Robotics and Autonomous Systems 62 (2014) 1187–1196

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Implementation and investigation of a robust control algorithm for an unmanned micro-aerial vehicle

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HIGHLIGHTS

- New method for implementation and realization of an robust control algorithm.
- Hardware-in-the-loop simulations for a micro-UAV.
- Consideration of non-linearity, uncertainty, and non-stationarity of UAV's parameters.
- The μ-Synthesis method applied to the UAV's dynamics control.
- The serial connection between the Gumstix micro-computer and the Kestrel autopilot.

ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form
29 March 2014
Accepted 7 April 2014
Available online 16 April 2014

Keywords:
Micro unmanned aerial vehicle (μUAV)
BULLIT
μ-Synthesis
Robust control
Real-time hardware-in-the-loop simulation

ABSTRACT

This paper presents a new method for implementation and realization of an optimal robust control algorithm in the real-time hardware-in-the-loop simulation environment for a mathematical model of the dynamics of the BULLIT micro-aircraft, with consideration of non-linearity, uncertainty, and non-stationarity of its parameters. The robust optimal control method, μ-Synthesis, applied to the autonomous flight dynamics control system of the unmanned aerial vehicle (UAV) meets desired control performances. The serial connection between the Gumstix micro-computer and the Kestrel autopilot extends the ability to implement high order robust controllers. The code of the control algorithm implemented (in the C++ language) in the memory of a Gumstix Verdex Pro single-chip micro-computer enables optimization of the threads-based approach. The hardware-in-the-loop (HIL) simulation mode was implemented in the Kestrel autopilot inner loop, and simulations of all stages of flight were performed in real-time using the actual model of the aircraft and autopilot. Finally, HIL simulations and tests were conducted in order to verify the developed control algorithm.

0. Introduction

According to DARPA (*Defence Advanced Research Projects Agency*), flying objects with overall dimensions up to 15 cm are classified as micro-class and designated with the acronym MAVs (Micro-Aerial Vehicles) [1]. MAV type objects have different aerodynamic properties than large aircraft, e.g. manned/passenger aircraft, and the approach to the design of the control system is also completely different for MAVs [2–4]. Due to the small control surfaces of MAV objects and low Reynolds numbers, alternative control methods are being developed [5–7]. Moreover, in the MAVs the interaction between unsteady aerodynamics and structural flexibility is critical [8–10]. Therefore, the boundary layer control (BLC) methods are being used [10–13]. After a micro-aircraft is equipped with on-board electronics for dynamic control in 3D space, navigation, and telemetric data transmission, it is able to perform autonomous flight missions. Such a micro-aircraft is called a UAV (Unmanned Aerial Vehicle). The subject matter concerning UAVs is the object of many scientific studies. The numerous applications of UAV objects and the requirements that are posed towards them are compiled in the work of the authors: Arning R.K. and Sassen S. [14].

MAV/UAV-controlled systems are unstable, non-linear, and multi-dimensional, with many cross-couplings [9,15]. The parameters and dynamic properties of a UAV model are non-stationary and variable during flight. The non-stationary nature of system parameters concerns its geometrical model (e.g. change of mass during flight—fuel consumption, change of the position of the center of mass, deformation of the airfoil, etc.), physical properties, and in particular, its aerodynamic parameters [16,17]. Considering the above, the design of a UAV control system cannot only be based

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http://dx.doi.org/10.1016/j.robot.2014.04.002

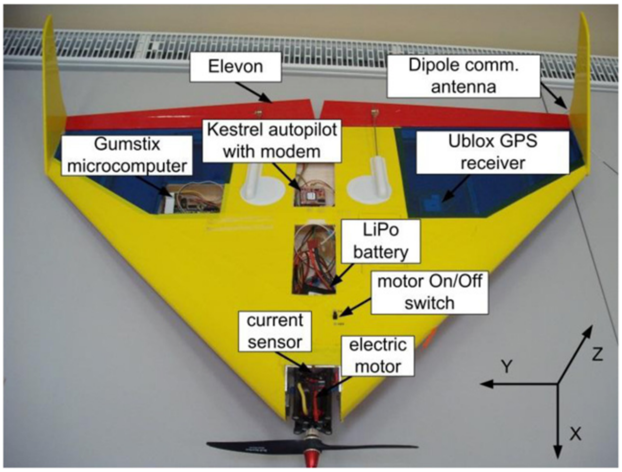

Fig. 1. BULLIT unmanned micro-aerial vehicle.

on determining a stationary/nominal model because it will not account for changes of the actual system.

