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A NEW DESIGN APPROACH FOR A PILOT ADVISORY SYSTEM IN AIR-TO-AIR INTERCEPTIONS

Y. Yaakov*, J. Shinar**, M. Wolfshtein**
Faculty of Aerospace Engineering, Technion, - Israel Institute of Technology, Haifa, Israel.
A. Boneh***
Department of Statistics, Hebrew University, Jerusalem, Israel

Abstract.

In future beyond visual range multiple target interception scenarios a ***pilot advisory system*** will be necessary not only for adequate performance, but even for mere survival. This study addresses the *pre-launch* phase of the interception at the tactical decision making level in conditions of uncertainty on the opponents behavior. The proposed ***pilot advisory system*** performs three functions: (i) situation assessment, (ii) evaluation of expected utility of options and (iii) tactical advisory. Since it is hard to quantify opponent behavior, a *fuzzy pattern identification* approach is applied. Against the family of expected opponent behaviors an adequate set of tactical options (*response strategies*) are devised. All feasible scenarios are simulated by using *object oriented* programming with *parallel* architecture. Weighting the outcomes, based on the normalized *fuzzy grades of membership*, allows to compute the expected utility of each option and to display to the pilot the *most favorable* option. In the paper a simple example is used to validate the new concept and the computational resources needed for a real-time implementation are estimated.

Introduction

Beyond visual range (BVR) interception of multiple targets, some of them equipped with guided missiles, will be one of the major tasks in future air warfare. One example of a likely scenario is an air-to-air combat of a few high performance fighter aircraft outnumbered by lower performance opponents. High performance in this context includes superior sensors and/or guided missile systems. A BVR air-to-air combat between mutually aggressive opponents is considered to be composed of three consecutive phases[1]: *pre-launch,, post-launch* and eventual *missile avoidance.* In such scenarios a ***pilot advisory system*** is needed even for mere survival.

In the last decade there has been an intensive R&D effort to characterize and develop such a ***pilot advisory system.*** The best known system concept was named **Pilot's Associate**, but very little about it[2-6] has been exposed in the open technical literature. Some *university studies* dealing with this topic[7-16] could be, however, identified. Most of them attempted to combine differential game theory and artificial intelligence techniques in the analysis and the preliminary design of such systems.

In this paper, based on the first author's M. Sc. thesis[17], a different approach is used. The study addresses the *pre-launch* phase of the interception at the tactical decision making level, while in most of previous works the emphasis was on the aircraft control in the *post-launch* and *missile avoidance* phases. The *pre-launch* phase is indeed the most critical phase in multiple target air-to-air interceptions because the decisions are taken at this phase in conditions of *uncertainty* about the opponents intentions and future behavior and these decisions have a dominant effect on the outcome of the engagement.

The paper outlines a ***pilot advisory system*** which has the potential to provide a "tactical real-time guidance" for multiple target air-to-air interceptions by performing three functions: (i) situation assessment, (ii) evaluating the expected utility of tactical options and (iii) tactical advisory. Since future behavior of the opponent is hard to quantify, it is proposed to use a *fuzzy* pattern identification approach. The family of expected future opponent behaviors is considered as an ensemble of *fuzzy* subsets[18]. The role of the situation assessment is to associate an actual opponent behavior, as perceived by the sensor data, with each of the expected behaviors by using normalized *fuzzy grades of membership.* Against the family of expected future behaviors of the opponent a set of *response strategies*[19], formulated as tactical options, are devised. In this way a matrix of possible scenarios is created and the outcome of each can be computed by simulating the engagement. Summarizing the utility of the outcomes between a given interceptor strategy and all considered opponent behaviors, each weighted by its normalized *fuzzy grade of membership,* allows to evaluate the expected utility of this strategy. The tactical advisory function selects and displays to the pilot the tactical option that achieves the highest expected utility. An efficient implementation of such a system, which must operate in a real-time environment, directly depends on the available computational resources. The large number of simulations are carried out by a *parallel computational* architecture using *object oriented* programming.

