A98-31683

ICAS-98-6,5,2

TOWARDS AUTOMATED AIRCRAFT'S TAXIING PHASES

H. B. Siguerdidjane
Supélec, Plateau de Moulon,
91192 Gif-sur-Yvette cedex, France

M. Pelegrin
Académie de l'Air et de l'Espace
31500,Toulouse cedex, France

Abstract

In this work, we are interested in automated aircraft's taxiing phases within the next decade, particularly for busy airports. The main objective is to automate all the ground motions from the gates to a given position of the runway exit in the near future. This is to optimize the whole movements on the airport according to a criterion which will tend to maximize the number of movements per hour. In this paper, it is studied automated steering vehicles, unlike our previous work on this subject, an another formulation, which displays a certain robustness with respect to any perturbations, is presented. In this first stage of the work, simulation results are given to show the obtained performances of the system.

Introduction

The airports will become very busy due to the foreseen growth in the transport of passengers and freight over the next decade. Efficient techniques and strategies have to be developed in order to ensure a fluid traffic, acceptable delays (if so) and to prevent a foreseeable bottleneck effects.

Some potential future developments which could further enhance the utilization of the airports have been evaluated and proposed by Pelegrin[11,12]. The main objective is to automate all the ground motions from the gates to a given position of the runway exit. This is to optimize the whole movements on the airport according to a criterion which will tend to maximize the number of movements per hour. Obviously, the same level of safely as today should, at least, be guaranteed.

It is thus suggested to develop fully automatic tractor systems. The aircraft will be moved by these tractors such as those presently used, for movements from the gates to a remote position from which the plane can move by itself everywhere on the airport except the runways (as shown in figure 1, for instance). The motion should be controlled by a centralized computer which will monitor all the traffic.

In previous work, some control solutions, of such vehicles, have been studied [14,15] as well as a possible way to avoid the mathematical singularities [16] which represent the main difficulty in controlling those systems particularly nonholonomic systems.

In Siguerdidjane and Pelegrin [15] it is studied the control of such vehicles in such a way that the system track a given prescribed trajectory, in the allowed airport space, to perform a cooperative rendezvous with the aircraft. The prescribed trajectory is split into simple arcs in order to derive the corresponding control laws. So, it is obtained equally number of control expressions than the number of arcs. The number of arcs depends on the configuration of the airports. It is shown in [16] that the expression of the feedback control, determined to track a parabola, may be sufficient to track any prescribed trajectory, so there is no need to split it into arcs.

The aim of this paper is to present another formulation, which displays a certain robustness with respect to any perturbations (wind, glaze ..), in controlling those vehicles. In addition, the vehicles may have any initial position and direction and the above mentioned singularities are overcome, unlike the way shown in previous work[16] . Moreover, they can track any prescribed trajectory towards the aircraft in order to first

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

perform a cooperative rendezvous with the aircraft (see figure 3).

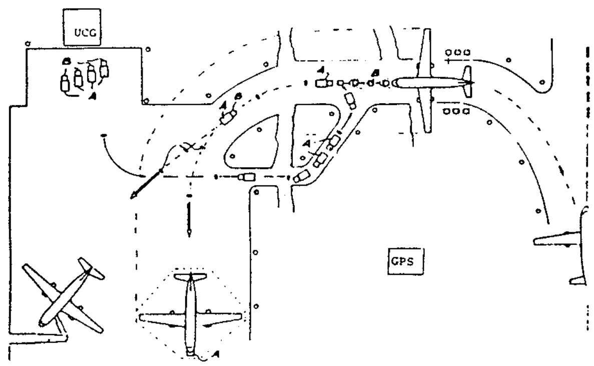

FIGURE 1 - The considered airport configuration

Prescribed trajectory

It is suggested in Pelegrin[11] that the tractor system may consist of two vehicles. The first vehicle (denoted by A in figure 1) is heavy and the second one (B) is light. The cart must track a trajectory which is generated by the computer once the airplane has reached the center line of the extended runway.

