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

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Application of model aided inertial navigation for precise altimetry of Unmanned Aerial Vehicles in ground proximity

Hadi Nobahari*, Hamed Mohammadkarimi

Department of Aerospace Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 30 May 2016
Accepted 23 July 2017
Available online xxxx

Keywords:
Inertial Navigation System
Model aided navigation
Unmanned Aerial Vehicle
Automatic landing
Altimetry
Ground effect

ABSTRACT

In this research, Model Aided Inertial Navigation (MAIN) is used during the automatic landing of an Unmanned Aerial Vehicle (UAV). A new MAIN algorithm is proposed which is fast and accurate enough to be used in this phase. In this algorithm, the six Degree of Freedom (6DoF) flight simulation of the UAV is integrated with the Inertial Navigation System (INS) such that the 6DoF model acts as an aiding system for the INS. In the last parts of the landing phase, when the UAV flies in proximity of the ground surface, the proposed integrated navigation system can estimate the altitude of UAV utilizing the “ground effect” phenomenon. Therefore, the method does not have the drawbacks of active altimeters such as cost, weight and dependency to weather conditions, surface type and attitudes. Simulation results show that the altitude estimation by the new MAIN algorithm converges in a fraction of second, and the accuracy is acceptable for a precise automatic landing.

1. Introduction

Nowadays, UAVs are widely used in military and civil operations. Over time, the percentage of flight autonomy in UAV operations has also been increased. One of the most challenging flight phases of an autonomous UAV is the landing phase. According to [1], flight control is one of the major causes of the UAV accidents in the landing phase. During the landing, the altitude control system makes the UAV to follow a desired altitude, with acceptable dynamic response [2]. Also, Ground-touch should occur with small vertical velocity to prevent structural damages [3].

Altitude controller needs accurate data of the altitude With Respect To (WRT) the ground. Such data are commonly measured by laser, radio or ultra-sonic altimeters. These systems have different drawbacks like cost, weight and dependency to surface type and attitude [4]. Thus, reliable, low weight and low cost altimetry of UAVs is a challenging problem.

The accuracy of laser altimeters depends on surface penetration and reflection [5]. Angled surface and hit on vegetation will reduce the accuracy. Also, local terrain slope or UAV attitude can cause inaccurate measurement of the altitude. One solution is active stabilization which is heavy and costly [5]. Another way is to use an arrangement of laser illuminators, separated a few degrees in angle to make a parallel measuring from the surface [6].

Ultrasonic and infrared altimeters fail under certain conditions like soft or transparent surfaces, smoke and bad reflections [4]. Infrared sensors are affected by color changes and reflections [7]. Ultrasonic performance is degraded by acoustic sources including wind, turbulence, vibration, and aircraft engines [8]. Also, it shows incorrect results over a grassy area because the ultrasonic waves bounce off of grass blades at different angles [9].

Radar altimeters can measure the ground altitude, precisely. But, they are complex, expensive, and heavy. Moreover, their performance depend on the characteristics of the surface as well as the attitudes [10]. Also, they are susceptible to jamming and they are inaccurate when the vehicle is flying over low-reflectivity surfaces [8].

Image processing techniques can provide the altitude feedback, utilizing a precise camera and a computer with adequate processing power [11]. These algorithms usually detect the landmarks with specified color and shape and the position of the UAV is estimated WRT the detected points [12,13]. So, they usually depend on external references such as a landing pad or marker, placed on ground [14]. The dependency on known, artificial landmarks and also on the visibility conditions, reduces the reliability of the vision based navigation in real-environment applications [15]. Furthermore, robustness to image noise, occlusion, background changes and clutter is another challenge [16].

A novel approach for determining the altitude of a UAV during the automatic landing phase is proposed in this paper. The pro-

---

* Corresponding author.
E-mail address: nobahari@sharif.edu (H. Nobahari).
URL: http://ae.sharif.edu/~nobahari (H. Nobahari).

http://dx.doi.org/10.1016/j.ast.2017.07.033
1270-9638/

Please cite this article in press as: H. Nobahari, H. Mohammadkarimi, Application of model aided inertial navigation for precise altimetry of Unmanned Aerial Vehicles in ground proximity, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.07.033