The structure of this paper is as follows. In the next section the generalized "tactical real-time guidance" problem for a multiple target air-to-air interception scenario is stated. A

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* Graduate Student
** Professor
*** Adjunct Professor

BVR interception scenario with a single 'blue' interceptor and two 'red' airplanes (a bomber and an escort) is used as a simple example. It is followed by the outline of the solution concept and its implementation. The operation of the proposed ***pilot advisory system*** is illustrated by the simple example. Finally the computational resources required for a real-time implementation in a realistic more complex scenario are estimated.

Problem Statement

The BVR air-to-air interception scenario is an engagement between a group of few high performance 'blue' fighter aircraft, assigned to defend a given region of friendly territory against any air to-ground attack contemplated by a group of 'red' bombers escorted by a group of 'red' fighters. Generally, it can be assumed, that the 'red' aircraft outnumber the 'blue' ones. The engagement starts when the 'blue' group detects, or becomes informed, on the position of a threatening group of 'red' bombers. We consider this scenario from the point of view of the 'blue' *group-leader* who is responsible to make a set of tactical decisions, such as:

a, whether to engage the enemy;
b, prioritize the targets;
c, assign each target to an available 'blue' fighter;
d, assign a *pre-launch* trajectory to each 'blue'.

The objective of this paper is to outline the elements of a ***pilot advisory system*** that provides decision support to the 'blue' *group-leader* for planning an efficient interception strategy. The number of alternative decisions, though it can be rather large (depending on the number of participating aircraft), is finite. In this study it is assumed that the actual control of the 'blue' fighters, as well as the timing of the available air-to-air missile delivery, follow a well determined (and well trained) fighting doctrine. Thus, we concentrate on the above described tactical decision level of the engagement.

The tactical advisory should lead to the *best* possible outcome of the engagement. Though the definition of the *most favorable* outcome in a multiple target air-to-air interception scenario may seem to be a straight forward task, the *preference ordering*[20] of all the possible outcomes strongly depends on the fighting doctrine. In the simplest 1x1 air-to-air combat there are only 4 possible outcomes:

1, 'red' is shot down, designated as (0,1);
2, 'blue' is shot down, designated as (1,0);
3, "draw" (none is shot down), designated as (0,0);
4, "mutual kill", designated as (1,1).

Naturally, the *most favorable* outcome for the 'blue' is 1 and the *least favorable* is 2. The *preference ordering* between a "draw" (3) and a "mutual kill" (4) is not soobvious. An aggressive fighting doctrine may prefer a "mutual kill" (4), while a more cautious one may give preference to a "draw" (3). The level of preference can be quantitized by associating with each outcome a non negative *utility* coefficient α. In the 1x1 air-to-air combat the vector of the *utility* coefficients for an aggressive 'blue' pilot can be $\alpha^T = (1.0, 0.0, 0.4, 0.8)$, while a cautious one may select $\alpha^T = (1.0, 0.0, 0.7, 0.5)$ for example.

In a multiple target interception scenario the preference ordering becomes much more complicated. Even in the simplest example (which will be used for illustrative purposes in the sequel) with one 'blue' interceptor against a group of a 'red' bomber and its escort, there are 8 possible outcomes:

1, (0,0,0) none is shot down, i.e. 'red' bomber attacks;
2, (0,0,1) 'red' bomber is shot down, fighters survive;
3, (0,1,0) 'red' escort is shot down, but bomber attacks;
4, (0,1,1) both 'red' bomber and escort are shot down;
5, (1,0,0) 'blue' is shot down, both 'red' survive;
6, (1,0,1) 'blue' and 'red' bomber are shot down;
7, (1,1,0) fighters are shot down, 'red' bomber attacks;
8, (1,1,1) all three are shot down.

