A COMPUTATIONALLY EFFICIENT GUIDANCE SYSTEM FOR A SMALL UAV

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Abstract: In this paper, a computationally efficient guidance algorithm has been designed for a small aerial vehicle. Preflight path planning only consists of storing a few waypoints guiding the aircraft to its target. The paper presents an efficient way to model no-fly zones and to generate a path in real-time in order to avoid the obstacles, even in the event of wind disturbance.

1 INTRODUCTION

Motion planning has been extensively studied over the last decade, especially in the context of ground robots. Path-planning methods based on potential field functions present the difficulty of choosing an appropriate potential function, and the algorithm may be stuck at some local minima (Koren and Borenstein, 1991). The Probabilistic Road Maps (PRM) method (Kavraki et al., 1996) explores all the possible paths within the configuration space, and finally selects the lower cost route. However, the computational load makes the PRM method impractical for real time path planning in small UAVs. An extension to the PRM method is presented in (Amin et al., 2006) and is called modified Rapidly-exploring Random Trees (RRT), which is capable of efficiently searching for feasible paths in the space taking into account constraints from the vehicle performance. However, efforts are still going on to implement a path replanning on-the-fly as pop-up obstacles are discovered, or when the performance of the vehicle degrade. Other path-planning techniques are based on optimization methods, such as Mixed Integer Linear Programming (Schouwenaars et al., 2005) or Model Predictive Control techniques (Kuwata et al., 2006), which still involve heavy computations.

This paper presents a guidance algorithm for an unmanned aerial vehicle (UAV), which generates online a flight path based on predefined waypoints, avoids known or appearing obstacles, is simple to implement and requires very low computational power. The complete guidance system is intended to run on small microcontrollers with limited floating point operations capability.

Most of the research dealing with obstacle avoidance seems to be directed towards advanced, relatively complex methods. These methods, mainly based on optimization algorithms, are appropriate for larger UAVs with sufficient processing power onboard or for systems where the data processing can be done at a base station with the flight path being relayed up to the aircraft. The work of this paper focuses on highly simplified methods for real-time path generation in order to avoid no-fly zone (NFZ).

Section II of this paper describes how the aircraft autonomously detects whether any approaching NFZs are a threat. Section III presents a strategy to avoid the NFZ, and Section IV considers cases of wind disturbances, and shows how the guidance algorithm still allows the aircraft to avoid the NFZ.

2 GUIDANCE CONTROL LAW

The control law used in the guidance algorithm is based on work done in (Park, 2004) and (Park et al., 2004). The control law chooses a reference point that is on the desired path and a distance L_1 ahead of the aircraft. It then calculates the angle between the aircraft's velocity vector and the line L_1 to generate a lateral acceleration command a_s using (1), which is converted into a bank angle command ϕ_{com} using (2). This control law is especially suited to follow curved paths, such as circles, and is also efficient to track

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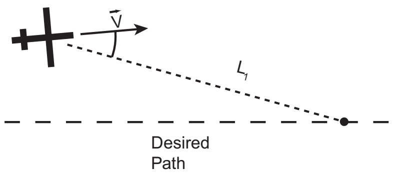

Figure 1: Diagram of Control Law Geometry.

straight line segments.

$$a_s = \frac{2V^2}{L_1} \sin \eta \tag{1}$$

$$\phi_{com} \approx \frac{a_s}{g} \tag{2}$$

3 NO-FLY ZONES

3.1 Definition of a No-Fly Zone

A no-fly zone is any airspace that an aircraft is not permitted to fly in. This airspace can be of any arbitrary shape. In order to simplify the guidance algorithm, two conditions are imposed on how the NFZ is represented.

First, the vertical limits of the NFZ are not considered so that the NFZ is essentially a two-dimensional surface. The aircraft is not allowed to pass over or under the NFZ.

Second, the shape of the NFZ is chosen to be a circle. In this way, the avoidance maneuver can be an arc of a circle in order to benefit from the guidance control law especially suited to track circles, which are described by only two parameters, their center and their radius.

Although this paper only discusses the avoidance of one circular NFZ, the algorithm can be extended to multiple no-fly zones with some simple modifications. Also, a complex no-fly zone shape can be represented by multiple circles.

