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Adaptive flight control law based on neural networks and dynamic inversion for micro-aerial vehicles

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ABSTRACT

The paper presents two new adaptive systems, for the attitude's control of the micro-aerial vehicles (MAV's) – insect type. The dynamic model describing the motion of MAV's with respect to the Earth tied frame is nonlinear and the design of the new adaptive control system is based on the dynamic inversion technique. The inversion error is calculated with respect to the control law and two matrices (inertia and dynamic damping matrices) which express the deviation of the estimated matrices relative to the calculated ones (the matrices from the nonlinear dynamics of MAV's) in conditions of absolute stability in closed loop system by using the Lyapunov theory. To completely compensate this error, an adaptive component (output of a neural network) is added in the control law. The system also includes a second order reference model which provides the desired attitude vector and its derivative. The two variants of the new adaptive control system are validated by complex numerical simulations.

1. Introduction

The results of the studies and research regarding the aerodynamics, the flight dynamics and the automatic control of the MAV's (micro-aerial vehicles) are numerous. Very important works for this research area have been obtained in [1] and [2]. Important results have been reported in the aerospace domain or in other related areas: mechatronics, automation, or electronics relative to the MAV's modeling, stabilization of the attitude, and the flight control [2–12]. The micro-aerial vehicles can be regarded sometimes as the physical models of the insects. Such mechanisms generally consist of three subsystems: a command subsystem (electrical engine or piezoelectric actuator), a wing actuation equipment (the cinematic mechanism), and a controller. Consisting of such advantages as limited volume, low mass, reasonable cost and rapid transportation, MAV's have demonstrated successful application in the military and civilian fields [13].

Progress has been also made towards: 1) the modeling and the manufacturing of the miniaturized highly performing servo-actuators (thorax of the MAV's – insect type) to achieve the wing's beat motion in the case of flying mini-robots and to command the MAV's motion through the modification of the wing's beat and attack angles; 2) the manufacturing of miniaturized sensors and transducers which merge the signals provided by the accelerometers, gyros, optical or magnetic sensors; 3) the design and software implementation of the linear or nonlinear observers which serve the navigation and flight control systems [3,6,14–16].

Because the atmospheric conditions and the dynamics of MAV's are changing during the flight, it is difficult to use conventional controllers. To design perfect conventional controllers, one has to know the precise mathematical model of the system to be controlled. Furthermore, the MAV's dynamics may vary with respect to the altitude and the flight conditions; therefore, the adaptive controllers are better choices. The adaptive control algorithms for a large class of aerospace vehicles can be modified and adapted to the stabilization and the flight control of the micro-aerial vehicles; some of them are based on the usage of the dynamic inversion and neural networks techniques [12,17–19]. Generally, the dynamic inversion relies on the philosophy of feedback linearization; the plant nonlinearities are canceled and the closed loop plant behaves like a stable linear system. The method is characterized by simplicity in the control structure, ease of implementation, global exponential stability of the tracking error and so on. On the other hand, the strong point of the neural networks (NNs) is their approximation ability, these being capable of approximating the dynamics of unknown systems through learning.

The aim of the flight control system is to attain the commands generated by the guidance system and to maintain steady conditions during flight [20]. A MAV – insect type is highly susceptible to atmospherics disturbances; in addition, the dynamics is highly

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nonlinear and time varying. Hence, neural networks based adaptive flight controllers with the ability to achieve desired performance are essential for automating the MAV – insect type. In order to achieve this autonomous flight, adaptive flight controllers with the ability to adapt to nonlinear dynamics of the MAV – insect type are necessary. Thus the main objective of the paper is the design and software implementation of such adaptive controller using either the quaternion vector or the vector of MAV's attitude; the design of the control law is based on the dynamic inversion technique and Lyapunov theory, this process involving the calculation of the controller's coefficients in conditions of stability.

Feedback linearization, in its various forms, is perhaps the most commonly employed nonlinear control method; to use it, all parametric plant uncertainties must appear in the same equation of the state-space representation as the control (the main disadvantage of the feedback linearization method). Feed-forward neural networks based on the back propagation learning algorithm have been used in [21]; the main disadvantage is that the neural networks require a priori training on normal and faulty operating data. Other approaches involves the usage of the time delay neural networks; a controller based on this type of neural networks has been designed in [22], but its main drawback is related to the flight path track accuracy and to the fact that it is enable only under limited conditions. Several neural network control approaches have been proposed based on Lyapunov stability theory [22,23]. The main advantage of these control schemes is that the adaptive laws were obtained from the Lyapunov synthesis and, therefore, guarantees the system's stability; the disadvantage is that some conditions should be assumed; these requirements are not easy to satisfy in practical control application [24]. Juang designed a new learning technique using a time delay network or networks with back-propagation through time algorithms to control the landing [25]; the main drawbacks are: 1) the number of hidden units was determined by trial; 2) the convergence time is high. Gain scheduling for PID controllers is the common adaptive control technique used in [26]. An advantage of the gain scheduling technique is that it allows the parameters to be changed quickly with change in the plant dynamics. However, the application of the technique is limited due to the absence of a learning process.

The number of neural network based adaptive controllers designed for MAV's flight control is extremely small; one of the few such neural network based controller is presented in [20], but the real-time implementation of this controller architecture is not practical due to the following reasons: 1) the feedback from the identifier model for the iterative change in the controller outputs requires at least one sample time and 2) the computation time to obtain the new set of plant inputs is considerably high for multiple iterations of training. In the time being, none of the neural network based adaptive controllers for MAV's flight control was designed for the attitude's control of the MAV's – insect type; this motivates our work. The recent studies and research have culminated in the development of efficient flying robots, but, from our information, none of them has adaptive controllers based on the attitude or the quaternion vectors, Lyapunov theory, dynamic compensators, reference models, and neural networks; this is achieved in this paper, being interesting to see if such adaptive controllers can guarantee the control of MAV's attitude. Thus, our goal is to design new adaptive systems for the control of the micro-aerial vehicles – insect type by using the attitude vector or the quaternion one. Taking into account the advantages of these elements (NNs, dynamic inversion, reference models etc.) and the fact that, till now, no paper deals with the control of MAV's by means of neural networks, dynamic inversion concept, linear dynamic compensators, reference models, and Lyapunov theory, the present paper represents an absolute novelty in the search area of controller's design for the MAV's flight.

