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► **To cite this version:**

Yasmina Bestaoui, Svetlana Dicheva. 3D Flight Plan for an Autonomous Aircraft. 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Jan 2010, Orlando, United States. 10.2514/6.2010-415 . hal-04551894

**HAL Id: hal-04551894**

**<https://hal.science/hal-04551894>**

Submitted on 18 Apr 2024

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# 3D Flight Plan for an Autonomous Aircraft

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The objective of this paper is to generate a 3D flight plan, based on the modified A\* algorithm for a partially reusable launcher vehicle. An autonomous aircraft constitutes the first stage of this RLV. Because the simple geometric path planning procedure can be implemented in real time, periodically updated paths can easily be generated to accommodate a slowly drifting wind direction and/or wind speed. The second part of the paper presents parametric curves. This study is based on the curvature and torsion properties of these curves.

## Nomenclature

$\alpha$	= angle of attack
$\gamma$	= Flight path angle
$\chi$	= Heading angle
$\sigma$	= bank angle
$\theta$	= pitch angle
$\kappa$	= curvature
$\tau$	= torsion
$\rho$	= atmospheric density
d	= distance
g	= acceleration of the gravity
H	= Hamiltonian function
V	= Vehicle airspeed.
W	= Wind speed
$(x, y, z)^T$	= position of the center of gravity
$A_{ref}$	= characteristic area
$C_d$	= drag coefficient
$C_L$	= Lift coefficient
h	= altitude
dt	= time step
s	= curvilinear abscissa
i	= time index during navigation
j	= waypoint index
q	= dynamic pressure

## I. Introduction

RECENT advances in guidance technologies have enabled some autonomous aerial vehicle to execute simple mission tasks without human interaction. Many of these tasks are pre-planned using reconnaissance or environment information. The actual trend is towards more autonomy. An autonomous flying robot will be suitable for applications like search and rescue, surveillance and remote inspection. Task planning and safe trajectory solutions are essential to the survivability and success of an autonomous system.

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The subject of this study is a partially reusable launcher vehicle. The considered launcher is a multi-stage vehicle. Its first stage consists of an autonomous aircraft of HALE category. The launcher is carried away by the independent aerial vehicle in a height of 16 000m where the launcher is thrown away and activated. Fig. 1 presents the mission parameters

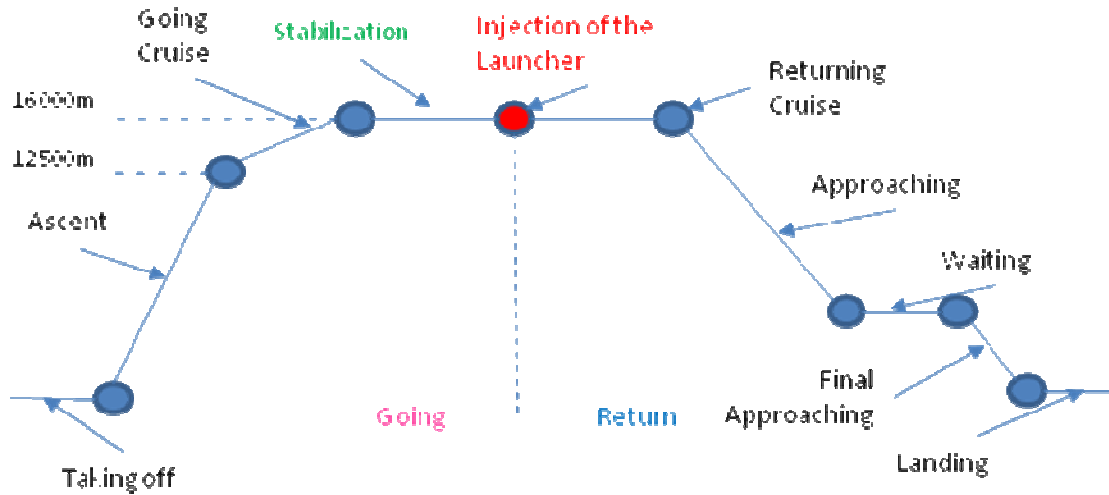


Figure 1: Mission parameters

The autonomous aerial vehicle is the first stage on the launching system and transfers a lot of his energy to the launcher. The aerial vehicle is reusable with a reduce of the cost of launching. The mission of separation occurs at Mach 0.8, with a zero slope for optimal launching trajectory of injection. At the moment of separation, the aerial vehicle encounters a specific transition phenomenon because of the significant lost of mass.

