Aerospace Science and Technology 77 (2018) 129–137

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Receding horizon guidance of a small unmanned aerial vehicle for planar reference path following

Yoshiro Hamada *, Taro Tsukamoto, Shinji Ishimoto

Japan Aerospace Exploration Agency, 7-44-1 Jindaiji Higashi-machi, Chofu-shi, Tokyo 181-8522, Japan

ARTICLE INFO

Article history:
Received 11 May 2017
Received in revised form 15 January 2018
Accepted 28 February 2018
Available online 2 March 2018

Keywords:
Receding horizon control
Guidance
Unmanned aerial vehicle
Flight demonstration

ABSTRACT

This paper describes a novel lateral guidance law for an unmanned aerial vehicle using nonlinear receding horizon optimization and shows its flight test results. The guidance law uses an extended Kalman filter which estimates steady wind velocities in order to follow a pre-specified reference path defined in a ground-fixed coordinate system. The guidance law can be applied to arbitrary reference path as long as the path is represented as a differentiable function of x and y in a ground-fixed coordinate system. A small-scale research vehicle developed by the Japan Aerospace Exploration Agency is used for flight tests, and the results demonstrate the high guidance performance of the proposed method.

1. Introduction

Receding horizon control (RHC), also known as model predictive control (MPC), is a powerful control technique, which solves open-loop optimal control problem along a prediction horizon in real time [1,2], and successful applications can be found in many literatures. For nonlinear systems, several receding horizon algorithms have been proposed and the continuation/generalized minimum residual (C/GMRES) method [3] is one of the most useful options among them. This is a combination of the continuation method [4] and GMRES method [5], which is characterized by lighter calculation load. Therefore, it is possible to implement the algorithm even with a powerless onboard computer.

In this paper, path-following guidance for small fixed-wing unmanned aerial vehicles (UAVs) under steady wind is realized by C/GMRES method. Wind disturbances have strong effects on path-following performance of UAVs and various methods have been proposed to overcome the effects. Liu et al. [6] adopted a disturbance observer-based control approach, in which wind velocities are estimated by the disturbance observer and a trimming angle is modified to cancel the wind effect. Park et al. [7] applied pure pursuit missile guidance law to UAVs. Beard et al. [8] used the theory of "nested saturation", which was introduced in [9], to deal with input constraints. These three approaches were validated by flight experiments and showed their robustness against wind disturbances. As for MPC approach, Slegers et al. [10] used Taylor expansion to apply nonlinear MPC technique to a rigid 6-degrees-of-freedom UAV model. Gavilan et al. [11] adopted explicit linearization scheme to solve nonlinear optimization problem for MPC path-following. These two approaches, however, were validated only by numerical simulations.

This paper realizes path-following guidance which is robust against steady wind while taking input constraints into account, by combining steady wind estimation using the EKF and the C/GMRES method with the estimation result. Although Beard et al. [8] realized the similar path-following guidance, their method needs to change the guidance law in the case of straight-line path following and circular path following. On the other hand, the proposed method in this paper can follow both straight-line path and circular path without changing the guidance law itself. This paper extends our previous work, described in [12] and [13], where only straight and circular reference paths were considered. Here, a much wider range of reference paths are available with the only restriction being that they be represented as a differentiable function of x and y in a ground-fixed coordinate system. Numerical simulation results of following an oval reference path are presented to show the effectiveness of the proposed guidance system. The results of reference path-following flight tests, which were conducted using the JAXA-developed small-scale research vehicle (SSRV), are also presented.

This paper is organized as follows. The overview of SSRV and its lateral equations of motion are presented in Section 2. Section 3 reviews C/GMRES method, a nonlinear RHC proposed in [3]. The proposed lateral guidance law using C/GMRES method with an extended Kalman filter is described in Section 4. Then the results of nonlinear simulations and flight tests using the proposed guidance law are presented in Section 5 and Section 6 respectively.

* Corresponding author.
E-mail address: hamada.yoshiro@jaxa.jp (Y. Hamada).

https://doi.org/10.1016/j.ast.2018.02.039

Fig. 1. Small-Scale Research Vehicle (SSRV).

2. SSRV: Small-Scale Research Vehicle

2.1. Overview of SSRV

Fig. 1 shows the subject vehicle, a small unmanned aerial vehicle called the "SSRV" developed by JAXA to enable flight experiments of challenging control methods to be conducted more frequently and at lower cost than when using full-scale aircraft. The SSRV is developed base on a radio-controlled vehicle. It has a length of 2.6 m and a wingspan of 4.2 m and its total weight is 33 kg. It has an onboard flight control system for autonomous control, air data sensors (ADSs) and a Micro-GAIA (GPS-Aided Inertial Avionics), MEMS-based Micro-GPS/INS integrated navigation system [14]. The onboard processor is an Advantech PCM-3370F-J0A1E PC/104-Plus CPU module with a ULV Intel® Celeron® 400 MHz CPU (fanless) and 512 MB of SDRAM memory.

