Tecnhical Summary Ph.D. Thesis

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Typical Sense and Avoid (S&A), or Conflict Detection and Resolution (CD&R) techniques can be defined as the sequence of processes that lead a vehicle to a) identify an hazards along its route, b) run decision making processes regarding the evasion action, c) plan, optimize, and schedule the avoidance maneuovre, d) and finally guide and control the vehicle along its conflict-free path.

The main goal of this Ph.D. activity is to find innovative and effective CD&R methods, in the field of optimization and path planning, for providing optimal deconfliction routes in presence of uncertainty. Since the sensing, decision, and guidance tasks are not treated in this work, the acronym CD&R is used here to refer only to the conflict resolution task, excluding the detection part. Beyond the Ph.D. main scope, this work is required also for safe integration of Remotely Piloted Aircraft System (RPAS) into existing current Air Traffic Management (ATM) network.

The first step of the work was to depict a wide spectrum of the CD&R algorithms already available in literature, and some relevant works under development on this topic. Thus, the problem of CD&R have been tackled via different approaches, and all of them have been based on the formulation of Optimal Control Problems (OCPs). This review has been done to test the effectiveness of some existing algorithms purposed for CD&R problems, and for building up a road-map leading finally to the method and the results presented in this work.

One of the method investigated for solving the CD&R has been the Hybrid Optimal Control Problem (HOCP) approach. Through this approach, the dynamics of various vehicle sharing the same airspace is activated by discrete variables leading to different flight phases. The choice of which flight phase has to be activated to avoid conflict between aircraft, i.e. speed or heading changes maneuvers, is dictated by the functional cost. The solution of the HOCP has been addressed as follow: the problem has been formulated has Mixed-Integer Optimal Control Problem (MIOCP), discrete variables (the switching variables that lead to the activation of flight phases) are relaxed as continuous leading to a Relaxed MIOCP, and finally, a penalization term is added to functional cost to force the switching variables to assume discrete values. As a result, the problem is cast as classical Non-Linear Programming (NLP) problem and solved via optimal control direct method.

Another approach to solve CD&R scenario between several aircraft has been studied, and it relies on the concept concept of Subliminal Speed Control (SSC) . The SSC method employs very small variations of the prescribed nominal speed to minimize the overall time of conflict between pairs of aircraft. By adopting very simple aircraft dynamics, and constraining the aircraft speed to small variations around a nominal value (e.g. $V = V_{nom}(1 \pm 5\%)$) the problem is formulated and solved as NLP.

Small perturbation theory combined with optimal indirect method has been also considered to solve CD&R problems. Although this approach has been usually used for space applications, it can be applied for CD&R in airspace in principle.

The method consists in developing a new strategy to formulate and solve the collision avoidance problem by applying an approximation scheme to the optimal dual problem. The approximation scheme is based on the perturbation theory, a method commonly used to solve ordinary differential equations in space applications. In particular, the algorithm consists in formulating the Hamiltonian 2-Point Boundary Value Problem, i.e., the necessary conditions for the optimality, perturbating the solution, and then solving the problem numerically. The perturbation parameter can be the minimum lateral separation that has be maintained between aircraft. This choice is supported by the following consideration: if a conflict occurs, this involves a region of the airspace which is very small compared to the characteristic length of the domain, i.e., the airspace dimension or the aircraft route lengths. In other words, except for the region close to the conflict, aircraft trajectories projected in the plane are essentially straight lines. Close to the region of conflict, if this occurs, free-conflict solution can be approximated as Taylor expansion with respect to the minimum separation distance. These considerations leads to approximate the solution of the CD&R problems by applying the perturbation theory to the necessary conditions of optimality derived from the optimal control indirect method.

After depicting a non-exhaustive big picture of the algorithms developed in the field of CD&R in the last years, the method developed in this work is presented. The method relies on an analytic tool providing optimal free conflict trajectories in presence of an obstacle affected by spatial uncertainty. The stochastic obstacle avoidance problem is formulated as Optimal Control Problem (OCP), and differential algebra techniques are then used to give an approximation of the optimal solution in presence of uncertainty.

In the current air transportation context, an imminent evolution is needed. More players and innovative solutions are required to cope with the continuous growth of air traffic demand, increasing fuel cost, and emerging concerns over the environmental impact of air transportation sector. Additionally, Unmanned Aerial Systems(UASs) are drawing ever more interest and attention in various civilian and military applications. In facts, due to their versatility, low cost, and vast capabilities in terms of intelligence, surveillance and reconnaissance purposes, UASs are the next novel aircraft that will share the sky with manned aviation. Nonetheless, the enabling technologies needed for the complete integration of UAS with the Air Traffic Management (ATM) context are still less developed in terms of maturity when compared to that of manned systems.

The hurdles for the safe integration of UASs in the mainstream manned airspace operations are numerous. The inabilities of current ATM paradigm can be grouped in four main areas: communication capabilities, onboard and ground-based reliable S&A technologies, aviation infrastructure and regulatory framework, and human-autonomous systems interaction.

Current communication capabilities, as an example, force civil UASs operation to share transmission bandwidth with mobile phones or other telecommunication infrastructure, limiting the ability to coordinate multi UASs and manned aircraft operations with ground. In UASs operations there are no flight rules, no visual-line-of-sight and beyond visual-line-of sight rules, and there could be areas where civil and military radars, or just solar panels, can interfere with the communications between manned and UASs vehicles. An important aspect concerns also the 4.5G telecommunications services. Indeed, some UTM developer using the 4.5G as communication network might experience incompatible latency to receive navigation messages.

Another obstacle is represented by the absence of robust and reliable S&A techniques which allows UASs to operate safely in presence of uncertainty, or unexpected events. The scenario become more complex if one compares centralized systems, i.e., those systems where an human o computer is put as central supervisor and monitor operations, with decentralized systems, where vehicles communicates each others, are entrusted with certain level of awareness and decision, and can take some actions autonomously.

The limitations of the current centralized ATM network, the lack of definitive and complete procedures and standards issued by certification authorities, and concerns related to airspace users and general public, are other challenges to cope with for allowing manned aircraft and UASs to cohabit in the same airspace. Finally, the interaction between autonomous systems and humans make more rocky the integration of UASs operations. Indeed, the current ATM infrastructure has been, since its birth, conceived as human-centric. When multiple autonomous operators are allowed to join into this paradigma, new studies are needed to understand how humans and autonomous systems can work collaboratively, optimizing their capabilities, without obliterating the advantages of autonomous systems.

As a result, it can be affirmed that there are still issues of integrity, security, availability and continuity for the UASs operation integration. Moreover, the above mentioned aspects indicate that the remaining challenges toward the safe and effective implementation of a human-automation collaborative system for UASs operations are still numerous.

Several efforts have been done to improve the telecommunication aspects in decentralize systems . Similarly, novels technologies and new protocols are growing to support Communication, Navigation, and Communication (CNS) systems among manned and unmanned vehicles. Advance in Flight Management Systems (FMS), as an example, allow modern aircraft to compute and plan precise trajectories even in presence of adverse meteorological conditions. Aerospace industry is also working on implementing important key technologies, such as, the Controller-Pilot Datalink Communication (CPDLC) protocol that could alleviate voice-communication frequencies and can reduce errors in voice message transmissions, Global Navigation Satellite Systems (GNSS), or the Automatic Dependent Surveillance-Boradcast (ADS-B). As far as sensing technique is concerned, ADS-B has gained considerable interest as sensing technology for the CD&R capability. ADS-B is a system used to transmit and receive information of 3D position, velocity, bearing and intent of other aircraft. The accuracy of navigation data broadcast airborne, the maturity of the well proven communication technology, and its flexible structure, make the ADS-B a favourable candidate for the integration of UASs in non-segregate space.

Concerning the computational compatibility of human and autonomous systems working collaboratively, and in a optimal manner, some works expose clearly the challenges, the methods, and the technological enhancements needed for the collaborative human-UASs interaction.

The European Aviation Safety Agency (EASA), EUROCONTROL, and the International Civil Aviation Organization (ICAO), have been working together in the last years to pave the way for a UASs regulatory framework. "*The key challenge for drone operators is to establish trust with the manned aviation stakeholders – traditional airspace users, air navigation service providers (ANSPs), pilots, controllers and airports – who are often still in resistance mode when it comes to sharing airspace*". The worlds of Philippe Merlo, EUROCONTROL's Director of ATM, shows that the parties involved in the UAS Traffic Management (UTM) are numerous. As a consequence, EUROCONTROL objectives are mainly focused on developing a strong and common operation area, where every single operator involved is precisely aware of the objectives, and speak the same language. On the other side, also United States have been working on addressing the key elements for UASs integration. In 2017 in facts, Federal Aviation Authority (FAA) gathered more than 60 people in the Unmanned Aircraft System (UAS) Integration Pilot Program (IPP) working on UASs integration issues.

It is clear that all partners agree on the following: the main aspect that need to be addressed for the development of a safe and reliable UTM, is the S&A technological part. Actually, in the course of the implementation of UAS operations into the existing ATM, it is requested that the S&A performance in UAS operations must offer a safety range equalling or exceeding that of manned aircraft. Albeit manned aircraft are already equipped by radars, transponders and other sensing techniques, the sense and avoid problem usually attempts to detect conflicts at very-near sensing limits, when the separation with the potential target is so short to make the response time the most critical factor. Thus, the potential midair collision avoidance is more dependent on the human eyesight capability, and without the human intervention, UASs has to solely rely on the S&A performance. As a consequence, delivering human-like capability for UASs makes the development of S&A very challenging. A part of an increased autonomy and robustness of UAS systems, it is also required that S&A system for UAS should be capable of operating under adverse weather conditions [**?**], and in presence of uncertainties or unexpected events. The growing interest in stochastic algorithms, i.e. methods which can handle with uncertain events, is motivated by the need to address specific objectives also in dynamic environments, those environments subject to unexpected conditions, such as, new tasks emerging, changing weather, and potential Ultra Violet (UV) degradations. In this view, S&A for UAS are the keys for a robust and safe integration of UASs to gain access to civil airspace.