Dynamic Mission Strategy is sought which comprises: Passing over the Zones of the Mission, Performance, Parameters, Management of the risks... Figure 2 presents the Guidance, Navigation and Control architecture.

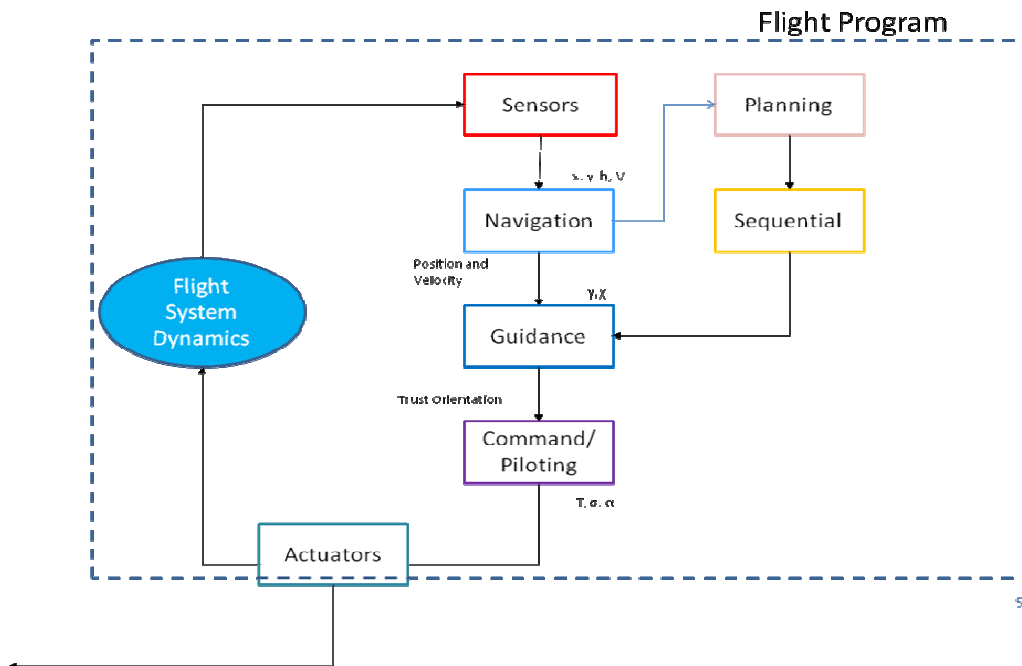


Figure 2 : GNC Architecture

A mission describes the operation of an aircraft in a given region, during a certain period of time while pursuing a specific objective. A flight plan is defined as the ordered set of movements executed by the aircraft during a mission. It can be decomposed in phases. Each phase is described by the coordinates of a pair of way-points and by the speed at which the aircraft is to fly between these way-points. A phase is completed when the second way-point is reached by the aircraft.

Path planning focuses on finding a path through free space from an initial to a final location. Classical differential geometry curve theory is a study of 3D space curves with orthogonal coordinate systems attached to moving points on the space curve<sup>1,6,7,9,18,20,21</sup>.

Trajectory planning is an optimization problem which generates an optimal trajectory between two configurations in the state space, considering a given performance index (time, energy or distance). Its feasibility depends on the choice of the optimization method, the performance index and a number of constraints from various nature, the latter depend essentially on the vehicle itself (architecture, dynamics and actuation modes) and the environment in which the vehicle moves (endurance, airspeed, altitude, landing and takeoff modes ...). Classically, in motion planning and generation, methods such as continuous optimization and discrete search are sought. Lavalley<sup>14</sup> presented a randomized motion planning algorithm by employing obstacle free guidance system as local planners in a probabilistic roadmap framework. Yakimenko<sup>20</sup> based path planning of autonomous fixed wing aircraft on a learning real-time A\* search algorithm, considering only the motion on a horizontal plane. A family of trim trajectories in level flight is used in all these references to construct paths. Frazzoli<sup>11</sup> described motion plans as the concatenation of a number of well defined motion primitives selected from a finite library. They use a 'manoeuvre automaton, defining rules for the concatenation of primitives in the form of a regular language, a manoeuvre being defined as a non trivial primitive which is compatible from the beginning and the end with trim primitives. Atkins<sup>2</sup> introduced the concepts of a parameterized flight plan, a plan with at least one symbolic parameter, and flight plan instantiation, the process by which symbolic parameters in a parameterized flight plan are instantiated to values for which specified requirements are satisfied.

