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Flight formation of UAVs in presence of moving obstacles using fast-dynamic mixed integer linear programming

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ABSTRACT

This paper proposes the implementation of fast-dynamic Mixed Integer Linear Programming (MILP) and Path Smoother for efficient path planning of Unmanned Aerial Vehicles (UAVs) in various flight formations. The UAVs taking part in a cooperative flight are assumed to be equipped with Automatic Dependent Surveillance Broadcast (ADS-B) which enables sharing the flight information with neighboring aircraft. The design and implementation of flights for various formations have been carried out in a generic manner such that multiple UAVs with arbitrarily geographically located base stations can take part in collision-free formation flight. The paper formulates the problem of path of planning in the framework of a novel fast-dynamic MILP and proposes a cost function that minimizes time and energy consumption. The paper presents elaborate construction of constraint equations to enforce the formation to visit pre-defined way-points and avoid the collisions with any intruder aircraft. The performance of the proposed algorithm has been verified and compared with respect to the standard MILP method via a number of simulations carried out using different scenarios featuring multiple UAVs flying in various formations.

1. Introduction

Unmanned Air Vehicles (UAVs) have traditionally been used in military operations for a number of years. Recently, UAVs have generated a lot of interest due to their potential application in civilian domains such as emergency management, law enforcement, precision agriculture, package delivery, and imaging/surveillance [46,32,38,30,29]. However, before the use of UAVs becomes a reality in civilian domains, the challenges emanating from integration of UAVs in the National Airspace System (NAS) are extremely critical to be solved. An important among these challenges is the ability for a UAV to not only plan its own path for fulfilling a mission but also to re-plan or adjust its trajectory in order to avoid collision with other aircraft. Furthermore, the increase in the number of aircraft has been dramatic over the last 50 years. This increase in manned aircraft along with incorporation of unmanned fleet in future will pose severe challenges to the current Air Traffic Control (ATC). Hence, the Radio Technical Commission for Aviation (RTCA) and also Federal Aviation Administration (FAA) have been charged with a responsibility to implement a seamless change from ATC to Air Traffic Management (ATM) by 2020 [40,35,33] that incorporates mechanisms to plan/replan the paths of UAVs to avoid collisions with other aircraft.

There are various methods for calculating escape trajectories that have been proposed for collision avoidance including classical control [4], Fuzzy Logic [28], E-Field maneuver planning [27,41], game theory [48] and their application in NC Machines path planning [11,50], automotive trajectory planning [2], and air traffic management [13].

Group cooperative behavior implies that the members share a common goal and act according to the common objective of the group. Effective cooperation often requires that each individual of the group coordinates its actions [34]. Using multiple UAVs for the different applications has attracted many researchers. Apart from the fact that multiple UAVs provide ability to perform complex and heterogeneous tasks, one of the advantages of cooperative flight performances is also fuel saving [8,12]. Path planning of such systems offers many challenging problems from both theoretical and practical points of view. Formation flight is referred to a particular problem of management of a group of UAVs flying in tight cooperation within a defined volume [23], and often with a predefined shape. Although studies on active path planning of a UAV have been considered many times (e.g., see [17,51,52]), cooperative path planning approaches for UAVs have only recently begun to