The vehicle (B) may be supposed inside the vehicle (A). They are anyway rigidly fixed, from the initial position to a given position from onwards they may be separated. When the relative distance between the cart and the plane is approximately 100 m, vehicle B then goes towards the plane in order to perform the rendezvous (see figure 3) without any stop of the plane. The cart (B) moves back when the plane is within few meters in such a way that both vehicles will have the same direction a very short time before the first rendezvous. The plane is supposed to be seized by its front landing gear. The light vehicle is equipped with sensors and can recognize, at a given distance, the landing gear of the plane to attach itself to. The employed navigation system is the GPS (Global Positioning System). The light vehicle can navigate with respect to the heavy one.

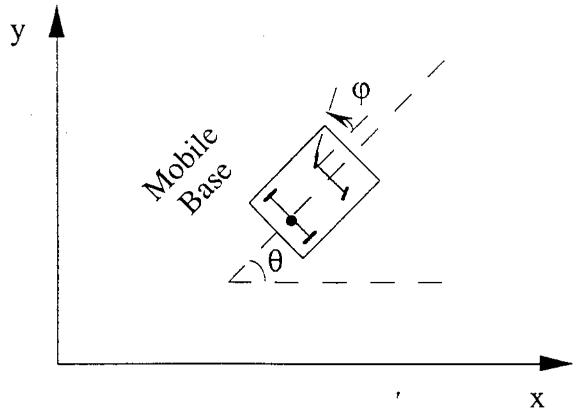

FIGURE 2- Tractor-system

Vehicle modeling

Till the separating point, the modeling of the vehicle turns out to be the one of a mobile robot. After this point, the trajectory of the vehicle B is considered only, since vehicle A is stopped meanwhile the first rendezvous between the aircraft and vehicle B. The second rendezvous, between the vehicle A and the system vehicle B-aircraft is not treated in this paper.

The modeling of mobile robot is extensively covered in the literature, see for example[6,9]. The kinematics equations are

$$\begin{aligned} \dot{x} &= \cos\theta \; v_1 \\ \dot{y} &= \sin\theta \; v_1 \\ \dot{\theta} &= -\frac{1}{L} v_2 v_1 \end{aligned} \qquad (1)$$

where x and y are the cart cartesian coordinates of the middle of the rear axle. θ is the orientation angle, with respect to a fixed frame (x, y). $v_2 = \tan\phi$ is the tangent function of the front wheels orientation angle with respect to a frame linked to the cart. v_1 is the translational speed, it is directed along the chassis of the cart. v_2 is the steering velocity angle. v_1, v_2 denote the control variables. L is the distance between the front wheel and the middle of the rear axle as shown in figure 2. Some papers considered the kinematics equations involving cartesian coordinates of the middle point of the front axle[18].

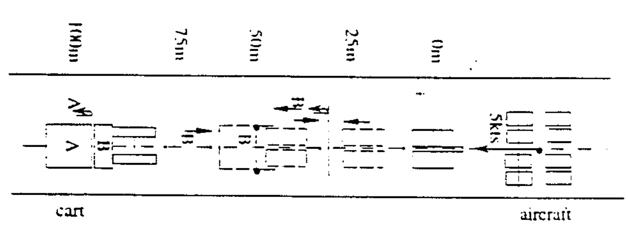

FIGURE 3- Rendezvous scheme

In order to derive the nonlinear control which will drive the system from its initial position to the prescribed trajectory moving towards the plane, it is used the asymptotic output problem as recalled in the following section.

Asymptotic output problem

Let us briefly review the asymptotic output problem. One may see Isidori[5], Nijmeijer and Van der Schaft[7] and particularly the work of Sira-Ramirez[17].

Consider the nonlinear system

$$\begin{cases} \dot{x} = f(x,u) \\ y = h(x) \end{cases} \quad (2)$$

y denotes the output. $f(x,u)$ is smooth vector field and $h(x)$ is a smooth function.

Let $y_R(t)$ be a prescribed reference output function differentiable at least n times with respect to the time t. The asymptotic output tracking problem consists in specifying a dynamic controller which depends on the reference output, a finite number of its time derivatives and the state variables and which forces the system output to asymptotically converge towards the reference desired one.