For non holonomic vehicles<sup>8</sup> such as mobile robots or aerial vehicles, dynamic model and actuators constraints that directly affect path are used to reject infeasible paths<sup>4,5,10,13</sup>. The term feasible means that the path will be continuously flyable and safe. The flyable path should be smooth, i.e. without twists and cusps. The smoothness of the path is determined by amount of bending of the path measured by curvature and torsion of the path. The amount of bending is measured by curvature and torsion of the path. If a non vanishing curvature and a torsion are given as smooth functions of  $s$ , theoretically both equations can be integrated to find the numerical values of the corresponding space curve (up to a rigid motion). Smoothness of paths is an essential feature of navigation of autonomous vehicles.

The focus is on turning a sequence of configurations into a smooth curve that is then passed to the control system of the vehicle. The curves used fall into two categories:

1. curves whose coordinates have a closed form expression for example B-splines, quintic polynomials or polar splines
2. parametric curves whose curvature is a function of their arc length for example clothoids, cubic spirals, quintic  $G^2$  splines or intrinsic splines.

However, significant research efforts are still needed to advance the state of the art of trajectory planning for autonomous aerospace vehicles. In the previous papers, the proposed trajectories are based on classical trim helices and non equilibrium trajectories are not considered. In these papers, the atmosphere was considered to be an isotropic and homogeneous medium, i.e. when there is no wind and the air density is constant with altitude<sup>15</sup>. Jiang<sup>16</sup> proposed 2D manoeuvres in the vertical flight for the approach and landing for unpowered reusable launch vehicle while Shanmugavel<sup>19</sup> are using the well-known clothoids arcs to join trim paths at constant altitude.

The originality of the present paper is the generation of possible 3D flight paths by a modified A\* algorithm. Some parametric curves are also presented for an aerial vehicle when maneuvers are considered. This work has been done under the auspices of the CNES (Centre National des Etudes Spatiales) within the program PERSEUS.

This paper consists of 6 sections. Section 2 introduces the aircraft translational dynamics. Section 3 presents parametric curves when curvature and torsion are function of the curvilinear abscissa. Section 4 introduces to a steering function while Section 5 has as subject the choice of the way-points. Finally, conclusions and perspectives are the subject of Section 6.

## II. Aircraft Translational Dynamics

The translational equations of an aerospace vehicle are directly derived from Newton's law. According to Zipfel<sup>22</sup>, if the vehicle flies in the atmosphere with speeds less than Mach 5 (below hypersonic velocity), the Earth

can be presumed an inertial reference frame. The aircraft equations of motion are expressed in a velocity coordinate frame attached to the aircraft, considering the velocity of the wind  $W = (W_x \ W_y \ W_z)^T$  (components of the wind velocity in the inertial frame). The kinematic equations of the aircraft are given by:

$$\begin{aligned}\dot{x} &= V \cos \chi \cos \gamma + W_x \\ \dot{y} &= V \sin \chi \cos \gamma + W_y \\ \dot{z} &= V \sin \gamma + W_z\end{aligned}\tag{1}$$

