ARTICLE IN PRESS
JID: JARAP [m5G;May 12, 2017;8:23]

Annual Reviews in Control 000 (2017) 1–33

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review article

Robust control under parametric uncertainty: An overview and recent results

S.P. Bhattacharyya

Department of Electrical and Computer Engineering, Texas A & M University, College Station, TX 77843, USA

ARTICLE INFO

Article history:
Received 7 December 2016
Revised 23 March 2017
Accepted 1 May 2017
Available online xxx

2010 MSC:
93D05

Keywords:
Robust control
Gain and phase margin
Quadratic optimization
PID control

ABSTRACT

Modern Robust Control has had two distinct lines of development: (a) Robustness through quadratic optimization and (b) Robustness under parametric uncertainty. The first approach consists of Kalman's Linear Quadratic Regulator and H_∞ optimal control. The second approach is the focus of this overview paper. It provides an account of both analysis as well as synthesis based results. This line of results was sparked by the appearance of Kharitonov's Theorem in the early1980s. This result was rapidly followed by further results on the stability of polytopes of polynomials such as the Edge Theorem and the Generalized Kharitonov Theorem, stability of systems under norm bounded perturbations and the computation of parametric stability margins. Many of these analysis results established extremal testing sets where stability or performance would breakdown. Starting in 1997, when it was established that high order controllers were fragile, attention turned to the synthesis and design of the parameters of low order controllers such as three term controllers and more particularly Proportional-Integral-Derivative (PID) controllers. An extensive theory of design of such systems has developed in the last twenty years. We provide a summary without proofs, of many of these results.

Contents

E-mail addresses: spb@tamu.edu, spb_tx@yahoo.com

http://dx.doi.org/10.1016/j.arcontrol.2017.05.001
1367-5788/

Please cite this article as: S.P. Bhattacharyya, Robust control under parametric uncertainty: An overview and recent results, Annual Reviews in Control (2017), http://dx.doi.org/10.1016/j.arcontrol.2017.05.001

1. Introduction

Robustness of a system, the subject of this article, is its ability to remain functional despite large changes. In control engineering, robustness has played a central and pivotal role, since its beginning in the 1860s. Thus Black's feedback amplifier (Kline, 1993), the Nyquist criterion (Nyquist, 1932), and gain and phase margins Bode (1945) were concepts dealing directly with robustness in the classical period.

Starting in 1960, the focus of control engineers shifted to optimization. However, the adequacy of an optimal design was ultimately judged by its robustness. Kalman's Linear Quadratic Optimal Regulator (Kalman, 1959) was found to be deficient when measured by its ability to deliver stability margins under output feedback (Doyle & Stein, 1979). The remedy proposed was high order H_∞ control (Doyle, Glover, Khargonekar, & Francis, 1989). In 1997, (Keel & Bhattacharyya, 1997) it was shown that even these controllers, and indeed all high order controllers, were fragile. This led of a renewed interest in direct studies on robustness resulting in a body of knowledge known as the parametric theory (Ackermann, 2012; Barmish & Jury, 1994; Bhattacharyya, Chapellat, & Keel, 1995; Bhattacharyya, 1987). This theory has two components: analysis and synthesis. The present paper gives an overview account of the analysis results, Kharitonov's theorem and its generalization (Chapellat & Bhattacharyya, 1989; Kharitonov, 1978), the Edge theorem (Bartlett, Hollot, & Lin, 1988), and related results as well as recent results on the parametric theory of synthesis and design (Bhattacharyya et al., 1995) of Proportional-Integral-Derivative (PID) controllers, Datta, Ho, and Bhattacharyya (2013), Silva, Datta, and Bhattacharyya (2007), Diaz-Rodriguez, Oliveira, and Bhattacharyya (2015), Diaz-Rodriguez and Bhattacharyya (2015).

1.1. Quadratic optimization and robustness

In Kalman et al. (1960) introduced the state-variable approach and quadratic optimal control in the time-domain as new design approaches. This phase in the theory of automatic control systems arose out of the important new technological problems that were encountered at that time: the launching, maneuvering, guidance and tracking of space vehicles. A lot of effort was expended and rapid developments in both theory and practice took place. Optimal control theory was developed under the influence of many great researchers such as Pontryagin, Bellman, Kalman and Bucy. In the 1960s, Kalman introduced a number of key state-variable concepts. Among these were controllability, observability, optimal linear-quadratic regulator (LQR), state-feedback and optimal state estimation (Kalman filtering).

The optimal state feedback control produced by the LQR problem was guaranteed to be stabilizing for any quadratic performance index subject to mild conditions.

In a 1964 paper by Kalman (1964) which demonstrated that for SISO (single input-single output) systems the optimal LQR state-feedback control laws had some very strong guaranteed robustness properties, namely an infinite upper gain margin and a 60 ° phase margin, which in addition were independent of the particular quadratic index chosen. This is illustrated in Fig. 1 where the state feedback system designed via LQR optimal control has the above guaranteed stability margins at the loop breaking point "*m*".