To this purpose, the focus of this work is to build a big picture of the sensing techniques available nowadays for S&A purposes, and provide a novel CD&R algorithm suitable for conflict-free optimal path planning in presence of uncertainty.

The overall objective of the work presented in this thesis is to propose a new method to solve CD&R problems in presence of uncertainty.

As discussed in previous sections, when uncertainties are included into CD&R problems, optimal control has to cope with unknown variables and parameters that add complexity to the OCP. Under this scope, the optimal control theory aims at finding the control variables of a system that minimize an user-defined cost in a stochastic manner, i.e., achieving the prescribed objective with a specific level of confidence. The aim of the work is also to provide different tools for modeling stochastic obstacles in CD&R problems. One one hand, pilots and remote controllers can be rely on such instruments to correctly applying avoidance maneuver while minimizing risk of collision and maintaining mission performance. On the other hand, autopilots and Guidance Navigation and Control (GNC) techniques could surely benefit from the results of such tools in the automatization of planning and tracking optimal conflict-free maneuvers.

The stochastic obstacle avoidance problem tackled in this work is formulated as Optimal Control Problem (OCP). The obstacle conflict is defined as the violation of the minimum distance between the vehicle and the fixed obstacle, and conflict avoidance maneuvers can be achieved by varying the heading angle of the aircraft. The CD&R OCP is solved via indirect optimal control method. Necessary conditions of optimality, namely, the Euler-Lagrange equations, are obtained from calculus of variations, the obstacle constraint is modeled as stochastic variable, and it is included in the OCP. The implicit equations of optimality lead to formulate a Multi-Point Boundary value problem (MPBVP) which solution is in general not trivial. The MPBVP is firstly approximated by Taylor polynomials space, and then solved via Differential Algebra (DA) techniques.

The key role of DA techniques is to provide efficient expansion of arbitrary functions as Taylor polynomial, by replacing floating point operations with corresponding DA operations on a computer. In DA environment, sufficiently smooth functions can be operated on in an algebraic fashion similarly to real numbers. Therefore, DA efficiently represents functions in a way such that they can be easily defined, combined and evaluated through simple arithmetic expressions. Additionally, it is also possible to perform inversion of functions, explicit solution of nonlinear system, and differentiation and integration of functions in DA framework. The term differential algebra therefore comprises both the complete set of the computer representation of polynomial expansion (DA objects), and the set of intrinsic functions and operations available to operate on the polynomials. DA techniques, within the Differential Algebra Computational Engine (DACE) computer framework, are used in this thesis to give an approximation of the optimal solution, and to map the obstacle uncertainty. As far as the uncertainty mapper is concerned, DACE is used here to introduce an optimality level, i.e., a probability indicator (related to the real probability) that a given trajectory is the optimal one in terms of flight time and constraint satisfaction. As a consequence, the solution of the OCP presented in this work is a set of polynomials representing the optimal controls in presence of uncertainty, i.e., the optimal heading angles that minimize the time of flight, while taking into account the uncertainty of the obstacle position.

Summarizing, the methodology employed for the resolution of the stochastic OCP has been developed by the following steps:

- conflict scenario is identified by an intended nominal aircraft 2D route conflicting with an obstacle modeled as circular shape;
- due to uncertainty affecting on-board sensors, it is assumed that position of the obstacle centre follows a bivariate Gaussian distribution probability density function, while the radius of the obstacle is a known parameter;
- time of flight is chosen as performance index or cost function of the problem, and together with boundary conditions and dynamics of the aircraft, the CD&R problem is formulated as classical OCP;
- the OCP is then solved via optimal indirect method, i.e., by setting and solve the first-order optimality conditions, namely the Euler-Lagrange equations. The result is a Multi-Point Boundary Value Problem (MPBVP) which solution is the heading angle control law leading to a conflict-free trajectory;
- Differential Algebra Computational Tool (DACE) is used to solve the MP-BVP by approximating the solution as Taylor polynomial expansion;
- obstacle uncertainty is propagated into the problem by using DACE, and optimal control probability map is obtained;
- Monte Carlo (MC) simulations are run to validate the results of DACE indirect method.

In order to reduce the computational burden required for stochastic methods, and obtain a closed-form analytical expression of the control solution, a novel approach based on indirect optimal control and differential algebra analytical tool is presented. In particular, an aircraft colliding with an uncertain fixed obstacle is considered, and the optimality conditions of the obstacle avoidance OCP are formulated by employing the indirect method approach. Once the CD&R problem is formulated as MPBVP, the polynomial approximation of the solution (solution map) is rapidly addressed by using the Differential Algebra (DA).

Summarizing the discussion above, the main contribution of this work can be stated as follow. A novel indirect optimal control method based on DA techniques to solve a stochastic OCP is introduced. The solution map of the stochastic OCP is obtained at the expense of a very low computational cost, and applicability of this method to other type of hazards (storms, no-fly zones, other aircraft) is straightforward.