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Flatness-based adaptive fuzzy control of electrostatically actuated MEMS using output feedback

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Abstract

The article presents an adaptive fuzzy control approach to the problem of control of electrostatically actuated MEMS, which is based on differential flatness theory and which uses exclusively output feedback. It is shown that the model of the electrostatically actuated MEMS is a differentially flat one and this permits to transform it to the so-called linear canonical form. For the new description of the system's dynamics the transformed control inputs contain unknown terms which depend on the system's parameters. To identify these terms an adaptive fuzzy approximator is used in the control loop. Thus an adaptive fuzzy control scheme is implemented in which the unknown or unmodeled system dynamics is approximated by neurofuzzy networks and next this information is used by a feedback controller that makes the electrostatically activated MEMS converge to the desirable motion setpoints. This adaptive control scheme is exclusively implemented with the use of output feedback, while the state vector elements which are not directly measured are estimated with the use of a state observer that operates in the control loop. The learning rate of the adaptive fuzzy system is suitably computed from Lyapunov analysis, so as to assure that both the learning procedure for the unknown system's parameters, the dynamics of the observer and the dynamics of the control loop will remain stable. The Lyapunov stability analysis depends on two Riccati equations, one associated with the feedback controller and one associated with the state observer. Finally, it is proven that for the control scheme that comprises the feedback controller, the state observer and the neurofuzzy approximator, an H-infinity tracking performance can be achieved. The functioning of the control loop has been evaluated through simulation experiments.

Keywords: Electrostatically actuated MEMS; Adaptive fuzzy control; Neurofuzzy approximation; State observers; Lyapunov stability; H-infinity tracking performance; Riccati equations

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1. Introduction

As micro and nanotechnology develop fast, the use of MEMS and particularly of microactuators is rapidly deploying. One can note several systems where the use of microactuators has become indispensable and the solution of the associated control problems has become a prerequisite. In [1–4] electrostatic microactuators are used in adaptive optics and optical communications. In [5,6] microactuators are used for micromanipulation and precise positioning of microobjects. Several approaches to the control of microactuators have been proposed. In [7–9] adaptive control methods have been used. In [10,11] solution of microactuation control problems through robust control approaches has been attempted. In [12] backstepping control has been used, while in [13] an output feedback control scheme has been implemented. Additional results for the stabilization and control of microactuators have been presented in [14,15]. In such control systems, convergence of the state vector elements to the associated reference setpoints has to be performed with accuracy, despite modeling uncertainties, parametric variations of external perturbations. Moreover, the reliable functioning of the control loop has to be assured despite difficulties in measuring the complete state vector of the MEMS. The present paper develops a new method for the control of micro-electromechanical systems (MEMS) which is based on differential flatness theory. The considered control problem is a nontrivial one because of the unknown nonlinear dynamical model of the actuator and because of the constraint to implement the control using exclusively output feedback (it is little reliable and technically difficult to use sensor measurements for the monitoring of all state variables of the micro-actuator). The differential flatness theory control approach is based on an exact linearization of the MEMS dynamics which avoids the numerical errors of the approximate linearization that is performed by other nonlinear control methods [16–20].

First, the article shows that the dynamic model of the studied microactuator is a differentially flat one. This means that all its state variables and the control input can be written as functions of one single algebraic variable, which is the flat output, and also as functions of the flat output's derivatives [21–25]. This change of variables (differential flatness theory-based diffeomorphism) enables to transform the nonlinear model of the actuator into the linear canonical (Brunovsky) form [26–29]. In the latter description of the MEMS, the transformed control input contains elements which are associated with the unknown nonlinear dynamics of the system. These are identified on-line with the use of neurofuzzy approximators and the estimated system dynamics is finally used for the computation of the control signal that will make the MEMS state vector track the desirable setpoints. Thus an adaptive fuzzy control scheme is implemented [30,31]. The learning rate of the neurofuzzy approximators is determined by the requirement to assure that the first derivative of the Lyapunov function of the control loop will be always negative.

Next, another problem that has to be dealt with was that only output feedback can be used for the implementation of the MEMS control scheme. The nonmeasurable state variables of the microactuator have to be reconstructed with the use of a state estimator (observer), which functions again inside the control loop. Thus, finally, the Lyapunov function for the proposed control scheme comprises three quadratic terms: (i) a term that describes the tracking error of the MEMS state variables from the reference setpoints, (ii) a term that describes the error in the estimation of the non-measurable state vector elements of the microactuator with respect to the reference setpoints, and (iii) a sum of quadratic terms associated with the distance of the weights of the neurofuzzy approximators from the values that give the best approximation of the unknown MEMS dynamics. It is proven that an adaptive (learning) control law can be found assuring that the first derivative of the Lyapunov function will be always negative, thus also confirming that the stability of the control loop will be preserved and that accurate tracking of the setpoints by the system's state variables will be succeeded (H-infinity tracking performance).

The structure of the paper is as follows: in Section 2 the dynamic model of the considered MEMS (that is of an electrostatic microactuator) is analyzed, in Section 3 it is shown how linearization of the MEMS dynamics can be performed with the use of differential geometry and the computation of Lie derivatives. In Section 4 it is proven that the dynamic model of the electrostatic microactuator is a differentially flat one. Moreover it is shown how exact linearization of the MEMS model can be performed using differential flatness theory. In Section 5 the stages of adaptive fuzzy control for the microactuator's model are analyzed. It is explained how differential flatness theory and output feedback can be used for computing finally the MEMS control input. In Section 6 Lyapunov stability analysis is performed for the proposed output feedback-based adaptive fuzzy control scheme. In Section 7 simulation tests are carried out to evaluate the performance of the adaptive fuzzy controller. Finally, in Section 8 concluding remarks are stated.