Engineering Applications of Artificial Intelligence 24 (2011) 278–294

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Energy conservation based fuzzy tracking for unmanned aerial vehicle missions under a priori known wind information

Georgios P. Kladis [a], John T. Economou [a,*], Kevin Knowles [a], Jimmy Lauber [b], Thierry-Marie Guerra [b]

[a] *Intelligent Propulsion & Emissions Lab, Aeromechanical Systems Group, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Swindon, Wiltshire SN6 8LA, United Kingdom*

[b] *Laboratoire d'Automatique, de Mècanique et d' Informatique industrielles et Humaines, LAMIH, Universitè de Valenciennes, BP 311, Le Mont Houy, 59313 Valenciennes Cedex 9, France*

ARTICLE INFO

Article history:
Received 12 February 2010
Received in revised form 26 July 2010
Accepted 14 October 2010
Available online 26 November 2010

Keywords:
Graph theory
Energy cost matrix
Pre-flight planning
Energy conservation
Parallel distributed compensation
Takagi–Sugeno fuzzy model
Linear matrix inequalities

ABSTRACT

The aim of this work is to include the navigation step for the waypoint-based guidance of a UAV system and to illustrate aspects such as tracking of the reference trajectory under wind presence, while conserving total energy requirements. The mission is represented utilising graph theory tools. The mathematical modelling of an aircraft controlled by an actuator surface is presented in terms of simple analytic relationships in order to simulate the actual horizontal motion of the vehicle. Its equivalence with a Tagaki–Sugeno (T-S) fuzzy system is illustrated that can aid the control methodology involved. Additionally, the advantages of utilising such an analysis is also stressed. The model formulated is an error posture model, that depends on current and reference posture. The control law is designed through parallel distributed compensation (PDC) and the gains are computed with the help of linear matrix inequalities (LMIs). Hence stability for the system is also guaranteed provided that the state variables are bounded in a priori known compact space. Moreover the energy requirements are described.

This article is contributing towards energy enhancing a UAV mission and generating safely-flyable trajectories to meet mission objectives. The control law used is calculated in the pre-flight planning and can be used in real time for any trajectory to be tracked under any environmental conditions. Provided that angular and linear velocities are bounded, the latter is feasible under the assumption that the magnitude of air speed is *small* compared to the ground velocity of the aerial vehicle. The methodology offers an improved visualisation to aid an analyst with the representation of a UAV mission through graph theory tools utilising energy requirements for the mission and fast computational schema using matrix analysis.

A simulation example of a UAV deployed from a source to reach a destination node under windy conditions is included to illustrate the analysis. The reference trajectory used is a piecewise Bezier–Bernstein curve referred to as the Dubins path.

1. Introduction

On board guidance and control systems are used to monitor flight performance. Apart from the time of arrival and endurance of flight they are also utilised to maintain updated fuel reserves. Presently, overall flight planning is performed on ground dispatch computers. However, it is crucial to be able to estimate, real-time, the fuel profile on board in order to increase automation and performance of the preflight planning when disturbances occur. In other words, wasting fuel due to unforecast disturbances can degrade the performance of the preflight planning mechanism. At the same end, if the time of arrival is available by a particular strategy then a fuel optimal trajectory can be possibly generated on-line with manipulation of flight parameters like speed, propulsion magnitude, angle, etc.

Existing research till recently, focused heavily on methods which improve the path planning algorithms. In particular, the optimum paths based on minimum distance or time travelled has been addressed from researches in Richards and How (2002) and Rathinam and Sengupta (2004a), among other interesting works. In practice, the optimum distance path solutions do not take into account the energy constraints. Without the energy utilisation the selected path may not be feasible or realisable. In other words, when disturbances occur in a path, such as an unforecast unfavorable wind, then the shortest distance path may not guarantee an energy optimum one. The latter was shown in work (Economou et al., 2007b) where the authors decoupled the problem of a shortest path from the Euclidean perspective and the energy one. In addition they proposed a methodology utilising energy graphs and pseudo-boolean expressions to describe the overall energy requirements. Consequently motivated by such an analysis there is a need to

* Corresponding author.
E-mail addresses: j.t.economou@cranfield.ac.uk (J.T. Economou), jimmy.lauber@univ-valenciennes.fr (J. Lauber).

0952-1976/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engappai.2010.10.013

investigate the problem of navigation from the energy perspective rather than the shortest distance one.

Apart from the *Navigation* phase the pre-flight planning involves also the *Guidance* phase. In fact if energy routes are of interest the problem becomes threefold. Firstly, a predefined trajectory needs to be followed, the ground speed of the vehicle should be regulated and decision making should be performed in order to find a *minimum sense* path to follow that will fulfil mission objectives. Thus energy requirements should be described and then the path of optimum sense to reach a goal should be calculated. In the proposed analysis a graph theory formulation of the problem, introduced in Economou et al. (2007a, b) and Kladis et al. (2007), is combined with the physical and functional limitations of the vehicle with a focus on energy conservation of the involved flight path.

The tracking problem remains even nowadays a challenging area. Depending on the application domain, an adequate control law needs to be designed in order to fulfil mission objectives. Among many interesting approaches solving the tracking problem are those of Fliess et al. (1995) and Laumond (1998). Those are focused on the motion planning problem. However, their limitation lies in asymptotic tracking when the ground velocity of the vehicle becomes zero. Moreover, other works by Kanayama et al. (1991) and Klančar and Skrjanc (2007) suggested the combination of state feed-forward and feed-back control actions. The stability of the system was proved through a Lyapunov function and the gains were computed by linearisation of the tracking-error model to zero. Although there is potential in such approaches a serious drawback is with respect to their performance in real-time. The latter occurs due to the fact that the gains calculated that stabilise the system need to be updated and recalculated when the trajectory to be tracked is altered due to an event while in flight.