A nonlinear simulation model of the SSRV has been constructed using aerodynamic coefficients obtained from wind tunnel tests. It is implemented as a MATLAB® Simulink® model which can be used not only for numerical simulation studies but also for Hardware-In-The-Loop (HIL) simulations.

2.2. Lateral motions of SSRV

In order to design a planar reference path-following guidance system, the SSRV's lateral equations of motion must be considered. Under the assumption that level flight is achieved (that is, the flight path angle γ is zero), these are described in the following form:

$$\dot{x}(t) = V_T(t)\cos\chi(t) + W_x(t), \tag{1}$$

$$\dot{y}(t) = V_T(t)\sin\chi(t) + W_y(t), \tag{2}$$

$$\dot{\chi}(t) = \frac{1}{mV_T(t)}(L(t) + T(t)\sin\alpha(t))\sin\sigma(t), \tag{3}$$

where

- x: x position in a runway coordinate system
- y: y position in the runway coordinate system
- χ: heading angle
- W_x: wind velocity component along the runway x-axis direction
- W_y: wind velocity component along the runway y-axis direction
- V_T: true airspeed
- α: angle of attack
- σ: angle of bank
- m: vehicle mass
- L: magnitude of the lift vector
- T: engine thrust

Here the runway coordinate system is a ground-fixed coordinate system with its origin on a runway threshold and the x-axis along the runway centerline. It is also used to describe reference paths.

3. Nonlinear RHC by C/GMRES method [3]

This section reviews the fast numerical algorithm for nonlinear RHC proposed in [3] briefly. It is a combination of the continuation method and the GMRES method. The former helps solve an optimization problem without iterative calculation, and the latter solves efficiently the linear equation which appears in an optimization problem. Consequently the computational complexity of the method is much lower than other methods. Comparisons of the computational time using an example are described in the reference.

The nonlinear system, equality constraints and the performance index are defined respectively by

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t)),$$

$$\boldsymbol{C}(\boldsymbol{x}(t), \boldsymbol{u}(t)) = 0,$$

$$J(\boldsymbol{x}_0, T_s, \boldsymbol{u}(\cdot)) = \phi_J(\boldsymbol{x}^u(T_s; \boldsymbol{x}_0)) + \int_0^{T_s} L_J(\boldsymbol{x}^u(\tau; \boldsymbol{x}_0), \boldsymbol{u}(\tau))d\tau,$$

where

- $\boldsymbol{x}$: state vector
- $\boldsymbol{u}$: input vector
- T_s: duration of the prediction horizon
- $\boldsymbol{x}_0$: state vector at the beginning of the prediction horizon ($\boldsymbol{x}_0 = \boldsymbol{x}(t)$)
- $\boldsymbol{C}(\cdot,\cdot)$: equality constraints (vector-valued function)
- $\phi_J(\cdot)$: terminal cost
- $L_J(\cdot,\cdot)$: integral cost

and $\boldsymbol{x}^u(\tau; \boldsymbol{x}_0)$ in L_J denotes the trajectory of the state along the τ axis from an initial state $\boldsymbol{x}_0$ at $\tau = 0$ as the result of time series inputs $\boldsymbol{u}(*)$.

The optimization problem here is to determine a control input $\boldsymbol{u}$ at each time t so as to minimize the performance index $J(\boldsymbol{x}_0, T_s, \boldsymbol{u}(\cdot))$ under the equality constraints $\boldsymbol{C}(\boldsymbol{x}^u(\tau; \boldsymbol{x}_0), \boldsymbol{u}(\tau)) = 0$ over the horizon $t \le \tau \le t + T_s$.

Let H denote the Hamiltonian defined by:

$$H(\boldsymbol{x}, \lambda, \boldsymbol{u}, \mu) := L_J(\boldsymbol{x}, \boldsymbol{u}) + \lambda^T \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}) + \mu^T \boldsymbol{C}(\boldsymbol{x}, \boldsymbol{u}),$$

where λ is the costate and μ is the Lagrange multiplier associated with the equality constraints. Then, nonlinear RHC is achieved by executing the following algorithm for each control step:

1. Divide the prediction horizon (from the current time t to $t + T_s$) into N steps and discretize the optimal control problem.

$$\boldsymbol{x}^*_{i+1}(t) = \boldsymbol{x}^*_i(t) + \boldsymbol{f}(\boldsymbol{x}^*_i(t), \boldsymbol{u}^*_i(t))\Delta\tau(t)$$

$$\boldsymbol{x}^*_0(t) = \boldsymbol{x}(t)$$

$$\boldsymbol{C}(\boldsymbol{x}^*_i(t), \boldsymbol{u}^*_i(t)) = 0,$$

$$(i = 0, 1, \ldots, N-1)$$

where $\boldsymbol{x}^*_i(t)$ is the predicted state at step i in the prediction horizon, $\Delta\tau(t) := T_s(t)/N$ and the duration of the horizon $T_s(t)$ is assumed as $T(0) = 0$ and $T(t) \to \text{const.}(t \to \infty)$. This yields the following first-order necessary conditions for optimal control: