MODELS FOR AIR COMBAT SIMULATION

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Abstract

Report describes models of an automatic battle manager and two artificial pilots for the simulation of multi-participant air combat. Models serve as tools for the development of tactical methods and for the evaluation of weapons systems performance. They are also used as intelligent active adversaries to human pilots in real time flight simulators.

1. Introduction

Air combat simulation has many uses. It lets you learn from your mistakes before you have made them or, if it is too late for that, lets you find out why you have done what you have done and what should have been done instead.

The automatic pilots and the battle manager described in this report serve both ends. They were developed as components of BABEL ([1] [2]), a general simulation environment for studying multi-participant air combat. They were to provide the tools for investigating a variety of problems relating to aerial warfare. e.g. tactical methods development, preliminary performance evaluation of airborne weapons systems, investigating the pilot decision process and its ramifications for the design of computer based decision support systems and, last but not least, training pilots in air combat against active adversaries using realistic offensive tactics.

The nature of air combat depends strongly on the distance at which it is conducted. The factors that are decisive for winning a fight in close combat are different from those determining the outcome of BVR engagements. While visual contact with the opponent is the main source of information in battle at close range, the adversary is hardly ever seen directly at the distances at which modern missile duels are conducted. A vital aspect of modern aerial engagements is, therefore, the problem of how to recognize and approach the opponent, both initially and as the battle progresses. Usually, pilots are assisted in performing this task by a combat control center (radar controller, battle manager) who, airborne or from the ground, attempts to lead the forces against the adversary such that the tactical positions are as favorable as they can possibly be before pilots take over during the final stages of an attack.

To simulate the various aspects of air combat, three tools are currently available within the framework of the BABEL system: An autonomous artificial pilot for short and intermediate range air combat carried out with either missiles or machine guns, an automatic pilot for engagements at large distances including BVR duels, and an automatic battle manager. The battle manager plans the engagement, assigns missions and goals to participants, leads the aircraft to optimal attack positions, monitors the progress of the battle and, if necessary, restructures the battle plan depending on the outcome. In a world populated by our forces and their forces, the artificial pilots can be programmed to fly either in a mode resembling our own tactical plans and dispositions, or they can be directed to simulate the behavior of potential adversaries using a known or hypothetical battle doctrine.

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2. Tools of simulation

Several successful implementations of artificial pilots are known today (e.g. [3] [4] [5]). Therefore, present report will be limited to a discussion of the solutions that are special to the approach chosen in the BABEL system.

The first (and chronologically older) kind of artificial pilot was modelled after an aggressive fighter pilot who, left to his own devices, attacks or defends himself with the weapons at his disposal as seems most appropriate at the moment. Situation assessment, planning and execution of the battle plan are based mainly on heuristic principles. This model is called the heuristic pilot or 'H-pilot'.

Designed for one-on-one air combat, he acts entirely on his own initiative and makes all decisions based only on his own judgement and his own perception of the world. Actions are planned with a temporal horizon of between 30 seconds and one minute. The corresponding spatial planning range amounts to approximately ten kilometers, which is the average distance at which an opponent can be made out by the naked eye.

The repertoire of the H-pilot was later extended by endowing him with the capability to acquire and engage opponents at BVR distances provided they are detectable by means of the on-board equipment. For combat beyond visual range the pilot model uses a tactical approach resembling that taught to Swedish fighter pilots. A second extension enabled the H-pilot to simultaneously follow and attack more than one target, e.g. a base target like a transport plane protected by a fighter escort. However, while the H-pilot can pursue multiple targets, he can only defend himself against a single adversary at a time.

The second kind of artificial pilot is designed for many-on-many combat from BVR down to visual distances. It is knowledge based and controlled by a rule driven expert system. It is termed the expert or 'E-pilot'. This pilot model flies in one of two possible modes. In the initial stages of an encounter it is firmly led by the battle manager. In accordance with the selected battle plan the battle manager issues the appropriate directives in order to maneuver his forces into favorable attack positions. During this phase, the E-pilot implements the instructions he receives but makes few decisions of his own (command mode). However, once in the vicinity of the opponent, the E-pilot becomes a free agent, fending for himself and trying to reach his mission objective to the best of his ability (autonomous mode). When this has been accomplished (or if it becomes evident that he has failed to do so) he reports back to the battle manager and is ready to be assigned a new task.

The combination of battle manager and E-pilots is intended to simulate the actions of an air arm that is used to plan far ahead, trained to fight under rigid discipline and whose units have been taught to collaborate closely in order to impose their will on the adversary and reach a common mission objective. The paradigm can be applied both to our forces and their forces, although the knowledge base must be adapted to reflect the different attitudes towards air combat.