The powered dynamic model used for flight over a flat Earth is the following

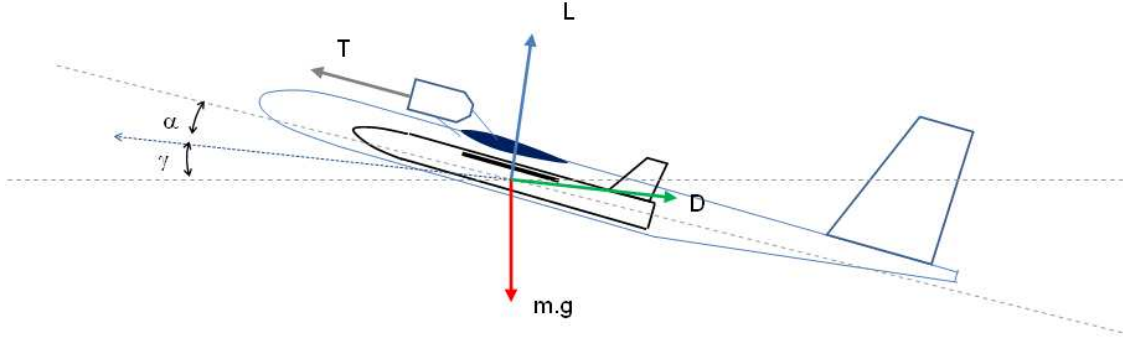
$$\begin{aligned}\dot{V} &= -\frac{C_D(M, \alpha) A_{ref} \rho V^2}{2m} - g \sin \gamma + \frac{T \cos \alpha}{m} - \dot{W}_x \cos \gamma \cos \chi - \dot{W}_y \cos \gamma \sin \chi - \dot{W}_z \sin \gamma \\ \dot{\gamma} &= \frac{C_L(M, \alpha) A_{ref} \rho V \cos \sigma}{2m} - \frac{g \cos \gamma}{V} + \frac{T \sin \alpha \cos \sigma}{mV} + \frac{\dot{W}_x \sin \gamma \cos \chi}{V} \\ &\quad - \frac{\dot{W}_y \sin \gamma \sin \chi}{V} - \frac{\dot{W}_z \cos \gamma}{V} \\ \dot{\chi} &= \frac{C_L(M, \alpha) A_{ref} \rho V \sin \sigma}{2m} + \frac{T \sin \alpha \sin \sigma}{mV \cos \gamma} + \frac{\dot{W}_x \sin \chi}{V \cos \gamma} - \frac{\dot{W}_y \cos \chi}{V \cos \gamma}\end{aligned}\tag{2}$$

Where  $x$  (downrange),  $y$  (cross range) and  $z$  (altitude) are the vehicle's position,  $\gamma$  is the flight path angle,  $\chi$  is the heading angle,  $\sigma$  is the bank angle,  $V$  is the velocity magnitude,  $\rho$  is the mass density,  $m$  is the aircraft mass,  $A_{ref}$  is a characteristic area for the body,  $C_L$ ,  $C_D$  are respectively the lift and drag coefficient functions that depend upon the Mach number  $M$  and angle of attack  $\alpha$ . The aircraft flight path angle is the angle  $\gamma$  measured from the horizontal plane to the aircraft's velocity vector in inertial coordinates; the aerodynamic angle of attack  $\alpha$  is measured from the aircraft  $x$ - $y$  plane to the relative wind velocity vector (figure 3). The aircraft pitch angle is the angle measured from the inertial horizontal plane to the aircraft  $x$  axis. The following relation is verified  $\theta = \alpha + \gamma$ . In this kind of applications, the airplane sideslip angle is usually held near zero. Thus the yaw angle  $\psi$  can be with

$\chi$ . The dynamic pressure is  $\bar{q} = \rho \frac{V^2}{2}$  where the air density  $\rho$  at altitude  $h$  is approximated using an exponential model  $\rho = \rho_0 e^{-\beta h}$  where  $\rho_0$  is the air density at sea level and  $\beta$  is the atmospheric density scale. Generally the lift coefficient is a linear function of the angle of attack  $C_L = C_{L_0} + C_{L_\alpha} \alpha$  and the drag coefficient is a quadratic function of  $C_L$

$$C_D = C_{D_0} + KC_L^2 = k_{D_0} + k_{D_1} \alpha + k_{D_2} \alpha^2\tag{3}$$

where  $C_{D_0}$  is the drag coefficient at zero lift,  $K$  is a coefficient relative to induced drag,  $k_{D_0}$ ,  $k_{D_1}$ ,  $k_{D_2}$  are resulting coefficients with respect to  $\alpha$



**Figure 3 : composite vehicle**

These equations are called pseudo 5 degrees of freedom. They have an important place in aerospace vehicle study because they can be assembled from trimmed aerodynamic data and simple autopilot designs. Nevertheless, they give a realistic picture of the translational and rotational dynamics unless large angles and cross coupling effects dominate the simulations.

