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Control Education for Mechatronics: Robust State-Feedback Controller Design

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Abstract: The paper surveys selected state space robust control methods suitable for implementation in motion systems, and their implementation on a laboratory plant – the Modular Servosystem. Robust control theory is taught within control engineering courses in the MSc study program Applied Mechatronics, robust methods and algorithms are developed and verified in the control engineering laboratory during the solution of student and research projects. The project-based learning on suitable laboratory plants is a well-established method for control engineering education in mechatronics.

Keywords: control education, mechatronics, motion systems, quadratic stability, robust control, linear matrix inequality (LMI), LQG/LTR, Kalman filter.

1. INTRODUCTION

The automotive industry is one of the pillars of Slovakia's economy, bringing investment, employment and innovations with the planned Jaguar Land Rover plant in Nitra as the latest example. Slovakia is already home to three carmakers, Volkswagen Slovakia, PSA Peugeot Citroën Slovakia and Kia Motors Slovakia. Over the past 20 years, car production increased from 2,952 vehicles in 1993 to more than 970,000 in 2014. The latter figure, equalling 178 cars per 1,000 citizens, has made Slovakia the biggest per capita producer in the world. Automotive is the largest industry in Slovakia with a share of 12% on the Slovak GDP in 2013 which was 41% of industrial production and 26% of Slovakia export. 80 000 people were employed in the automotive industry in 2015, which will be even increased when Jaguar Land Rover will start production in Nitra in 2018.

In 2013, following these development trends and in line with the Slovak government priorities, the Institute of Automotive Mechatronics (IAM) was established at the Faculty of Electrical Engineering and Information Technology of the Slovak University of Technology in Bratislava. IAM provides education in Mechatronics in three study programs: Automotive Mechatronics (Bc. Study), Applied Mechatronics and Electromobility. As mechatronics is a multidisciplinary engineering field comprising synergistic integration of mechanics, electronics, control theory, and computer science within product design and manufacturing, curricula of the above study programs have to focus on modern methods of mathematics, physics, modelling and simulation, mechanics, electronics, sensor systems, communications and information technologies.

Based on high quality research and teaching traditions in control engineering as well as ongoing basic research projects, robust control methods and algorithms are being developed; achieved research results are verified and included in the related control engineering course Advanced Control Methods for Mechatronic Systems. Verification and testing of theoretical results are carried out on laboratory plants within student projects, and diploma and dissertation projects. To demonstrate common problems encountered in motion plants and their solution using state control, the Modular Servosystem, MSS (INTECO, 2007) is one of the most appropriate laboratory plants for mechatronic engineering students. The paper surveys selected state space robust control methods suitable and their implementation on the MSS.

The paper is organized as follows: in Section 2 the mechatronic laboratory plant Modular Servosystem is presented along with its mathematical description and problem formulation. Section 3 deals with robust control design based on polytopic description of the uncertain plant using Lyapunov stability theory which leads to LMI solution. Section 4 deals with robust reference tracking design under plant and measurement noises using the LQG/LTR methodology.

2. THE MODULAR SERVOSYSTEM

2.1 Plant description

The Modular Servo System (MSS) consists of the INTECO digital servomechanism and open-architecture software environment for real-time control experiments (INTECO, 2007). The measurement system is based on the RTDAC4/USB acquisition board equipped with a D/A and A/D converters. I/O board communicates with the power interface unit. The whole logic necessary to activate and read the encoder signals and to generate the appropriate sequence of the PWM pulses to control the DC motor is configured in the Xilinx® chip of the RT-DAC/USB board. All functions

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of the board are accessed from the Modular Servo Toolbox, operating directly in the MATLAB Simulink environment.

MSS consists of the following modules arranged in the chain (Fig. 1): a DC motor with a generator, inertia load, encoder, magnetic brake and the gearbox with the output disk. In our experiments the backlash module was not applied. The servomechanism is connected to a computer where a control algorithm is based on measurements of the angular displacement and the angular velocity.

The MSS can be viewed as a motion system with two output variables (angular velocity and angular displacement); it is advantageous to consider them as state variables and apply state control.

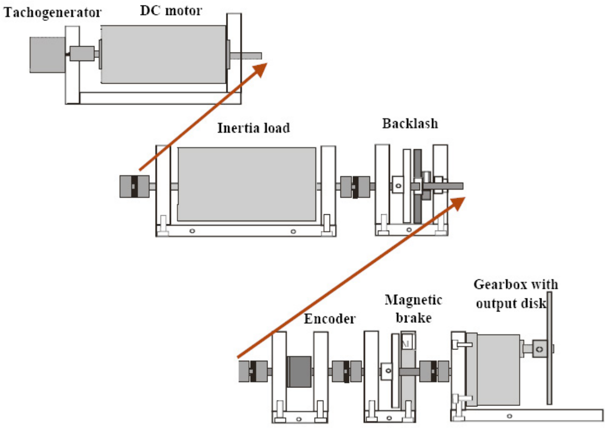

Fig. 1. Modular Servo System (MSS)

2.2 Modelling MSS in the plant state space

In the state space, the MSS is described as a linear continuous-time system

$$\begin{aligned}\dot{x}(t)&=Ax(t)+Bu(t)\\ y(t)&=Cx(t), \qquad x(0)=x_0\end{aligned} \tag{1}$$

where $x(t)\in R^n$, $u(t)\in R^m$ and $y(t)\in R^r$ are state, control and output vectors, respectively and A, B and C are known constant matrices.

A) If the MSS is considered as an uncertain plant, a polytope of linear dynamic systems can specified by the list of its vertices:

$$\{(A_1,B,C_1),\dots,(A_N,B,C_N)\} \tag{2}$$

where N is number of vertices respective to parameter box.

B) The state-space model describing the plant corrupted by the plant and the measurement noises *ξ(t)* and *θ(t),* respectively, is in the form

$$\begin{aligned}\dot{x}(t)&=Ax(t)+Bu(t)+\Gamma\xi(t)\\ y(t)&=Cx(t)+Du(t)+\theta(t)\end{aligned} \tag{3}$$

where $\xi(t)$ and $\theta(t)$ are independent white Gaussian noises specified by their covariance matrices $Q_f\geq 0$ and $R_f>0$, respectively.

2.3. Problem Statement

A state-feedback controller will be considered in the form

$$u(t)=-Kx(t) \tag{4}$$

yielding the resulting closed-loop system

$$\dot{x}(t)=(A-BK)x(t)=A_cx(t) \tag{5}$$

Two problems are studied in the sequel:

1. For the linear continuous-time system a robust state feedback controller (4) is to be designed such that the closed loop system (5) is stable for all admissible uncertainties given by (2). Three LMI based methods have been used to design robust state feedback controller; they are described and compared in Section 3.

2. For the system (3) corrupted by the plant and measurement noises, which moreover has not all output variables accessible for measurements, a state feedback controller is to be designed to make the selected system output to track a selected reference input signal; this is called tracking or servo design problem. In particular, based on noisy measurement of angular displacement, the angular velocity controller will be designed to track a constant reference. Solution to this problem known as the LQG/LTR design is presented in Section 4.

3. ROBUST STATE-FEEDBACK CONTROLLER DESIGN

3.1 Robust state-feedback controller design for quadratic stability

According to the Lyapunov stability theory, the closed-loop system (5) is stable if and only if there exists a symmetric matrix $P=P^T>0$ such that

$$A_c{}^TP+PA_c<0 \tag{6}$$

The stability condition (6) is formulated as a linear matrix inequality and can thus be used also for uncertain systems.

State-feedback robust controller design for quadratic stability is based on the polytopic description (2) yielding the respective closed loop uncertain system

$$\dot{x}(t)=(A_i-B_iK)x(t)=A_{c_i}x(t) \quad i=1,\dots,N \tag{7}$$

The problem to be solved is formulated as a set of inequalities (8) applied for the polytopic system, and is readily transformable into LMIs, (Boyd *et al.*, 1994, Hypiusova and Rosinova, 2015).

Robust state-feedback design procedure for quadratic stability

Solve LMIs (8) for unknown symmetric positive definite matrix $Q\in R^{n\times n}$ and a full matrix $Y\in R^{r\times n}$.

$$\begin{aligned}&A_iQ+QA_i{}^T-B_iY-Y^TB_i{}^T<0, \quad i=1,2,\dots,N\\ &Q>0\\ &Q=P^{-1}\\ &Y=KP^{-1}\end{aligned} \tag{8}$$