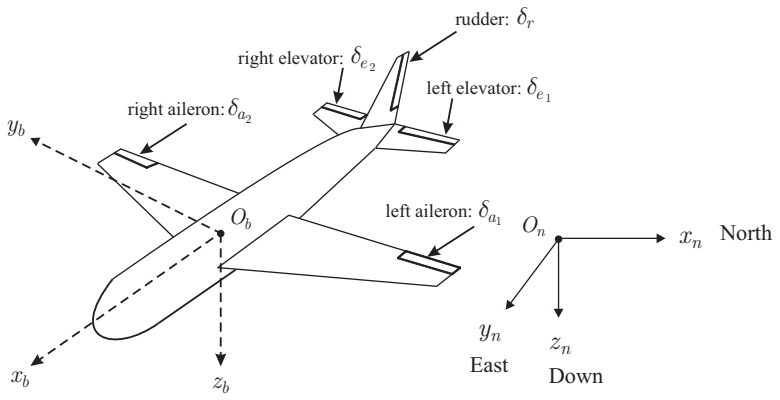
Eidgenössische Technische Hochschule Zürich
Ecole polytechnique fédérale de Zurich
Politecnico federale di Zurigo

Lecture Notes for the Class:
Unmanned Aircraft Design, Modeling and Control

A Reconfigurable Guidance System

Application to Unmanned Aerial Vehicles (UAVs)



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Chapter 1
Reconfigurable Guidance System

This chapter presents a guidance algorithm for a UAV. It combines a nonlinear lateral guidance control law, originally designed for UAVs tracking circles for mid-air rendezvous, with a new simple adaptive path-planning algorithm. Preflight path planning consists only of storing a few waypoints guiding the aircraft to its targets. The chapter presents an efficient way to model no-fly zones (NFZ), to generate a path in real time to avoid known or "pop-up" obstacles, and to reconfigure the flight path in the event of reduced aircraft performance. Simulation results show the good performance of this reconfigurable guidance system which, moreover, is computationally efficient [1, 2, 3].

1.1 Introduction

Over the last two decades, many path-planning algorithms have been investigated, especially for ground robots, for a single UAV, and more recently for a formation of UAVs. Among the methods used in path planning, we can mention the PRM method [4], which explores all the possible paths within the space surrounding the vehicle and finally selects the lowest 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 has recently been presented in [5]. It is called modified *rapidly-exploring random trees*, which is capable of efficiently searching for feasible paths in the space while taking into account constraints from the vehicle performance. However, efforts are still going on to implement an on-the-fly path-replanning system as pop-up obstacles are discovered or when the performance of the vehicle degrades.

There are other methods based on *potential field* functions. However, the primitive forms of potential field functions present some difficulties when choosing an appropriate potential function, and the algorithm may be stuck at some local minimum [6]. Since then, a whole family of potential field methods with superior performance has been developed. They are known as *navigation functions* [7, 8]. Other path-planning techniques are based on optimization methods, such as *mixed integer linear programming* or MPC techniques [9], which still involve intensive computations.

In this chapter, we present a reconfigurable guidance algorithm for a UAV. It newly combines the lateral guidance control law from [10] and [11], originally designed for UAVs tracking circles for mid-air rendezvous, with a new, simple adaptive path-planning algorithm, which takes advantage of the curve path-following property of the above-mentioned lateral guidance law. This path-planning method generates on-line a flight path based on predefined waypoints, takes into account the aircraft performance, avoids known or appearing obstacles, is simple to implement, and requires low computational power.

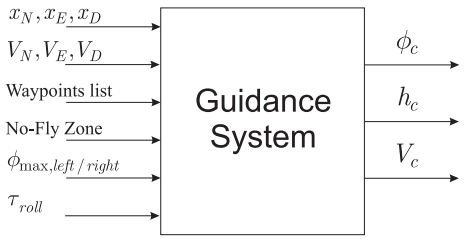


Fig. 1.1 Guidance system inputs and outputs

As shown in Fig. 1.1, the guidance system needs six inputs. The first input concerns the aircraft's current ground position ($x_N,\ x_E,\ x_D$). The second input is the aircraft's ground velocity ($V_N,\ V_E,\ V_D$). The mission of the aircraft

is defined by a list of waypoints through which the aircraft is to fly. Furthermore, if in the area of the flight operation some obstacles or NFZ are known in advance or appear during the flight, their location and dimensions can be specified to the guidance system via the fourth input. A constraint on the maximum bank angle $\phi_{max,left/right}$ is given to the guidance system. Finally, the parameter τ_{roll} is provided as an estimate of the maximum time needed to bank the aircraft to ϕ_{max}. Note that the last four inputs can be changed dynamically, and the first two inputs are obviously constantly updated.

