M candidates.

Table 3 Regional constraint candidates

A. Threat relation
  1. Relative location and direction to ownship
  2. Relative weapon effectiveness
  3. Their lethalities

B. Ownship relation
  1. Safety and survivability
  2. Weapon effectiveness
  3. Target positions

4. *Regional Constraint Table*

Regional constraints are based on the ownship and threat information to generate relative relations. These relations are listed in Table 3.

The tactical planner also associates each node of a search tree with every constraint relation. The constraint relations provide a qualitative measure of the constraint satisfaction. The weights of constraint relations that dictate constraint ordering in a constraint table is a function of tactical criticality. The tactical planner can selectively assess the values of the table.

Ideally, a plan should not have any violated constraints. However, it is naive to believe that planning problems have solutions in which all constraints are satisfied. A partial satisfaction can happen. The experts use seven linguistic levels (PB, PM, PS, ZO, NS, NM, and NB) to assign each constraint. The system designers assign numerical values between the interval of [0,1] to these qualitative levels; thus, a look-up constraint table is generated. The value of the table reflects the degree of a constraint relation being satisfied. The tactical planner verifies all constraints by traveling the search tree. The branches of the tree are the weights of constraints which dictate violation orderings. The aggregated values of violation constraints are defined. Three distinct courses are possible: continuing, backtracking, and reselecting.

5. *Global Constraint Table*

To develop a global plan for an air-to-air engagement mission, one begins by assembling information about the "aircraft survivability" and "combat effectiveness" that make up the plan. Weapon delivery and threat avoidance are the essential requirements for a global plan construction. Each fighter has its own capabilities (e.g., entry Mach, pitch plane orientation, entry AOA, target performance, etc.) and its specific tactical missions to be accomplished during the maneuver timing interval. A regional plan corresponds to a sequence of primitive super-Ms. At any given time, the effective and survivable constraints of the global plan are evaluated by the executive planner and a determination is made of the need for regional plan modification. During combat operation, the original mission could be redirected to a specific goal and sometimes could change to a new tactical situation. The information to be assembled within "constraints" will determine whether or not any set of selected maneuvers is satisfactory.

The aggregation of each position is performed by the executive planning algorithm. The global plan checks survivability and effectiveness constraints satisfaction. The following constraints are listed in Table 4 for electing maneuvers.

Table 4 Global constraint candidates

A. Effective constraints
  1. Maintain mutual support
  2. Anticipate multiple attacks
  3. Exploit full weapons envelopes:
     —get chance for first lethal shot opportunities
     —deny threat shot opportunities
  4. Maximize offensive maneuver efficiency
  5. Maximize defensive maneuver efficiency
  6. Maximize neutral maneuver efficiency
  7. Maximize relative geometry position advantage:
     —maximize visual acquisition
     —minimize visual signature

B. Survivable constraints
  1. Thrust required for maneuver must be equal to the setting power
  2. Fuel weight must be greater than a minimum required for a given fuel consumption rate and range
  3. Thrust reversing must be greater than or equal to the given values
  4. Missed approach range must be less than the given range
  5. Roll rate must be within limits
  6. Angle of attack must be within limits
  7. Load factor rate must be within the given values
  8. Load factor must be within the given values
  9. Flight envelope area must be within the given specific engagement envelope
  10. Turning radii must be within the given values
  11. Maneuver timing must be within the given values

B. System Components

The MASAS consists of three main components: super-M selector, tactical planner, and executive planner. They are described in the following sections.

1. *Super-M Selector*

The super-M selector utilizes a max-min operator on fuzzy relation matrices to calculate candidates. In the selection procedures, a look-up table search is performed for each selection criterion and the selector evaluates the resulting relation matrix to obtain the max-min value corresponding to the desired candidate within time constraints. This involves selection requirements and candidates computations.

a) Selection requirements. These consist of the following:

1) Selection activities shall be consistent with pilots' experiences, tactical analyses, and simulation tests.

2) For selection, criteria and super-M characteristics shall be well defined so that the fuzzy relation matrix can be assigned successfully for any given condition.

