ITERATIVE LEARNING CONTROL FOR NONLINEAR SYSTEMS

by

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Certificate

This is to certify that the thesis entitled **"Iterative Learning Control for Nonlinear Systems"**, being submitted by **Mr. S. Gopinath** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bona-fide research work carried out by him under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other University or Institute for the award of any degree or diploma.

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To my parents,

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Abstract

Learning control starts with a fundamental recognition that repeated practice is a common mode of human learning. Learning control is most suitable for operations where the same task is to be performed over and over again. Many industrial systems and machines perform their tasks which are repetitive in nature, for e.g., robots, steel mills, hard-disk drives and many more. These systems are required to carry out tasks with precision and high speeds subject to modeling variations and disturbances (both repetitive and non-repetitive). Iterative learning control (ILC) is a new domain in control system that motivates, whether mechanical robots can learn a prescribed ideal motion by themselves using information represented by the measured data gathered in the previous practice. In ILC, the necessary control input can be synthesized by repeated trials based on tracking errors.

In this thesis, two different types of series approximation based learning controller design methods are proposed for a class of nonlinear systems. They are wavelet series and Hermite series expansions. These series approximation approaches are used to approximate the desired and actual trajectories of the system into finite number of wavelet/Hermite coefficients. A learning controller is designed in wavelet/Hermite domain which forces the coefficients of the actual output approach to the corresponding coefficients of the desired trajectory, which are known constants. Equivalently, this achieves the tracking control problem in time domain. In wavelet series based approach, only the coefficients of basis functions of approximation subspace in wavelet transform are used for the updation of control. Thus the control input to the system is free from high

frequency components, which may correspond to the disturbances. Interesting characteristics such as reduced computation and easier implementation of orthonormal Hermite basis functions are exploited for the design of proposed Hermite series based learning controller. Convergence and stability analysis of the proposed wavelet & Hermite series based approaches ensure the convergence of coefficients of actual trajectory to the respective coefficients of desired trajectory. Numerical experimentation on robot systems show the ability of the proposed learning controller designed in wavelet/Hermite domain in the presence of system parameter uncertainties.

For each new desired trajectory task, the learning controller has to start its learning with zero initial input assumption. Instead of such zero initial input assumption, in this thesis the idea of using the past trajectory tracking experiences on the initial input selection for tracking a new trajectory tracking tasks has been explored. In this thesis, fuzzy modeling based experience inclusion approaches for ILC are proposed. Approximate fuzzy data model (AFDM) and Type-1 fuzzy logic system (FLS) based experience inclusion techniques have been developed for the purpose of appropriate initial input selection. Initial iteration error reduction and error convergence issues are proved for the proposed methods. Comparison studies with local learning technique show the efficacy of the proposed fuzzy rule based modeling approaches.

A 2-D Roesser's model for a class of learning controllers is established, which reveals the connections between ILC systems and 2-D system theory. After proper transformation of ILC system into a 2-D system model, certain fundamental results from the state feedback stabilization of 2-D systems are utilized for the design of ILC. A simple design procedure is proposed for the design of 2-D system theory based ILC algorithm. The design of state feedback controller for the 2-D system is simplified into stabilization problem of two reduced order 1-D systems. Proposed methodology considerably reduces the computational complexity in comparison with existing approaches. Proposed ILC design approach is tested numerically for an injection molding process control problem. Results show the robust performance of the proposed 2-D system theory based ILC over the perturbations on system parameters and on initial conditions.

A close relative of ILC is repetitive control (RC). In learning control, the system is designed to return to the same initial condition before each new execution of the task, as in the case of a robot performing a task on each item that arrives one by one on an assembly line. Repetitive control, on the other hand, applies to the situation where the desired trajectory to be tracked is a periodic function of time, and there is no resetting between periods, e.g. high speed cam follower systems. Due to the spillover of the cam systems the same initial condition assumption during each cam cycle is practically not possible. Results of proposed wavelet series and 2-D system theory based ILC approaches are extended for the RC design problems. Proposed RC design approaches are applied for the elimination of residual vibrations in high-speed cam follower systems.

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