89-3630-CP

A MEDIUM-RANGE AIR COMBAT GAME SOLUTION BY A PILOT ADVISORY SYSTEM

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Abstract

Air-to-air combat between two aggressive aircraft, both equipped with medium-range guided missiles, is a key element of future air warfare. This dynamic conflict can be viewed as an interaction of a two-target differential game (between the aircraft) and two independent missile-aircraft pursuit-evasion games. The information structure is, however, rather intricate: though perfect information can be assumed between the two aircraft, the missiles have a limited detection range, beyond which information has to be forwarded by the launching aircraft. Moreover, missile firing cannot be assumed detectable. Problems of such complexity haven't been treated yet in the frame of classical differential game theory. In this paper a prototype Pilot Advisory System (PADS), designed to solve the problems facing the pilot in such an engagement, is described. PADS proposed to be an expert System, which operates in real-time and has a "knowledge base" incorporating differential game concepts and solution elements. PADS simultaneously evaluates potential success with the respective risks and advises the pilot when to fire his missile and when to start an evasive maneuver. This advisory system can guarantee survival when so desired by the pilot. but in most situations it maximizes the probability of victory with an accepted level of risk.

1. Introduction

A future air-to-air combat scenario can be characterized as a dynamic conflict between two adversary groups of high performance supersonic aircraft (such as ATF, EFA, Raffale, etc end 'Red' equivalents), both equipped with advanced medium-range guided missiles. The significant events in such a multiple aircraft scenario (i.e., eventual aircraft destruction) are in most cases direct consequences of relatively brief duels between two opponents. This observation suggests that one can consider the 1x1 air-to-air engagement not only as the simplest example, but also as a building block of more complex scenarios. Successful analysis of such an air combat duel is undoubtedly a prerequisite for further investigation. For these reasons the present paper concentrates on the analysis of air-to-air combat between two aggressively operating aircraft, both equipped with similar guided missiles. The objective of each pilot in such a duel is to shoot down the opponent aircraft without being hit.

The conflicting nature of the scenario calls for a non-cooperative differential game formulation [1]. This dynamic conflict can be viewed as an interaction of a "two-target differential game" (between the aircraft) and two independent missile-aircraft "pursuit-evasion games". The target sets in the two-target game are the respective missile firing zones, each being the "capture zone" of a missile-aircraft pursuit-evasion game of kind [2]. The encounter between the two aircraft (Blue and Red) exhibits a "threat reciprocity" [3] and must terminate with one of the following outcomes:

a. Red alone is shot down = Blue wins.
b. Blue alone is shot down = Red wins.
c. Both are shot down = Mutual kill.
d. Both survive = Draw.

The solution of the relevant two-target differential game with the given target sets is the decomposition of the set of admissible initial conditions into the respective zones of fixed outcome.

Inside the Blue and Red winning zones many zero-sum games of degree can be played. According to the concept of "combat games" [4] the winning player is minimizing and its opponent is maximizing the same cost function. Different cost functions may yield different optimal strategies, but all games have the same guaranteed outcome, namely the termination of the game (in some finite time) on the target set of the winning player.

If the engagement starts in the "mutual kill" zone both players have to play aggressively otherwise the state of the game may slip to the opponent's winning zone. However, cooperative strategies can drive the state of the game to the "draw" zone.

In the "draw" zone each player can guarantee his own survival against any action of the opponent, but cooperative aggressive strategies may lead to "mutual kill".

In future air combat most engagements will start beyond visual ranges (BVR), thus the initial conditions of the above described two-target game are generally in the "draw" zone. The only guaranteed outcome of such non-cooperative game is a "draw".

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This result, which is in contrast to the very essence of an air-to-air combat and denies the justification of the high cost of advanced aircraft and missile development, is clearly unacceptable from an operational point of view. At the other end, cooperative strategies are also inadmissible in a hostile environment.

The inherent non-cooperative nature of the scenario requires each player to determine his "preference ordering" [5] between "mutual kill" and "draw" and to act accordingly. Such "preference ordering" is one of the elements of the players' strategy. and therefore one cannot assume that it is known by the opponent. This uncertainty implies, as pointed out recently [6], a major difficulty in the proper mathematical formulation and consequently in a meaningful analysis of future air combat.

Nevertheless, the challenging problem of air combat analysis has attracted substantial research interest ([7-10] just to mention a few), without yielding yet any satisfying solution.

In [7] a zero-sum formulation is used with a cost function which is the difference between the respective missile-aircraft miss distances. The authors of [8] propose a non zero-sum formulation with the same cost function taking into account the lethal range of the missiles. Both papers present numerically solved examples with prescribed timing for missile launch. Unfortunately, such an assumption denies the most important control element of the game, namely the optimal selection of missile firing time. An interesting new approach is presented in [9] by using a zero-sum bicriterion game formulation and proposing pareto-optimal security and response strategies. However. the example given in the paper did not demonstrate the potential advantage of the bicriterion formulation.

In [10] the simplified dynamic model of the "game of two cars" is used for a qualitative two-target game analysis, extending the solution of a previous paper [2] for vehicles of different speeds. In both works the respective target sets represent the "no-escape" firing envelopes (the "capture" zones) of advanced all-aspect, fire and forget air-to-air missiles. This modelling assumption implies that game termination on one of the target sets is equivalent to a missile firing which guarantees the destruction of the opponent, even if it employs an optimal missile avoidance strategy. Curiously, the interpretation of the apparently satisfactory results obtained in [10] indicates a conceptual incompleteness of the two-target game formulation, as explained briefly in the sequel.

Inside the Blue winning zone Red may have no interest in playing defensively as an evader. Though he cannot force the game to his own target set (the no-escape envelope of his missile), he can still fire a missile within its classical (kinematic) firing envelope. Such a firing disrupts the original two-target game by starting an unexpected pursuit-evasion game between the Red missile and Blue aircraft. In order to survive, Blue must take evasive action. This action will lead to his successful escape from the missile, but it may prevent him at least temporarily from reaching an effective firing opportunity, i.e., the victory guaranteed by the two-target game solution. Moreover, during this evasive maneuver Red may even be able to escape from the Blue winning zone. The insight gained by this interpretation illustrates the difficulty to model future air combat [6], within the frame of classical differential game theory.

In the present paper a new approach is outlined for the analysis of a medium-range aggressive air-to-air engagement. It is based on combining Artificial Intelligence (AI) techniques with concepts of differential game theory. It turns out that these two seemingly different disciplines can successfully complement each other in analyzing complex dynamic conflicts. such as an air combat game. This paper reports the design and the development of a Pilot Advisory System (PADS) prototype - mentioned first in a recently presented invited paper [11] - which implements the combination of the two disciplines for the analysis of an air combat duel with advanced medium-range missiles. PADS is designed to be the prototype of a real-time Expert System with a "knowledge base" composed of differential game concepts and solution elements.

In the next section the medium-range air combat duel with guided missiles is formulated and simplified modelling assumptions for the prototype design are outlined. This section also states the requirements that PADS has to satisfy. It is followed by the outline of the implementation concepts and the description of the system structure. Finally an example with some preliminary results is presented.

2. Problem Statement

The air combat duel of interest is between two supersonic fighters (Blue and Red) of similar performance and it is assumed to start at the limit of airborne radar detection range. Both aircraft are assumed to be equipped with a small number (2-4) of similar advanced medium-range air-to-air missiles (AMRAAM).

An AMRAAM type missile has two different guidance modes. After being fired it uses inertial midcourse guidance towards the predicted position of the target. For this purpose both the missile and its target have to be kept in the information cone of the launching aircraft. At some shorter range the missile's active radar seeker is turned on, it searches and "locks-on" the target. These missiles are fired beyond visual range and therefore the firing event is generally undetected by the target. Both aircraft may use radar and are also equipped with a passive warning system that detects missile "lock-on".

The entire duel can be considered as a sequence of missile firing exchanges composed of several phases: target detection, pre-launch maneuver, missile deployment (launch), post-launch maneuver (to forward information to the missile until it locks-on), eventual disengagement (to avoid opponent missiles) and possible reengagement. The objective of each pilot (as stated in the Introduction) is to shoot down the opponent with certainty $(P(K)=1)$ while guaranteeing own survival $(P(S)=1)$. In most cases this ideal objective cannot be achieved because the engagement starts in the "draw" zone, where each player can guarantee his survival $(P(S)=1)$. By using practical air combat terms one can say that unless a missile is fired inside its "no-escape" envelope it can be avoided if the target performs a proper disengagement maneuver. Generally, in order to reach a "no-escape" firing opportunity, own survival has to be put at risk. The need for a post-launch maneuver (a consequence of AMRAAM properties) is an additional constraint.

For these reasons the practical objective of the air-to-air duel (in contrast with the ideal objective) has to be redefined by using a more flexible mathematical formulation, which can be stated (for the Blue aircraft) as: "Maximize $P_R(K)$ - the probability of shooting down the Red opponent - while guaranteeing that the probability of own survival satisfies $P_B(S) \geq \bar{P}_B(S)$, where $\bar{P}_B(S) < 1$ is prescribed".

Note, that the value of $0 \leq \bar{P}_i(S) \leq 1$ $(i=B,R)$ can be used as a measure of relative preference ordering. $\bar{P}_i(S)=1$ indicates a clear preference of "draw", while $\bar{P}_i(S)=0$ stands for preferring a "mutual kill".

Such formulation defines a game which (in game theory terms) is always "strongly playable". This game may result, however, in a very low, even zero value of $P_R(K)$, because in the "draw" zone the survival of an optimally evading player is guaranteed. No player can expect an outcome other than the "guaranteed draw", unless his opponent behaves nonoptimally. Whenever this situation occurs there exists an appropriate "reprisal" strategy [12], which allows to exploit such nonoptimality. The pilot can also prescribe the lowest acceptable value for the probability of opponent destruction $\bar{P}_j(K)$ $(j \neq i,\ j=B,R)$.

One can thus summarize. that in reality both pilots are willing to play "reprisal" games in the hope of identifying and taking advantage of the opponents errors. For a given nonoptimal opponent strategy such a "reprisal" game is reduced to an optimal control problem. Nevertheless, the gaming aspect of the engagement is preserved, because a continuing and predictable nonoptimal opponent behavior cannot be taken for granted.

In the air-to-air combat duel each pilot has two types of controls at his disposal:

(i) the actual control variables for aircraft maneuver.
(ii) a set of decisions: when and whether to perform a transition from one engagement phase to another.

The most critical decision is the proper timing of missile firing.

In future air combat the above formulated complex differential game of imperfect information has to be solved in real time. It is therefore required to design for the Blue aircraft a system which can aid the pilot in selecting the controls at his disposal in order to achieve the best possible outcome.