Nomenclature

b	Wing span.
$\bar{c}$	Mean aerodynamic chord.
$\bar{q}$	Upstream dynamic pressure.
S	Wing area.
u, v, w	Linear velocity components of the body frame WRT the local frame, expressed in the body frame.
p, q, r	Angular velocity components of the body frame WRT the local frame, expressed in the body frame.
ψ, θ, ϕ	Euler angles of the body frame WRT the local frame.
X, Y, Z	Components of non-gravitational forces in body frame.
L, M, N	Components of the external moments in body frame.
C_D, C_Y, C_L	Aerodynamic force coefficients in stability axis.
C_l, C_m, C_n	Aerodynamic torque coefficients in body axis.
g	Gravity acceleration.
I_{xx}, I_{yy}, I_{zz}	Diagonal components of the Inertia matrix.
I_{xz}	Non-diagonal component of the Inertia matrix.
$T_{\max}$	Maximum thrust.
α, β	Angles of attack and side slip.
δ_t	Throttle.
δ_e, δ_a, δ_r	Elevator, aileron and rudder deflection angles.
h, $\bar{h}$	Dimensional and non-dimensional altitude.
ε	Perturbation operator.
δf_x, δf_y, δf_z	Accelerometers error in body frame.
$\delta\omega_x$, $\delta\omega_y$, $\delta\omega_z$	Gyros error in body frame.
f_n, f_e, f_d	Accelerometers output in local frame.
v_n, v_e, v_d	Velocities in north, east and down directions.
$\hat{x}$	Estimation of x.
$\hat{\mathbf{p}}_N$, $\mathbf{v}_N$, $\hat{\boldsymbol{\varphi}}_N$	Position, velocity and attitude computed by the navigation module.
$\hat{\mathbf{p}}_I$, $\mathbf{v}_I$, $\hat{\boldsymbol{\varphi}}_I$	Position, velocity and attitude estimated with KF.
$\hat{\mathbf{p}}_M$, $\mathbf{v}_M$, $\hat{\boldsymbol{\varphi}}_M$	Position, velocity and attitude estimated with UKF.
$\hat{\mathbf{p}}_F$, $\mathbf{v}_F$, $\hat{\boldsymbol{\varphi}}_F$	Position, velocity and attitude fused from KF and UKF.
$\varepsilon\hat{\mathbf{p}}$, $\varepsilon\mathbf{v}$, $\varepsilon\hat{\boldsymbol{\varphi}}$	Error of computed position, velocity and attitude

posed approach integrates the UAV dynamic model with the INS. The UAV model in the proximity of the ground is influenced by the ground effect phenomenon and since this effect depends on the relative altitude (between the UAV and airstrip), the integrated navigation system will have the ability to estimate the altitude, accurately. This method causes no extra cost or weight, and just imposes additional computations. Also, this system has less dependency on the surface characteristics and the UAV attitudes.

The Possibility of using the aircraft dynamic model as an aided navigation system was first reported in [17]. By the aircraft dynamics, a 6DoF model is intended, which interprets the relation between an aircraft's controls (elevator, rudder, aileron & throttle) and its physical states (position, velocity & attitude). Reference [18] has integrated the aircraft perfect model with the INS to estimate the constant components of the wind velocity. The exactness of the model is then degraded by adding 5–10 percent of error to the aerodynamic coefficients. It has been shown that the performance of the integrated system is more sensitive to lateral aerodynamic errors than the longitudinal ones. It is also concluded that under specific conditions (such as GPS jamming in a GPS/INS system), the model aided INS is more accurate than a sole INS.

Reference [19] has compared two different configurations of using aircraft model to aid the INS. In the first method, velocity and attitude, computed by aircraft's model are fed back to INS and in the second method, acceleration and angular velocity are fed back. It has been shown that the second configuration is less successful. It has been concluded that the major value in using the vehicle model in an integrated INS is that it enhances the observability of the navigation errors.

The first report on the implementation of model aided INS is presented in [20], where accurate knowledge of a submarine dynamics is used for underwater navigation. Experimental results show that without the velocity measurement, it is possible to improve the accuracy of an underwater INS by utilizing an accurate model of the vehicle. The study has been improved in [21,22], where the estimation of the water velocity has been added to the previous work and also, the robustness of the integrated system has been improved.

References [23,24] have used vehicle dynamics as a mean of aiding in a low-cost INS, with application to underwater vehicles. Based on Monte-Carlo simulation, it is concluded that the performance of the proposed navigation system is robust to model uncertainties and underwater disturbances.

This paper presents a novel approach to estimate the altitude during the automatic landing of a UAV. A new MAIN algorithm is utilized for navigation of the UAV. The algorithm integrates the 6DoF model of the UAV (including the model of Ground Effect (GE)) with the INS. Since GE model is a function of the altitude, the MAIN algorithm is capable to estimate the ground altitude of the UAV rapidly and accurately. The method does not have the drawbacks of active altimeters and does not impose extra cost or weight to the navigation system.

The remainder of this paper is organized as follows: In Section 2, problem is formulated and the mathematical model of the subsystems are presented. Section 3 describes the MAIN algorithm and its structure. In Section 4, nonlinear observability analysis of the MAIN algorithm is presented. Simulation results are given in Section 5 and the conclusion is made in Section 6.

2. Problem formulation

In this section, the mathematical models used in the proposed MAIN algorithm, consisting 6DoF flight simulation model, navigation equations and the ground effect model, are presented.

2.1. Flight simulation model

In order to build up the 6Dof flight simulation, the following assumptions are made [25]:

- The aircraft is a rigid body with constant mass and fixed mass distribution.
- The atmosphere is at rest relative to the Earth (no steady wind, gusts, or wind shears).
- The Earth frame is used as the inertial frame and the local surface of the Earth is assumed to be flat.

The body frame (B) is used to write the equations of motion. The linear and angular velocities are defined in this frame as follows:

$$\begin{aligned}\left[\mathbf{v}_B^L\right]^B &= [\,u\ \ v\ \ w\,]^T\\ \left[\boldsymbol{\omega}^{BL}\right]^B &= [\,p\ \ q\ \ r\,]^T\end{aligned} \tag{1}$$

where L denotes the local level (flat Earth) frame, $[\mathbf{v}_B^L]^B$ and $[\boldsymbol{\omega}^{BL}]^B$ are the linear and angular velocity of the body frame WRT

Please cite this article in press as: H. Nobahari, H. Mohammadkarimi, Application of model aided inertial navigation for precise altimetry of Unmanned Aerial Vehicles in ground proximity, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.07.033