Clearly in this case, the *most favorable* outcome for the 'blue' is 4 and the *least favorable* outcome is 5. The preference ordering between the others is, however, not obvious at all. For illustrative purposes we can propose (and use in the sequel) the following *utility* vector for the 'blue' pilot $\alpha^T = (0.2, 0.9, 0.3, 1.0, 0.0, 0.5, 0.1, 0.6)$. This *utility* vector is an inherent part of the problem statement for the example interception scenario.

Another element of the problem statement is the set of expected tactical behaviors patterns of the 'red' aircraft. This set has to be constructed on the basis of information (intelligence) available on the fighting doctrine and the performance of the opponents. Similarly, the set of feasible tactical options of the 'blue' group have to be clearly defined.

The objective of the proposed tactical decision support system is to assist the 'blue' *group-leader* in achieving, in a given scenario (i.e. number and type of participants, initial conditions, guided missile performance, tactical behavior patterns of both sides) the *best* possible outcome based on the available information (intelligence and sensor input). Assuming a well stated interception scenario, the solution concept of a tactical decision support system can be now addressed.

Solution Concept

The tactical decision support system has to carry out three functions: (i) situation assessment, (ii) evaluating the expected utility of the alternative tactical options and (iii) tactical advisory.

Situation Assessment.

In the situation assessment phase the 'blue' *group-leader* faces a major difficulty which has its origin in the inherent uncertainty related to the behavior (strategy) of the 'red' group. If this behavior were known in exact (*crisp*) terms, it would be possible to determine an optimal *response strategy.* Unfortunately however, even if the fighting doctrine of the enemy is known, the expected behavior of each 'red' aircraft cannot be expressed in *crisp* terms. It is rather described in general terms using *linguistic* variables, which are not unambiguously defined. In order to deal with problems of such nature, an approach based on the concept of *fuzzy sets* seems useful.

Let us assume in the sequel that all expected tactical behavior patterns of the 'red' group (as well as the available 'blue' *response strategies*) are defined by using *linguistic* variables. Therefore, each of these tactical behavior patterns can be considered as a *fuzzy* subset. Every actual tactical behavior of the 'red' group belongs to the set called "Red Strategies" (the ensemble of these *fuzzy* subsets) and can be associated with some of the *fuzzy* (*linguistically* described) subsets by a non negative real number between 0 and 1, called the *grade of membership.* Due to the *linguistic* description of the expected tactical behavior patterns an actual tactical behavior may belong to more than one *fuzzy* subset with different *grades of membership.*

The objective in the situation assessment phase is to determine for each actual 'red' behavior, as perceived by the sensor data, the *grades of membership* which relate it to the expected tactical behavior patterns. It is done by carrying out the following steps: (i) fuzzifying the available sensor data describing the actual scenario, (ii) using a set of *fuzzy* rules in order to determine the *grade of membership* of the input associated with each of the expected tactical behavior patterns. One may consider this phase as a *fuzzy* identification process.

Evaluation of Expected Utility

Based on the output of the situation assessment phase which characterizes the 'red' behavior and the available blue *response strategies* a matrix of alternative scenarios is created. Each alternative scenario is deterministicly defined by the initial conditions, the data base of the participating aircraft and missiles and the guidance laws derived to implement the respective behaviors and tactical options (strategies). Thus, each scenario can be simulated using the well known equations of motion. The outcome of each simulation is then associated with its assigned utility coefficient which becomes an element of the scenario outcome matrix. Once all the outcomes associated with a single 'blue' tactical option are available, the expected utility of this tactical option can be evaluated.

In this evaluation the *grades of membership* of the actual scenario (described by the sensor input) with respect to each of the expected 'red' tactical behavior patterns are considered as *fuzzy* probability measures on a finite set. This *fuzzy* probability measure expresses the likelihood that the actual scenario is indeed belongs to one of the expected 'red' tactical behavior patterns. In order that such an operation, be meaningful (both in terms of mathematical rigor as well as for application) one has to assume that all possible 'red' tactical behaviors have been taken into account and that the membership functions have been properly normalized. Based on these assumptions the expected utility of each 'blue' tactical option can be directly obtained as the weighted sum of the different utility coefficient. As soon as all possible scenario alternatives have been simulated the expected utility of all 'blue' tactical options can be also evaluated.