In this paper, a prototype "Pilot Advisory System" (PADS) is proposed for performing the above described task. For the sake of simplicity needed in an exploratory investigation, the prototype system uses a set of assumptions, which preserves the essential elements of the missile firing sequences, but decouples them from secondary effects of detailed aircraft dynamics. A recent Simulation study [13] has demonstrated that such simplification is very important for gaining insight into the problem. The assumptions used in the prototype design are:

1. The engagement takes place in a horizontal plane of given altitude (h) (see Fig. 1).
2. Aircraft models are characterized by: constant speed (V), maximum load factor (n_{max}), maximum radar detection range (r_a), maximum radar look angle $(\Delta\lambda)$.
3. Both aircraft are equipped with identical missiles Characterized by: thrust profile, aerodynamic drag model, PN guidance law, minimum turning radius, fixed range for active seeker "lock-On" (r_a).
4. A missile scores a hit if it can reach the vicinity of its target satisfying a set of inequalities concerning the time of flight, the final speed and the final closing rate.
5. The information available for both aircraft is the following: perfect knowledge of own and opponent parameters, perfect measurements by radar, passive detection of radar illumination including missile lock-on.

6. The inherent uncertainties of the engagement are results of undetectable missile firings and unknown preference ordering of the opponent.
7. The Red aircraft has a conventional firing control system which computes own missile envelopes, but does not have a system like PADS. Consequently, Red is assumed to decide on missile firing by using some heuristic doctrine and to start a disengagement maneuver if missile lock-on is detected.

Remark, that based on assumptions 1 and 2 the optimal post-launch and disengagement (missile avoidance) maneuvers can be uniquely determined. The post-launch maneuver is a turn away from the opponent but keeping it, as well as the recently fired missile, within the radar "look angle" limit. The optimal missile avoidance maneuver is a "hard" turn away from the missile line of sight towards a "tail-chase'' geometry. (See Fig. 2, where for sake of simplicity only the Blue maneuver sequence is depicted and Red continues on a straight line until Blue missile lock-on is detected).

As a consequence of the last remark, the present section can be concluded by formally stating the requirements to be satisfied by the pilot advisory system (PADS) prototype designed for the above described simplified medium-range air combat duel scenario. The essential role of PADS is to establish a plan and propose to the Blue pilot an "optimal" (or at least satisfactory) missile firing sequence, which includes the following elements:

a) the optimal pre-launch maneuver,
b) the optimal timing for own missile launch,
c) the time to start disengagement to avoid the advisory missile,
d) an eventual reengagement.

This proposed plan is to be based on the last available information and- on some specific pilot inputs such as $P_B(S)$ and $\bar{P}_R(K)$. PADS must display together with the "plan" the estimated outcome of the proposed firing sequence by $P_B(S)$ and $P_R(K)$.

The pilot can either accept the proposed "plan" and carry it out as dictated by the flight and firing directives provided by PADS, or to change his inputs and request a modified "plan".

3. PADS – The Concept of Implementation

3.1 General outline

PADS is designed to be the prototype of a "real-time" Expert System with a very particular structure, which integrates classical quantitative computation methods with rule based AI type techniques of qualitative reasoning. The "knowledge base" of this Expert System incorporates concepts of differential game solutions, as well as a special module for simulating the outcomes of eventual missile firings.

The basic idea for implementing such a system is to decompose the complex original differential game of imperfect information into a set of solvable subgames. As a consequence of unknown "preference ordering" of the opponent, these sub-games are merely "reprisal" sub-games with some assumed opponent strategy.

One can distinguish between "aggressive" and "defensive" subgames. The solution of an aggressive reprisal subgame is the earliest time for missile firing and the length of the respective post-launch maneuver for obtaining the destruction of an opponent which uses a given assumed strategy. The solution of a defensive subgame is the latest time for starting an optimal missile avoidance maneuver in order to evade a missile launched by the opponent at a given assumed time.

In fact, both types of reprisal subgames correspond to missile firing envelope computations, assuming a given target behavior. The firing envelope is the equivalent of the "barrier" in a differential game of kind which separates the capture zone from other parts of the state space.

In a dynamic environment the barrier of each reprisal subgame defines a critical point on the predicted trajectory. These points and the corresponding critical. timings can be obtained and verified by a set of appropriate simulations of the respective missile-aircraft engagements. The outcome of each simulation is the "miss distance" obtained when one of the prescribed stopping conditions is satisfied. The reprisal subgame solution, i.e. the critical point on the predicted trajectory is characterized by a miss distance which is equal to the lethal range of the missile.

The design concept of PADS is implemented in two subsequent levels:

a) In order to solve the relevant reprisal subgames PADS has to manipulate the respective set of simulations.
b) At a higher level, the subgame results have to be evaluated by a rule based automated reasoning process.

3.2 "Reprisal" subgames

Each reprisal subgame, being essentially a firing envelope computation of a guided missile against a target of an assumed strategy, can be defined in the context of an air combat duel by the following elements:

a) the aircraft .which fires (launches) the missile at $t=t_L$ (Blue or Red),
b) the post-launch behavior of the firing aircraft,

c) the post-launch behavior of the target aircraft.

It is assumed that the post-launch trajectory of each aircraft is composed of three segments:

a) straight flight for a period of $(\Delta t)_1$, $[t_1 = t_L + (\Delta t)_1]$,
b) a turn (either to the right or to the left) until the "look-angle limit" is reached, continued by a segment satisfying this constraint,
c) an optimal missile avoidance maneuver starting at the time t_e.

As a consequence of this assumption the post-launch behavior of each aircraft is characterized by the triplet $[(\Delta t)_1, (dir), t_e]$ where (dir) is a binary variable having the values "right" and "left". The selection of this binary variable can be based either on geometrical conditions or can be a random process.

In general, the value of $(\Delta t)_1$ for the firing aircraft is zero, since after firing its own missile the pilot wishes to minimize the closing speed with any eventually fired missile of the opponent. A post-launch turning maneuver, however, can be easily detected by the adversary aircraft and thus providing a strong "hint" OR the event of missile firing. In order to deny the adversary such information the pilot can consider selecting $(\Delta t)_1 > 0$. For the firing aircraft the value of t_e is associated generally with the event of own missile "lock-on" the target and becoming "active" $(t_e = t_a)$. Another reasonable strategy calls to start evasion when the "warning" on the opponent missile lock-on is received $(t_e = t_w)$. In such a case with $t_w < t_a$ the probability of own missile lock-on has to be considered.

The post-launch behavior of the target aircraft depends on two elements, namely the decision of its pilot on an eventual firing (aggressive target) as well as his "preference ordering".

In the next subsection some reprisal subgame examples are given.

3.3 Subgame examples

In typical defensive reprisal subgames, introduced in 3.1, the time of missile firing t_L is assumed to be given while the strategy of the launching aircraft is characterized by $\Delta t_1 = 0$ and $t_e = t_a$. The target aircraft trajectory is assumed to be prescribed and the solution required to find the critical value of "t_e" for a marginal escape.

In most aggressive reprisal subgames the strategy of the launching aircraft remains the same $(\Delta t_1 = 0,\ t_e = t_a)$. These subgames can thus be characterized by target behavior. The first distinction is between non-aggressive and aggressive target behavior, the former implying that no counter-fire is considered and consequently the "look-angle limit" segment is absent. The most important examples of such a subgame are:

a) The target (probably unaware of the missile) continues to fly in a straight line until the end of the simulation $(t_1 = t_f)$. This subgame is called the R_{max} subgame, because the resulting firing range is maximal.
b) The target starts the missile avoidance maneuver at missile launch $(t_e = t_1 = t_L)$. This subgame, the worst case from the firing aircraft point of view, determines the "no-escape'' range of the missile and thus called the **NE** subgame.
c) The target continues to fly in a straight line until missile lock-on warning is received $(t_e = t_1 = t_w)$. The result of this subgame, called the **LNE** subgame, is between the results of the two extremes stated in (a) and (b).

Aggressive reprisal subgames against aggressively behaving targets have a very large variety. Interesting examples are those where both aircraft fire simultaneously and both start the post-launch turn with $\Delta t_1 = 0$.

In PADS two examples of such subgames are used frequently. The first is called the **SNE** (shoot/no-escape) subgame and the other is called the **NES** (no-escape/shoot) subgame. In both subgames the firing aircraft continues the post-launch "look-angle limit" constrained trajectory until its missile becomes active $(t_e = t_a)$. The difference between these subgames lies in the target behavior. In the **SNE** subgame the target aircraft prefers a mutual survival (i.e. "draw") on a "mutual kill" and therefore starts the evasion when the warning of opponent missile lock-on is detected $(t_e = t_w)$, while in the **NES** subgame its behavior is similar to the firing aircraft $(t_e = t_a)$.

3.4 Opponent behavior model

As mentioned earlier the original complex differential game is decomposed into a set of "reprisal" subgames. In each such subgame a different opponent strategy (behavior) is assumed, as has been already illustrated by the examples given in the previous subsection. In order to evaluate the different subgame solutions in the planning process carried out by PADS it is necessary to have some behavior model of the opponent (the pilot of the Red aircraft).

The first element in such a behavior model relates to the motivation of the opponent, reflecting either an aggressive or defensive nature. As was already pointed out, if the Red pilot wishes to behave defensively and follows the corresponding optimal evasion strategy it might be impossible to shoot him down, unless the initial conditions of the engagement are very unfavorable to him. In the sequel it is assumed that the basic motivation of the opponent is aggressive, namely he wishes to launch a missile against the Blue aircraft. Such aggressive attention is directly verified by PADS by observing the positive closing speed component of the Red aircraft.

The strategy of an aggressive opponent can be characterized by his "firing doctrine", i.e. the conditions (the range) when missile launch is planned to take place, and his post-launch behavior. In the present prototype version of PADS the "firing doctrine" of the opponent is described by a probabilistic model, expressed by the accumulated a priori probability of missile launch at any given range. In generating this model it is assumed that the Red aircraft is equipped with a conventional firing control system, which can compute the firing envelopes associated with R_{max}, NE and **LNE** subgames. An example of such accumulated launch probability model is presented in Fig. 3. In this example no missile launch takes place before R_{max} is reached, as well as after the so-called "no-escape'' range. Under these assumptions the model is determined by two parameters. The percentage of the missiles launched between R_{max} and the **LNE** firing envelope and the probability density (the slope of the accumulated probability) at that range.

The post-launch behavior of the opponent is defined by the elements in subsection 3.2. It is assumed that the Red aircraft starts the post-launch turn with $(\Delta t)_1=0$. The direction of this turn can be either to the left or to the right with equal probability, unless the interception geometry provides a definite advantage for one of the alternatives.

The next element of the opponent behavior model is "t_e" the start of the missile avoidance maneuver. This is probably the most critical element of the Red strategy reflecting clearly his "preference ordering" and the level of his aggressiveness. In the presently used model 4 different Red strategy alternatives are considered:

a. "cautious defensive" determined by
   $t_e=\min[t_a,t_w]$
b. "nominal defensive", determined by
   $t_e=t_w$
c. "nominal aggressive", determined by
   $t_e=t_a$
d. "strongly aggressive" determined by
   $t_e=\max[t_a,t_w]$

In the opponent behavior model of PADS each alternative is associated with a probability such that $P(a)+P(b)+P(c)+P(d)=1$.

As can be seen, even in the present prototype there is a great variety of possible opponent models, from which one has to be selected. Such a selection has to be based on previous knowledge (intelligence) of the opponent as well as on the intuition of the Blue pilot operating with PADS. Some of the information is deterministic, but some element has to be "guessed" by the Blue pilot. These guesses can be verified in some degree by observing the Red aircraft trajectory and comparing it to an expected one. Real-time intelligence from the ground can also be incorporated in the Red behavior model and PADS is designed to perform such model updating.

3.5 Planning strategy

The key function of PADS is the planning of a firing sequence to be proposed to the Blue pilot. The elements of such a plan are outlined in the last part of Section 2. For this purpose PADS has to define a set of relevant reprisal subgames. It has to manipulate the respective simulation models for obtaining the required subgame solutions. Finally it has to evaluate these results, by using a rule based automated reasoning process, for completing a satisfactory firing sequence plan. If the pilot inputs, determining the acceptable values of $\bar{P}_B(S)$ and $\bar{P}_R(K)$ and real-time state measurements do not lead to such a plan, the pilot has to be warned and alternative action has to be proposed. The functional block diagram of PADS is given in Fig. 4.

The first phase of the planning is to assess the possibility of a "safe winning", the best outcome for the Blue aircraft, defined by $P_B(S)=P_K(R)=1$. The test for the feasibility of a most favorable outcome involves finding a firing sequence (t_L, t_1, t_a) for which $t_a\le t_e^*$, where t_e^* is the lowest value obtained from the set of envisaged defensive subgame solutions. If this test provides an affirmative answer the Blue pilot is guided to carry it out.

In many (probably in most) cases the "safe winning" test will yield a negative answer. Therefore, the most important task of an efficient advisory system, such as PADS, is to plan and propose other acceptable alternative options. In the present prototype design the following options are considered:

a. disengagement as soon as possible in

order to avoid any risk,

b. not to launch own missile but delay disengagement as long as safe escape (solution of the defensive subgames) is possible,

c. an "early" but "safe" launch characterized by $t_a \le t_e^*$, knowing that own missile can be avoided by the opponent [$P_R(K)$ can be zero],

d. a "late", but probably "effective" firing, the success of which depends on the level of risk taken by the Blue pilot expressed by $\bar{P}_B(S)$.

The Blue pilot can make his decision either before the Red aircraft is identified as an aggressive opponent or after the "safe winning" test is completed. If option (a), is selected the task of PADS is terminated after the first phase. If the Blue pilot selects option (b), he generally has the intention to wait for an eventual mistake to be made by the opponent, which may improve the situation and lead to a "safe winning". In this case PADS continues to repeat the "safe winning" test as long as the time for safe disengagement arrives.

Selection of options (c), or (d) by the Blue pilot requires PADS to carry out a search, guided by an appropriate automated reasoning process, for a satisfactory firing sequence. In these cases the outcome is evaluated, by using the opponent behavior model described in 3.3, and compared to the pilot's requirements.

The "early" firing of option (c), generally implies $P_B(S)=1$ and may be intended to prevent the opponent from accomplishing his aggressive task at the cost of a noneffective own missile firing. The planning for option d, is a search for a compromise solution (if it exists) or to determine the highest value of $P_R(K)$ for the given $\bar{P}_B(S)$. If such a search fails [i.e. $P_R^*(K) < \bar{P}_R(K)$] then the Blue pilot is asked either to select another option or to change at least one of the input values $\bar{P}_B(S)$, $P_R(K)$.

Once a plan is accepted by the Blue pilot PADS continues to test its validity and at the same time provides flight and firing directives to the pilot. Accepting a plan based on option (d), involves a delayed decision of the pilot, as is explained in the sequel.

As long as actual missile launch has not taken place the Blue pilot can change his mind and the selected option. After missile launch PADS function is concentrated on computing the predicted time for own missile lock on (t_a) and the time for the last "safe" disengagement t_e^*. If $t_a \le t_e^*$ the actual firing sequence can be completed without any risk. If, however, $t_a > t_e^*$ - a case likely to happen if option (d), is selected - a decision has to be made by the pilot whether to follow the previously selected plan or act either defensively $(t_e \le t_e^*)$ or aggressively $(t_e = t_a)$. Of course interim decisions can also be taken. Detection of an actual missile warning may be used for verifying assumed opponent missile firing.

4. On PADS'S Structure

The schematic structure of PADS is presented in Fig. 5. PADS's functions, as described in the previous section, involve interface with the pilot. At pre-flight the pilot has to transfer, with the help of the knowledge engineer, his subjective knowledge (experience, preference ordering etc.) for solving the "subjective optimal" game to be played. Moreover, updated intelligence data on the potential opponents have to be verified and stored. General knowledge concerning fighting doctrine, own aerodynamic and missile data, as well as inference rules used in the automated reasoning process can be equally updated at the same time.

During flight, PADS must display its advice, answer any questions and explain how different conclusions are derived. For acting properly in flight, PADS needs to receive sensor-data and to communicate with the differential "reprisal" subgame simulation module. After the flight a debriefing may take place.

The tasks of PADS can be qualitatively performed using an Expert System structure. An Expert System is a rule based AI application program for performing a task which requires expertise. It generally consists of the following elements: user interface, data base, knowledge base and inference engine. The user interface allows interaction with the user such as asking questions and getting answers about the knowledge base, including the process of deduction. The knowledge base includes the definition of differential game concepts as well as a simulation module for "reprisal" subgame solution. The inference engine manipulates the subgame simulations and drives the automated rule based reasoning process. In our prototype design only a small set of such rules was implemented. Nevertheless, we laid the ground and prepared the tools and mechanism for a larger, more complex system that will be required both for a more realistic duel and for a multi-aircraft scenario, where the number of rules and the complexity of rule interaction may increase by orders of magnitude.

The rules and data in PADS are organized in a so called "frame based system" [14] as shown in Fig. 6 showing the upper level knowledge base corresponding to aircraft Blue. A "frame" is a data structure that contains pointers to all information items relevant to the concept that is represented by the frame. For example, the Blue aircraft is such a concept. An aircraft in general is another. Relevant information can be the aircraft's maximal velocity, its weapon arsenal, its pilot's identity, etc. The frame bears the name of its concept, and the pointers inhabit "slots" of different types (called "facets") in the frame as can be seen in Fig. 7. Frames are arranged in a hierarchy of class inclusions, linked by so called "IS-A" pointers. This hierarchy enables, for example, the Red aircraft to "inherit" the fact that it has wings from the data associated with the general aircraft frame, and thus reduces duplication of data.

As mentioned earlier an important part of the knowledge is generated on-line by manipulating differential subgame simulations. This manipulation is based on measured data, pilot input and target information as illustrated in Fig. 4.

5. Numerical Results

A typical operation of PADS is an example of equal speed aircraft ($V_B=V_R=350$ m/sec) was illustrated in a previous paper [11]. In that example a "safe winning" $[P_R(K)=P_B(S)=1]$ was not possible because the first time for an "effective firing opportunity" (34.5 sec) was later than the last time for a "safe and completed firing sequence" (32.3 sec). Thus, PADS had to plan and evaluate compromise solutions leading PADS to propose to the Blue pilot a firing sequence starting at $32.3 \leq t_{LB} \leq 34.5$. In the same example it was also shown, that by continuously updating the planning process PADS can take advantage of any nonoptimal action of the opponent by proposing to the Blue pilot a firing sequence of an improved outcome.

In the present section some numerical results, indicating the effect of speed differences $(V_B \neq V_R)$, are presented. In all examples the air combat duel takes place at the altitude of 8 km and the turning rate of both aircraft is limited by a load factor of $n_{max}=9$.

First the example of $V_B=380$ m/sec and $V_R=350$ m/sec is considered, followed by the case of $V_B=350$ m/sec but $V_R=380$ m/sec.

In each case PADS starts the planning phase by computing three critical times for the Blue aircraft:

(i) The last time for "safe disengagement" from all possible missiles, assuming straight flying trajectories of both aircraft. This "last escape" time serves merely as a reference value for the cases where the pilot decides not to deploy his weapon. For the first example $(V_B>V_R)$ $t^*_{eB}=42.6$ sec, the most threatening missile being launched at $t_{LR}=35.5$ sec at a range of 24.1 km. For the second example $(V_B<V_R)$ $t^*_{eB}=40.4$ sec and the most threatening missile corresponds to $t_{LR}=40.0$ sec at a range of 20.8 km, very near to the "no-escape'' range.

(ii) The first "effective firing opportunity" is computed by the SNE subgame. For the first example $(V_B>V_R)$ it starts at $t_{LB}=34.5$ sec ($r=24.9$ km) and missile lock-on is achieved at $t_{aB}=48.8$ sec. For the second example $(V_B<V_R)$ $t_{LB}=37.8$ sec ($r=22.4$ km) and $t_{aB}=50.1$ sec. If the Red aircraft launches after t_{LB} and starts missile avoidance only when warning is received it will be hit by every Blue missile fired after the above computed time (if it can lock-on the target).

(iii) The last time for a "safe and completed firing sequence" against an aggressively acting intelligent opponent taking into account the most threatening missile. This firing sequence starts for the first example $(V_B>V_R)$ at $t_{LB}=35.0$ sec ($r=24.5$ km) and allows missile updating until $t_{aB}=48.4$ sec on a post-launch trajectory. For the second example $(V_B<V_R)$ $t_{LB}=31.6$ sec ($r=26.9$ km) and $t_{aB}=47.1$ sec.

These results clearly indicate how speed advantage is directly translated to tactical advantage in an air combat duel. The first indicator is the 2.2 sec difference in the last time for "safe disengagement", allowing longer time for deciding on a final action. The main difference is exhibited by the fact that in the first example $(V_B>V_R)$ a "safe winning" is possible while in the other case $(V_R<V_B)$ the situation is seriously degraded in comparison to the equal speed case.

In the first example $(V_B>V_R)$ PADS will propose to the Blue pilot to start a firing sequence $34.5 \text{ sec} \leq t_{LB} \leq 35.0$ sec guaranteeing him a "safe winning". In the second example $(V_B<V_R)$ the situation is more complex. Depending on the pilot's preference ordering an acceptable firing sequence may arise. Moreover, any non-optimal action of the opponent can be exploited by PADS to improve the situation. In any case PADS provides the Blue pilot with a "safe disengagement" option, which may be used particularly in an initially disadvantageous tactical situation.

6. Conclusions

In the present paper a prototype design of a pilot advisory system {PADS) for a medium-range air combat duel with advanced air-to-air missiles is described. The design is based on a new approach of proposing to combine differential game concepts and Artificial Intelligence techniques, in order to benefit the complementing features of both disciplines. Such synergisms shouldn't be a surprise, if one recalls that any game can be presented in extensive form by a decision tree. Since the problem of interest is too complex to fit in the frame of classical differential game theory, it is decoupled into a set of "reprisal" subgames. Each subgame is characterized by a different assumed opponent behavior and it represents a branch of the decision tree.

PADS is designed to operate as a real-time Expert System with a "knowledge-base", which incorporates concepts of air-to-air combat and differential game theory. Its inference engine manipulates "reprisal" subgame simulations and evaluates their outcome. The results of this automated reasoning process serve as the basis for planning the optimal multiphase missile firing sequence and determining the optimal timing of missile deployment and disengagement maneuver. The planning is continuously updated taking into account the actual events of the engagement.

PADS provides a meaningful solution for one of the basic and probably the most challenging tasks of a future Pilot Associate System. It is designed to present to the pilot vital information which can be used either to guarantee survival, or to maximize the probability of winning with an accepted level of risk. Moreover, the system allows to take advantage of any nonoptimal action of the opponent.

In the presently used PADS prototype, designed for an air-to-air duel of a simplified dynamic model, the genuine AI elements form only a smaller part of the active software. But, since the investigation is planned to be extended for three-dimensional multiple aircraft scenarios with realistic variable speed aircraft models, this proportion will dramatically change in the future. The prototype design laid the ground and prepared the tools for such an extension.

The results presented in the paper are part of an ongoing investigation, and due to the simplified dynamic model are merely of an exploratory nature. They are, however, very encouraging. They demonstrate that the new approach, based on judicious combination of AI techniques and concepts of differential game theory, can be successfully implemented and applied in solving a complex dynamic conflict, such as an air-to-air combat duel. The results also indicate some of the great tactical advantage that a Pilot Advisory System can provide to its user.

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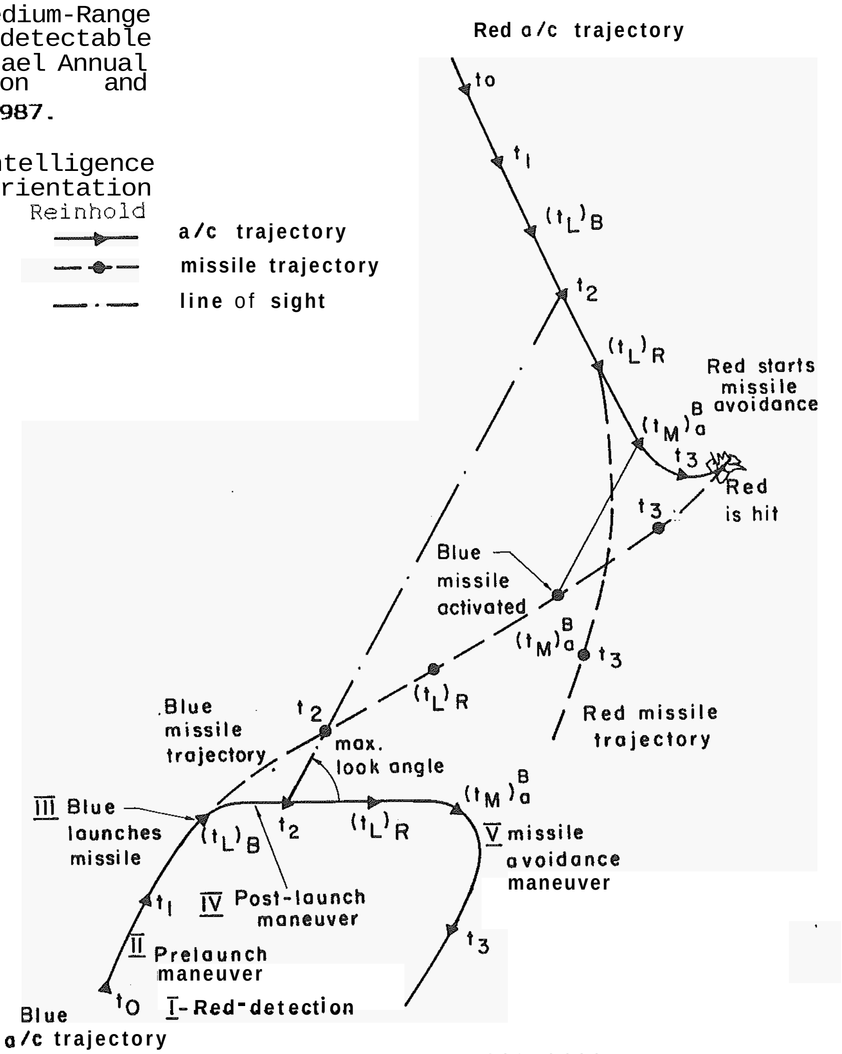

Fig. 2. Blue maneuver sequence

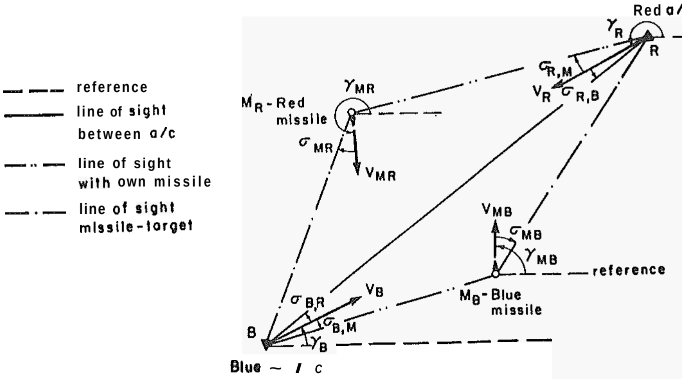

Fig. 1. Engagement geometry.

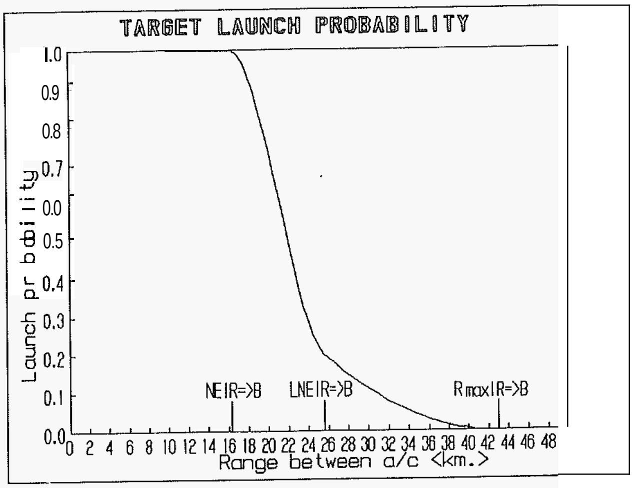

Fig. 3. Opponent behavior model.

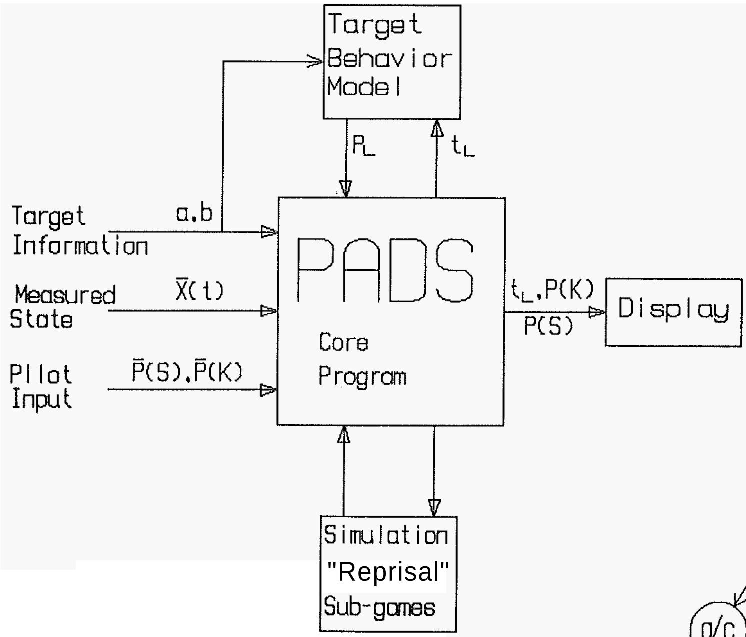

Fig. 4. PADS - Functional block diagram.

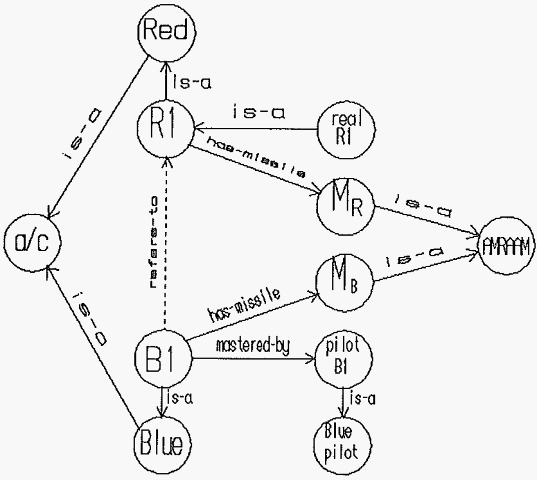

Fig. 6. Upper level knowledge base of B1.

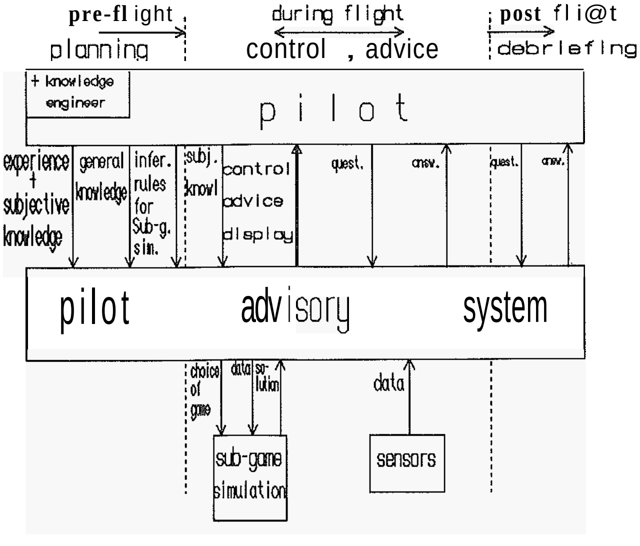

Fig. 5. PADS - General structure.

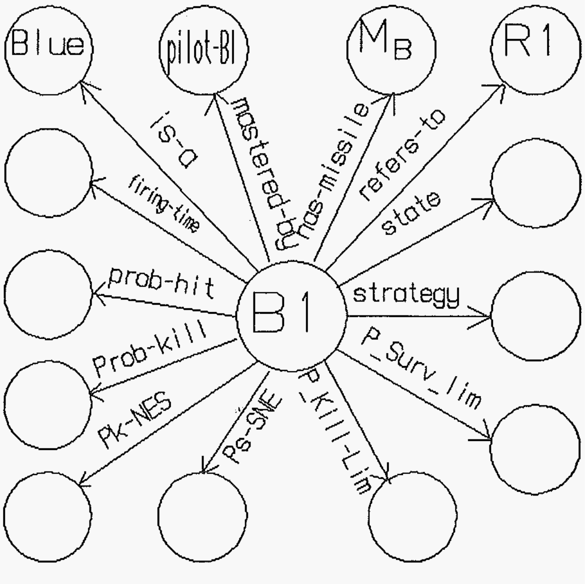

Fig. 7. Slots of frame B1.