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Dr. Custos, Dr. Opponent, Ladies and Gentlemen

Warfare is intrinsic to humankind. Regarding the outcome of war, the importance of military resources and strategy has been recognized for a long time. Arms and doctrines of warfare have been developed by many engineers and soldiers, such as a Chinese general Sun Tzu, universal genius Leonardo da Vinci, and a Prussian military theorist Carl von Clausewitz to name but a few. The first mentioned contributor defined the strategy and tactics of ancient era by his influential military treatise, The Art of War, whereas the last one can be considered as the father of modern strategic study.

Due to the technological development, the methods of warfare have improved over time. The battlefield extended to the skies after the Aeronatical Division of U.S. Army Signal Corps bought an airplane from the Wright Brothers in 1908. During the First World War, dogfights were carried out by poorly armoured fighters equipped with fixed forward-firing machine guns. By the Second World War, the progress in aircraft performance had led to improved armour and more efficient armament. In 1950's, propeller-powered fighters were finally overtaken by jet fighters and the armament was improved by air-to-air missiles.

In modern warfare, air supremacy is evidently a necessary condition for winning a battle. Satisfaction of this condition asks for both competent air combat arsenal and subtle tactics. One way to improve these elements is to conduct flight tests and learn by trial and error, which is obviously an expensive and risky course of action. A safer and less expensive way is to use mathematical modelling, simulation, and analysis. From the mathematical point of view, performance of air combat arsenal and tactics can be analyzed by means of constructive simulation, optimal control theory, and game theory.

In single-sided air combat missions that contain only one actor such as a fighter aircraft, optimal flight paths with respect to a given goal can be determined using optimal control theory. Typical missions include aircraft minimum time problems where the aircraft tries to reach a given target set as soon as possible. For example, the objective could be to reach certain altitude and velocity in minimum time, or to turn the aircraft to a certain heading as soon as possible. Another salient problem is the minimum fuel problem, where the target set must be attained using as little fuel as possible. Interest to these problems is evident, since the energy advantage and the ability to turn fast are important factors in air combat.

Another central problem concerns the ability of an aircraft to avoid a guided missile. In air combat, the particular problem is of the utmost importance, since the avoidance of guided missiles is crucial for the survival. Missile avoidance problems where control commands of the missile are given by a guidance law can be formulated as optimal control problems as well. In such problems, typical objective of the aircraft is to maximize the interception time or the miss distance of the missile.

When the engagement comprises two independent actors with conflicting goals, the duel can be modelled using concepts of non-cooperative game theory. If the evolution of the engagement is described by a differential equation, the setting can be modelled as a differential game. Since the motions of the aircraft and the missile can be conveniently described by differential equations, aerial duels are typically modelled as differential games.

The aforementioned missile avoidance problems have been traditionally described as pursuit-evasion differential games originated by Rufus Isaacs in 1950’s. In such a game, the pursuing player, for example a missile, tries to capture the aircraft that plays the role of the evader. In a pursuit-evasion game, the roles of the players are unchanged over the encounter. In a dogfight between two aircraft, the roles of the players cannot however be fixed. Such a duel can be modelled as a two-target game, where each player tries to capture the other one, and avoid being captured by the adversary.

Due to the complexity of the aforementioned optimal control problems and games, at most optimal open-loop solutions related to a particular initial state can be obtained. Optimal open-loop solutions provide insight about characteristics of optimal flight paths, but cannot reckon with unpredictable disturbances and uncertainties appearing in air combat. In other words, the solution does not necessarily remain optimal, if the aircraft is deviated from its nominal flight path at some point during the flight. Furthermore, the computation of optimal open-loop solutions must be usually performed off-line, since the problems of interest tend to be computationally demanding. In short, open-loop solutions cannot be applied directly in the guidance of an aircraft.

On the other hand, feedback solutions related to the current state and time are suitable for the purposes of guidance and control of an aircraft. Unlike open-loop solutions, feedback solutions can take into account uncertainty. Although optimal feedback solutions are practically impossible to obtain for complicated air combat problems, several methods exist for the on-line computation of near-optimal feedback controls. From the practical point of view, global optimality is not even necessary, but feasible near-optimal solutions are usually considered sufficient. This justifies the development of suboptimal feedback controllers for aircraft, which is a main theme of my thesis.