Before the flight, the location of the known no-fly zones to be encountered during the mission are stored in the memory of the autopilot. If the UAV is equipped with scanning sensors that can detect pop-up obstacles, their position can be taken into account by the path-planning system to recompute on the fly a new trajectory that avoids the threat and continues the mission as soon as possible.

In order to determine whether an NFZ or an obstacle interferes with the planned path, an imaginary "detection line" is used. It has a length R_{LA} and is located in front of the aircraft, as shown in Fig. 2.

3.2 Definition of the Look-ahead Distance R_{LA}

The distance R_{LA} defines the so-called "look-ahead distance". If any part of this detection line penetrates an NFZ or an obstacle, avoidance action is immediately taken as described in the next section.

The guidance algorithm determines whether a NFZ interferes with the planned path using current aircraft position, velocity, and aircraft performance information such as the maximum bank angle that is allowed ϕ_{max}. Although the location of an NFZ is known to the guidance algorithm, the guidance algorithm will only take action if the NFZ is an immediate obstacle.

An NFZ is considered to be an immediate obstacle if any part of it is touched by the imaginary "detection line" of length R_{LA} in front of the aircraft.

Choosing a good value for R_{LA} is important. Too large of a value will cause the guidance algorithm to take unneeded action or to take action too early, while too small of a value will not allow the aircraft enough time to maneuver away from the NFZ without penetrating it.

R_{LA} is chosen such that the aircraft will fly an arc that stays just outside the NFZ at the point of closest approach, which means that the turn was started as late as possible. R_{LA} depends on the radius of the NFZ, R_{NFZ}, the ground speed of the aircraft V, and the maximum bank angle of the aircraft ϕ_{max}.

Given these parameters, and assuming a coordinated turn, the minimum turn radius the aircraft can fly is given by

$$R_{min} = \frac{V^2}{g \tan(\phi_{max})}. \tag{3}$$

In the case of a NFZ with infinite radius, the aircraft would have to make a $90°$ turn, in which case $R_{LA,min} = R_{min}$. For any NFZ with a finite radius, the aircraft has to turn less than $90°$ to avoid it. Assuming that the path of the turning aircraft is tangent to the edge of the NFZ, a triangle can be set up as shown in Fig. 2, with vertices at the center of the NFZ, at the aircraft, and at a point R_{min} off the right wing-tip. The aircraft is at the point where it must begin its turn. $R_{LA,min}$ is then given by

$$R_{LA,min} = \sqrt{2R_{min} + R_{NFZ}}\sqrt{R_{NFZ}} - R_{NFZ}. \tag{4}$$

To obtain the final value for R_{LA}, compensation must be made for the delay needed to initiate the turn, including the time to roll to ϕ_{max}. The delay needed to initiate the turn, τ_{roll}, is compensated for by adding a representative distance to $R_{LA,min}$. The assumption is made that while the aircraft is initiating the turn

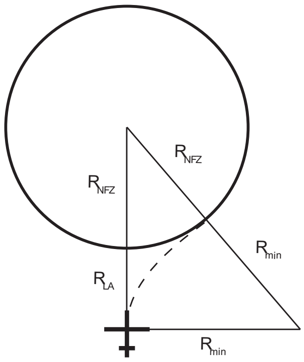

Figure 2: Diagram of R_{LA}.

it continues to fly level, and then as soon as it reaches ϕ_{max} it makes a minimum radius turn. The characteristic time τ_{roll} can be multiplied by the aircraft's speed to get the distance the aircraft will travel during this delay, which is added to $R_{LA,min}$.

The resulting look-ahead distance is

$$R_{LA} = R_{LA,min} + V\tau_{roll}. \quad (5)$$

3.3 Detection of the No-Fly Zone

As mentioned before, the algorithm monitors a line ahead of the aircraft. First, the distance D_{NFZ} from the aircraft to the center of the NFZ is calculated.

$$D_{NFZ} \leq R_{NFZ} + R_{LA} \quad (6)$$

If the condition set in (6) is satisfied, where R_{NFZ} is the radius of the NFZ, then the aircraft is considered to be within range of the NFZ. In this case, a further check is made to see if a part of the NFZ is touching the detection line.

For the second check, there are two possible cases, depending on the position of the aircraft. A pair of triangles is created as shown in Fig. 3 or Fig. 4. The edges h and R_{LA}, and the angle α are known. The length of edges y and a can easily be calculated, using

$$\begin{aligned} y &= h\sin(\alpha) \\ a &= h\cos(\alpha). \end{aligned} \quad (7)$$

Case 1 applies if $a \leq R_{LA}$. The limiting case is when edge a is tangent to the NFZ, in which case y will have a length equal to R_{NFZ}. Thus, the NFZ touches the detection line if

$$y \leq R_{NFZ}.$$

Case 2 applies if $a > R_{LA}$. The limiting case occurs when the end of the detection line is on the edge of the NFZ. This can be checked by comparing

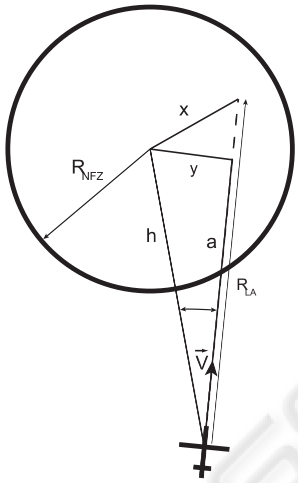

Figure 3: Diagram of NFZ Detection Algorithm, Case 1 (detected).

the length of the edge x to the radius of the NFZ, so that the detection line touches the NFZ if

$$x \leq R_{NFZ}, \quad (8)$$

where

$$x = \sqrt{y^2 + (a - R_{LA})^2}. \quad (9)$$

The check for Case 1 or Case 2 is only done if α is less than or equal to $90°$. If α is greater than $90°$, then the center of the NFZ lies behind the aircraft and no action is taken.

The no-fly zone detection method that was presented provides sufficiently early notice of any impending NFZ penetration for the guidance algorithm to take action to avoid the NFZ. The algorithm for avoiding the NFZ is described in the following section.

4 NO-FLY ZONE AVOIDANCE ALGORITHM

The no-fly zone avoidance algorithm guides the aircraft around any NFZ that the aircraft encounters. The avoidance method is designed to be simple to implement while allowing the aircraft to reach waypoints close to the edge of the no-fly zone.

4.1 Path Template

One key feature of this avoidance method is the selection of a circular arc around the NFZ as a reference path. Such a path minimizes the distance the aircraft flies to avoid the NFZ. Moreover, we saw at the beginning of this chapter that our lateral guidance control

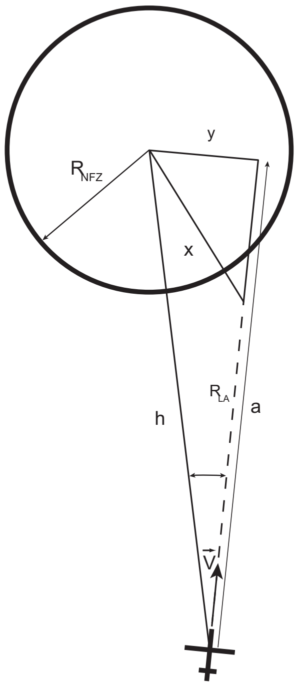

Figure 4: Diagram of NFZ Detection Algorithm, Case 2 (not detected).

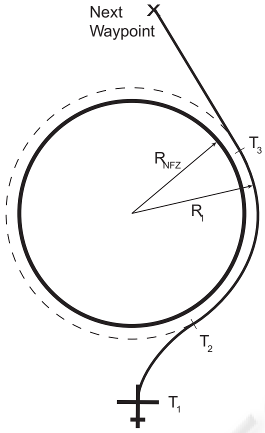

Figure 5: Avoidance Path Template.

law is particularly efficient in tracking such a path. Choosing the reference path to be circular allows the path to be easily defined in relationship to the NFZ dimensions.

The aircraft follows this path until it is able to continue towards the next waypoint in a straight line and without passing through the NFZ. As shown in Fig. 5, the arc has the same center as the NFZ but has a slightly larger radius. The distance between the reference path and the edge of the NFZ serves as a safety margin against deviations the aircraft makes from the reference path.

No complex calculations have to be made to determine where the path lies; it is defined by the center of the NFZ and a path radius, R_1, which is simply the NFZ radius plus a safety margin. R_1 must be chosen to be larger than or equal to the minimum turn radius of the aircraft, such that the reference path represents a feasible path. Also, the point at which the guidance algorithm transitions back to normal guidance towards the next waypoint is easily chosen. This transition occurs when there is a clear line-of-sight from the aircraft's current position to the next waypoint.

