ROBOTIC UNMANNED AERIAL VEHICLE TRAJECTORY TRACKING CONTROL

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Abstract: Control of Unmanned Aerial Vehicles is a difficult task. One of the most challenging problems are nonlinear nature of the vehicle dynamics and the second is related to the nonminimum phase system. There are several methods to design nonlinear controller. One of them is so-called feedback linearization. Even, after successful design of nonlinear controller several important issues like nonminimum phase problem remain. The system with nonminimum phase dynamics needs to have outputs redefined. The output redefinition technique is used in a way such that the resulting system to be inverted is a minimum phase system. The complex calculation related to the system dynamics redefinition make a real-time computation very difficult. The real-time control system needs to be fast and reliable. In order to make a real-time control possible, a neural networks method has been developed and presented.
The NARMA-L2 Neural Network is trained off-line to identify the forward dynamics of the UAV model with the redefined output, which is subsequently inverted to force the real output to approximately track a command input. Simulation results show that the proposed neural network method has overall good performance.

Keywords-- Robotics, Unmanned Aerial Vehicle (UAV), Lateral Control, Nonminimum phase systems

1 INTRODUCTION

In recent years, UAV technology has experienced a rapid growth in popularity. To improve the performance of UAV systems, researchers nowadays are working on highly maneuverable UAVs which have enhanced operational capability in a constrained environment such as an air space with static or moving obstacles or a battle field with enemy threats. The high maneuverability of a UAV can be achieved by improving the flight control system using nonlinear control methodologies. Over the last three decades, feedback linearization or dynamic inversion has been extensively studied and more recently, was applied in flight control especially in designing high maneuverable fighter-aircrafts and UAVs. (Enns *et al,1994*). Compared with traditional flight control design, which is often based on gain scheduling approach by dividing the flight space into linearisable subspaces, feedback linearization transforms the nonlinear dynamics of an aircraft to an equivalent linear system over the entire flight envelope, thus allowing us to use a global linear controller. However, the full-envelope nonlinear inversion of a UAV model is computationally intensive, because the UAV is a multi-input-multi-output (MIMO) system and it must be inverted in real time (Kim, and Calise, 1997, Yan, and Li, 1997, Plett, 2003). Furthermore, the exact input-output feedback linearization cannot be directly applied to a non-minimum phase UAV model.

To reduce the computational burden of the onboard computer, off-line trained neural network controllers are proposed to model the inverse dynamics of nonlinear systems. A direct way to do this is to train a neural network off-line to model the inverse dynamics of an aircraft using input-output pairs, as proposed by Kim and Calise, 1997. However, since the mathematic model of the inverse dynamic is not known a priori, the modeling errors could be significant. Therefore, adaptive control or on-line learning must be used to cancel out the modeling errors (Calise, 1997, Yan, and Li, 1997) or other method developed by Green and Sasiadek, 2005. An alternative way to apply inverse dynamics approach is to train two neural networks to model the forward dynamics of an affine system, and then invert the neural network model to obtain an approximate inverse model of the system (Su and Khorasani,, 2001, Narendra and Mukhopadhyay, 1997, He *et al*, 1997). This method, codified as a MATLAB® toolbox NARMA-L2, can be treated as a neural network based feedback linearization. Since the control inputs are computed algebraically in NARMA-L2 controller and no on-line learning is needed, the burden of computation is greatly reduced compared with exact feedback linearization. Hauser *et al*, 1992 described a set of neural networks that are trained to approximate the Lie derivatives, such that the feedback linearization can be implemented step-by-step using these networks and, most importantly, the nonlinearity cancellation can be achieved. However, when a system is of high order, training a large set of neural networks could be time consuming. Non-minimum phase systems result into an unstable system when subject directly to exact feedback inversion. A solution in this case is the so called approximate feedback linearization. This is done by approximating a non-minimum phase system with a minimum phase system, such that a bounded error tracking can be achieved (Slotine, J E. and Li, 1992). In (Hauser *et al*, 1992 , Oishi and Tomlin, 2000), an approximate minimum phase model of a Vertical Takeoff and Landing (VTOL) aircraft is obtained by neglecting the coupling between the rolling moment and lateral acceleration. Similarly, for a slightly non-minimum phase Conventional Takeoff and Landing (CTOL) aircraft, dropping small force, caused by control surfaces, from the equations of the system, will give a minimum phase model (Romano, J. J. and Singh, 1990). However, this method is only valid for slightly non-minimum phase systems and results in a loss of performance due to the un-modeled dynamics. Another interesting method is output redefinition (Hauser *et al*, 1992). The idea is to redefine the output function so that the resulting zero dynamics is stable. Output redefinition method has been successfully applied to control flexible manipulators. In (Moallem *et al* 1997), outputs are defined near the tip positions, such that the system becomes marginally minimum phase. In the field of flight control, the output redefinition method was also called controlled variable (CV) selection (Stevens, B L. and Lewis, 2003). In (Enns *et al, 1994*), recommendations for properly selecting the CVs are presented. The selection of CVs is suitable for most conventional flight regimes and piloting tasks. However, this selection may have to be modified for high-angle-of-attack or very-low-speed flight. Furthermore, the selection of CVs still relies to some extent on trial and error. In (Telebi et al, 1999), the output is redefined using stable/anti-stable factorization performed on the zero dynamics of a discrete-time nonlinear non-minimum phase system. This is equivalent to moving the positive zero to the left half of s plane in continuous-time. This approach is however valid only for a class of non-minimum phase system whose nonlinearities appear in output terms. In (Benvenuti, L. and Benedetto, 1994), a method is proposed to modify the output of the nonlinear aircraft model based on a transformation performed on the Jacobian linearization of the system. This transformation dose not affect the left-half zeros, thus the resulting system is essentially the same as the original one in the frequency range of interest. Using this approach, however, the system performance becomes worse when the frequency of desired output exceeds certain limits. This limitation must be carefully considered in the context of designing tracking controllers for high maneuverable UAV. The non-minimum phase problem is still an open area of research in feedback control, given that all the methods mentioned above have their merits but also many limitations.

2. MATHEMATICAL MODEL

The formulation and verification of the mathematical model is a difficult and tedious task. In general, the model has to be accurate enough to represent the real UAV, but also has to be sufficiently simple to run in real-time operation. If system is nonlinear, it has to be linearized. One of the possibilities is so called, Jacobian linearization.

Consider a nonminimum phase nonlinear time invariant system of the form

$$\dot{x} = f(x) + g(x)u$$

$$y = h(x)$$