3) Selection and planning processing shall be integrated and shall lead to a continuity of decision making.

b) Candidate computation. To determine the super-M candidate, the consequences of given information in accordance with selection criteria are evaluated. A cubic relation matrix can be represented as a ternary fuzzy relation of $X \times Y \times Z$, where X is the set of selection criteria, Y is the set of linguistic variables, and Z is the set of super-M candidates. The entries are the values of preference score; that is, $a(i,j,k)$ for the ith value of X, the jth value of Y, and kth value of Z. If R is a relation from X to Y for any fixed z in Z and S is a relation from Y to Z for any fixed x in X, then the composition of R and S is a fuzzy relation denoted by R o S and defined by

$$R \circ S \doteq \max_{z} \min_{x} \{a[x,y(x),z]\} \neq a(x^*,y^*,z^*)$$

where R o S is the max-min operation. For given criteria, there is a super-M candidate based on the max-min value $a(x^*,y^*,z^*)$ and $y(x)$ is the yth row with respect to the xth criterion of the fuzzy relation matrix. The fuzzy relation matrix $\{a[x,y(x),z]\}$ is formulated in Table 5.

Table 5 Fuzzy relation matrix[a]

	M_1	M_2 ...	M_{24}	M_{25}
C_1	$a[1,j(1),1]$	$a[1,j(1),2]$ ...	$a[1,j(1),24]$	$a[1,j(1),25]$
C_2	$a[2,j(2),1]$	$a[2,j(2),2]$ ...	$a[2,j(2),24]$	$a[2,j(2),25]$
C_3	$a[3,j(3),1]$	...		
⋮		⋮		...
C_n	$a[n,j(n),1]$	$a[n,j(n),2]$ ...	$a[n,j(n),24]$	$a[n,j(n),25]$

[a] $C_1, C_2, ..., C_n$ are criteria and $M_1, M_2, ..., M_{24}, M_{25}$ are super-M candidates.

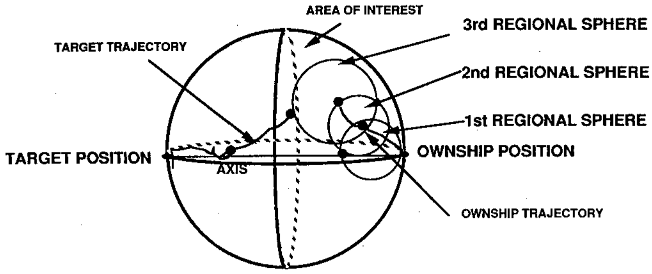

Fig. 2 Tactical region for regional plan.

2. Tactical Planner

The regional plan, formulated from the tactical planner (T-planner), qualifies regional threat effects. The T-planner can be characterized as a problem solver for generating a flight-path set, each member of which is formed by linking two super-M's satisfying initial conditions and current tactical situations. The T-planner is responsible not only for linking segments of super-M candidates to form regional plans, but also to check the lack of violation of regional constraints.

The major tool of the T-planner is considered by using GEMPLAN which satisfies its needs. By explicitly partitioning an area of interest (AOI) into regions, each region with its own set of regional constraints, GEMPLAN can operate within each region of event-based temporal and constraint-satisfaction reasoning architecture. The current GEMPLAN is implemented in Prolog programming language on a Sun workstation system. The disadvantage is that plan repairing and replanning are not currently handled in GEMPLAN. Thus, repaving and replanning are treated as new planning problems.

An AOI is a sphere, the opposite-end points of whose axis are the ownship and target positions. Using the initial position as center and half of the axis as radius, another sphere is formed. Continuing this bisecting method of nested spheres, with a common center, a regional sphere is created. The major purpose of the process is to determine the different radius of a local region. The next positions of the previous maneuver and target are predicated and then the second region is created. It repeats the process until the target disappears. Each resulting region shown in Fig. 2 will contain locations of threats, friends, and neutrals.

The method of planning is characterized in terms of searching a constraint-satisfaction tree of each region. Each node of the constructed tree is associated with regional constraints. The procedure is to check whether constraints are satisfied and, if not, either to backtrack to an earlier node or to invoke the exception handler. The handler advances and modifies the plan so that it represents a modification of the plan associated with its ancestor. For modification, the search tree branches for each of the possible ways of repairing or replanning. These fixes may involve the addition of new events or event interrelationships, or even the addition of new regional search trees. All constraints are described in terms of regular expressions that describe desired patterns of events, the maintenance of state-based conditions, and nonatomic-event expansion. The T-planner also includes a facility for accumulating constraints on the values of an unbound event parameter. The procedure of the search table is to use a depth-first search strategy. Four types of information are provided by the regional constraint table, which is described in the system table.

1) The order in which to apply constraints.
2) The order in which to try constraints fixes.
3) When and where to backtrack.
4) When to halt.

Planning halts either when no new options can be explored or when all constraints have been checked successfully. The tree search is quite powerful and is a flexible means of guiding the planning process. The tree can easily be constructed to take advantage of locality properties when node values limit these regions and constraints that could be affected.