For motion planning purpose, the inverse problem has to be solved. We can thus deduce the velocity

$$V^2 = (\dot{x} - W_x)^2 + (\dot{y} - W_y)^2 + (\dot{z} - W_z)^2 \quad (4)$$

and the thrust using these relations:

$$T^2 = u_1^2 + u_2^2 + u_3^2 \quad (5)$$

where

$$\begin{aligned} u_1 &= m\dot{V} + \frac{1}{2}C_D(M, \alpha)A_{ref}\rho V^2 + mg\sin\gamma + m\dot{W}_x \cos\gamma \cos\chi + m\dot{W}_y \cos\gamma \sin\chi + m\dot{W}_z \sin\gamma \\ u_2 &= mV\dot{\gamma} - \frac{1}{2}C_L(M, \alpha)A_{ref}\rho V^2 \cos\sigma + mg\cos\gamma - m\dot{W}_x \sin\gamma \cos\chi + m\dot{W}_y \sin\gamma \sin\chi + m\dot{W}_z \cos\gamma \\ u_3 &= mV \cos\gamma \dot{\chi} - \frac{1}{2}C_L(M, \alpha)A_{ref}\rho V^2 \sin\sigma - m\dot{W}_x \sin\chi - m\dot{W}_y \cos\chi \end{aligned} \quad (6)$$

Trajectory studies, performance investigations, navigation, guidance evaluations can be successfully executed with simulations of these equations.

### III. Choice of the Way-Points

Two methods for Way Point Generation are used: genetic algorithms and algorithms based on Dijkstra's algorithms. This algorithm is one of the most known algorithm to find the shortest optimal path between the waypoints from the beginning to the end of mission. They are suitable for the mission called "completely reversible", which means that the reusable vehicle must return to the launching side. Ibrahim<sup>12</sup> proposed a method to separate the Waypoint Navigation System into three main units: The Reactive Unit, Knowledge Base and Deliberative Units. The Reactive Unit is the primary navigation when the vehicle is placed in the unknown environment. The information from the sensors is stored in the Knowledge Base. The already available waypoints are recorded over a Telematics network to Deliberative unit for preplanning, planning or replanning. The way point navigation is looking for the generation of intermediate series of points which can navigate the vehicle to reach the mission goal. This series may be introduced in a database from the current information of the environment and the current state of vehicle energy level proportional to the necessary time. The current position and orientation of the vehicle is connected directly with the list of waypoints used for the planning. This problem can be solved in the Planer which accepts the information for the next waypoint coordinates and control the navigation process. The information for the distance to next point, travel time and path cost is needed. Mulvaney<sup>14</sup> suggested that the next point can be determined by the coordinates of the previous waypoint, the heading and the time travel. This path is generated in the ordinate system of the earth surface inertial reference frame. The airspeed is supposed constant and the average wind speed  $W$  and direction already known.

In this paper, the idea is simple: as uncertainty always exists due to numerous reasons, a way of taking care of it is to update periodically the flight path thus the way points, in dynamic replanning mission mode. If due to the wind effect, the aircraft has overshoot the way point it was supposed to go through, then the next way point should be considered. The immediate measurements of the position and orientation are taken as initial conditions for the next chosen waypoints, as well as the updated information about the weather conditions. The proposed waypoint generation does not require a complete knowledge of the environment. This is an advantage in this path planning system. For the purpose of 3D mission we are interested in a pathfinder enabling the vehicle to reach the mission goal and also creating a path to satisfy different constraints during the mission. This pathfinder generates the path from the initial point to the mission goal and navigates the vehicle. From the sensors data the position, orientation and speed of the vehicle are known as well as information about the meteorological conditions and probable obstacles.

The following A\* algorithm modified is used as:

**Initialization:**

**Place** all the waypoints into the *listM* (register of the initial mission waypoints )

**Place** *n1* into the *listQ*

**Treatment:**

**While** (*listQ* is not empty and the final waypoint is not reached) **do**

**For** each *ni* into the  $S(\hat{u})$  **do**

*listT*=0

**For** each possible action *A* **do**

Build the itinerary from *n1* to *niA* (Generate the trajectory to satisfy the constraints of mission time and resources)