I will next shortly describe the methodologies and uncertainty models that I have used as the basis of the on-line solution methods developed in my thesis. These include receding horizon control, Bayesian reasoning, and influence diagrams.

In receding horizon control, the controls are optimized on-line by using a limited planning horizon, which enables real-time implementation due to the reduced computational load. The optimized controls for the current instant are then implemented, and the whole process is repeated at the next decision instant. Obviously, the utilization of a limited planning horizon is typical for humans when acting in a dynamic environment. Consider for example driving a car on a curvy and unfamiliar road, in which case the planning horizon would correspond to the visual range of the driver.

In addition to optimal control problems, receding horizon control is a suitable methodology for the approximate solution of dynamic games as well. Receding horizon control also enables incorporation of additional methods that can cope with uncertainty. First, the feedback mechanism of receding horizon control enables the consideration of unpredictable disturbances. Other sources of uncertainty such as performance parameters of the missile or threat situation of the combat can be handled by using Bayesian reasoning derived from the work of Reverend Thomas Bayes, and decision theoretical frameworks such as influence diagrams introduced by Ronald Howard and John Matheson in 1984.

Bayesian reasoning provides a way to update the degrees of belief assigned to uncertain parameters on the basis of the observed evidence. In general, the updating process feeds the degrees of belief in the true value of the parameter, and lowers the degrees of belief in the false values.

Influence diagrams provide an understandable way for describing decision problems under conditions of uncertainty. Influence diagrams enable graphical representation of relationships between variables and factors included in the decision problem. On the other hand, influence diagrams allow the solution of optimal decisions of the actor. Importantly, the framework offers an intuitive way to incorporate expert knowledge in the modelling process. It is noteworthy that Bayesian reasoning is applied in the evaluation of uncertain variables within the diagram.

In my thesis, I have developed new modelling approaches and on-line solution methods for various aircraft trajectory optimization and one-on-one air combat settings which I will next shortly describe.

Considering missile avoidance problems, I have developed a new on-line aircraft guidance scheme based on receding horizon control. This scheme can be applied using various performance measures that exploit different weaknesses of the missile system. The guidance law of the missile can also be selected freely. In addition, I have extended the guidance scheme such that the aircraft can identify the guidance law of the missile as the missile closes the target aircraft. The result of this development is an adaptive controller for the avoidance of an air-to-air missile.

I have also studied a missile duel between two aircraft, and developed a game model and a real-time solution method for solving optimal support time of an air-to-air missile. The support time means the duration for which the launching aircraft relays target information for the missile before starting to evade a closing enemy missile.

In another game model, I have studied a dogfight between two aircraft. I have continued the previous work of my colleagues to model such a setting using influence diagrams. The resulting influence diagram game allows an understandable presentation of this particularly complicated game setting and consideration of the pilot's uncertainty about the threat situation of the combat. I have also developed a receding horizon control based method for the on-line solution of the influence diagram game, which allows on-line optimization of the pilot's maneuvering decisions in a dogfight.

I have also developed an automated approach for the computation of realistic near-optimal aircraft trajectories, and implemented it as software called Ace. With Ace, various aircraft minimum time and missile avoidance problems can be analyzed. In the approach, the basic idea is to first optimize the trajectory of the aircraft by using a rough but computationally lightweight model, after which the optimal trajectory is followed by a more delicate aircraft model by using inverse simulation. If the optimal and inverse simulated trajectories are sufficiently similar, the latter one can be considered as a realistic near-optimal trajectory.

The computational results obtained in the thesis indicate that receding horizon control based methods are suitable for the on-line solution of complicated air combat optimization problems and games. In addition, additional methods can be integrated into a receding horizon control based controller for handling uncertainties. This supports a conclusion that the presented approaches provide the basis for the onboard guidance system of an aerial vehicle.

Although it is unlikely that automated guidance systems would totally replace human pilots in future, such systems provide valuable decision support for pilots, whose capabilities to observe and process the information about the combat is necessarily limited. I dare to say that the truly practical approaches for the modelling and on-line solution of salient air combat problems developed in my thesis pave the way towards more realistic analysis of air combat tactics.