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Collision-Free Rendezvous Maneuvers for Formations of Unmanned Aerial Vehicles

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Abstract: This article discusses the rendezvous maneuver for a fleet of small fixed-wing Unmanned Aerial Vehicles (UAVs). Trajectories have to be generated on-line while avoiding collision with static and dynamic obstacles and minimizing rendezvous time. An approach based on Model Predictive Control (MPC) is investigated which assures that the dynamic constraints of the UAVs are satisfied at every time step. By introducing binary variables, a Mixed Integer Linear Programming (MILP) problem is formulated. Computation time is limited by incorporating the receding horizon technique. A shorter planning horizon strongly reduces computation time, but delays detection of obstacles which can lead to an infeasible path. The result is a robust path planning algorithm that satisfies the imposed constraints. However, further relaxation of the constraints and fine-tuning is necessary to limit complexity.

Keywords: Path planning, Optimal trajectory, Obstacle Avoidance, Mixed integer linear program, Unmanned aerial vehicle, Model predictive control, Collision avoidance, Receding horizon

1. INTRODUCTION

With the development of cost-competitive small fixed-wing unmanned aerial vehicles, interest in the control, trajectory generation, and formation flying of such vehicles has greatly increased. Many applications have been studied, such as surface-to-air missile jamming, monitoring of farms and irrigation control, and forest fire monitoring. (Chao et al., 2008) However, reliable real-time control of fleets of UAVs still remains difficult to achieve because of varying wind conditions (Wu et al., 2011) and limited communication range between UAVs (Beard and McLain, 2003). Furthermore, on-line calculation of the global optimal trajectory in terms of mission time or fuel consumption is often not feasible due to the required computation time. Therefore, a number of approximate methods have been developed such as a two-phase strategy and the receding horizon approach (Kamal et al., 2005; Richards et al., 2002; Bemporad and Rocchi, 2011; Hwangbo et al., 2007). These techniques do not calculate the globally optimal trajectory, but allow for a significant reduction in computation time.

One of the most crucial parts of formation flying is the rendezvous maneuver performed in order to achieve a specific formation. The principal objective of this study is to implement a path planning algorithm which minimizes the time required for this maneuver while satisfying an elaborate set of constraints. Collisions with other UAVs and static or dynamic obstacles have to be avoided at all times. The algorithm is based on Model Predictive Control (MPC) and reduces the optimization problem to a Mixed Integer Linear Program (MILP). A MILP approach can be applied for optimization problems of which part of the variables in the cost function and/or constraints are integers. Commercial packages, such as AMPL/CPLEX, are often used to solve this type of problem. In this paper, a receding horizon strategy (Kamal et al., 2005; Schouwenaars et al., 2001) is incorporated in the MILP framework and solved by means of the `intlinprog` command in Matlab.

Firstly, section 2 gives a precise problem statement. Secondly, an overview of the applied methodology is given in section 3. This section also elaborates on the cost function and the constraints of the MILP problem to be solved. Thirdly, the performance of the controlling algorithm is evaluated in section 4 for a benchmarking scenario. Special attention is devoted to the influence of different parameters on the computation time. Finally, possible improvements and extensions to the algorithm are discussed in section 5.

2. PROBLEM STATEMENT

A trajectory planning algorithm for a fleet of small fixed-wing UAVs was developed. The main goal of the controller is to minimize the time required for the rendezvous maneuver while avoiding collisions with static and dynamic obstacles. The considered maneuver consists of the rendezvous between a number of follower UAVs and a leader which follows a trajectory that is independent of the followers. A formation should be obtained in which all followers have a parent to which they maintain a fixed displacement vector expressed in the local reference frame of the leader, while avoiding the hazardous zones within

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the wake vortices of other UAVs. However, maintaining the formation after a successful rendezvous does not lie within the scope of this project and can be achieved with a separate controller.

The trajectory generator is non-cooperative and information exchange between UAVs is limited to the positions and velocities of each UAV. The controller determines the position and velocity of the UAV at each time step. A separate controller, that is not considered in this paper, determines the commands that are applied to the UAV in order to follow this trajectory. Furthermore, computation time should be limited. It is assumed that wind conditions remain uniform. The algorithm was developed using Matlab/Simulink and was tested by means of an existing Multi-UAV simulation environment.

3. METHODOLOGY

This section discusses how the path planning problem and its constraints are formulated as a Mixed Integer Linear Program (MILP). Firstly, the main cost function is defined in order to minimize the rendezvous time. A zero-order hold discrete system is proposed for the dynamic model of the UAV. Furthermore, maximum velocity and acceleration, as well as minimum velocity, are imposed as constraints. Subsequently, avoidance of static and dynamic obstacles is implemented. Finally, the cost function is adapted to suit a receding horizon approach.

3.1 Cost function

The objective of the trajectory generator is to minimize the duration of the rendezvous maneuver while avoiding collisions. Consequently, the optimization problem can be written as follows:

$$\min_{\mathbf{s}_k} J = \min_{\mathbf{s}_k} N_G. \tag{1}$$

Where J is the cost function and $\mathbf{s}_k = (x\ y\ z\ v_x\ v_y\ v_z)_k^T$ the position- and velocity-vector of the UAV in the global reference frame at the k-th time step. The UAV reaches its goal position at the N_G-th time step, therefore N_G should be minimized. In order to determine N_G as a function of the optimization variables $\mathbf{s}_k$ while imposing that the UAV reaches its goal position with its goal velocity, a constraint is added to the optimization problem:

$$\min_{\mathbf{s}_k} N_G, \tag{2}$$

subject to

$$\exists! N_G \in \{1, ..., N_T\}$$
$$\mathbf{s}_{N_G} - \mathbf{s}_G = \mathbf{0}.$$

Where $\mathbf{s}_G = (x_G\ y_G\ z_G\ v_{x,G}\ v_{y,G}\ v_{z,G})^T$ is a vector with the goal position and goal velocity, and N_T the total number of considered time steps. The goal position is equal to the sum of the current position of the leader and a displacement vector. This vector is defined as a fixed vector in the local reference frame of the leader. In order to determine $\mathbf{s}_G$, this vector is expressed in the global reference frame using conventional transformation matrices based on the current attitude of the leader. This problem can be rewritten in a mixed integer linear form by adding a binary variable g_k for each time step. These variables denote whether the goal position is reached at the corresponding time step ($g_k = 1$). This method is similar to the one used by Richards et al. (2002) to detect when a UAV passes by a waypoint. This leads to the following optimization problem:

$$\min_{\mathbf{s}_k, g_k} N_G = \min_{\mathbf{s}_k, g_k} \sum_{k=1}^{N_T} k g_k, \tag{3}$$

subject to

$$\sum_{k=1}^{N_T} g_k = 1$$
$$\forall k \in \{1, ..., N_T\} \ : \ \begin{aligned} \mathbf{s}_k - \mathbf{s}_G &\leq M(1-g_k)\mathbf{1} \\ \mathbf{s}_G - \mathbf{s}_k &\leq M(1-g_k)\mathbf{1} \\ g_k &= 0 \text{ or } 1. \end{aligned}$$

Where $\mathbf{1}$ is a 6x1-vector of ones. M is an arbitrary number that is larger than the possible difference in position or velocity between the UAV and its goal. Therefore, if $g_k = 0$, the constraints of the k-th time step are satisfied even if the UAV has not yet reached its goal position or has passed it. If $g_k = 1$, the UAV reaches its goal at the k-th time step. By imposing that the sum of g_k equals one, the UAV reaches its goal at one time step only.

3.2 Model Predictive Control

The UAV is considered as a point mass with position and velocity $(x\ y\ z\ v_x\ v_y\ v_z)^T$. The control input is its acceleration: $(u_x\ u_y\ u_z)^T$. The equivalent zero-order hold discrete system is the following:

$$\begin{pmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \end{pmatrix}_{k+1} = \begin{pmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \end{pmatrix}_k + \begin{pmatrix} \Delta t^2/2 & 0 & 0 \\ 0 & \Delta t^2/2 & 0 \\ 0 & 0 & \Delta t^2/2 \\ \Delta t & 0 & 0 \\ 0 & \Delta t & 0 \\ 0 & 0 & \Delta t \end{pmatrix} \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix}_k \tag{4}$$
$$\Leftrightarrow \qquad \mathbf{s}_{k+1} = A\mathbf{s}_k + B\mathbf{u}_k.$$

Where Δt denotes the length of each time step. This approach is also used by Kamal et al. (2005). Its limited complexity allows for a decrease in computation time while generating feasible trajectories. The exact model of the UAV is encapsulated by the assumed inner loop controllers that track the demanded accelerations $\mathbf{u}_k$, see e.g. (Bolting et al., 2016).

For each considered time step, the dynamic model of the UAV should be satisfied. Therefore, the above state space equations are added as constraints to the optimization problem.

3.3 Velocity and acceleration constraints

It is assumed that the maximum velocity and acceleration of each UAV are norm-constrained. Furthermore, a minimum velocity should be imposed for fixed-wing UAVs in