Tactical Advisory

Having the set of all expected utilities, the tactical advisory function becomes straight forward. All that has to be done is to find the 'blue' tactical option with the *highest* expected utility and display it to the pilot. At the end of every computational cycle, repeated as frequently as possible, a new set of sensor inputs are analyzed and the tactical advisory is updated.

Implementation

Since the number of alternative scenarios to be simulated can be rather large, the execution of every updating cycle requires large computational resources, in particular for a real-time use where a high update frequency is required. Therefore the key issue in the realization of the above outlined solution concept is to design an efficient implementation scheme. The design concept of the proposed ***pilot advisory system*** for tactical real-time guidance in air-to-air interception scenarios is based on two important elements. In view of the large computational effort it is self evident that the execution requires using a *parallel* architecture with several processors. At the software level the very nature of the air-to-air interception suggests the use of an *object oriented* programming approach.

Parallel Architecture

The appropriate *parallel* architecture for the proposed ***pilot advisory system*** seems to be a "Master-Slaves" *processor farm* type with dynamic memory allocation. Such an architecture suits very well the execution of a very large number of (similar, but of different duration) scenario simulations. The main reason for this suitability is the relatively low volume of communication between the "Master" and the "Slaves". The main processor (the "Master") monitors the actual scenario, allocates the "Slaves" in the *processor farm* to carry out the different simulations, collects the outcomes and based on them performs the tactical advisory function. There are all together six processes carried out by the main processor: (i) the input process, (ii) scenario characterization, (iii) the coordination of the scenario simulations, (iv) the collection of the simulation outcomes, (v) the evaluation of the expected utilities and (vi) the output process.

The main role of the input process is the interpretation of the available sensor inputs for creating a "picture" of the actual air-to-air interception scenario. One of the functions is to allocate memory to every newly detected object. The other function is the continuous updating of the states of all the participating objects. The characterization of each scenario is based on the situation assessment, which associates the actual state of the scenario obtained via the sensor input with a set of expected opponent behaviors (having non zero *grades of membership*). A scenario is characterized by an available 'blue' tactical option and an expected 'red' behavior. For each 'blue' option a series of simulation scenarios are defined and each scenario simulation is assigned to one of the free "Slave" processors. When a simulation is terminated the "Slave" reports to the "Master". The status of all the "slaves" is monitored in order to guarantee an efficient computational process. The outcomes resulting from each simulation are collected by the "Master". When all simulations relating to a given 'blue' tactical option are completed, the evaluation of the expected utility of this option takes place. At each computational cycle the "grade" of all 'blue' tactical options are modified according to the last evaluation. The tactical advisory function points out the *best* tactical option and displays its "grade". The flow diagram of the main process is shown on Fig. 1.

Object Oriented Design

The suitability of *object oriented* programming approach for air-to-air combat simulation is based on its modularity and flexibility. Indeed several large air combat simulation programs were designed in the past[21] using this approach. For the present tactical advisory system the *object oriented* design approach is illustrated in Fig. 2. Every element in the "world" of the air-to-air interception simulation is an *object*. The relationships (hierarchy and/or inheritance) between different *objects* represents reality. A *class* is a set of definitions of its *attributes* and *operations*. An *object* is an *instance* of a *class*. When a new participant in the scenario is detected by the sensors, this information is forwarded by the "Master" to all the "Slaves" in order to *instantiate* (create) a new *object* having the characteristics of its *class*.