Define the tracking error $\varepsilon(t)$ as the difference between the actual system output $y(t)$ and the reference output $y_R(t)$

$$\varepsilon(t) = y_R(t) - y(t) \quad (3)$$

Let us impose a dynamic equation to the error by forcing $\varepsilon(t)$ to satisfy

$$\varepsilon^{(m)}(t) + \alpha_1 \varepsilon^{(m-1)}(t) + \ldots\ldots + \alpha_0\, \varepsilon(t) = 0 \quad (4)$$

The parameters α_i are chosen in such a way that the polynomial

$$P(s) = s^m + \alpha_1 s^{m-1} + \alpha_2 s^{m-2} + \ldots\ldots + \alpha_0 \quad (5)$$

be Hurwitz.

By defining $\varepsilon_i = \varepsilon^{(i-1)}$ (i=1,..., m) as components of an error vector ε, hence equation (4) may be expressed as

$$\begin{cases} \dot{\varepsilon}_1 = \varepsilon_2 \\ \dot{\varepsilon}_2 = \varepsilon_3 \\ \ldots\ldots\ldots \\ \dot{\varepsilon}_{m-1} = \varepsilon_m \\ \dot{\varepsilon}_m = c\left(\left(Y_R(t) - \mathrm{E}\right), u, \dot{u}, \ldots, u^{(k)}\right) - y_R^{(m)}(t) \end{cases} \quad (6)$$

$Y_R(t) = col(y_R(t), \dot{y}_R(t), \ldots, y_R^{(m-1)}(t))$ and $E = col(\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_m)$.

The dynamic (or static) control is then computed from the implicit last equation of system (6) and by using equation (4).

Nonlinear feedback control

Numerous methods are used, in the literature to control and to stabilize mobile robots. For example, in Canudas de Wit and Sordalen[3], Tilbury[19] et *al.*, it is used an exponential stabilization or multisteering trailer system. An optimal path is designed in for example Zhu[20] et *al.* Hybrid approach is applied in Fan[4] et *al.* Motion planning using sinusoids are described in Murray and Sastry[8]. Let us hereafter apply the asymptotic output problem approach, it leads to more simple expressions of the feedback control laws if it is used together by combining appropriately some equations.

Let

$$\varepsilon_x = x_R - x \quad (7)$$

and

$$\varepsilon_y = y_R - y \quad (8)$$

It comes that by using a second order differential equation for both errors according to equation (4) and by appropriately combining the resulting equations, one may obtain an expression of the dynamic feedback control which does not involve any singularities:

$$\begin{aligned} \dot{v}_1 &= \cos\theta\, (\ddot{x}_R + \alpha_1(\dot{x}_R - v_1\cos\theta) + \alpha_2\varepsilon_x) \\ &+ \sin\theta\, (\ddot{y}_R + \alpha_1(\dot{y}_R - v_1\sin\theta) + \alpha_2\varepsilon_y) \end{aligned} \quad (9)$$

This dynamic controller represents the acceleration of the cart. The second control law, namely the tangent of the front wheels orientation is static feedback and is not defined for zero translational speed cart. This corresponds to the case where the cart is stopped.

$$\begin{aligned} v_2 &= \frac{L}{v_1^2}(\sin\theta\, \ddot{x}_R - \cos\theta\, \ddot{y}_R + \\ &\sin\theta(\alpha_1\dot{x}_R + \alpha_2\varepsilon_x) - \cos\theta(\alpha_1\dot{y}_R + \alpha_2\varepsilon_y)) \end{aligned} \quad (10)$$

One may write again this equation in the form

$$v_2 v_1^2 = L\,(\ddot{x}\sin\theta - \ddot{y}\cos\theta) \quad (11)$$

when $v_1 = 0$, from (1) it comes that $\dot{x} = \dot{y} = 0$ and therefore $\ddot{x} = \ddot{y} = 0$ which, in consequence, implies that $v_2 = 0$ or $v_2 \neq 0$, in other words, $\phi = 0$ or any nonzero physically acceptable orientation of the front wheels.

Some simulation results

It is shown in the following some figures that the cart track the prescribed trajectory from any initial position under perturbations or under no perturbations. This is in order to perform the first rendezvous with the aircraft according to the considered airport configuration. It is observed that even under large perturbations the system remain stable. The simulations are performed in taking into account that the maximum value of the cart speed is 12m/s, the aircraft speed is supposed to be, in the taxiway, 5knts. $L = 8m$.

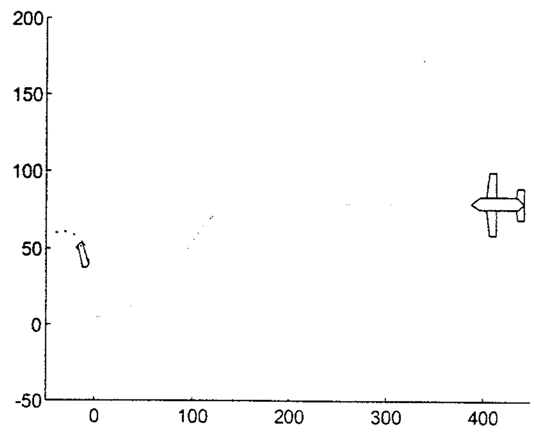

Figure 1. Tractor and aircraft trajectories $y = f(x)$ (in m) under no perturbations $(x_0, y_0) = (-40, 60)$; $\theta_0 = 0$ rad, $\phi_0 = -pi/8$ rad.

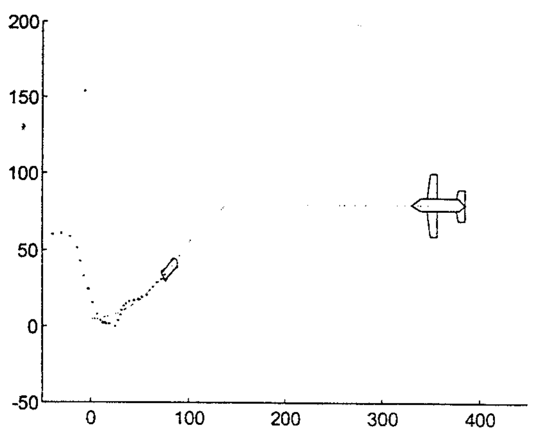

Figure 2. Tractor and aircraft trajectories $y = f(x)$ (in m) under perturbations $(x_0, y_0) = (-40, 60)$; $\theta_0 = 0$ rad, $\phi_0 = -pi/8$ rad., perturbations = (3,-3).

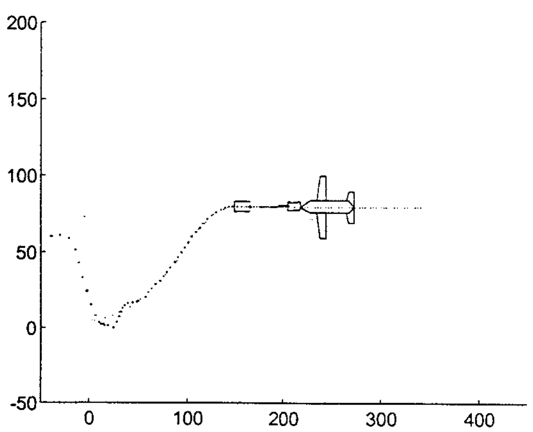

Figure 3. Rendezvous between vehicle B and the plane meanwhile vehicle A is stopped

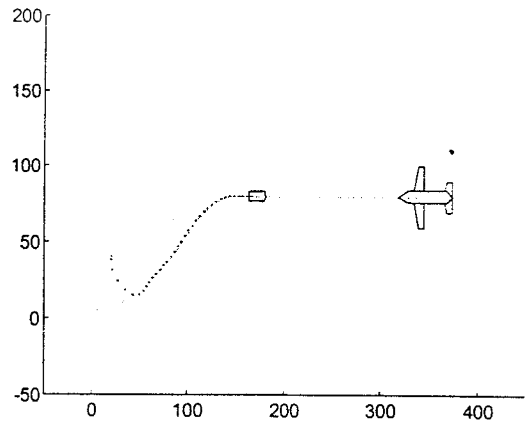

Figure 4. Tractor and aircraft trajectories $y = f(x)$ (in m) under no perturbations $(x_0, y_0) = (20, 40)$; $\theta_0 = -pi/2$ rad, $\phi_0 = 0$ rad.