The role of the battle manager (radar controller) can be inferred from the above description. The main source of information on which the controller acts is a GCI radar located either on the ground or carried aboard an airborne command post. Additional input and feedback comes from the crew of the aircraft carrying out the mission.

The properties of the models are summarized in Table I.

	H-pilot	ABM + E-pilot
Decision horizon:		
Temporal (sec) (1)	30 (150)	< 3000
Spatial (km) (1)	0-30	1-300
Control:		
Autonomous (self)	yes	yes
Ground control (remote)	no	yes
Human operator	yes	no
Number of opponents	1-2	many
Weapons:		
Missiles	yes	yes
Machine guns	yes	yes
Number of missiles simultaneously controlled	1-2	many
Flying in real time against human pilot	yes	yes
Hardware required	Sparc10	Sparc10
Situation updates per second in real time	4-7	2-4

Table I: Properties of artificial pilots

(1) The first figure refers to the autonomous mode, the value in parentheses to BVR mode

The platforms flown by the artificial pilots include models of all modern aircraft currently in the arsenal of the major powers. The weapons systems considered in the simulation are IR-guided missiles, radar controlled missiles and machine guns, either singly or in combination. Sensor models can be incorporated as required.

As far as the computer implementation is concerned, all models have been coded in the spirit of agent oriented programming. BABEL simulations are run in a distributed processing environment on networks of workstations. Simulations are event, not time, driven. The control topology is hierarchical with a central system controller and pace-setter at the top of the pyramid. The system controller also acts as a global blackboard manager disseminating observable information to participants.

3. Planning a mission

Flying a combat mission (or simulating one) is an exercise in planning. The essence of planning is the application of knowledge for recognizing and selecting between alternatives that present themselves for reaching a given goal. Some goals can be attained in a single step and by a single decision. Others must be approached in stages leading over many subgoals, substates and secondary decisions, frequently in a dynamically changing environment. The task a pilot faces is of this kind.

The goal of a mission is to attack and destroy the opponent with a minimum of own losses. Pilots and battle manager must plan accordingly. In this sense, both are planners, planning far ahead in time while they can, and planning on the fly if they must. If they are to do their jobs properly their knowledge base must include deep knowledge, expert knowledge and procedural knowledge.

Plans are made on many levels and with different time perspectives. The H-pilot plans only for himself, but the battle manager plans initially for the whole squadron, then for parallel groups and finally for every single E-pilot under his supervision. At times, E-pilots are also left to themselves, obliged to coordinate actions with each other at the local level. A battle plan, therefore, is no linear procedure. It is a shifting multi-layer structure in which quite often the one who makes the plan is not the one who executes it.

Good plans let a pilot approach his goal swiftly and efficiently, bad ones slowly or never. Good procedures may be hard to discover. It is the ability to quickly devise an efficient plan for coping with a particular situation that distinguishes the experienced pilot from the less experienced one. More than once our knowledge engineer, a seasoned fighter pilot, who had flown most aircraft in service with the Swedish Air Force, surprised us with tales of how differently less and more experienced pilots address one and the same task.

The aim of the BABEL project was to evaluate trends and tendencies, not to discover niches and singular points in the performance spectrum of particular pilot/platform/weapons combinations. Hence, both artificial pilots are intended to simulate pilots of average proficiency, not flying aces of unique achievement. However, by modifying the resolution of the sensor models it is possible to adjust the level of experience and the degree of awareness of both the automatic pilots and the battle manager.

4. Flying a mission

As a mission proceeds, the battle manager and the pilots must, in order to reach the objective, repeatedly solve the following sequence of subproblems:

- Observe the environment
- Assess the situation
- Plan what to do, consider alternatives, select a plan
- Implement the plan
- Advance in space and time

The first step serves to collect information (visual, radar, data link, voice link, etc.) in order to answer questions like: What (or who) is out there, where is it, what is it doing and what can be inferred from its behavior, what are its future plans ?

The second step is necessary to classify the situation. It evaluates the threats exerted by and to various participants and defines the constraints that may have to be imposed on future actions. It tells an agent whether the current battle plan can be continued, or whether circumstances have changed to a degree that necessitates the creation of a new plan. Basically, this step lays the groundwork for planning.

The third step serves to consider the future course of action. It should result in the selection of a plan that is feasible under the circumstances and that gives the agent a chance to reach or at least approach the desired goal.

Once a decision has been made what to do about a situation, the plan is put into effect in the fourth step.

The fifth step is one that is important in simulations only. It implies that models of the participants must be moved to their new locations as time advances and that the new state of the world (to the degree it is observable) must be made known to the participants. In the real world, this is not much of a problem since one is swept along with the flow of time whether one likes it or not.

