Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-17 (2016) 266–271

Embedded Model Control for UAV Quadrotor via Feedback Linearization

M. A. Lotufo * L. Colangelo * C. Perez-Montenegro *
C. Novara * E. Canuto *

* *Department of Control and Computer Engineering, Politecnico di Torino, 10129 Torino, Italy (luigi.colangelo@polito.it)*

Abstract: This study investigates the use of the feedback linearization approach as a novel way to design the internal model for Embedded Model Control (EMC). The feedback linearization allows to collect all the non-linearities at command level. EMC, by means of a disturbance dynamics model, makes possible to estimate and then reject the non-linear terms through the control law. This idea is applied to the control of an Unmanned Aerial Vehicle: the Borea project quadrotor. Embedded Model Control methodology implies the design of an internal model (Embedded Model) coded into the control unit and running in parallel with the plant. The attitude reconstruction problem is faced by means of a state observer developed on purpose and fully integrated with the model. A two-modes control strategy is proposed in order to reject systematic sensor errors, thus enhancing the attitude estimation capability. Using a high-fidelity numerical simulator, the feasibility of the proposed control strategy was demonstrated. This indicates that a feedback linearization approach allows the extension of EMC techniques to non-linear systems control. What is more, the EMC was successfully applied to the control of the Borea quadrotor.

Keywords: UAV, Quadrotor, Feedback Linearization, Non-linear systems

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) and, more specifically, n-copters have come to prominence in the last few years. Indeed, unmanned vehicles may have several applications in modern society, spanning from complex operations, also in potentially hazardous environments for humans to more entertaining purposes. Furthermore, UAVs have drawn great attention in the control engineering research community. This is mainly due to two reasons. First of all, designing a control for this non-linear and underactuated system can represent a stimulating challenge for control researchers. Secondly, n-copters, being typically mechanically simple and fast-prototyping devices, are widely considered as a good technology for the testing of a wide range of control algorithms and designs, also employing a wide range of sensors.

The Borea[1] quadrotor has been developed within the Space and Precision Automatics group (S&PA), from Politecnico di Torino, in order to test planetary landing algorithms. The Borea UAV has been endowed with a complete control system in order to control its position, velocity, and attitude. The Borea quadrotor has been equipped with a wide range of sensors: three MEMS gyroscope and accelerometers, magnetometers, a barometric altimeter, a sonar and a GPS receiver. The control system has been designed within the framework of the Embedded Model Control (EMC) methodology [Canuto et al. (2014a), Canuto et al. (2014b)] using non-linear control techniques (i.e. feedback linearization). In order to achieve this integration, the quadrotor attitude estimation problem has been addressed. This represents a paramount step towards the integration of the sensor measurements with the feedback linearised model. To enhance the attitude reconstruction, a sensors calibration procedure is proposed, introducing a multi-mode flight control strategy. A high-fidelity simulator, based on Matlab/Simulink, has been also developed in order to test the control design safely before the experimental flight tests.

This paper is organized as follows: after a general introduction, the addressed control problem is presented in section 2, together with the feedback linearised model of the quadrotor. In section 3, there is the EMC control design. Specifically, the design of the state observer is described in 3.1, while the attitude reconstruction problem is addressed in 3.2 and the calibration algorithm is presented in 3.3. In addition, the main simulated results are presented in section 4. Finally, section 5 draws some conclusions and implications of this research.

2. PROBLEM STATEMENT AND DYNAMIC MODEL

The model used to describe the quadrotors dynamics is non-linear and multiple-input multiple-output (MIMO). Furthermore, the quadrotor here considered has non-tiltable propellers therefore the horizontal displacement is coupled with the quadrotor attitude. Hence, in order to follow an horizontal trajectory the controller must control the attitude (under-actuated system). For this reason, the attitude reconstruction is an important point in quadrotor UAV control. Among the several attitude observers applied to the quadrotor UAV problem, Hoffmann et al. (2010)

---

[1] In Greek mythology, Borea was the purple-winged god of the north wind, one of the four directional Anemoi (wind-gods).

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.09.046

leverages a standard Kalman approach via a sensor fusion. The concept of sensor fusion is also developed by Leishman et al. (2014). Specifically in Leishman et al. (2014) the accelerometer model and its effects are studied in-depth and the aerodynamic rotor drag is leveraged to reconstruct an attitude estimate.

Given the quadrotor dynamics, there are many possible ways to control it. Three main approaches can be found in the literature: feedback linearization, sliding control, and back-stepping [Madani and Benallegue (2006)]. In Benallegue et al. (2006), Mistier et al. (2001), Voos (2009) the quadrotor model is input-output linearised with the feedback linearization method. This method requires a full state measurement to achieve the new linear model. Therefore the design of a state observer is mandatory. In literature many state observers have been applied to a quadrotor UAV. Among them, the most common is the Kalman filter and the extended Kalman filter (EKF), as described in Alexis et al. (2011) and Sebesta and Boizot (2014), whereas in Benallegue et al. (2006) a high-order sliding mode observer is implemented. Differently, in Mistier et al. (2001) the state vector is assumed to be known. Feedback linearization method, involving high order derivative terms, implies great sensibility to sensor noises and external disturbances while the sliding control approach succeeds in overcoming some of these limitations, as appears in Lee et al. (2009). On the other side, large input gains as well as chattering phenomena affect the sliding mode controller. In Benallegue et al. (2006) the feedback linearised model, although without measurement errors, is complemented by an high-order sliding mode observer aiming at ensuring a reliable estimate of the transformed states of the linearised model. In addition, the reference state trajectory is not explicitly addresses, as in Lee et al. (2009), thus implying a possibly non-smooth state trajectory with large tracking errors while reaching the target point. Finally, in Madani and Benallegue (2006) the model, split into three interconnected subsystems, is endowed with a back-stepping control, based on Lyapunov theory, able to stabilize the whole system.