The T-planner must receive various kinds of information in order to operate. First, input information is supplied from the pilot and the mission computer in which the event types and relative configurations of each region are described. Second, the constraint-satisfaction tree can be furnished with the input heuristic information for guiding its search. These heuristics will help the T-planner decide the ordering of constraints, apply fixes, and pursue search in a different region. Finally, the T-planner uses the exception handler for replanning and repairing. Whenever a fixing choice is about to be made, T-planner checks for any special heuristic information that can be accessed for backtracking and then searches for repairing. Indeed, the T-planner is designed in such a way that two segments of super-M can be properly linked in a constraint-satisfaction environment.

3. Executive Planner

The executive planner (E-planner) is responsible for linking all of the regional plans to form global plans that satisfy the potential survivability and effectiveness of the resulting maneuvers. It is a metaplanner which monitors, validates, and smooths regional plans.

The combined sequence of regional plans can be efficiently represented as flight trajectories. Because of rapidly changing situations, uncertainties may create an unsuitable trajectory. These uncertainties include lack of information about the initial state values, about the effects of actions, and about the location of threats. Monitoring and validation are important to check and to update constraints against any plan that violates survivability and effectiveness for smoothing regional plans in generating trajectories. Survivability and effectiveness constraints are described in the system library.

The executive planning algorithm receives the input information, invokes the super-M selector and T-planner, accesses the trajectory effectiveness and ownship survivability, and interfaces with the pilot and vehicle. The global plan that describes a piecewise-continuous trajectory is a combination of regional plans. Thus, the trajectory consists of the most effective combination of super-M candidates from initial location to the goal position. The recommended course of super-M is the one with the highest preference. The algorithm is described in the following steps:

a) Initialization.

Step 1. Call super-M selector.

Step 2. Assess maneuver safety and survivability.

Step 3. Assess maneuver effectiveness.

Step 4. Compute combination scores for the plausible maneuvers.

Exception. If violation score is high, backtrack.

b) Predication.

Step 5. Call tactical planner.

Step 6. Link future regional plan to current regional plan.

Step 7. Validate future positions of threats, neutrals, and friends.

Step 8. Assess ownship survivability after changing position from the current position to what the threat status would be.

Step 9. Assess combat effectiveness of positional advantage.

Exception. If the advantage score is low, repair or replan.

c) Updating.

Step 10. Update to the current information.

Step 11. Updating initial variables.

Step 12. Repeat until mission accomplishment.

d) Knowledge base. The knowledge base is a collection of fuzzy matrices, look-up tables, facts, goals, constraints, and planning trees. During plan construction, the procedure of finding the solutions is to search the planning trees. The interpretation of various constraints that interact is dependent upon the declaration of constraints which creates a data structure with the following attributes:

1) Threats positions: locations and pointing directions.

2) Involved targets: goals' position for which the terminations are enforced.

3) Ownship's position: initial location and directions.

4) Invocation (fact): particular situation in which the constraints are relevant.

5) Relationship (predicate): possible predication of the constraints.

In dealing with the constraints-satisfaction problem of global plan generation, some relationships should always be enforced, i.e., there are no limiting conditions under which the constraint does not apply. These relationships are expressed as predicates applied to constants and variables. Following a LISP-like syntax, a relationship may look like

```
[constraint-one (predicate-symbol arg1 arg2 ...)
 constraint-two ...
 ....]
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For example, a set of constraints that enforces ownship weapon effectiveness is the range between aircraft and target position. Magnitude of acceptable range is dependent upon ownship weapons' characteristics. The range must be shorter than some predetermined distance and can be expressed as

