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New reference trajectory optimization algorithm for a flight management system inspired in beam search

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Abstract With the objective of reducing the flight cost and the amount of polluting emissions released in the atmosphere, a new optimization algorithm considering the climb, cruise and descent phases is presented for the reference vertical flight trajectory. The selection of the reference vertical navigation speeds and altitudes was solved as a discrete combinatory problem by means of a graph-tree passing through nodes using the beam search optimization technique. To achieve a compromise between the execution time and the algorithm's ability to find the global optimal solution, a heuristic methodology introducing a parameter called ''optimism coefficient was used in order to estimate the trajectory's flight cost at every node. The optimal trajectory cost obtained with the developed algorithm was compared with the cost of the optimal trajectory provided by a commercial flight management system(FMS). The global optimal solution was validated against an exhaustive search algorithm(ESA), other than the proposed algorithm. The developed algorithm takes into account weather effects, step climbs during cruise and air traffic management constraints such as constant altitude segments, constant cruise Mach, and a pre-defined reference lateral navigation route. The aircraft fuel burn was computed using a numerical performance model which was created and validated using flight test experimental data.

1. Introduction

Several studies by aeronautical authorities and associations have estimated that the number of aircraft in service will increase in the forthcoming years.[1] Having more aircraft airborne will bring new challenges to air traffic management to guarantee safe and efficient flights.

Worldwide, several programs have been initiated for the research, development and implementation of systems,

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regulations and procedures for future air traffic management. These programs include the Next Generation Air Transport System (NextGen) in North America, led by the United States, the Single European Sky Air Traffic Management(ATM) Research (SESAR) in Europe, and the Collaborative Actions for Renovation of Air Traffic Systems (CARATS) in Japan. These programs improve ATM to guarantee safety, expand air space capacity, reduce polluting emissions, and to provide flight trajectories as efficient as possible.

Efficient flight reference trajectories result in both flight time and fuel burn reductions. Flying these trajectories is extremely desirable, since fuel burn reduction directly diminishes polluting emissions, as well as saved on costs. As pointed out by the Air Transport Action Group (ATAG), around 2% of the carbon dioxide (CO_2) emissions released to the atmosphere are caused by aeronautical activities.[2] The industry has set itself the goal of reducing its CO_2 emissions to 50% of those generated in 2005 by 2050.[3] Many organizations have been created to address and solve the pollution problems. One such example is the Business-led Network of Centers of Excellence Green Aviation Research & Development Network (GARDN) in Canada, which encourages services and products to reduce polluting emissions.

Several new technologies and aircraft modifications have already been considered with the aim to reduce polluting emissions in which winglets have been proven to improve aircraft efficiency.[4] What's more, changes in materials and avionics equipment have reduced aircraft weight, as well as the introduction of biofuels,[5] and engine improvements have also reduced fuel burn. Airlines can achieve fuel savings with their current fleets by implementing different operational measures, such as the single engine taxiing, ground power units, engine washing, and flight reference trajectory optimization as presented in Ref. 6 Therefore, implementing these improvements in current fleets is becoming a necessity, since the newer aircraft generations alone will not be enough to fulfill the industry's polluting reduction goals.[7]

The Continuous Descent Approach (CDA), an operational procedure related to flight reference trajectory optimization, has been proven to reduce fuel consumption. With this procedure, the aircraft descends with the engines in the IDLE mode (least fuel consuming setting) instead of descending in the conventional step descent pattern. Several airports have implemented this technique because it contributes to fuel savings and noise reduction.[8–11] The CDA must be implemented correctly to avoid the need to execute a missed approach procedure, which is expensive in terms of fuel burn and pollution emission release.[12,13] Other approaches, such as air to air refueling was studied in Ref. 14 and aircraft ground movement optimization was suggested in.[15]

For "en-route" operations, Jensen et al. 16,17 in stated that aircrafts in the United States do not fly at their optimal speed or altitude. Other discussions have been conducted regarding the savings that flying at low cruise speeds may bring, as well as at how lower cruise speeds would affect other aircraft flying near the low-speed cruise aircraft.[18,19] Turgut et al. 20 developed equations to obtain the fuel flow for different aircrafts and found out that flight trajectories for national flight within Turkey can be improved.

Current reference trajectory optimization was done by ground teams or by airborne avionics such as the commercial Flight Management System (FMS). The former can use algorithms that require many computational resources to find the optimal reference trajectory; the latter require fast algorithms to find an optimal or a sub-optimal reference trajectory.

The reference trajectory could be studied in two different dimensions: The vertical dimension and the lateral dimension. The first consists in the speeds and altitudes that provide the most economical flights, and the latter consists in the geographical waypoints where no obstacles are present, and where the aircraft can take advantage of weather, such as tail winds, to reduce the flight cost.

A number of optimization algorithms have been implemented to solve the reference trajectory optimization problems. Different optimal control techniques considered various constraints and optimization objectives.[21–27] Equations of Motion (EoM) were used in these optimal control based algorithms in order to find the optimal solution. Other authors applied the dynamic programming; such as Yoshikazu et al. 28 who developed a moving search space algorithm by taking into account both weather and the Required Time of Arrival (RTA) constraints. Ng et al. 29 also used dynamic programming, by taking into account winds for a fixed Mach number and by allowing changes in the flight level during the cruise regime. Hagelauer and Mora-Camino[30] utilized the EoM to implement dynamic programming with neural networks to optimize trajectories, underscoring the fact that FMSs use numerical performance databases instead of EoM.

In Reference trajectory optimization focusing on avoidance (obstacles or weather constraints) has also been investigated. Cobano et al. 31applied the Particle Swarm Optimization (PSO) for a 4D (RTA constraint considered) trajectory. Ripper et al. 32 used graph search algorithms to optimize the route of a general aviation aircraft while avoiding obstacles. The dynamic physical principles of a stream avoiding obstacles were adapted to the path trajectory optimization. This methodology allowed the avoidance of objects of different shapes.[33] An algorithm able to optimize the flight trajectory of cooperative Unmanned Aerial Vehicles (UAV) able to avoid obstacles was developed using a combination of the central force optimization algorithm and genetic algorithms in Ref. 34.

All these optimization algorithms were able to optimize the flight reference trajectory by fulfilling their imposed constraints. However, solving the EoM to find the optimal trajectory in a system with limited processing power, such as an FMS, can be very much time consuming, leading its implementation to be impractical. Therefore, the FMS do not normally use these equations, and instead use a set of look up tables with experimental data called a numerical performance model.

Numerical performance models provide fuel consumption information, and therefore researchers have developed fuel burn estimators that work with this type of models to compute the cost of a cruise segment.[35] These estimators were later used to optimize flights in cruise.[36] Félix et al. 37 used genetic algorithms to find the optimal trajectory by taking advantage of winds. Murrieta and Botez 38 used the Dijkstra's algorithm to find the optimal trajectory by taking advantage of winds and temperatures.

The vertical reference trajectory optimization problem applied on a numerical performance model for all flight phases can be treated as a combinatorial problem. The number of possible solutions (feasible or not) are defined by combinations of Indicated Air Speeds (IAS), Mach numbers and altitudes

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