The feedback linearization approach allows to collect all the non-linearities at the command level. In our approach, based on the Embedded Model Control (EMC) Canuto et al. (2014a), Canuto et al. (2014b), such result can be greatly leveraged. Indeed, EMC encompasses a disturbance dynamics model which makes possible to compensate the unknown disturbances through the control law. In addition, a wide range of sensor models are included with proper noise and error levels. Further, also the guidance algorithm (i.e. the reference generator) is built, based on the same model used for the control algorithm.

The model of the Borea quadrotor is presented briefly. Two main reference frames have been used throughout the study. First of all, an inertial reference frame whose origin matches with the take-off point. Secondly, a body frame, centred in the quadrotor CoM, whose axes are assumed to be principal of inertia. The (1) represents the attitude matrix of the body frame with respect to the inertial frame, given an 123 Euler angles rotation sequence.

$$R_b^i(\boldsymbol{\theta}) = X(\phi)Y(\theta)Z(\psi) = R_b^i(\phi,\theta)Z_\psi \tag{1}$$

The states variables are inertial position ($\mathbf{r}$), velocity ($\mathbf{v}$), attitude angles ($\boldsymbol{\theta}$) and body angular rate ($\boldsymbol{\omega}$). These states are collected in the state vector $\mathbf{x} = [\mathbf{r}\ \mathbf{v}\ \boldsymbol{\theta}\ \boldsymbol{\omega}]^T$.

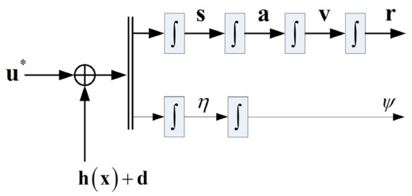

Fig. 1. Global scheme of the new equivalent model, as result of the feedback linearization.

The four available commands are the vertical acceleration in body frame (u_1) and three angular acceleration commands (u_2, u_3, and u_4), about the body axes. In the feedback linearization approach, the choice of the output vector is extremely important in order to realise the input-output linearization. At this proposal, the position ($\mathbf{r}$) and yaw attitude angle (ψ) have been selected. For the sake of brevity, let us now report in (2) the result of the feedback linearization input/output procedure. The new state vector ($\mathbf{z}$) is composed by the quadrotor inertial position ($\mathbf{r}$), velocity ($\mathbf{v}$), acceleration ($\mathbf{a}$), jerk ($\mathbf{s}$), yaw angle (ψ), and its derivative (η).

$$\begin{aligned}\begin{bmatrix}\dot{\mathbf{s}}\\ \dot{\eta}\end{bmatrix} &= \mathbf{B}(\mathbf{x})\bar{\mathbf{u}} + \mathbf{h}(\mathbf{x}) + \mathbf{d}\\ \bar{\mathbf{u}} &= \left[\ddot{u}_1\ u_2\ u_3\ u_4\right]^T, \quad \mathbf{y} = \left[\mathbf{r}^T\ \psi\right]^T\end{aligned} \tag{2}$$

where $\mathbf{B}(\mathbf{x})$ is called decoupling matrix, $\mathbf{h}(\mathbf{x})$ collects all the non-linearities collocated at command level, $\mathbf{d}$ represents all the possible model errors and external disturbances non-explicitly modelled. In addition, due to the needed dynamic extension, a new command vector $\bar{\mathbf{u}}$ is introduced. Figure 1 shows the scheme of the quadrotor UAV model reported in (2) in which the command $\mathbf{u}^\star = \mathbf{B}(\mathbf{x})\bar{\mathbf{u}}$ is considered. The two integrator chains refer to the CoM position and the yaw angle dynamics.

3. EMBEDDED MODEL CONTROL

Starting from the **input-output** linearized model of the quadrotor in (2), a linear model-based control can be pursued. In this paper, the control of the quadrotor is performed through the Embedded Model Control (EMC) methodology. Indeed, EMC allows to treat all the non-linear effects collected in $\mathbf{h}(\mathbf{x})$ as disturbances which can be estimated by the internal model. Moreover, these disturbances are easily cancelled by the control law since they are collocated at the command level. The EMC is based on the definition of a proper embedded model (EM) of the quadrotor. Actually, the EM is composed by a controllable dynamics plus a disturbance dynamics. The controllable dynamics is a simplified representation of the input-output dynamics. By contrast, the disturbance dynamics, being purely stochastic and parameter-free, aims at modelling the unknown disturbances and parametric uncertainties. The disturbance dynamics is driven by a noise vector playing the role of a disturbance input, to be real-time retrieved from the model error (plant output less model output) by means of a suitable noise estimator (NE). The union of the EM and the NE represents a state observer, affected by prediction errors. As a property of the EM, all the state variables, forced either by command, or noise, must be observable from the model output. By tuning the