4.2 Relevant Control Law Properties

The properties of the chosen control law used in the guidance algorithm, namely its inherent ability to follow a circular path, make the chosen path easy to follow. As shown in (Park, 2004), the aircraft is able to follow a circle without any steady-state error, even with wind. This is because the bank angle command given by the controller causes the aircraft to fly an arc that is tangent to the aircraft's current velocity and that crosses the reference path at a given distance in front of the aircraft. In the case of a circular reference path, the proper bank angle command is given so that the aircraft flies exactly along the this reference path. When the aircraft is on the reference path and flying along it, the bank angle that is commanded provides the right lateral acceleration to fly a circle of the same radius as the reference path. When the aircraft is off the reference path, the bank angle command is such that the aircraft will converge with the reference path.

4.3 Avoidance Guidance Schedule

Upon detecting a no-fly zone, the aircraft initiates a maximum bank turn either to the left or right and then flies around the NFZ along the reference path. This method allows the guidance algorithm to initiate the avoidance maneuver as late as possible. This is desirable since it makes more waypoints reachable than if the avoidance maneuver were started earlier. The only unreachable waypoints are those that lie within a radius of $R_{NFZ} + R_{LA}$ from the center of the NFZ[1].

4.3.1 Choice of Avoidance Side, T_1

Whether the guidance algorithm chooses to go left or right around the NFZ is determined by which side of the NFZ center the aircraft is already flying towards.

[1] In the case of approaching a NFZ head-on, the guidance algorithm begins its avoidance maneuver when it reaches a distance of $R_{NFZ} + R_{LA}$.

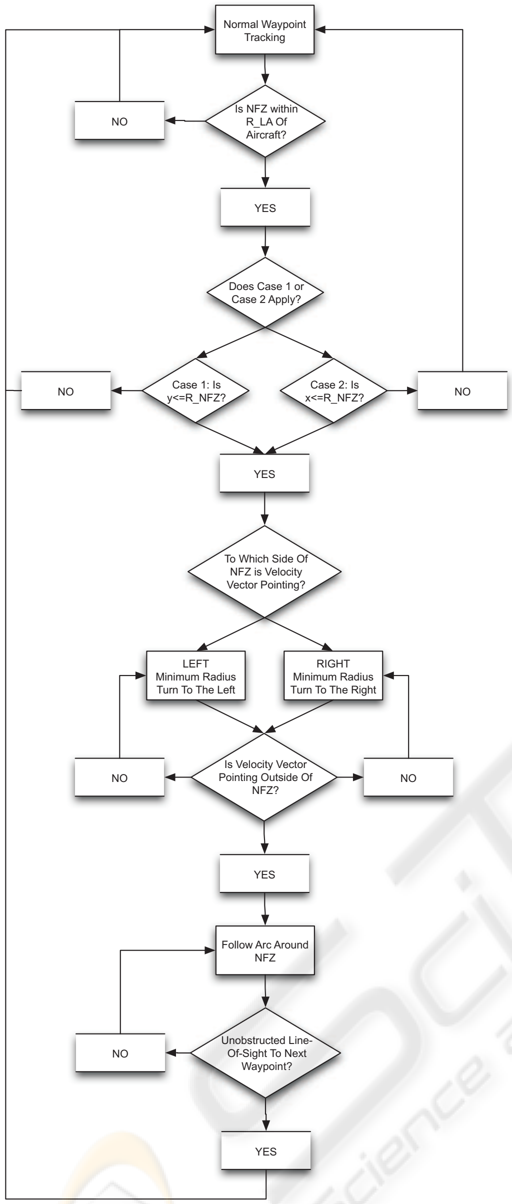

Figure 6: Finite State Diagram of Avoidance Algorithm.

If the aircraft's velocity vector is pointing to the right of the NFZ center, then the aircraft will fly around the right side of the NFZ. If the velocity vector is pointing to the left side, then the aircraft flies around the NFZ on the left side. A circular NFZ makes this decision easy.

4.3.2 Transition to Reference Path, T_2

Once the aircraft begins its turn, it continues to turn until its velocity vector is tangent to, or points outside of the NFZ. At this point the guidance switches to following the circular reference path.

4.3.3 Transition to Normal Waypoint Tracking, T_3

Once the aircraft is following the reference path, it will continue to do so until it has a line-of-sight to the next waypoint that is unobstructed by the NFZ. At this "switchover point", the guidance switches out of avoidance mode and guides the aircraft to the next waypoint. It follows a reference line from the switchover point to the next waypoint. Once the next waypoint is reached, guidance continues as normal. A possible alternative solution is to avoid the obstacle and then follow again the original reference path that passed through the no-fly zone, but this makes the aircraft fly a longer path to finally reach the desired waypoint.

4.4 Properties of the Guidance Schedule

The presented guidance schedule has several desirable properties. It attempts to minimize the number of waypoints that are unreachable, it avoids complex logic to decide how to avoid the no-fly zone, and it minimizes the time and distance to return to the original flight path.

4.4.1 Minimizing Unreachable Waypoints

The guidance schedule minimizes the number of unreachable waypoints by initiating the avoidance maneuver as late as possible. A waypoint is deemed unreachable if it cannot be flown over while following the original path and without causing the aircraft to penetrate the NFZ. Waypoints within R_1 of the center of the NFZ are unreachable.

4.4.2 Avoiding Complex Logic

The guidance schedule avoids complex logic. The main decisions that have to be made are when to begin the avoidance maneuver, which side to fly around the NFZ, and when to begin flying directly to the next waypoint. The first decision is made by the NFZ detection algorithm; the avoidance maneuver begins as soon as the NFZ is detected, which is when the aircraft is within a distance of R_{LA} of the NFZ edge. The side around which the NFZ is circumnavigated is chosen simply by the side to which the velocity vector of the aircraft points at the time the decision is made. In the case of the aircraft approaching the NFZ head-on, the decision can be made arbitrarily. The final decision is also simple, in that the aircraft continues on to the next waypoint when it has a clear line-of-sight to it. A clear line-of-sight can be checked by using an algorithm similar to the NFZ detection algorithm, but with the “detection line” pointed towards the next waypoint, instead of ahead of the aircraft.

4.4.3 Minimizing Time and Distance to Return to Original Flight Path

After the avoidance maneuver is initiated, the goal of the guidance algorithm is to minimize the distance and time to return to the original flight plan. It does this by flying directly to the next waypoint after the NFZ as soon as is safely possible. A possible downside of this is that it may create an excessively sharp turn leaving the waypoint, but the control law is able to handle even sharp turns (with an overshoot that most control laws would have).

5 SIMULATION

5.1 Simulation Setup

Simulations were done on a nonlinear 6-DOF computer model of a radio controlled aerobatic aircraft. The model has a 4-axis low-level autopilot which allows to directly give the autopilot a bank angle command. The airspeed, altitude, and side-slip are kept constant.

5.2 Simulation Scenario

Three similar scenarios were simulated with the results presented below. In all scenarios, the aircraft is following a desired path that passes through a no-fly zone. The simulation was done with maximum banks angles of $\phi_{max} = 30°$.

5.3 Simulation Results

5.3.1 No Wind

This first scenario, shown in Fig. 7, highlights the basic response of the aircraft to a NFZ blocking its path. The aircraft begins south of the NFZ and flies north along the desired path defined by the waypoints 1 to 5 and returns back to the runway. The desired path passes through a no-fly zone, but the aircraft deviates around it before returning to the desired path. The simulation was run at three different flight speeds, 15, 30, and 45 m/s. It can be seen that the aircraft begins its turn much later when flying at 15 m/s than when

