CHAPTER 9. CONCLUSIONS AND FUTURE RESEARCH

In this thesis, the formation mission design problem in the presence of uncertainties has been solved using stochastic optimal control techniques, with the aim of demonstrating the economical feasibility of formation flight in commercial aviation.

First, the formation mission design problem for commercial aircraft has been studied in the absence of uncertainties. A novel framework to solve the problem has been presented, in which the formation mission is modeled as a switched dynamical system, aircraft are assumed to have two flight modes, namely solo and formation flight, and the discrete state of the switched dynamical system is the result of their combination. The discrete dynamics of the system has been modeled using logical constraints in disjunctive form. Thus, the formation mission design problem has been formulated as an optimal control problem for a switched dynamical system with logical constraints in disjunctive form. The optimal control approach allows accurate flight dynamics models and meteorological forecast to be taken into account, improving trajectory predictability and the estimation of both flight time and fuel consumption of the aircraft involved in the formation mission design problem.

The switched optimal control problem has been solved using the embedding approach. The embedding approach is a unifying technique able to efficiently tackle both the switching dynamics and the logical constrains of the switched optimal control problem, transforming it into a smooth optimal control problem, which has been solved using classical numerical optimal control techniques. Specifically, direct numerical optimal control techniques based on pseudospectral knotting methods have been used. The main advantages of this approach are that the multiphase formulation is avoided, as well as the use of binary variables, decreasing the computational time and effort in finding the solution. This approach is substantially different from previous approaches, which are based on exhaustively analyzing every possible formation mission individually and then comparing the results. Additionally, this approach is easily scalable to design formation mission problems with an arbitrary number of aircraft.

Several numerical experiments have been conducted with two and three transoceanic flights. Additionally, an analysis of the solutions has also been carried out in order to study how the delays in the departure time and changes in the fuel saving scheme influence the formation mission. The results indicate that delays and changes in the fuel savings scheme have significant influence on the formation mission. This suggests that a deeper understanding of the effects of uncertainties in these and other parameters on the formation mission is needed.

Therefore, the formation mission design problem for commercial aircraft in the presence of uncertainties has been addressed. Uncertainties are represented by random variables characterized by probability density functions. The formation mission design problem in the presence of uncertainties has been formulated as an stochastic switched optimal control problem and solved using the generalized polynomial chaos expansion, by means of which the original stochastic switched optimal control problem is transformed into an equivalent deterministic switched optimal control problem in a higher dimensional state space. The generalized polynomial chaos expansion allows, not only a statistical analysis, but also a sensitivity analysis of the stochastic solutions to be conducted at a low computational cost to estimate the relative contribution of each random variable to the variability of the components of the solution.

Several numerical experiments have been conducted with two and three transoceanic flights. The results of the numerical experiments indicate that uncertainties have a significant impact on the potential benefits of a formation mission. The results of the sensitivity analysis reveal that one random variable may have predominant influence on the variability of a component of the solution. They also indicate that the relative influence of the random variables on the variability of a component of the solution may change during the flight.

The results of the numerical experiments demonstrate that formation flight is economically beneficial in the presence of realistic levels of uncertainty in the fuel savings for the trailing aircraft and in the departure times of the aircraft. The results of the numerical experiments also show that the proposed frameworks for formation mission design in the presence of uncertainty is fast and accurate. These features, makes the proposed approach suitable to be incorporated in a ground-based system which could be used by flight dispatchers as a support system to design formation missions for airlines or airline alliances. The computational time of the proposed algorithm makes it suitable for the strategic and tactical planning phases of the flight, as well as for the operational phase, that is, during the flight.

9.1. Open problems and future research

Due to the complexity of the formation flight planning problem, after studying the formation mission design problem, there are several open problems, which will subject of future research. They will be described in this section.

As said in Chapter 2, the formation flight planning problem can be split into two subproblems, namely the partner allocation problem and the formation mission design problem. The former, which consists in establishing how to group a set of longhaul flights into smaller subsets that contain potential partners of beneficial formation missions in terms of the overall DOC, has not been studied in this thesis. Thus, due to its close relation with the formation mission design problem, the partner allocation problem will be one of the first to be studied. Preliminary research indicates that this problem could be solved by first calculating the optimal solo flight trajectories using the numerical optimal control methods described in Chapter 5 and, then, applying a suitable spatiotemporal geo-referenced data clustering algorithm [Ansari et al., 2020] such as those introduced in [Vieira et al., 2009] and [Jeung et al., 2010], to solve the problem of finding objects that move together in a spatiotemporal geo-referenced dataset, which are referred to as flocks or convoys. In [Aung and Tan, 2010] an extended version of this problem is studied, in which the members of the convoy can change over time.

As explained in Chapter 3, a fuel consumption reduction model has been employed for the trailing aircraft, instead of an induced drag reduction model. Therefore, to improve the estimations of the benefits achieved by formation flight and, consequently, the DOC of the formation mission, the latter model should be adopted.

In all the experiments described in this thesis, only one type of formation has been considered and the leader of the formation has been set in advance. Therefore, to improve the methodology proposed in this thesis, after a thorough study of the aerodynamics of formation flight, some other functionalities should be included, such as the possibility of choosing the optimal type of formation for a given formation mission and the optimal positions of the leader and the trailing aircraft in the formation.

In this thesis, accurate dynamic models of the aircraft have been considered to solve the formation mission design problem. However, some simplifying assumptions, which have been outlined in Chapter 3, have been introduced, such as the reduced two degree of freedom point variable-mass dynamic aircraft model. Therefore, to improve the accuracy of the solutions and the predictability of the resulting aircraft trajectories, a non-reduced three degree of freedom point variable-mass dynamic aircraft model should be employed.

Although the wind field has been included in the dynamic models of the aircraft in all the numerical experiments, it has been considered as a deterministic vector field, which is not a realistic assumption. Therefore, to improve the accuracy of the solutions and the predictability of the resulting aircraft trajectories, uncertainties regarding the wind forecast should be considered. Being a random function of space and time, the wind field should be modeled as a stochastic process. Although the generalized polynomial chaos expansion can be employed to represent stochastic processes, specific techniques are needed for their representation, such as the Karhunen–Loève expansion.

In Experiment B described in Chapter 8, two sources of uncertainties have been considered, namely the departure time of the flights, which have been quantified using the generalized polynomial chaos expansion. However, they have been assumed to be independent random variables. In the presence of dependent random variables, the Vine Copula technique [Torre et al., 2019] must be used before applying the generalized polynomial chaos expansion. In both cases, increasing the number of sources of uncertainties considered in the problem, increases the dimensionality of the problem and, consequently, sparse grid numerical methods should be used such as the Smolyak sparse quadrature [Xiu, 2010].

Finally, most realistic instances of the formation mission design problem could be solved including probabilistic constraints, also known as chance constraints [Kim and Braatz, 2012] in the formulation of the problem. Chance constraints can be included in the formulation of the problem using the generalized polynomial chaos expansion.