LECTIO PRAECURSORIA
KAI VIRTANEN **1.4.2005**

Dr. Custos, Dr. Opponent, Ladies and Gentlemen:

Conflicts, such as political, economical and military conflicts are an integral part of human life. In most of conflicts, successful decisions are preceded by some form of rational reasoning. In this sense, the search for the best or optimal decisions and strategies is an important objective of all decision makers.

The modeling of conflicts and combat is present already in the cave paintings of the stoneage. The advantage of complex modeling of a combat has been recognized at least since the fifth century before Christ, when the Chinese general and philosopher Sun Tzu observed the correlation between victory in a combat and well calculated planning. In the last century, formal mathematical frames for decision and conflict analyses have been created.

One of the most complex dynamic conflict situation is air-to-air combat in which decision makers, the pilots, face complicated decision-making problems that concern, for example, maneuvering. In addition to the aircraft performance and the effectiveness of onboard equipments and weapon systems, the decisions and actions taken by the pilots determine, naturally, the ultimate outcome of the combat. Thus, analyses of air combat tactics and technologies as well as pilot training are essential when considering the success of a force in the combat.

Air combat analyses can be conducted with a trial and error experiment, but typically such an experiment requires several airborne test flights. The practical experiments are expensive, time-consuming and pose a risk to life and property. In most cases, the application of mathematical air combat models and computer simulation is the most convenient, cheapest and quickest way to obtain information about system performance or the value of new ways of conducting air combat missions. On the other hand, computer based simulation systems offer good possibilities for supporting pilot training.

Existing air combat models can be classified into two major branches: optimization models providing optimal flight trajectories and simulation models applying synthesis approaches of pilot decisions. The history of both of the branches can be tracked back to the early 1900’s. First, I focus on military flight simulations.

After the Wright brothers have sold the US Army its first airplane, the military began flight training for pilots. The first ground training system appeared around 1910. It consisted of a barrel, cut in half lengthwise, and ropes attached to the four corners. The pilot sat in the barrel while instructors pulled on the ropes to simulate the sensation of flight.

The first modern era man-in-the loop simulator was called the Blue Box trainer that was developed to give pilots a feeling for the cockpit, navigation, and the interaction with other aircraft included in air-to-air gunnery. The trainer was used in the US military through the Second World War, and, in fact, its modified versions were used for initial flight training well into the late 1960's.

Batch, or engineering, air combat simulators made their first appearance in the 1960's as well. They were built to provide a planning and training environment for engineers, which supported the development of aircraft operational concepts and flight testing.

Current military flight simulators are part of aircraft development and pilot's training programs. The simulators of today use the same aerodynamic and flight control models that are used by the aircraft and contains a propulsion model, a cockpit, controls and displays, as well as a visual system.

As examples of today's simulation systems, I would like to mention the Weapons Tactics Trainer and X-BRAWLER. The former is a man-in-the-loop simulator that enables tactical experimentation and training of pilots in a realistic environment. X-BRAWLER is a batch air combat simulator for evaluating system performance and tactical effectiveness. It allows the study of tactics and aircraft performance in a controlled and repeatable environment where multiple actors can be involved.

The air combat simulators use computer guided aircraft for emulating, for example, hostile or target aircraft. The computer guided aircraft require a decision-making model for synthesizing the control and other combat decisions of the pilots. Such synthesis models are considered in my thesis, but before I discuss the thesis in more detail, I review shortly the origin of quantitative analysis of air combat, which is a theme addressed in my work as well.

Quantitative analysis of air combat can be conducted with the help of optimization and game theoretical models. Its roots are in the theory of optimal control, also referred to as dynamic optimization, that allows the determination of the controls transforming the state of an aircraft from its initial state to another state in the best possible way.

One of the first trajectory optimization problems of this type was posed by an American rocket scientist Robert Goddard in 1919. He formulated the following question: Given a certain mass of rocket fuel, what should the thrust history be for the rocket to reach maximum altitude? An analytical solution for this problem was given in 1951 and the problem still persists as a benchmark problem for numerical solution methods of trajectory optimization problems.

In air combat related trajectory optimization problems, the flight time is a commonly used performance index. Perhaps one of the oldest problems is minimum time climb, where one tries to reach a given velocity at a given altitude in the shortest possible time. The problem is interesting since in an air combat the party with more total energy usually has an advantage. On the other hand, optimal trajectories are utilized in air combat mission planning which can be based on estimated risk minimization as well as on the avoidance of detection by the radar of a hostile force. Optimal control theory can also be applied for designing optimal avoidance maneuvers for an aircraft that is pursued by a missile using a known guidance law.

The theory of optimal control can be used for planning optimal trajectories in air combat settings in which only a single actor optimizes maneuvering. What will happen if several pilots with conflicting goals attending the combat. Clearly, the theory of optimal control is void, since we do not know the actions of the adversaries. The theory of differential games can be used for the analysis of such encounters.

Static game theory was essentially established by John von Neumann and John Morgenstern in their classical book "Theory of Games and Economic Behavior". In most cases, such as in air combat, the conflict environment is not static. Its evolution in time must be somehow taken into account in the mathematical formulation of the combat. Typically, the dynamic is described by a set of differential equations. Such a mathematical model brings us to the domain of dynamic conflicts and the theory of differential games.

The study of differential games as a model for dynamic military conflicts started during the Second World War. In the 50's, it emerged from the pioneering work of Rufus Isaacs on optimal pursuit and evasion attempting to model tactical air combat problems. It is often argued that the work of Isaacs with pursuit-evasion games inspired the broader extension of game theory into the dynamic case.

I would like to give few examples on air combat game formulations. An encounter between a missile and an aircraft can be represented by a pursuit-evasion game whose cost function, e.g., the elapsed time, is minimized by the missile and maximized by the aircraft. On the other hand, the pursuer can also be an aircraft that tries to reach the launching position of weapons. In the pursuit-evasion games, however, the roles of the players must be fixed beforehand. This is usually not the case for two aircraft committing to a combat because the pilot may switch several times from a pursuing to an evasive maneuver and vice versa. For such situations, so called two-target game models have been proposed. In such a game, the objectives of the players are to avoid the adversary's weapons while attempting to drive the state of the game to the launching area of their own weapons.

Among other disciplines, I have applied optimal control and game theory in my work that concerns, in broader sense, the design of optimal flight trajectories and the analysis and synthesis of pilot decision-making. Considering optimal trajectory design, I have introduced an approach towards the interactive automated solution of deterministic aircraft trajectory optimization problems. Based on this approach, an example implementation called – Visual Interactive Aircraft Trajectory Optimization - has been implemented.

This modeling work deals with deterministic problems, but my main emphasis has been on developing uncertainty and preference representations in both synthesis and optimization frameworks, which is a theme ignored almost totally in the current air combat related literature, although the pilots must take the combat decisions, typically, under conditions of uncertainty.

In my work, the uncertainty and preference issues are taken into account by tackling optimal air combat maneuvering and decision-making from the perspective of decision analysis, that is a discipline for formalizing the analysis of decisions. The foundations of decision analysis are related to the roots of utility theory introduced by John von Neumann and John Morgenstern, the same persons who established the static game theory.

The main goal of decision analysis is to help the decision maker think systematically about his or her objectives, preferences, as well as about the structure and uncertainty of a decision problem. In the field of decision analysis, there exists a versatile set of techniques for modeling decision situations in a formal manner and for formally solving them.

A primary decision theoretical modeling paradigm used in my work is the methodology of influence diagrams introduced by Ronald Howard and John Matheson in 1984. The influence diagram allows the structuring and analysis of decision problems under conditions of uncertainty. On the one hand, it is a graphical representation for describing variables and factors affecting a decision situation as well as their relationships. On the other hand, the influence diagram enables quantitative analysis of the decision problem by providing a methodological basis for the ranking of the available decision alternatives.

I have constructed an influence diagram that represents the maneuvering and missile launching decisions in on-one-on air combat. This model takes into account the inherent features – dynamics, uncertainty, and multiple conflicting objectives – appearing in air combat. I have also taken another perspective on the same modeling problem and formulated the maneuvering decisions of the pilots as an influence diagram game.

On the other hand, I have considered the representation of preferences and uncertainties in the design of optimal air combat maneuvering with the help of influence diagrams. A multistage influence diagram representing the series of maneuvering decisions is constructed and the new solution procedure for such a model is presented.

In addition to the influence diagram models, I have studied the synthesis and analysis of team decision-making in a multiple aircraft scenario by formulating a value-focused prioritization model where issues on uncertainty are tackled with interval analysis. This modeling work provides a new way to rank and select tactical data included in messages that are transmitted between cooperating air units by a data link system, that allows the pilots to share information about the combat state and to enhance their situation awareness.

The problem area of my thesis – optimal air combat decision-making and maneuvering – is challenging because of difficulties in the formulation of air combat models that are both interesting and feasibly solvable. Optimal air combat tactics leading to the ultimate goal “win the war” are, and will be, unobtainable. Hence, one could ask about the pragmatic value of the thesis: Can we really improve our understanding of air combat by utilizing the ideas and the models innovated in the thesis? Although the new approaches offer several benefits compared to the current air combat modeling frameworks, it is impossible to give a unique answer within the scope of this thesis. Nevertheless, I argue that the thesis has taken the state of the art one step further by introducing a set of new ways of treating uncertainties in air combat modeling.

My work on influence diagrams can also be seen as the extension of the methodology to dynamically evolving decision situations involving possibly multiple actors with conflicting objectives. From the practical point of view, all the synthesis models proposed in the thesis can be utilized in decision-making systems of air combat simulators. On the other hand, the information prioritization approach can be implemented in an onboard data link system.

My thesis may also give insights into issues on the development of technologies required for commanding and controlling unmanned aerial vehicles that are a modern alternative to manned aircraft for conducting critical air missions.

I ask you Dr. Stéphane Le Ménec, as the opponent appointed by the Department of Engineering Physics and Mathematics to make any observations on the thesis which you consider appropriate.