Calculate *J* the optimization criterion

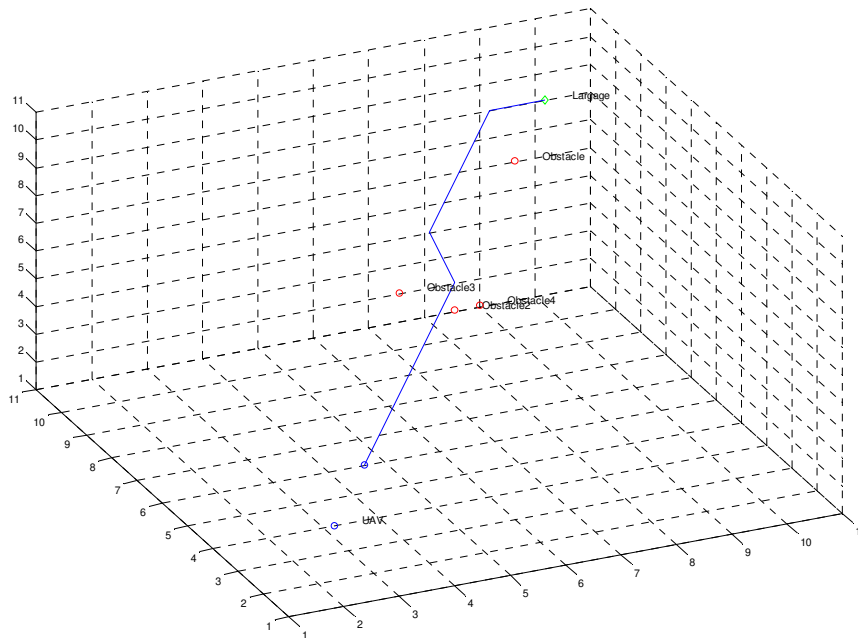
Calculate *hi* (the distance between the *niA* and the final waypoint for the current configuration)

**Place** *niA* into the *listT*

**Place** the next waypoint into the *listQ*

**End**

Figure 4 shows the path that should be followed by the autonomous aircraft.



**Figure 4 : Choice of the waypoints**

As it is impossible to predict everything that could happen during the mission, the flight plan is periodically updated. The structure necessary for the update of the waypoints is a hierarchical structure. There exists an upper level of decision making and a lower level where the choice of the way-points is solved.

#### IV. Parametric Curves

For convenience, time is not chosen to be the independent variable in this paragraph. We are interested by the curvilinear abscissa  $s$  instead of the time, let's consider the curve  $C(s)$  representing the motion of this vehicle in  $\mathbb{R}^3$ , where  $V = \frac{ds}{dt}$ . This coordinate system will be used to study the shape of a space curve. In 3D space, the following flight path is characterized:

$$\frac{dx}{ds} = \cos \chi \cos \gamma \quad \frac{dy}{ds} = \sin \chi \cos \gamma \quad \frac{dz}{ds} = \sin \gamma \quad (7)$$

Two non-holonomic constraints can thus be deduced:

$$\frac{dx}{ds} \sin \chi - \frac{dy}{ds} \cos \chi = 0 \quad \left[ \frac{dx}{ds} \cos \chi + \frac{dy}{ds} \sin \chi \right] \sin \gamma - \frac{dz}{ds} \cos \gamma = 0 \quad (8)$$

The shape of a space curve can be completely captured by its curvature and torsion. Using the Frenet-Serret formulation in the airframe, curvature  $\chi$  as well as torsion  $\tau$  can be deduced:

$$\kappa(s) = \frac{\|C' \times C''\|}{\|C'\|^3} = \sqrt{\left(\frac{d\gamma}{ds}\right)^2 + \left(\frac{d\chi}{ds}\right)^2} \cos^2 \gamma(s) \quad (9)$$

$$\tau(s) = \frac{(C' \times C'') \cdot C'''}{\|C' \times C''\|^2} = \frac{\chi' \gamma'' c\gamma + 2\chi' \gamma' \gamma'^2 s\gamma - \gamma' \chi'' c\gamma}{\gamma'^2 + \chi'^2 c^2 \gamma} + \frac{-\gamma' \chi'^2 c\chi c\gamma s\chi s^2 \gamma + \chi'^3 c^2 \gamma s\gamma}{\gamma'^2 + \chi'^2 c^2 \gamma} \quad (10)$$

The path planning generates a feasible flight path for an autonomous aircraft to reach the target. The purpose of this paragraph is to propose a 3D flight path to the aerial vehicle joining two consecutive waypoints configurations.

The inputs of this path planning algorithm are the  $i$ th way-point configuration parameters  $x_i, y_i, z_i, \chi_i, \gamma_i$  and the  $(i+1)$ th configuration parameters:  $x_{i+1}, y_{i+1}, z_{i+1}, \chi_{i+1}, \gamma_{i+1}$ . Depending on these parameters, many possibilities exist. The most obvious one is to propose a polynomial variation of  $x$ ,  $y$  and  $z$ . However the main drawback is a complicated formulation of the curvature and the torsion making control of smoothness (twists and cusps) a difficult task. The approach followed in this paper aims to propose a simple formulation of these two parameters.

##### A. Constant Curvature and Torsion

The heading and flight path angles can be given by the following relations

$$\chi(s) = \chi_0 + s\chi_1 \quad \gamma(s) = \gamma_i \quad (11)$$

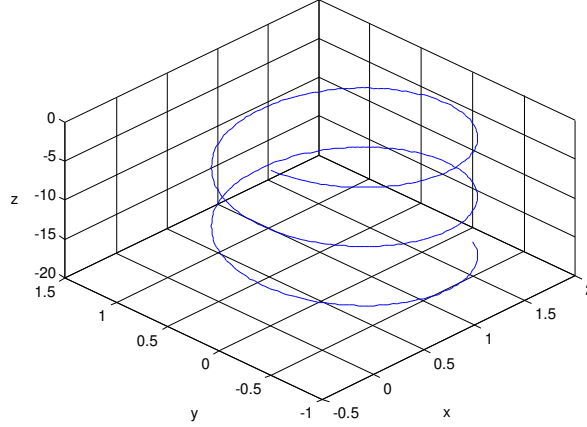
While the curvilinear abscissa is given simply by a linear temporal relation as the velocity is constant.

$$s = V_i t \quad 0 \leq t \leq \tau \quad (12)$$

with the constant curvature and torsion

$$\kappa(s) = \chi_1 \cos(\gamma_0) \quad \tau(s) = \chi_1 \sin(\gamma_0) \quad (13)$$





**Figure 5 : Constant torsion and curvature flight path**

Cylindrical helices are classically known in aeronautical science to be trim conditions. A trimmed flight condition is defined as one in which the rate of change of magnitude of the aerial vehicle state vector is zero (in the body fixed frame) and the resultant of the applied forces and moments are zero. The following non linear equations system has to be solved in order to determine the reference thrust and bank angle.

$$0 = -C_D(M, \alpha) A_{ref} \rho V^2 - 2mg \sin \gamma + 2T \cos \alpha$$

$$0 = C_L(M, \alpha) A_{ref} \rho V \cos \sigma - 2mg \cos \gamma + 2T \sin \alpha \cos \sigma$$

$$0 = C_L(M, \alpha) A_{ref} \rho V^2 \sin \sigma \cos \gamma + 2T \sin \alpha \sin \sigma$$

In a trimmed maneuver, the aerial vehicle will be accelerated under the action of non zero resultant aerodynamic and gravitational forces and moments: effects such as centrifugal and gyroscopic inertial forces and moments will balance these effects.

### B. Linear Curvature and Torsion

The flight path angle is still constant while the heading angle is given by a quadratic polynomial

$$\begin{aligned} \chi(s) &= \chi_0 + s\chi_1 + s^2\chi_2 & \gamma(s) &= \gamma_i \\ s &= \frac{1}{2} \frac{V_{i+1} - V_i}{\tau} t^2 + V_i t & 0 &\leq t \leq \tau \end{aligned} \quad (14)$$

with the linear curvature and torsion

$$\kappa(s) = (\chi_1 + 2\chi_2 s) \cos(\gamma_0) \quad \tau(s) = (\chi_1 + 2\chi_2 s) \sin(\gamma_0) \quad (15)$$

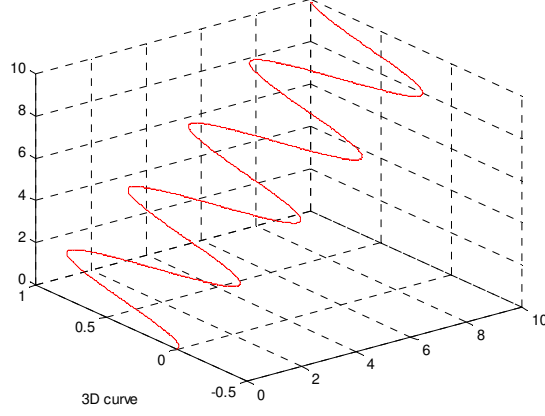


Figure 6 : Constant torsion and linear curvature flight path

The units are in (1000m). In the x-y plane, this is a clothoid: a well known path in robotics and highway design.

