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Height Control Scheme without Using Pitch Angle for Fixed Wing UAVs

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Abstract:
Classical height control loop usually uses a pitch angle measurement in an inner loop to properly damp the short period and phugoid modes for a fixed wing UAV. The pitch angle measurements from low cost sensors can have significant biases under large maneuvers. This paper presents an alternate linear height control scheme based on the vertical acceleration measurement. An added advantage of this 'g-control' scheme is that load factor can be controlled precisely during pull-up or pull-down maneuvers. Secondly high performance can be achieved using low cost sensor measurements. The controller parameters are tuned in a nonlinear optimization setup that satisfies various controller design requirements. The presented height control scheme is tested in a high fidelity nonlinear simulation of the King Saud University testbed UAV with satisfactory results.

Keywords: UAV control, linear control, optimization based control design.

1. INTRODUCTION

With ever increasing presence of UAVs in various military and civilian applications the requirements of robust, high performance and low cost control schemes for UAVs are also arising in various applications. Classical height control loop usually uses a pitch angle measurement in an inner loop to properly damp the short period and phugoid modes for a fixed wing UAV. The pitch angle measurements from low cost sensors can have significant biases under large maneuvers. In the following paragraphs a concise review of height control schemes available in open literature and applicable to UAVs is presented.

Most of the work related to height control for Unmanned Aerial Vehicles is based on using the pitch angle θ measurement and the literature lacks significant contributions on altitude control exclusive of θ. In Abusleme et al. (2003) an altitude control system for a small UAV (4 Kg weight and 1.98m wingspan) is developed without using pitch angle θ as a tool for automatic control education at university level. It uses Rate Of Climb (ROC) and vertical acceleration for generating the required elevator deflection necessary to achieve the desired altitude. However, no proper ROC estimation technique was employed and no pitch rate feedback was used in the loop for short period damping. Priyamvada et al. (2011) discuss a missile height control system design, based on an extended state observer approach. No pitch angle measurement was employed; one accelerometer was used to provide the main feedback for height control while rate gyro feed back was used for damping and stability. A C^* controller (Lewis and Stevens (2003)), primarily intended for manned aircraft, is the classical approach for height control which uses only vertical acceleration and pitch rate.

On the other hand, there have been several studies that aim to address the height control problem using pitch angle. Souanef and Fichter (2013) describe a height controller for a fixed wing UAV based on L_1 adaptive output feedback control with switching adaption laws. This feedback-adaption combination has the advantage of reducing the prediction error and limiting the performance bounds without needing large adaption gains.

Mondragon et al. (2010) present an interesting approach for controlling the height by using visual systems as primary sensor. A stereo system fitted on the UAV is used to perform the height estimation by first detecting salient features in the environment and then applying a correlation algorithm to find similarities between left and right images. By employing the stereo disparity principle height can then be found by calculating the distance from the cameras to the plane that contains the features. Fuzzy controllers are also making their way in the field of UAV attitude and height control and work by Salman and Anavatti (2012), Shengyi et al. (2009) are two good examples in this regard.

This paper presents an alternate linear height control scheme based on the vertical acceleration measurement. An added advantage of this g-control scheme is that load factor can be controlled precisely during pull-up or pull-down maneuvers. Secondly high performance can be achieved using low cost sensor measurements. The presented scheme requires a measurement of vertical velocity in the inertial frame or Rate Of Climb (ROC). High rate GPS vertical velocity measurements can be directly used. If high rate GPS measurements are not available then ROC can be estimated with the help of a complimentary filter by fusing vertical acceleration and low rate GPS velocity measurements. The height control loop gains are tuned by setting up an optimization problem. The optimization problem minimizes the rise time, elevator deflection, and over-

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shoot while achieving a predefined minimum gain and phase margins. With this setup, the fixed architecture controller design problem for any aircraft reduces to inserting the longitudinal model of the aircraft in the optimization problem and setting the desired performance objectives. The designed controller performance is verified in a high fidelity nonlinear simulation against wind disturbances and sensor biases. Simulation results show the effectiveness of the control scheme in the presence of measurement errors and biases.

Remainder of the paper focuses on the development of mathematical model and height control scheme for UAV without using the pitch angle. ROC estimation technique is also discussed in a separate section. The results obtained from a high-fidelity non-linear simulation environment for the KSU (King Saud University) test bed UAV is also discussed.

2. LONGITUDINAL DYNAMIC MODEL AND CONTROL SCHEME

In this section longitudinal dynamic model for height control is presented. Then the control scheme to be used for height control is discussed. The control scheme uses a linear approach employing only normal acceleration for height control without any need of θ. The effect of using vertical acceleration on short period and phugoid damping is also discussed in the subsequent section.