The approach proposed in this article, which is coupled with the routing problem, is based on the equivalent Takagi–Sugeno fuzzy model to the nonlinear error posture model of the vehicle's kinematics, introduced in earlier work (Tanaka et al., 1996). The control law used (parallel distributed compensation, PDC, Sugeno and Kang, 1986 and later improved by Wang et al., 1995) is computed utilising liner matrix inequality (LMI) techniques (Tanaka and Wang, 2001). The methodology proposed can be implemented for any type of reference trajectory provided that linear and angular velocities are bounded and $|V_w| \ll |V_g|$. $|V_w|$, $|V_g|$ are the magnitude of the wind and ground velocity, respectively. The latter can be interpreted with respect to the physical and functional limitations of the vehicle. The trajectory used in this work is the Dubins (1957) path. Additionally, disturbance rejection conditions are included in order to accommodate real world conditions. Stability is proven for any initial condition of the system for a priori known compact space of the state variables.

This article is contributing towards energy-enhancing a UAV mission and generating safely-flyable trajectories to meet mission objectives. The control law used is calculated in the pre-flight planning and can be used in real time for any trajectory. Additionally, it offers an improved visualisation to aid an analyst with the representation of a UAV mission through graph theory tools utilising energy requirements for the mission and fast computational schema using matrix analysis.

In this work preliminaries are addressed in Section 2. Those involve the graph theory tools. The vehicle's kinematics, the trajectory to be used, the model of environmental conditions and the description of the energy requirements are also included. Thereafter, in Section 3 the error posture model used and its equivalence to the Takagi–Sugeno (T–S) model are described. Additionally, the architecture of the controller and LMI conditions that stabilise the system are also included. Finally through a simulation example the analysis is illustrated in Section 4.2. In Section 5 concluding remarks are stated. Lastly an Appendix is added that includes the gains calculated for the control law for the T–S fuzzy model.

2. Preliminaries

2.1. Graph theory tools in the context of UAVs

In this section the graph theory preliminaries and the relevance to the waypoint-based formulation of the UAV mission are stated. Adopting the notation in Christofides (1975), a graph G is an ordered triplet (V,E,φ), where V is the set of vertices or nodes ($V=\{1,2,3, \ldots,V_{\max}\}$), E is the set of edges, ($E=\{c_1,c_2, \ldots,c_l\}$), which represent every possible connection created between a pair of nodes and φ the direction for every different element in the set of E, respectively, ($\varphi=\{(1,1),(1,2),\ldots,(i,j),\ldots,(j,i)\}$), where $i,j \in \{1,2,\ldots, V_{\max}\}$. A graph G can be represented in a form of the adjacency matrix $\mathbf{A}=[a_{ij}]$, where $\mathbf{A} \in \mathbb{R}^{nxn}$. For our cause *energy graphs* are utilised as suggested in earlier works (Economou et al., 2007b; Kladis et al., 2008a). The description of the energy requirements for the UAV mission is explained in Section 2.5.

In addition, properties included in Economou et al. (2007b) such as the flight adjacency matrix, the reachable matrix, the energy matrix bounded on perturbations, mission reachability matrix, etc., provide a solid framework for the use of graph theory in the context of unmanned aerial vehicles. Among them a useful graph theory property is concerned with reachability $\mathbf{R}=[r_{ij}]$. Its importance lies in the fact that through elementary calculations it can be decided whether or not a path is feasible prior to computing the optimum waypoint based sequence to reach a goal. The particular was also stressed in our earlier work (Kladis et al., 2007).

2.2. Modelling the motion of an aircraft

For the purpose of the simulations the kinematics model (1) is considered, for bank to bank turns under wind presence, with the necessary assumptions, as explained in Vinh (1995). Thus assuming that the thrust and the velocity vector are collinear (the thrust angle of attack becomes zero), the altitude and the ground velocity V_g are maintained constant (flight path angle and dV_g/dt becomes zero) then a full nonlinear aircraft model reduces to (1). This captures the most important key parameters for lateral motion of an electrically powered aircraft. In particular maintaining constant altitude can be assumed under realistic scenarios where the operational regime requires for the UAV to fly at an altitude within which there are no conflicting paths with flight traffic. Furthermore due to atmospheric properties a particular altitude can be fuel saving. Additionally, it can be assumed due to mission constraints (e.g. on reconnaissance missions the UAV needs to photograph a region in a stealthy manner). In practice, the point mass kinematics model (1) is valid only for small deviation of angles. Thus a more complex model, such as the one described in Stevens and Lewis (1992), can handle greater deviations since the coupling between variables is considered. However, the latter is beyond this work. An important reason is the fact that coordinated[1] bank to bank turns are taken into account for the UAV.

The motion of the point mass aircraft model (1) can be defined by the position coordinates x, y, the speed V_g, the heading angle θ and the mass m. Assuming a relatively short segment of flight path the weight of the fuel propelled aircraft, calculated as $W=mg$, can

[1] A coordinated turn in the horizontal plane is one in which there is no sideslip angle and the velocity vector is in the plane of symmetry containing the aerodynamic and the propulsive forces.