Object oriented programming has several useful properties such as *data encapsulation* which allows to conceal data from other parts of the program and *data abstraction* which lets an outside calling function to ignore the details how the data is presented inside an *object*. Another important feature of *object oriented* programming is *inheritance*. It allows to create a new more specialized *class* from an existing one. For example from the *class* of "Flying Objects" the *classes* of "Airplanes" and "Missiles" can be created. In the *class* of "Flying Objects" one have only those *attributes* and *operations* which are common to "Airplanes" and "Missiles". Such a specialization can continue by creating further new *classes* (for different types of "Airplanes" and "Missiles") as it needed. For example, each *class* of a specialized type of "Air-to-Air Missile" includes the data base, the guidance law, the firing envelope etc. of the particular missile.

There is also another type of hierarchy in *object oriented* programming. *Objects* as "Pilot" or "Air-to-Air Missiles" belong to some "Airplane" in the program and move with it as the simulation develops. When an "Air-to-Air Missile" is launched it inherits the initial conditions from the "Airplane", but becomes an independent *object*. Going into further details seems to be out of the scope of this paper. Let us summarize by stating that the *object oriented* programming creates a very flexible and comfortable environment for operation and software modifications.

Illustrative Example

In this section we try to illustrate the operation of the proposed ***pilot advisory system*** by using a simple of a BVR interception scenario with a 'blue' interceptor and two 'red' airplanes: a bomber and an escorting fighter, as already introduced earlier. In spite of its extreme simplicity, this example has some important salient features of more complex expected future scenarios, one of them is the numerical disadvantage of the 'blue' side. In this example both fighters have the same aerodynamic performance (similar to F-15). The numerical disadvantage is partially compensated by a better 'blue' radar (longer range and faster acquisition). Both fighters are equipped by the same IR guided missiles (similar to AIM-9L). The firing doctrine of the fighters is, however, different. The 'blue' interceptor fires the first missile at the "no-escape" range[22], monitors its flight and in the case of a miss another missile is fired. The 'red' escort fires its first missile at maximum range and continues to fire the second one at the "no-escape" range.

The behaviors of the aircraft in this example are also very simple. The intentions of each side is very clear and only a few tactical options are available. The 'red' bomber always flies straight to its target, disregarding the 'blue' interceptor. The fighter aircraft are both committed to an aggressive behavior and can select to reach a firing position (due to the *all-aspect* properties of the missiles) either in a frontal or a "beam" attack. The 'blue' interceptor has to decide also which 'red' aircraft to attack first, the bomber or the escort. It means that it has four tactical options against only two possible 'red' behaviors. This is indeed a very significant simplification, but it allows to follow the operation of the system in detail without getting confused. Three cases of different initial conditions were selected for testing this example. For each initial condition there are eight different simulations to examine. All engagements start at the altitude of 10,000 feet and assumed to remain horizontal. The initial conditions (positions and velocities) are summarized below.

Case 1	'blue'	'red' escort	'red' bomber
X_0 [Kft]	0	60	60
Y_0 [Kft]	60	70	60
V_x [ft/sec]	900	-500	-500
V_y [ft/sec]	0	700	0

Case 2	'blue'	'red' escort	'red' bomber
X_0 [Kft]	0	120	60
Y_0 [Kft]	130	70	60
V_x [ft/sec]	900	800	-600
V_y [ft/sec]	0	100	0

Case 3	'blue'	'red' escort	'red' bomber
X_0 [Kft]	0	150	100
Y_0 [Kft]	80	120	60
V_x [ft/sec]	900	-800	-400
V_y [ft/sec]	0	0	-500

A simulated engagement scenario ends when one of the following events takes place:

a, the 'red' bomber crosses the line $X = 0$;
b, the 'blue' interceptor is shot down;
c, both 'red' aircraft are shot down.

If the two fighters approach each other to visual range, it is assumed that the engagement between them evolves to a *close-in* air-to-air combat resulting in a "mutual kill".