2.1 *Longitudinal Dynamic Model*

For control design purposes we want the longitudinal model of the aircraft to be independent of the lateral model. Thus the elevator should affect only longitudinal dynamics and the ailerons should affect only the lateral dynamics. Practically this independence is possible only for small maneuvers of the aircraft. For our case, this assumption works reasonably well as the UAV is not highly maneuverable. Also, in order to achieve the decoupling, we have to select the trim conditions such that the longitudinal variables do not affect the lateral variables. The linearized longitudinal equations of motion, as derived and discussed in Lewis and Stevens (2003) and Yechout et al. (2003), are given in state space form in (1):

$$\begin{pmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{h} \end{pmatrix} = \begin{pmatrix} (X_u + X_{Tu}) & X_w & (X_q - W_0) & -gcos\Theta & 0 \\ Z_u & Z_w & (Z_q + U_0) & -gsin\Theta & 0 \\ M_u & M_w & M_q & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ sin\Theta & -cos\Theta & 0 & (U_0 cos\Theta + W_0 sin\Theta) & 0 \end{pmatrix} \begin{pmatrix} u \\ w \\ q \\ \theta \\ h \end{pmatrix} + \begin{pmatrix} X_{\delta e} \\ Z_{\delta e} \\ M_{\delta e} \\ 0 \\ 0 \end{pmatrix} \delta_e \tag{1}$$

Table 1. Airframe Parameters

Parameter	Value	Parameter	Value
m	35 kg	S	1.075 m^2
U_0	59.9 kt	b	3.7 m
W_0	2.9 kt	X_u	-0.1
Θ	2.8°	X_w	0.48
Z_u	0.46	X_q	0.051
Z_w	-3.5	M_u	0.12
Z_q	-1.03	M_w	-2.6
$X_{\delta e}$	-0.2	M_q	-4.5
$Z_{\delta e}$	-13.1	$M_{\delta e}$	-97.5

Table 1 summarizes various important King Saud University testbed UAV airframe parameters used in the simulation, whereas u is forward velocity, w is downward velocity, q is pitch rate, θ is pitch angle and h is height. Θ is the trim value of pitch angle and W_0 and U_0 represents the trim values of velocities. The quantities like X_u, Z_u etc. are the dimensional derivatives that represent either the linear or angular acceleration imparted to the airplane as a result of a unit change in its associated motion or control variable, e.g., X_u gives the change in X force as u changes. δe is the respective input representing elevator. See Lewis and Stevens (2003) for further details on various dimensional derivatives. The outputs in matrix form is given by (2):

$$\begin{pmatrix} q \\ h \\ a_z \\ \dot{h} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ Z_u & Z_w & (Z_q + U_0) & -gsin\Theta & 0 \\ sin\Theta & -cos\Theta & 0 & (U_0 cos\Theta + W_0 sin\Theta) & 0 \end{pmatrix} \begin{pmatrix} u \\ w \\ q \\ \theta \\ h \end{pmatrix} \tag{2}$$

where a_z is vertical acceleration and $\dot{h}$ is rate of climb.

2.2 *Height Control Scheme: Design and Linear Analysis*

The block diagram of height control scheme is shown in Fig. 1. Instead of pitch angle, vertical acceleration is used in the inner loop for generating elevator command. The innermost loop is for damping pitch rate before using it in the a_z loop. An optional lead network may also be added in the feedback loop in order to compensate the phase delay introduced by servo in the system.

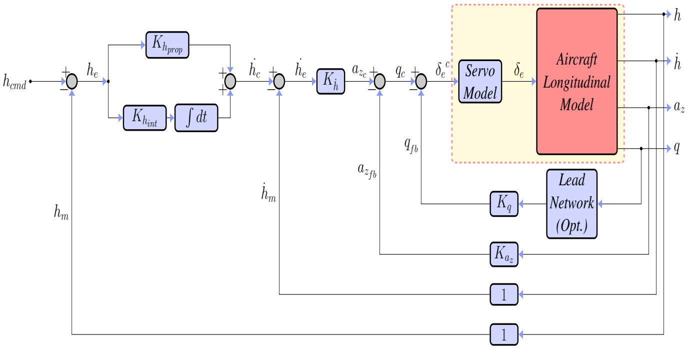

Fig. 1. Design of Height Control Scheme without using Pitch Angle

It is shown in subsequent section that using a_z, the control scheme is able to achieve reasonable damping for phugoid and short period modes. In order to generate the normal acceleration command, a_{z_c}, we need to use the rate of climb measurement. If high rate ROC measurement is not available then it may be estimated. Complimentary filtering technique may be used for this purpose as discussed later. To avoid steady state error, a proportional plus integral compensator is also used on the height error, h_e. The scheme performs well as shown by the linear simulation results in Fig. 2.