Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Fast real-time three-dimensional wind estimation for fixed-wing aircraft

Haichao Hong [a], Mengmeng Wang [b], Florian Holzapfel [c], Shengjing Tang [a,*]

[a] *Beijing Institute of Technology, Beijing, 100081, China*
[b] *Beihang University, Beijing, 100191, China*
[c] *Technische Universität München, Garching, 85748, Germany*

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 7 July 2017
Accepted 17 July 2017
Available online xxxx

Keywords:
Inflight safety
Wind estimation
G-MPSP
Optimal control

ABSTRACT

This paper proposes a fast real-time estimation algorithm which is inspired by the philosophy of the generalized model predictive static programming and solves the three-dimensional wind estimation problem in an optimal control manner. The wind estimation problem is transformed into a static optimization problem featuring a highly efficient solving framework. The proposed algorithm estimates the three-dimensional wind components without considering any hypothesis on the structure of the wind, and without relying on airspeed measurements either. The measurement noise and the model uncertainties are applied. Simulations demonstrate the rapidity and accuracy of the proposed method.

1. Introduction

The wind is a critical risk factor for the inflight safety, especially during the take-off and landing phases [1]. This paper was motivated by attempts to fast indicate the wind condition on-board to enhance the pilots' situational awareness in some emergency cases. Through the investigation and analysis of the reality and some accidents, we summarize three important factors that must be considered for an adequate wind estimation algorithm for emergency cases.

1. The estimation algorithm must be fast. The fastness is embodied in two aspects. The algorithm must be computationally efficient and it must be able to indicate the wind variation in a short time. Firstly, a successful implementation of the online estimation method is subject to the limited computing power on-board [2]. A traditional numerical method may not be efficient enough to be run onboard. Hence, the estimation algorithm must employ an advanced solution, preferably an explicit closed-form solution. Secondly, there is plenty of evidence to suggest that the quick changing wind structure played a hazardous role in some accidents. The Air France Airbus A340-313 crashed because of a sudden wind velocity variation [3]. If the estimation method produces estimates with some time delay, it offers little help to the crew's judgment and behavior during emergency cases [4].
2. The wind estimation must be three-dimensional (3-D) and the algorithm must consider unknown wind structures. Firstly, in most passenger airplanes mainly the horizontal wind situation is displayed in strength and direction. However, the low-altitude vertical wind shear, one of the most dangerous atmospheric activities for civil aviation was considered as a major contributory factor in some severe accidents [5]. In March 2009, a McDonnell Douglas MD-11F cargo flight had a severe accident due to the vertical gusty wind [6]. The Boeing 737-236A of Bhoja crashed on approach in the extreme vertical wind shear condition [7]. Secondly, the unknown rapidly changing wind was often one of the major contributing factors in some tragic accidents. In June 2012, the severe wind disturbance was so strong that a Boeing 767 of All Nippon Airways seriously damaged [8]. Moreover, in modern manned flight, the constant wind usually poses minor impact on operation. Therefore, for emergency cases, the predefined wind structure should not be considered as an assumption that the algorithm is based on.
3. The algorithm may not rely on the airflow measurements. We suppose that in some extreme cases, the airspeed sensor failure can happen. In June 2009, the crash of the Airbus A332 of Air France may serve as an example [9]. We intend to use only non-airflow measurements, which can be more feasible and reliable.

---

* Corresponding author.
E-mail address: tangsj@bit.edu.cn (S. Tang).

http://dx.doi.org/10.1016/j.ast.2017.07.019
1270-9638/

Please cite this article in press as: H. Hong et al., Fast real-time three-dimensional wind estimation for fixed-wing aircraft, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.07.019

Wind estimation algorithms were broadly addressed in the literature. Conventionally, the wind models were subject to several assumptions while the estimation algorithm was being developed, e.g. the steady wind model. Petrich et al. estimated the quasi-constant wind using Kalman filters [10], as they were interested in estimating the steady state components of the wind instead of gusts for emergency cases. The constant wind with random gusts was estimated by Pachter et al. using an unscented Kalman filter (UKF) [11]. It is reasonable to assume that the Micro Air Vehicles (MAV) fly in a constant wind field during the short flight. However, our efforts are made towards the gusty wind field.

Some of the existing approaches consider two-dimensional (2-D) wind models. Based on the UKF, Palanthandalam-Madapusi provided a 2-D wind field estimation scheme [12]. The effect of the unknown wind disturbance to the MAV navigation concerned them in the defined scenarios for planer flight. Assuming that the wind existed in the horizontal plane, Kumon et al. proposed a wind estimation method using an unmanned air vehicle with delta wing [13]. From the case reviews, we evidenced accidents caused by vertical wind shear, so it stands to reason to incorporate the additional vertical components of wind.

The airflow measurements are widely required in prior wind estimation methods (e.g. [10–12,14] and [15]). However, required by our mission statement, these approaches are not available for our problem without the presence of the airflow measurements.