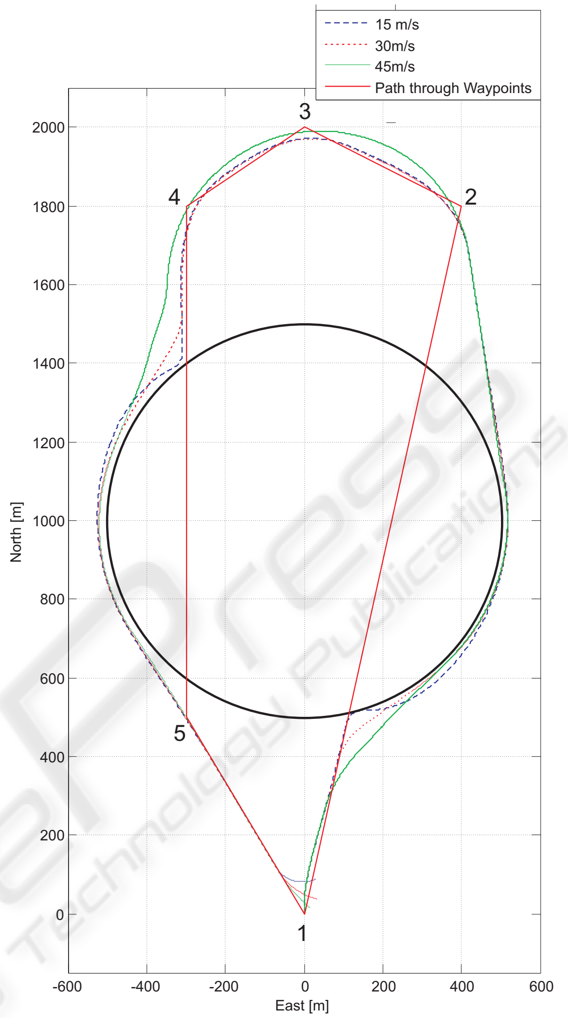

Figure 7: Obstacle avoidance in no wind condition at different speeds.

flying at 45 m/s. The airplane stays outside the no-fly zone at all three speeds.

5.3.2 With Wind

This second scenario, shown in Fig. 8, highlights the response of the aircraft in wind conditions. The desired path remains the same as in the first scenario. The path taken by the aircraft without wind and with wind are shown for comparison. The aircraft is flying at a nominal airspeed of 30 m/s.

A first flight is made with a 6 m/s crosswind blowing from east to west. In this case, the path followed by the aircraft is almost identical to the one without wind.

Another flight simulation is made with wind blowing from south to north with a speed of 6 m/s. The

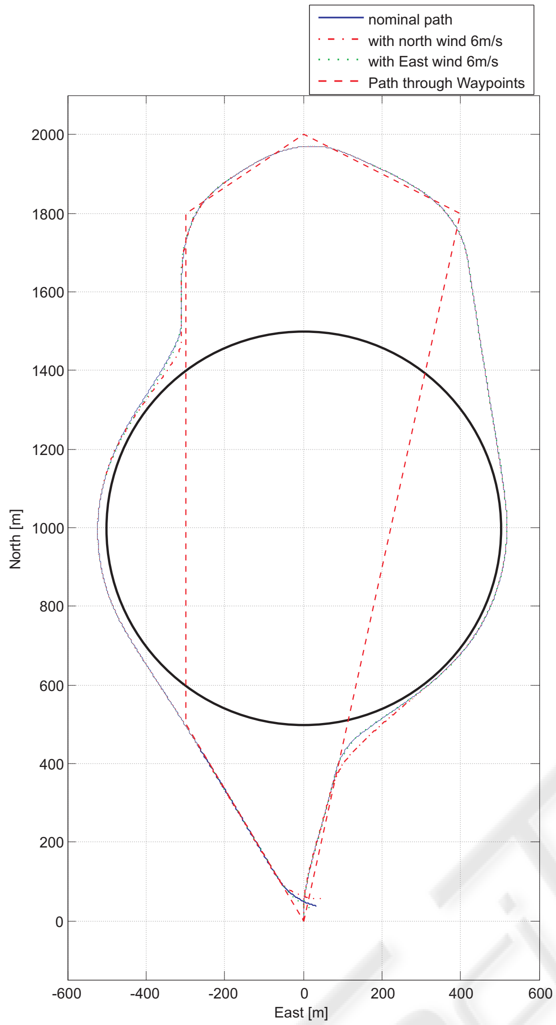

Figure 8: Obstacle avoidance in wind conditions.

trajectory in the latter windy condition differs from the the nominal track (without wind) in the two turns that avoid the obstacle, where there is a maximum difference of 20 m.

In both cases the no-fly zone is avoided. After the obstacle has been avoided, the guidance system resumes normal waypoint tracking.

6 CONCLUSIONS

This paper presented a guidance algorithm that combines simplicity and the ability to avoid no-fly zone. The algorithm successfully demonstrated in simulation its ability to guide the aircraft around the no-fly zone and then to resume flying along the desired path. It demonstrated this ability in wind conditions. Finally, the method is computationally efficient.

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