In each of the three cases the tactical advisory succeeded to select a tactical option for the 'blue' interceptor that lead to achieve the *most favorable outcome:* shooting down both of the 'red' airplanes. The suggested tactical option was different for each case. In Case 1, it consisted of a frontal attack first on the 'red' escort followed by an attack on the bomber. In Case 2, starting a frontal attack on the 'red' bomber with a subsequent frontal attack on the escort was the best option. In Case 3, the tactical advice was to start with a "beam" attack on the 'red' bomber followed by a frontal attack on the escort. Close examination of the results indicated that selection of other tactical options yielded less favorable outcomes.

Estimation of Required Resources

Within the limited resources of a graduate research the implementation of an operating ***pilot advisory system*** with real parallel hardware was not feasible. Nevertheless, the computational resources reqired to handle a more complex interception scenario was estimated. For this purpose an available PC-486/50 Mhz computer with 1.5 MFLOP was used. By simulating a large number of simple engagements (similar to those in the previous section) starting at an initial range of 80 miles, it was found that the average time to simulate such a scenario is of the order of 1.5 seconds. Based on this data the number of advanced parallel processors that can deal with a realistical more complex scenario are estimated.

We consider an air-to-air interception between four 'blue' interceptors against four 'red' bombers and the same number of escorts, as a representative multiple target engagement and a processors of 300 MFLOP (processors whith such peak performance are available today in advanced workstations). Taking into account that the time required to complete the simulation of an interception scenario is roughly proportional to the number of participating objects, a 300 MFLOP processors can execute about 30-35 scenario simulations per second.

An efficient real-time ***pilot advisory system*** requires that the tactical guidance be updated *at least* once in 20 second. (Of course a higher updating rate is always better.) The number of simulations to be executed in order to fulfill the tactical advisory function depends on the number of the participants and on the respective behaviors and tactical options. If a direct combinatorial approach is used, this number can be very high for the above considered complex engagement. Enumeration of all the possible combinations yielded 128 different 'red' behaviors and 96 'blue' tactical options, resulting in a matrix of 12,288 elements. Assuming a *parallel efficiency* of 0.9, the simulation of all these scenarios in the frame of a real-time tactical advisory requires 21 advanced 300 MFLOP processors. Such a huge scenario matrix is, of course, the *worst* case for the given multiple engagement.

Fortunately, the number of interesting scenarios can be much smaller. One can establish a limited set of relevant opponent behaviors by using updated intelligence on their fighting doctrine. Moreover, all 'red' behavior patterns that are associated with a zero (or negligible) *grades of membership* can be eliminated at the situation assessment phase. The number of viable tactical options of the 'blue' side can be also reduced by eliminating obviously inefficient options. It means that either a smaller number of parallel processors may be sufficient, or that the update rate of the tactical advisory can be increased. The rapid development of more powerful processors being a clear trend, the above results seem very encouraging.

Summary and Concluding Remarks

This paper presents the ideas developed in a recent research study for the design of a ***pilot advisory system*** in beyond visual range multiple air-to-air interception scenarios. There are two particularly innovative aspect in this research. The first one is the focus on the *pre-launch* phase of the interception. The other one is the use of a *fuzzy* identification approach addressing the inherent uncertainty of opponent behavior. The simplified example, of a single 'blue' interceptor against a 'red' bomber and its escort, succeeded to demonstrate the validity and viability of the approach. The computational resources required for an operational system, coping with realistic larger scenarios seem to be in the reach, particularly if one considers the rapid development of advanced processors.

It is important to note that the proposed ***pilot advisory system*** can be important not only if it is installed onboard an advanced fighter aircraft. This may require a long engineering development phase. It may be possible to install such a system in an AWACS type airplane supporting the interception. Such a system can be also very useful as an operational training device. As a ground based training device, which doesn't have to obey airborne volume and weight constraints, the ***pilot advisory system*** can bean excellent tool in developing and testing air-to-air combat doctrines.