Control systems in a UAV can generally be divided into a global system and a local system [18,19]. The global system constitutes a superordinate system control loop relative to the coordinate system of reference associated with the earth, e.g. it is responsible for the trajectory of flight. Control in the global system is realized by means of a way-point controller. The output signal of the superordinate control system also constitutes the input signal for the local system. The local/subordinate control system is responsible for stabilization of the MAV as for a body with 6 degrees of freedom according to the coordinate axes Ox, Oy, Oz related to the body's center of mass. Control signals in the subordinate systems are generated on the basis of measured angular and linear shifts/velocities and on the basis of input signals from the way-point controller. The control signal of the local controller is sent directly to on-board control/executive devices, e.g. control surfaces (ailerons, elevator/rudder, throttle). The local control system is multi-dimensional, which is why it is often decoupled into separate feedback control loops or feedforward control loops [18,20]. Local control loops are responsible for pitch control, roll control, yaw control, and throttle control. The design of a local controller requires an accurate system model, consisting of linear and non-linear dynamics of the MAV, the dynamics of executive and measuring components, delays in signal loops, signal and disturbance filters and estimators, etc. Such a system model is called an augmented model. In control theory, the augmented model of a control system is decoupled into a linear time-variant (LTV), a model of the known part of the system's non-linear dynamics, and unmodeled dynamics [21,22].

Small-scale unmanned aerial vehicles (UAVs) have a high level of autonomy. This autonomous operation requires trajectory planning, trajectory control and communication tasks to be completely automated. Due to limited on-board computation capabilities and fast dynamics, designing of the control for micro-UAVs is a challenging problem. In this paper, the proposed solution consists of an embedded system with external (with greater computing power) single-chip micro-computer which extends the autopilot's computational capacity.

In this work, a method of implementing a robust control algorithm, in a digital controller combined with an autopilot, the construction of a UAV control system, and the results of investigation of a local control system have been presented. The robust optimal control method is applied for control of the MAV's local dynamics (inner loop). The main goal of the paper is to optimize and effectively apply the robust optimal control method, μ-Synthesis, to the autonomous flight dynamics control system of the micro-class UAV. In order to quickly and easily test proposed control law, the 3D flight simulator is used. The hardware-in-the-loop simulation results are presented. The applied control law met desired control performances due to control plant uncertainties. The designed robust controllers demonstrate robustness and good performances characteristics within an uncertain UAV dynamics in longitudinal and lateral directions. The main advantage to the presented robust μ-Synthesis control design approach is that the μ-controller is valid for UAV dynamics in the case of UAV model uncertainty.

1. Robust control of a micro-aerial vehicle

Robust control of a micro-aerial vehicle signifies the provision of system stability (the required margin of phase and modulus), as well as the required control criteria (static and dynamic), in spite of outside disturbances, non-linearity, uncertainty, and its non-stationary parameters [23,24].

The robust optimal control methods are commonly used for control of the MAV's local dynamics [18,19,21,24–27]. The modern robust optimal control method, μ-Synthesis, makes it possible to effectively account for the system's non-linearity and non-stationary nature and to impose control criteria in individual control channels [28–30]. It is based on measurements of the system's robustness and on the application of the H-infinity algorithm for control of a system with structural uncertainty [31–36]. However, this method has several flaws. First, it is complicated, and second, it requires an accurate system model. This leads to a high controller order. Despite the high order of the controller, the μ-Synthesis algorithm is often used in UAV control systems [16,17,37–40]. The robust dynamic inversion control and loop shaping techniques are also very popular in UAV applications [19,23,24,27,41,42]. The application of the robust control method makes it possible to account for many system properties that cannot be accounted for in other control methods, e.g. with a PID controller. The parameters of a PID controller are only valid for a nominal model that presents a description of the system only in the close proximity of the operating point. This is why a PID controller will not provide such quality of control as a μ-Synthesis controller in a variable environment of the system's operating point. In addition, the μ-Synthesis controller accounts for non-stationary system parameters and system uncertainty models [21,22]. Moreover, thanks to weight functions, the robust control method makes it possible to account for the constraints of signals and to shape the properties of the control system's transfer function. Weight functions form part of the augmented model of the controlled system. The nominal model of the controlled system represents the linear dynamics part and the uncertainty models of the system represent non-linearity, non-stationarity, and unmodeled dynamics.

In this work, a method of robust optimal control is applied for control of the MAV's local dynamics. The model of the control plant, the method of design of weight functions and uncertainty models, as well as calculations of the μ-Synthesis controller have been specifically described in work [16,17,20]. The BULLIT model, made by the Topmodel company in the Czech Republic, was used as the MAV [43]. The BULLIT MAV has a BELL540 airfoil (NACA 0012 modification) and has the shape of a single delta (Fig. 1). Certain parameters of the MAV have been presented in Table 1. The linear model of the controlled system is constituted by roll and pitch motion models. The full model for two control axes has 3 control inputs (elevons and throttle) and 8 measuring outputs. The outputs due to body frame's coordinates $[X, Y, Z]$ (Fig. 1) in the case of the lateral–directional control are: velocity along Y (v, m/s), roll rate (p, rad/s), yaw rate (r, rad/s) and roll angle (ϕ, rad), and in the case of the longitudinal–directional control: velocity along X (u, m/s), velocity along Z (w, m/s), pitch rate (q, rad/s) and pitch angle (θ, rad) [44]. This is why the nominal model for control on