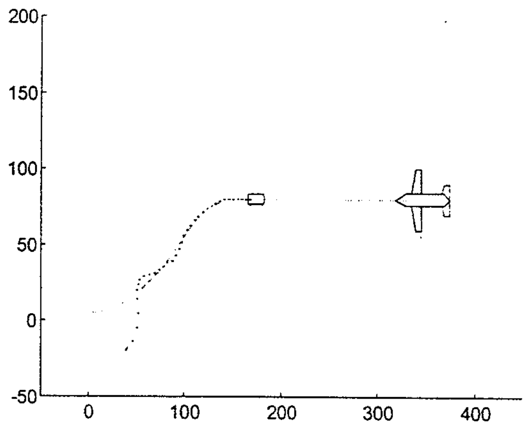

Figure 5. Tractor and aircraft trajectories $y = f(x)$ (in m) under perturbations $(x_0, y_0) = (40, -20)$; $\theta_0 = pi/4$ rad, $\phi_0 = pi/8$ rad., perturbations = (3,-3).

References

[1] Bloch, A. M., M. Reyhanoglu and N. H. McClamroch (1992). Control and stabilization of nonholonomic dynamic systems. *IEEE Trans. Aut. Contr.* 37, 11, pp. 1746-1757.

[2] Campion, G., G. Bastin and B. d'Andréa-Novel (1996). Structural properties and classification of kinematic and dynamic models of wheeled mobile robots. *IEEE Trans. Robotics and Automation.*, 12,1, pp. 47-62.

[3] Canudas de Wit, C. and O.J. Sorbolen (1991). Exponential stabilization of mobile robots with nonholonomic constraints. *30th IEEE Conf. Dec. and Contr.*, pp. 692-697

[4] Fan Z., Y. Koren and D. Wehe (1995). Tracked mobile robot control hybrid approach. *Control Eng. Practice,* 3, 3, pp. 329-336.

[5] Isidori A. (1995), Nonlinear control system. Springer Verlag.

[6] Kanayama, Y. and G. Hartman (1990). *Autonomous Robot Vehicles,* Springer Verlag, pp. 62-67.

[7] Nijmeijer H. and Van der Schaft A. (1990) Nonlinear dynamical control systems. Springer Verlag.

[8] Murray, R. M. and S. S. Sastry (1993). Nonholonomic motion planning: Steering using sinusoids. *IEEE Trans. Aut. Contr.*, 38, pp. 700-716.

[9] Nelson, W. and I. Cox (1990). *Autonomous Robot Vehicles,* Springer Verlag, pp. 38- 44.

[10] Pappas, G.J. and K. J. Kyriakopoulos (1992). Modeling and feedback control of nonholonomic mobile vehicles. *IEEE Conf. Dec. Contr.*, pp. 2680-2685.

[11] Pelegrin, M. (1991), SAATMAS-Système Assurant Tous les Mouvements d'Avions au Sol. Patent n° 9105129.

[12] Pelegrin, M (1992). Towards a fully automatic flight for passenger aircraft. *12th IFAC Aerospace Control Symp.* pp. 1-17.

[13] Pelegrin. SAATMAS: Fully automatic tractors for planes. IFAC workshop on Autonomous Intelligent vehicles, 1993, Southampton.

[14] Siguerdidjane H. (1996). Dynamic control of automated steering vehicles at busy airports. Workshop *on Optimal Control*, Oberwolfach, January 21-27, 1996.

[15] Siguerdidjane H. and M. Pelegrin (1996). Towards a rendezvous problem between an aircraft and automated steering vehicles. *Control Eng., Practice,* 4, 7, pp. 951-955. *13th IFAC Symp. on Aerospace Control* 94, Palo Alto, 1994.

[16] Siguerdidjane. H. (1997), A possible way to avoid the singularities in automated steering vehicles control. *8th IFAC Symp. On Transportation System*, Greece.

[17] Sira-Ramirez H., (1993). A dynamical variable structure control strategy in asymptotic output tracking problems. *IEEE Trans. Aut., 38, 4,* pp. 615-620.

[18] Stotsky A. and X. Hu, (1997). Control of car like robots using sliding observers for steering angle estimation. *8th IFAC Symp. On Transportation System*, Greece.

[19] Tilbury D., J. Sordalen, L. Bushmell and S. Sastry (1995). A multisteering trailer system: conversion into chained form using dynamic feedback. *IEEE Trans. on Robotics and Automation,* 11, 6, pp. 807-818.

[20] Zhu S. Q., F.L. Lewis, S.L. Campbell and K. Ito (1995). A new method for maneuver planning and a family of paths. *Europ. Contr. Conf.*, pp. 3080-3085.