```
[shooting-range (less dist(?own-loc ?target-loc)
                 defined-range)]
```

The variables, syntactically flagged by a leading "?" such as ?own-loc and ?target-loc, are current data from the pilot and from mission computation. "Defined-range" is predefined and resides in the data base. "Less" is a predicate and when the distance is less than the predefined range, the predicate becomes true and the target is within the firing range.

III. Example

Formulation of an aiding system does not lead directly to its implementation. Further study of functional requirements and its feasibility are necessary. The MASAS tends to have very generic and broad functional requirements. Supermaneuvers mentioned herein include both conventional maneuvers and nonconventional maneuvers such as Herbst's maneuver, dynamic-stall maneuver, rapid-pointing maneuver, and increased turn-rate maneuver.[11] The intent of this project is to explore, expand, and establish requirements for aiding-system technology. The requirements will be technology oriented. Currently, the prototype and functional requirements are being developed at the Artificial Intelligent Laboratory of Grumman. The development environment uses Common LISP programming language on Symbolic 3765 LISP machines.

A scenario chosen for the super-M selection is an air-to-air missile (AAM) defense, which requires instant analysis and rapid reaction. The tactical strategies to be employed in any conceivable situation must be predetermined so that they become automatic. To illustrate the system function, the first thing is to prevent missile firing. If it fails, then the pilot attempts to use electronic countermeasures (ECM) which consists of noise jamming and deception jamming. Assume that the smarter missile has sufficient information-processing capability to outsmart almost any defensive deception technique. In spite of the defender's best efforts, the pilot suddenly receives a warning either visually or through threat warning receivers (TWRs). They give pilot and MASAS the orientation of the guidance platform. Pilot's sensing knowledge provides threat direction, and is often a good indication of range and possible knowledge of the type of the missile involved. His/her immediate action is to employ the ECM, chaff, flares, and decoys. Simultaneously, MASAS executes super-M selection algorithms and begins providing information. Now the CRT indicates "Target: AIM-9 Sidewinder-AAM. Action: evasion strategy. Use a super-M break turn and reduce power quickly, because a heat seeker exists. You need to increase your line-of-sight rate. Suggestion: use a descending break turn, then reduce speed and make a high AOA break." Seconds later a message says "Ease up. Alert: watch for second missile."

Within the domain of AAM defense, the precoded knowledge base provides the following items:

1) Super-M candidates. The defense candidates are loaded into the system from system library.

2) Selection criteria. The choice of criteria is determined by the defense super-M candidates. All relevant data are updated from the mission computer data base and pilot input.

3) Fuzzy relational matrices. The matrices are essential elements of the system and also determine system feasibility and performance. Because the super-M pilots are unavailable, a Monte Carlo simulation method is substituted for generating the matrix of fuzzy results. The results are checked by fighter pilots and by consulting with combat operation analysis people.

4) Regional constraint tables. These tables are concerned with combatant's state of knowledge of the local situation. The formats are listed in the system library and current data are provided by TWRs. In addition, accurate range data are based on other platforms.

5) Global constraint tables. These tables have the same form as the regional tables except for their contents and purpose. Within a particular time period and space volume, the constraints show the fuzzy measures that permits the pilot to maneuver effectively with a high degree of survivability.

The software is invoked by either input from keyboard or sensor data from TRWs. Design variables are updated by the mission computer. The super-M selector module is called first. The fuzzy matrix is loaded in and manipulated by the max-min operator for determining the candidate with the highest score. The pilot can choose the candidate he/she likes. In the regional constraint table, fuzzy scores are summed. The candidate is selected based on the scores. If the scores do not reach the acceptable level, then the other candidate will be chosen from the fuzzy matrix. The next step is to predict the first candidate's position in the particular time period. The tactical planner is invoked. This position is used as the initial position to define a sphere for determining the second maneuver candidate along with the information of situation awareness. The executive planner joins these two candidates into a larger sphere. The major function is to check the fuzzy measure scores in the global constraint table. If the sum of fuzzy scores is too low, then it reports to the pilot immediately and invokes the tactical planner again for a repairing strategy and/or replanning.

IV. Summary and Recommendations

A. Summary

The MASAS is intended to help pilots realize the aircrafts' potential operational capabilities and to assist him/her to meet combat performance demands within time limits. The method for designing MASAS requires two steps: The first step is to create a library and the second is to develop a maneuver-selection aiding system. Some important remarks are summarized as follows:

1) Cubic fuzzy relation matrix is sufficient for utilizing the selection criteria to choose a super-M canadidate. Different types of super-M fighter will provide different criteria to select its super-M candidates.

2) The two-step-ahead planning methodology surpasses the hierarchical planning through the use of time-varying, multivariable state-space forms. The table look-up searches will meet the real-time requirement of the systems.

3) The fuzzy measurements have met the knowledge-acquisition requirements of MASAS. The fuzzy constraints can be considered as fuzzy rules which are used in conventional expert system.

4) The knowledge and data as yet remain under investigation, but are required to be sufficiently general for handling supermaneuver missions.

5) The selection criteria and supermaneuver candidates that are correlated with the pilot's experience need further refinement.

B. Recommendations

The primary recommendations for future research include the following:

1) The plan executor has to be very careful in coupling two regional plans either by using dynamic coupling or control cross coupling. A tradeoff study of trajectory decomposition is required.

2) The maneuver-selection aiding system can be flown with advanced avionic systems to yield a more unified system that requires a knowledge data base management system.

3) A study of the handling qualities must include pilot aiding systems for the super-M maneuverability and controllability.

4) Pilot-in-loop simulation is needed for calibrating the fuzzy relation matrix in the knowledge base.

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