The outputs of the guidance system are the commanded bank angle ϕ_c, whose value is computed by the lateral guidance system detailed in Sects. 1.2 and 1.3. The altitude command signal h_c is computed by the altitude guidance system described in Sect. 1.4. Finally, the commanded aircraft velocity V_c can be adaptively controlled by the guidance system in order to efficiently avoid obstacles and reach the goals of the mission optimally. Note, however, that in this chapter the velocity command V_c is kept to a constant value.

1.2 Lateral Guidance System

1.2.1 Lateral Guidance Control Law for Trajectory Tracking

Consider Fig. 1.2, where an aircraft has to be guided to track the desired path. From the current location of the aircraft O, we can draw a circular arc that intersects the desired path at a "reference point" P, where R is the radius of the circle-arc OP, L_1 is the segment that joins the center of the aircraft O to the reference point P, and η is the angle between the aircraft's velocity vector and the line L_1.

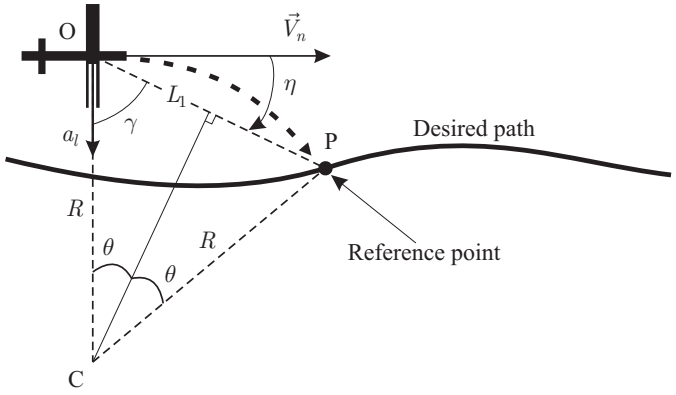


Fig. 1.2 Guidance law geometry

The lateral acceleration required to bring the aircraft to the reference point following the arc of a circle is

$$a_l = \frac{V_n^2}{R} \,, \tag{1.1}$$

where the ground speed of the aircraft (taken in the local navigation frame) is $V_n = \sqrt{V_N^2 + V_E^2}$. Let us express R in terms of the distance L_1 and the angle η. The triangle (OCP) is isosceles in C, therefore, we have $L_1 = 2R\sin\theta$, or also $L_1 = 2R\cos\gamma$. Moreover, the angle $\gamma = \frac{\pi}{2} - \eta$, and consequently, the length L_1 can be expressed in terms of the angle η as follows:

$$L_1 = 2R\sin\eta \,, \tag{1.2}$$

$$\iff R = \frac{L_1}{2\sin\eta} \,. \tag{1.3}$$

The lateral acceleration in (1.1) can now be written as

$$a_l = \frac{2V_n^2}{L_1}\sin\eta \,. \tag{1.4}$$

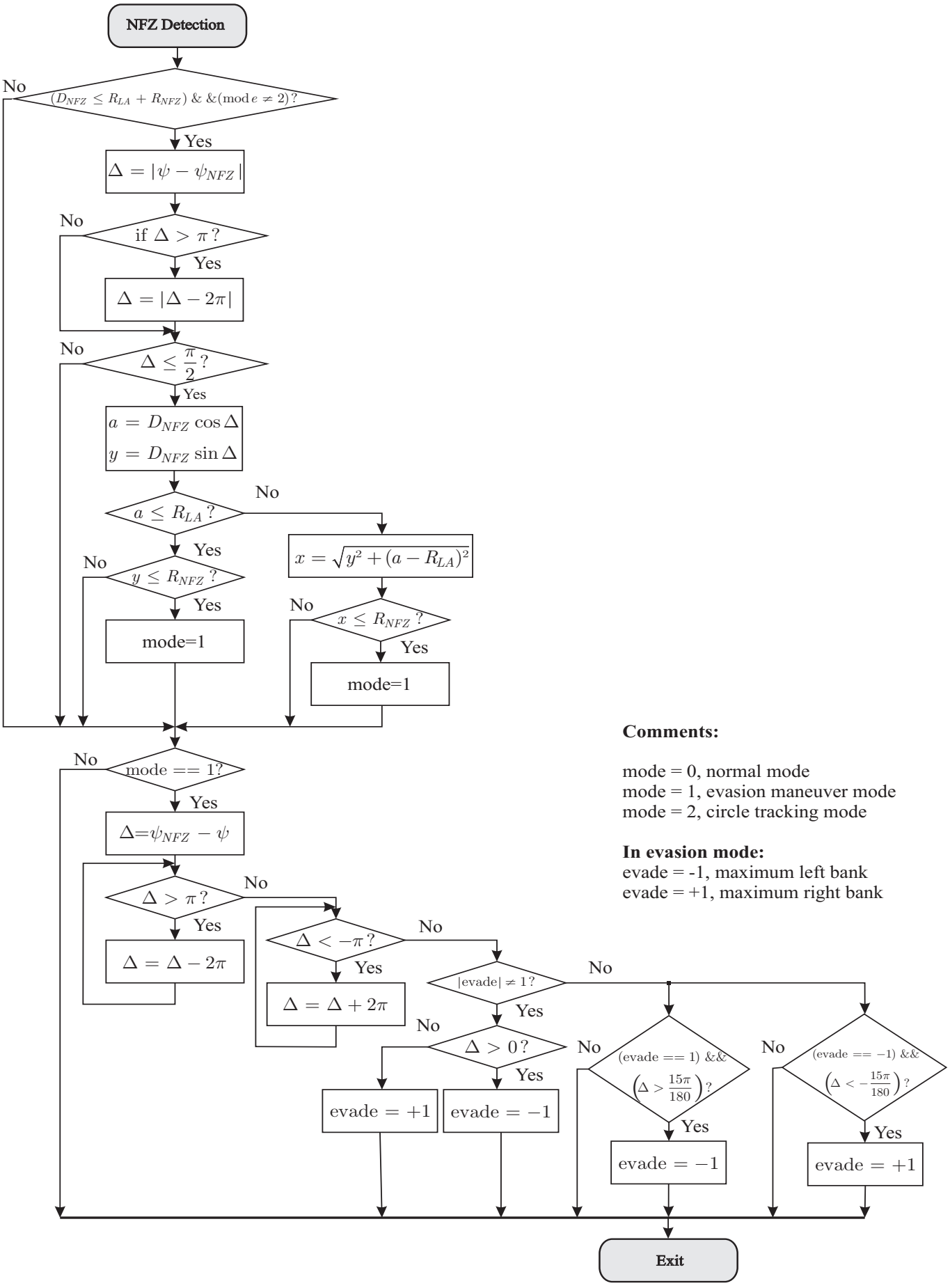


Fig. 1.13 Diagram of NFZ detection algorithm

1.7.1 On-line Selection of an Avoidance Path Template

One key feature of this avoidance method is the on-line generation of a circular arc around the NFZ as a reference path, drawn as a dashed line in Fig. 1.14. Such a path minimizes the distance the aircraft flies to avoid the NFZ. Moreover, we saw at the beginning of this chapter that the lateral guidance control law is particularly efficient in tracking circles.

Furthermore, choosing the reference path to be circular allows the template path to be easily defined in relationship to the NFZ dimensions. It is indeed defined by the center of the NFZ and a path radius, R_1, which is simply the NFZ radius plus a safety margin. 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.

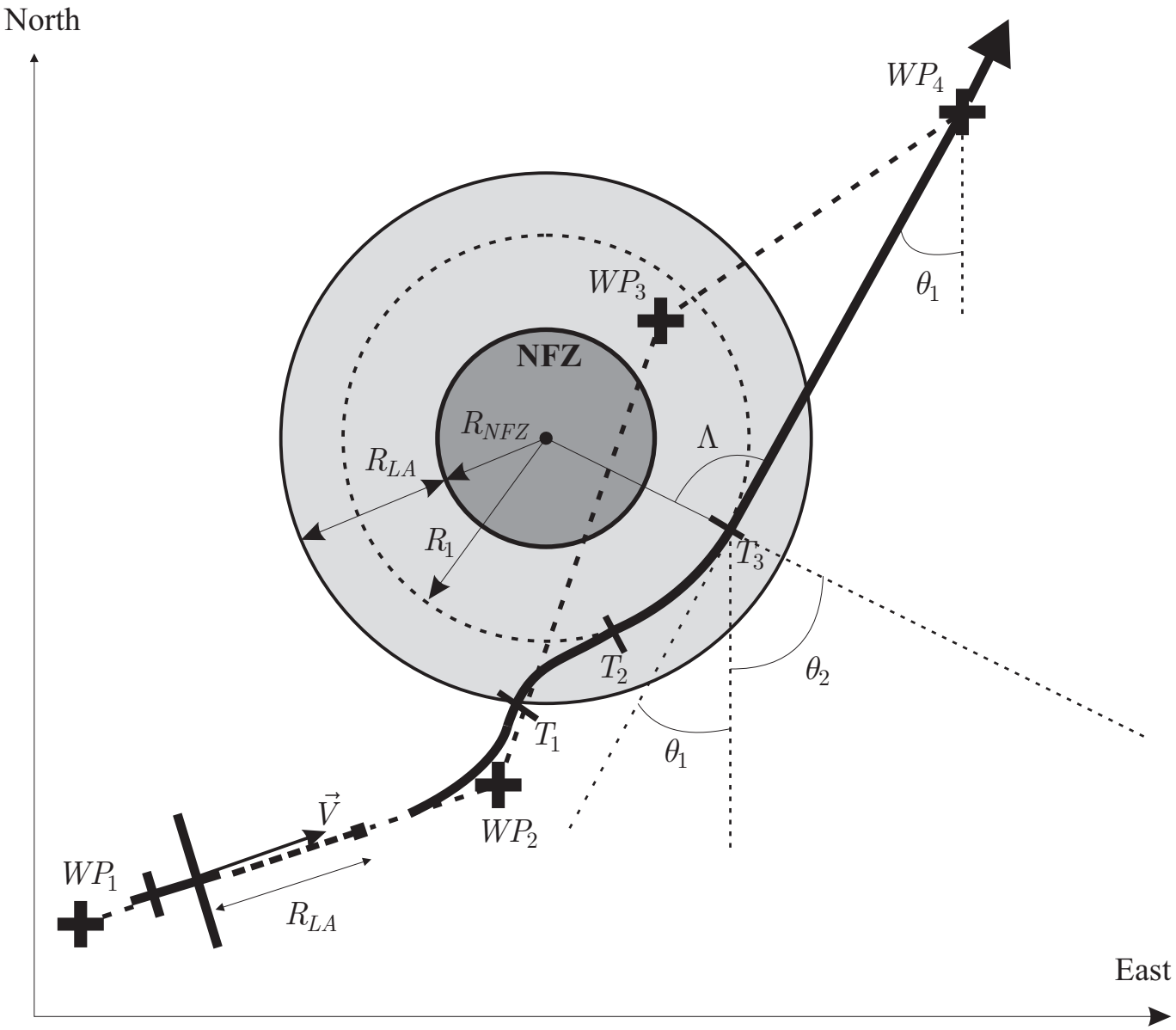


Fig. 1.14 Circular template path, waypoint tracking and reconfiguration

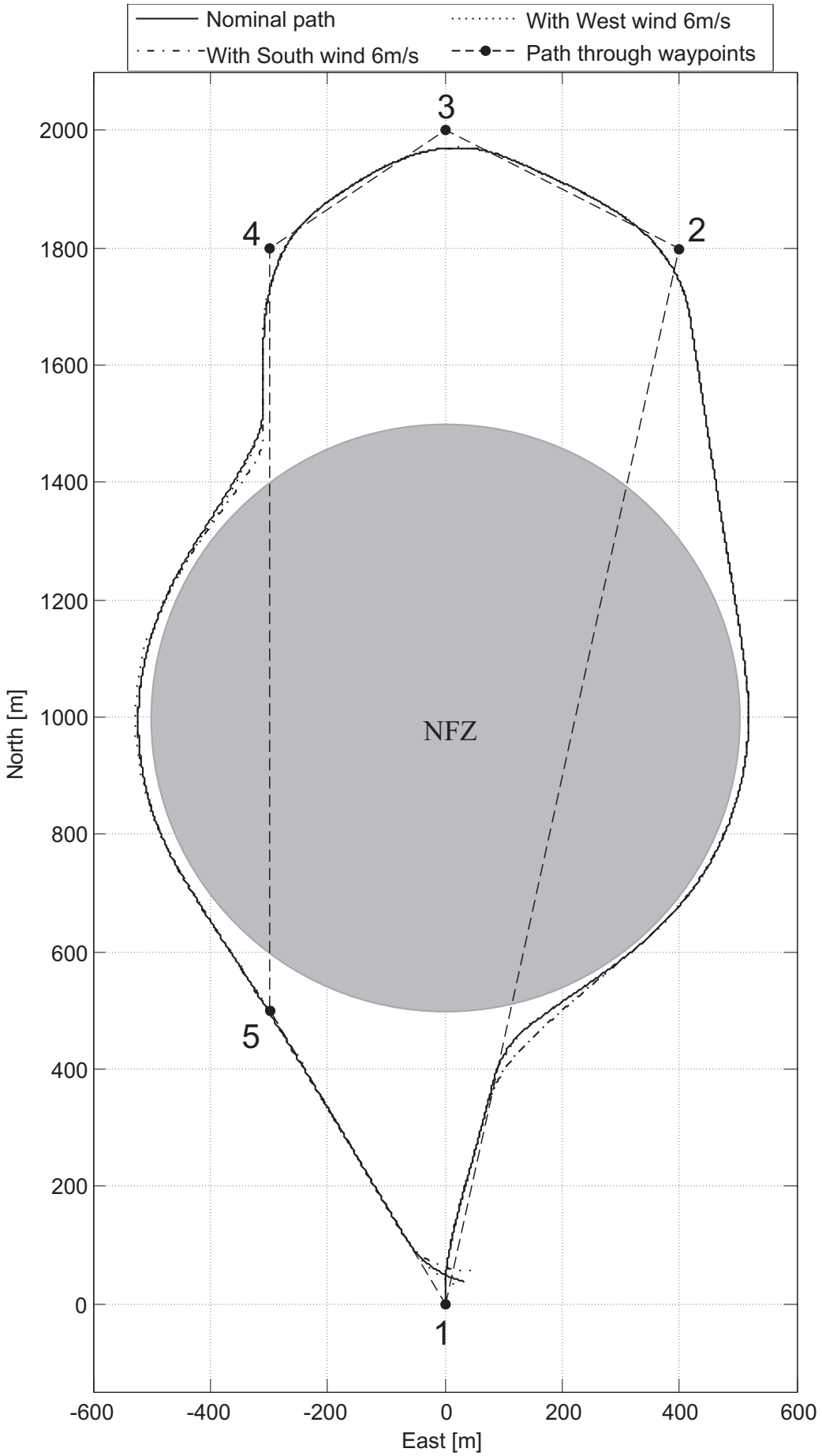


Fig. 1.20 Obstacle avoidance in wind conditions, $V_T = 30\,\mathrm{m/s}$

1.9 Conclusions

This chapter presented a guidance algorithm that combines simplicity of implementation and ability to avoid an NFZ. The algorithm successfully demonstrated in simulation its ability to guide the aircraft around the NFZ and then to resume flying along the desired path. The guidance system intrinsically takes into account the wind condition via the ground speed of the aircraft. Finally, the method is computationally efficient.

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