Kalman Filter and its extensions are broadly employed by researchers for wind estimation (e.g. [10–12,14] and [16]). However, when we carefully studied the presented results, some potential drawbacks including the converging speed, the higher order correlation and the additional tuning effort concerned us for practical reasons. For example, the changes of the wind speed is modeled by using the first-order Gauss–Markov process which is frequently utilized for estimating some slowly varying signals [16], which is in contrast to our motivation to fast indicate the quickly changing wind variations, such as the gusty wind and wind shear. An unconventional algorithm overcoming all the aforementioned drawbacks is therefore developed and presented.

This paper developed a 3-D wind estimation algorithm featuring high computational efficiency and fast indication using the non-airflow measurements. The generalized model predictive static programming (G-MPSP) is a computationally efficient method developed for solving finite-horizon nonlinear optimal control problems [17]. The proposed real-time wind estimation method is inspired by the philosophy of the G-MPSP – the terminal error of a finite time horizon between the predicted and actual outputs can be minimized by updating control variables using an explicit closed-form solution. The overall idea of the proposed algorithm is that the wind components are considered as "virtual" inputs to the model, and with the measured information during a previous finite horizon, the predicted kinematic velocity states with the velocity expressed as absolute value and direction with respect to the ground are calculated. Then, based on the error between the predicted and the measured states, the inputs, i.e. the wind vector can be updated using the customized G-MPSP so that the terminal errors are eliminated.

Four key points are addressed in the proposed algorithm. Firstly, the main achievement of the paper is a new, non-standard optimization method for wind estimation which does not involve computationally intensive numerical procedures. This is the reason why the scheme is not only computationally efficient but also can be run onboard in real-time. We see this proposed scheme (which is in contrast to standard numerical optimization procedures) as a significant contribution, particularly for its potential to be used in onboard applications. Secondly, as a supplement to the main achievement, any observed terminal error will immediately lead to the indication of the wind variation. The situational awareness in the emergency cases is only valid when the response is fast enough. The proposed approach does not inherently feature the low-pass characteristic, which is considered to be an important aspect of the contribution to the proposed "fastness". Thirdly, the algorithm is not developed for any specific structure of the wind model, as the non-constant wind variations, especially the vertical wind changes, are the inevitable challenge to the inflight safety. As an important feature, the 3-D non-constant wind components are taken into consideration in the algorithm. Finally, only non-airflow measurements are utilized by the estimation method. Therefore, the proposed wind estimation algorithm fulfills the needs and contributes to the prior art of the wind estimation.

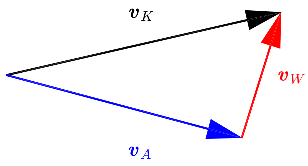

Fig. 1. Velocity triangle.

This paper is presented as follows. The necessary mathematical details of the nonlinear aircraft model using the 3-D wind vector as the virtual input are covered in section 2. In section 3, the wind estimation algorithm is introduced. The simulation results are presented in section 4. Finally, conclusions are drawn in section 5.

2. Aircraft model

For the proposed wind estimation algorithm, the 3-D wind components are considered as "virtual" inputs to the model and the expected response in translation is to be calculated with the inputs and the measured variables.

This section details the 6 degrees of freedom (6-DoF) non-linear model of a fixed-wing aircraft in the presence of a 3-D wind condition. The definition of basic rotation matrices is given in the Appendix, while in this section, the subscripts denote the frames, in which the components are notated. Vectors are associated with the center of gravity. The inertial frame is earth-fixed with axes parallel to the north east down (NED) frame O. The model is based on the models presented in Refs. [18,19]. The overall idea of this section is that we calculate the air data, i.e. the aerodynamic velocity, angle of attack, angle of sideslip and aerodynamic bank angle using the information from non-airflow measurements and the wind components provided by the algorithm to give the state prediction in translation.

The 3-D wind vector $\boldsymbol{v}_W$ in Fig. 1 is given in the O-Frame as

$$(\boldsymbol{v}_W)_O = \begin{pmatrix} u_W \\ v_W \\ w_W \end{pmatrix}_O . \tag{1}$$

The wind information in the system is provided by the wind estimation algorithm.

Via the velocity triangle approach, the relation between the aerodynamic velocity $\boldsymbol{v}_A$, the wind velocity $\boldsymbol{v}_W$ and the kinematic velocity $\boldsymbol{v}_K$ is obtained as follows,

$$(\boldsymbol{v}_A)_O = (\boldsymbol{v}_K)_O - (\boldsymbol{v}_W)_O . \tag{2}$$

Furthermore, the aerodynamic velocity can be described with 3-D components in the O-frame as,

$$(\boldsymbol{v}_A)_O = \begin{pmatrix} u_A \\ v_A \\ w_A \end{pmatrix}_O = \begin{pmatrix} V_A \cos\chi_A \cos\gamma_A \\ V_A \sin\chi_A \cos\gamma_A \\ -V_A \sin\gamma_A \end{pmatrix}_O \tag{3}$$

where χ_A, γ_A and V_A are the aerodynamic flight-path course angle, the aerodynamic flight-path climb angle and the aerodynamic speed, respectively, which can be obtained as follows,

Please cite this article in press as: H. Hong et al., Fast real-time three-dimensional wind estimation for fixed-wing aircraft, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.07.019