In simulations, the first two steps must be repeated periodically, usually every n time units or whenever an important event occurs in the world. If the analysis shows that the battle plan remains valid, step three can be bypassed, otherwise the plan is revised or replaced. Steps four and five then implement whatever plan has been adopted.

The usefulness of a simulation model is largely determined by steps two and three. It is here where the main differences between the H-pilot on the one hand and the battle manager/E-pilot combination on the other lie. Their modes of operation are briefly reviewed.

4. Situation assessment

The criteria employed for situation classification and planning depend on the view one applies to the underlying structure of the problem. One option is to construct the problem space purely based on geometric considerations (e.g. positions, velocities, angles, cones, volumes, rates etc.) and to define the actions of an agent in terms of the spatial relations that exist between objects. An alternative is to condense the many geometric factors together with the performance parameters of the platforms and those of the weapon systems into fewer, but instead more abstract variables that make the classification and decision process more explicit and render it more tractable.

The situation classification performed by the battle manager/E-pilot is based entirely on geometric relations. These are embodied in a rule system which combines simple estimates and rules of thumb with knowledge gathered from experience, training and the tactical doctrine taught to radar controllers and pilots. By the introduction of suitable parameters describing the resolution of sensors and the alertness of the operators varying degrees of skill can be simulated.

The reasoning programmed into the H-pilot is different. It starts out from a simple psychological model and is based on the assumption that what a pilot engaged in close combat decides to do next depends mainly on how he perceives the current threat situation. The latter has two ingredients: The threat which the H-pilot poses to his opponent (f-to-a), and the threat which the H-pilot believes that his opponent poses to him in return (a-to-f).

The combinations of possible values for f-to-a and a-to-f can be displayed in a threat matrix. The one shown in Fig.1 relates specifically to two adversaries engaged in a missile dual at short range. The threat components are very coarsely graded. Each variable measures launch opportunities and can assume only one of three possible values: Can launch now, can launch in the foreseeable future, can never launch. What the terms 'foreseeable' and 'never' mean depends on the planning horizon of the H-pilot. It lies usually between 30 and 60 seconds. Hence, foreseeable is anything that happens within that time horizon, never means everything beyond.

Two more fields denoting exceptional conditions have been appended to the matrix. They pertain to situations, in which a missile is already on the way from the pilot to the adversary, or in which a missile is underway in the opposite direction.

The fields of the threat matrix describe in a symbolic manner the tactical (and, implicitly, the geometric) positions of the combatants relative to each other, taking into account the relative performance of their weapons systems.

It is important to note that the state of the H-pilot is determined on the basis of information which is objectively true. In contrast, the evaluation of the options open to the adversary is made by using information which the H-pilot believes is true, but which in reality may be uncertain, distorted or false.

The basic assumption in the design of the H-pilot was that short term tactical decisions and maneuver selection are determined exclusively by which field of the matrix the H-pilot believes himself to be in. One goal is to reach field seven of the threat matrix, another to never end up in a situation corresponding to fields two or three. Which of these goals prevails at any given moment depends on whether aggressiveness or self-preservation takes precedence.

The fields of the matrix are determined by a generate-and-test procedure. For both participants trial tracks are generated to compute the points which the aircraft could possibly reach within a given time span. The tracks are circular arcs, in some cases sequences of arcs, which are assumed to be traversed at constant speed. A search along each arc then attempts to find potential launch positions. It is determined from where a missile could be launched, when it would reach its targets, when and from where the adversary could launch a missile and when his missile would hit. Trial tracks for the aircraft are generated in bundles with a fairly coarse resolution. At this stage only a rough ball-park estimate of missile performance is used. It is assumed that missiles fly at a constant speed. They have a given range irrespective of how they maneuver or in which direction they fly. While in transition, missiles are required to keep the target in sight.

Typically, between 1000 and 10000 alternatives are investigated in each situation. Sorting the results in terms of the classes employed for describing the threat situation yields the position of the H-pilot in the threat matrix.

While the assumptions and procedures used for evaluating the threat situation are fairly crude, humans, when applying heuristic principles, also evaluate situations in an approximate and fuzzy sense. Somewhat pragmatically is was assumed that, despite the procedural differences, the results of both approaches would be roughly the same.

5. Actions

Once pilots and battle manager have evaluated the situation they have to decide what the next steps should be in order to achieve the mission objective.

The procedures built into the models were conceived solely on heuristic principles. They were established on the basis of the relevant literature, discussions with pilots, intelligence reports, as well as the methods and tactical doctrine taught to air force trainees. Methods were then improved by a large number of practical tests in which the models were flown either against copies of themselves or against human pilots.