The structure of the paper is the following one: the MAV's nonlinear dynamics is presented in the paper's Section 2; the design of the new adaptive control system is achieved in Section 3; in Section 4, complex simulations to validate the new designed adaptive control system have been performed and the obtained results are analyzed; finally, some conclusions are shared in Section 5 of the paper.

2. The dynamics of the micro-aerial vehicles

2.1. The general dynamics of the micro-aerial vehicles

The dynamics of MAV's is generally nonlinear; in the case of the gliding flight, the dynamics is linear. The uncertainties cased by the MAV dynamic's incomplete knowing lead to the necessity of a robust controller. In these circumstances, the Lyapunov direct method is used.

Let us denote with $\boldsymbol{\Theta} = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^T -$ the attitude vector of the MAV, where ϕ is the roll angle, $\theta -$ the pitch angle, and $\psi -$ the flight direction angle. These angles express the angular position of the MAV (of the MAV's body tied frame $oxyz$, $ox -$ the longitudinal axis (pointing the flight direction), $oy -$ the axis oriented towards the right wing, and $oz -$ the axis perpendicular to the plane oxy and downward oriented with respect to the Earth tied frame (Darboux frame – $OXYZ$) having the axis OX tangent to the parallel and East oriented, $OY -$ tangent to the meridian and North oriented, and $OZ -$ the locus vertical line (Zenith oriented).

Let us also consider $\boldsymbol{\omega}_p = \dot{\boldsymbol{\Theta}} = \begin{bmatrix} \dot{\varphi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^T -$ the angular rate's vector of the MAV relative to the Earth tied frame. We denote with $\boldsymbol{\omega}_b = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T -$ the vector of MAV's angular rates with respect to the axes of the $oxyz$ frame. The connection between the above presented vectors is: $\boldsymbol{\omega}_p = \dot{\boldsymbol{\Theta}} = W^{-1}\boldsymbol{\omega}_b, \boldsymbol{\omega}_b = W\boldsymbol{\omega}_p = W\dot{\boldsymbol{\Theta}}$, where the matrix W has the form:

$$W = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\varphi & \sin\varphi\cos\theta \\ 0 & -\sin\varphi & \cos\varphi\cos\theta \end{bmatrix}. \tag{1}$$

The vector of the resultant moments acting upon the micro-aerial vehicle is [14]:

$$\vec{\boldsymbol{M}}_b = \vec{\boldsymbol{M}}_b^a + \vec{\boldsymbol{M}}_b^g + \vec{\boldsymbol{M}}_b^v \cong \vec{\boldsymbol{M}}_b^a, \tag{2}$$

where $\vec{\boldsymbol{M}}_b^a, \vec{\boldsymbol{M}}_b^g, \vec{\boldsymbol{M}}_b^v$ are the aerodynamic, the weight, and the dynamic damping components, respectively; because $\vec{\boldsymbol{M}}_b^g$ and $\vec{\boldsymbol{M}}_b^v$ have very small values, we can make the approximation $\vec{\boldsymbol{M}}_b \cong \vec{\boldsymbol{M}}_b^a$. We denote with $\vec{\boldsymbol{F}}_b^{al}$ and $\vec{\boldsymbol{F}}_b^{ar} -$ the vectors of the aerodynamic forces produced by the left and the right wings and with $\vec{r}_l$ and $\vec{r}_r -$ the position vectors of the left and right wing's pressure centers with respect to the MAV's mass center (point "o"); the following equation connects these variables:

$$\vec{\boldsymbol{F}}_b^a = \vec{\boldsymbol{F}}_b^{al} + \vec{\boldsymbol{F}}_b^{ar}, \vec{\boldsymbol{M}}_b^a = \vec{r}_l \times \vec{\boldsymbol{F}}_b^{al} + \vec{r}_r \times \vec{\boldsymbol{F}}_b^{ar}. \tag{3}$$

The vectors of the aerodynamic forces and moments produced by the two wings have the expressions [1]:

$$\boldsymbol{F}_a^a = \begin{bmatrix} \boldsymbol{F}_d^l \cos\phi_L + \boldsymbol{F}_d^r \cos\phi_R \\ \boldsymbol{F}_d^l \cos\phi_L - \boldsymbol{F}_d^r \cos\phi_R \\ \boldsymbol{F}_l^l + \boldsymbol{F}_l^r \end{bmatrix}, \boldsymbol{M}_a^a = r_a \begin{bmatrix} -\boldsymbol{F}_d^l \cos\phi_L + \boldsymbol{F}_d^r \cos\phi_R \\ -\boldsymbol{F}_d^l \sin\phi_L - \boldsymbol{F}_d^l \cos\phi_R \\ \boldsymbol{F}_d^l - \boldsymbol{F}_d^r \end{bmatrix}, \tag{4}$$

with $r_a -$ the position vector of the two wing's resultant aerodynamic force $\vec{\boldsymbol{F}}_a^a$, $\vec{\boldsymbol{F}}_l^l$, $\vec{\boldsymbol{F}}_l^r -$ the lift forces, $\vec{\boldsymbol{F}}_d^l$, $\vec{\boldsymbol{F}}_d^r -$ the wing's