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Nomenclature

γ	Assumed angle between the waypoints and the path
σ	Parameter added to the size of obstacles for safety factor
τ^b	Control inputs of the aircraft
τ_{other}	Disturbance
τ_{wind}	Forces exerted to the body caused by wind
C	Total number of UAVs in formation
D	Damping matrix
f_{max}	Maximum force in xy direction
$f_{x,t}$	Force in x direction exerts on the UAV
$f_{y,t}$	Force in x direction exerts on the UAV
$f_{z,max}$	Maximum force in z direction
$f_{z,t}$	Force in x direction exerts on the UAV
g^n	Gravity vector in NED
L_1	Length of the cube where finite horizon is generated in different scenarios
L_2	Length of the cube where finite horizon is generated in different scenarios
L_3	Length of the cube where finite horizon is generated in different scenarios
L_4	Length of the cube where finite horizon is generated in different scenarios
m	Mass of the body
M_{big}	Constant number
O	Number of IAs in finite horizon
Q_1	Constant number
Q_2	Constant number
Q_3	Constant number
Q_4	Constant number
R	Rotation matrix
r	Constant number
T	Total time of flight in finite horizon
t	Time step in finite horizon
t_1	Time the UAV starts collision avoidance
T_d	Sample time of discretization
t_G	Time for the UAV to reach local goal
$t_{collision}$	Time predicted for the UAV till the collision
T_{total}	Total time of flight
v^b	Velocity of object in body frame
$v_{c,t}$	Velocity of UAV c at time t
$v_{max,forward}$	Maximum velocity of UAV in xy plane
$v_{max,o,forward}$	Maximum velocity of IA in xy plane
$v_{max,o,total}$	Maximum possible velocity of IA o
$v_{max,o,z}$	Maximum velocity of IA in z direction
$v_{max,z}$	Maximum velocity of UAV in z direction
$v_{rel,o,t}$	Relative velocity of IA o at time t
$v_{t,o}$	Velocity of IA o at time t
$v_{x,c,t}$	Velocity of UAV c in x direction at time step t
$v_{y,c,t}$	Velocity of UAV c in y direction at time step t
$v_{z,c,t}$	Velocity of UAV c in z direction at time step t
$x_{c,t}$	x position of UAV c at time t
$x_{IA,t}$	x position of IA at time t
$x_{max,o}$	Maximum x of the obstacle o
x_{max}	Maximum x in finite horizon
$x_{min,o}$	Minimum x of the obstacle o
x_{min}	Minimum x in finite horizon
$x_{t_{collision}}$	x position of the prediction where collision might happen
x_{w_c}	x position of the waypoint c
$y_{c,t}$	y position of UAV c at time t
$y_{IA,t}$	y position of IA at time t
$y_{max,o}$	Maximum y of the obstacle o
y_{max}	Maximum y in finite horizon
$y_{min,o}$	Minimum y of the obstacle o
y_{min}	Minimum y in finite horizon
$y_{t_{collision}}$	y position of the prediction where collision might happen
y_{w_c}	y position of the waypoint c
$z_{c,t}$	z position of UAV c at time t
$z_{IA,t}$	z position of IA at time t
$z_{max,o}$	Maximum z of the obstacle o
z_{max}	Maximum z in finite horizon
$z_{min,o}$	Minimum z of the obstacle o
z_{min}	Minimum z in finite horizon
$z_{t_{collision}}$	z position of the prediction where collision might happen
z_{w_c}	z position of the waypoint c

appear. The problem of formation flight is widely studied in literature. Considering only the flight control, classical leader-wingman configuration is investigated via proportional-integral control [9] or non-linear control [47]. A reactive behavior-based controller is discussed in [5]. Proposed solution for trajectory optimization of large formations using centralized or distributed algorithms is discussed respectively in [25,39], taking into account some constraints on the shape of the formation. Reconfiguration in the formations is introduced in Ref. [54] by proposing a scheme where trajectories are computed off-line for switching between a limited number of formation configurations. In [43,1,19,18], by implementation of mixed-integer linear programming (MILP), tightly-coupled task assignment problems with timing constraints are solved for a group of UAVs.

This paper focuses on developing a method for a team of UAVs, in this case quad-copters, to navigate through an environment filled with static and dynamic obstacles while in formation. The proposed method formulates the path planning problem in the framework of MILP, the solution of which provides the waypoints for each UAVs. The main contribution of the paper is proposing a fast-dynamic approach to the MILP using a hybrid branch and bound method for obtaining exact solution of the MILP over rational numbers. Since the aim is to exactly and efficiently solve MILP with application to UAV trajectory planning, a version of branch-and-bound is proposed that attempts to combine the advantages of the pure rational and safe-Floating Point (FP) approaches, and compensates for their individual weaknesses. The solution is to work with two different and hybrid branch-and-bound processes. The aim of the *main process* is to implement the rational approach. The other part of the process is the *slave process* where the faster FP approach is applied. Furthermore, a concept of using dynamic finite horizon is implemented in the paper that solves the MILP is a local spatial region that keeps updating as the UAV continues on its path.

A cost function is proposed that includes two components: i) total time to minimize the time of flight; and ii) control inputs to minimize energy consumption. The paper then implements a path smoothing strategy to adapt the generated path to the dynamics of the UAV. The paper considers two scenarios of flight formations in order to simulate flight performances. In the first scenario, the UAVs break the formation in presence of obstacles and try to get to their goal path while minimizing the cost function. In the second scenario, the constraint of the fixed formation is applied on UAVs for the whole duration of flight so that UAVs navigate from initial