The actions taken by the battle manager and the artificial pilots in response to a given situation are described by three rule systems (one for each model). Each system is subdivided into smaller rule groups reflecting the subgoals to be followed and the measures to be taken under various circumstances. What these circumstances are follows from the evaluation of the threat situation. The flight procedures recommended in each case are defined in terms of parametrized maneuvers or supermaneuvers. The main difference between the H-pilot and the E-pilot lies in the time span for which the maneuvers are planned. The H-pilot plans with a horizon of tens of seconds, the E-pilot with one in the order of minutes and the battle manager with one amounting to tens of minutes. Naturally, if during the execution of a plan an event occurs or information becomes available that is relevant to the plan, the situation is re-assessed immediately. Plans are reviewed if one of the following conditions apply:

* The next local (internal) event time is reached.Along with the establishment of a plan always goes an estimate of its duration. When that time expires, a new decision must be made.
* The next global event time is reached. Global events are events external to an object, such as the estimated impact time of a missile in transition.
* The state of an opponent has changed more than a given percentage. The amount depends on the sensor model used.
* A missile is detected.
* A new opponent has been acquired or, for some reason, the current one has vanished
* Circumstances prevail that override all other considerations, e.g. the danger of ground impact.
* Lack of fuel
* Time-out occurs. If no other events are detected, the situation is by default re-examined every n time units (n = 10 to 60).

During the action phase, realistic platform models based on an accurate description of the aerodynamic properties are used. Also, decisions if and when to launch missiles (or use guns) are taken on the basis of realistic missile models. The times applied to target acquisition and verification procedures as well as those used for aiming, arming and launching the weapons are based on experiential data.

6. Discussion

Currently, efforts are concentrating on establishing the credibility of the models by flying them against human opponents in a real time flight simulator. The combination battle manager/E-pilots offered few surprises. As far as tactical considerations are concerned, the action pattern produced by the rule system is strictly in line with the current school of thought. Hence, the proof of credibility rests not so much with the computer implementation as with the source from which the basic specifications had been obtained.

The problem is different where the H-pilot is concerned. In this case, the validity of the concept must be demonstrated. The response of human pilots to flying combat missions against the H-pilot has generally been favorable, although most pilots initially viewed such tests with a great deal of skepticism. In its most agile form the H-pilot proved to be virtually unbeatable, mostly because of its keener perception and faster decision making ability. To have an edge of two or three seconds over the opponent is often all that is needed to gain the upper hand. The application of various delays and inaccuracies in the decision process and the processing of visual information makes the H-pilot more human-like. Even experienced pilots often cannot tell whether they are flying against an artificial or a human opponent. A surprise to human pilots is frequently the unpredictability of the H-pilot who, even in seemingly similar circumstances, practically never repeats himself. This is a consequence of the large search space, so that already small variations in a situation can lead to different behavioral patterns.

A source of criticism was the observation that the H-pilot does not seem to make mistakes. Of course the H-pilot commits errors, but because they are usually masked by subsequent decisions which are essentially correct they are not easy to detect. This raises some serious questions. Experienced pilots claim that gaining the upper hand in air combat is not just a question of superior hardware, better tactics or more refined flying skills. More often they win, because they are able to capitalize on an opponent's mistakes, be they tactical or operational. What pilots would like to see (particularly for training purposes) is an opponent who is not flawless, but who, like humans, occasionally is guilty of miscalculation, observational errors, errors of judgement, etc. Only then would they accept him as a valid adversary. It is imperfection that would make an H-pilot perfect. How to do this remains an open question.

Finally, a remark on an angle that is currently being investigated. In his present form, the H-pilot selects his battle plan by looking at all the options at the disposal of his opponent. He bases his decision on the most threatening alternative, but does not make an attempt to determine the specific intentions of the adversary. Methods are now available to deduce pilot intent from observations of his actions ([6] [7]). It is likely that the use of intent recognition procedures will both increase computational efficiency and further enhance the human-like qualities of the H-pilot.

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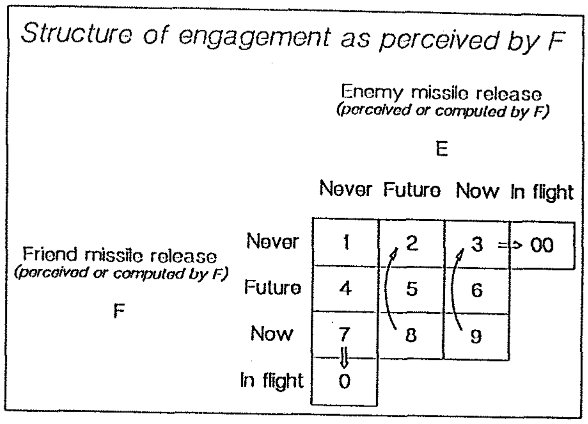

Fig. 1. Threat Matrix