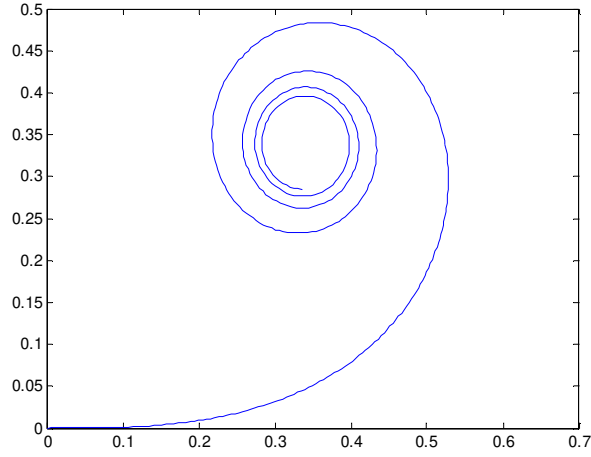


Figure 7 : Clothoid curve

The reference thrust and bank angle can be determined via the resolution of this system of nonlinear equations.

$$\begin{aligned}
 \frac{V_{i+1} - V_i}{\tau} &= -\frac{C_D(M, \alpha) A_{ref} \rho V^2}{2m} - g \sin \gamma + \frac{T \cos \alpha}{m} \\
 0 &= \frac{C_L(M, \alpha) A_{ref} \rho V \cos \sigma}{2m} - \frac{g \cos \gamma}{V} + \frac{T \sin \alpha \cos \sigma}{mV} \\
 \frac{\chi_{i+1} - \chi_i}{\tau} &= \frac{C_L(M, \alpha) A_{ref} \rho V \sin \sigma}{2m} + \frac{T \sin \alpha \sin \sigma}{mV \cos \gamma}
 \end{aligned} \tag{16}$$

### C. Nonlinear Curvature and Torsion

In the simplest case, the following first order polynomials can be proposed

$$\begin{aligned}
 \chi(s) &= \chi_0 + s\chi_1 & \gamma(s) &= \gamma_0 + s\gamma_1 \\
 s &= \frac{1}{2} \frac{V_{i+1} - V_i}{\tau} t^2 + V_i t & 0 &\leq t \leq \tau
 \end{aligned} \tag{17}$$

with the following relations

$$\begin{aligned}
\frac{V_{i+1} - V_i}{\tau} &= -\frac{C_D(M, \alpha) A_{ref} \rho V^2}{2m} - g \sin \gamma + \frac{T \cos \alpha}{m} \\
\frac{\gamma_{i+1} - \gamma_i}{\tau} &= \frac{C_L(M, \alpha) A_{ref} \rho V \cos \sigma}{2m} - \frac{g \cos \gamma}{V} + \frac{T \sin \alpha \cos \sigma}{mV} \\
\frac{\chi_{i+1} - \chi_i}{\tau} &= \frac{C_L(M, \alpha) A_{ref} \rho V \sin \sigma}{2m} + \frac{T \sin \alpha \sin \sigma}{mV \cos \gamma}
\end{aligned} \tag{18}$$

with the nonlinear curvature and torsion

$$\kappa(s) = \sqrt{\gamma_1^2 + \chi_1^2 \cos(\gamma_0 + \gamma_1 s)} \quad \tau(s) = (\chi_1 + 2\chi_2 s) \sin(\gamma_0) \tag{19}$$

The role of the trajectory generator is to generate a feasible time trajectory for the aerial vehicle. Once the path has been calculated in the Earth fixed frame, motion must be investigated using the dynamic model and reference trajectories determined taking into account actuators constraints (inequality constraints) and the under-actuation (equality constraints) of an aerial vehicle and limitations on curvature and torsion. Moreover, it is desirable that the plan makes optimal use of the available resources to achieve the goal optimizing some 'cost' measure: the time, energy, ... required for the execution.

## V. Conclusion

Path planning is still one of the open problems in the field of autonomous systems. It is a complex problem involving respect of physical constraints on the vehicle, on the environment and other operational requirements. The first part of this paper presents an updated flight plan based on a modified A\* algorithm.

The second part of this paper addresses the problem of characterizing continuous paths in 3D. Parametric paths with given curvature and torsion are investigated. Two particular cases are studied: constant, linear and quadratic variation of the heading angle versus the curvilinear abscissa, with the assumption of a constant or linear variation of the flight path angle, to consider different kinds of maneuvers. Maneuvers should be kept only to join two trim flight paths. Trajectory planning then incorporates dynamics into planning processes. Depending on the mission, time variable velocity must be considered, giving more flexibility to the trajectory generator, with respect to the limitations on actuators, on curvature and torsion. This is the subject of future work.

## Acknowledgments

The authors gratefully acknowledge the financial support of the CNES/PERSEUS project.

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