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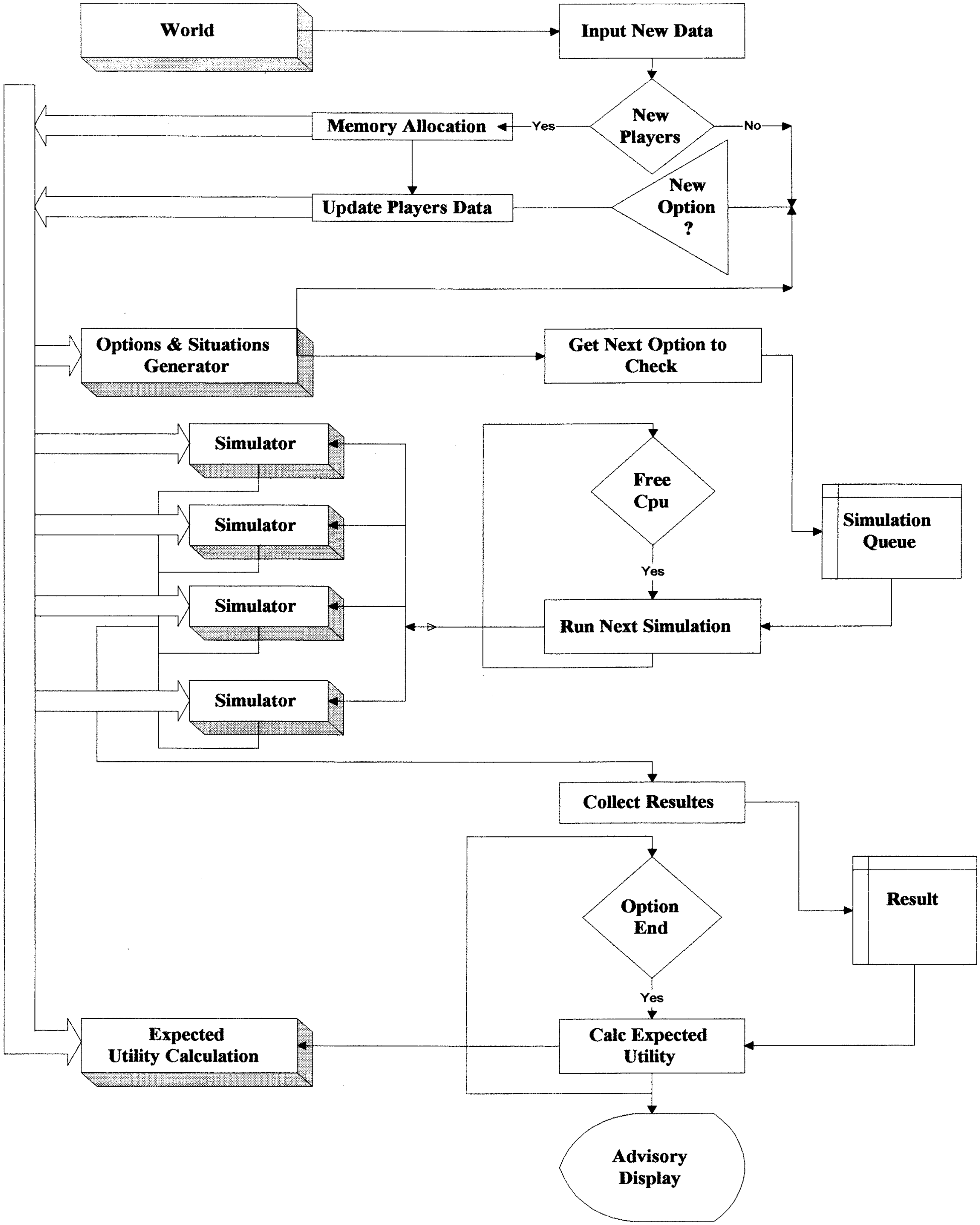

Fig. 1: System Outline.

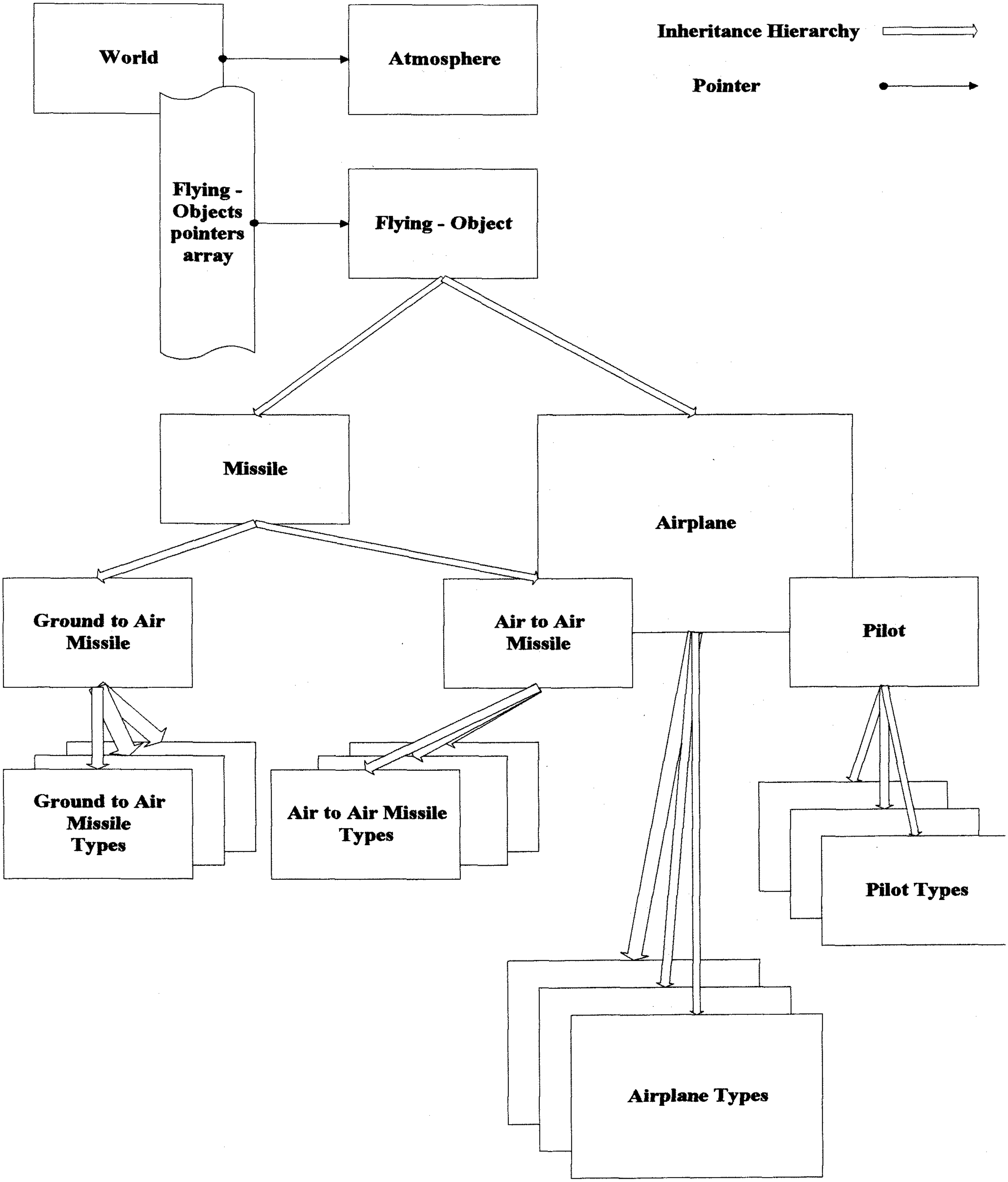

Fig. 2: Object Oriented Architecture.