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Review article

Robust control under parametric uncertainty: An overview and recent results

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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 early 1980s. 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.

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Contents

1. Introduction	2
1.1. Quadratic optimization and robustness	2
1.2. Robustness under parametric uncertainty	3
2. Kharitonov's theorem	3
3. Extremal properties of edges and vertices	4
3.1. Extremal parametric stability margin property	4
3.2. Extremal gain margin for interval systems	4
4. Robust state feedback stabilization	4
5. The edge theorem	5
6. The generalized kharitonov theorem	6
Construction of the extremal subset	6
7. Computation of the parametric stability margin	8
7.1. The image set approach	8
7.2. Stability margin computation	9
7.3. ℓ_2 stability margin	10
7.4. ℓ_∞ and ℓ_1 stability margins	11
8. Controller fragility of high order controllers	12
8.1. Robustness using high gain feedback	12
8.2. Fragility of high order controllers	12
9. Robust parametric synthesis: modern PID control	14

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9.1.	Robustness and integral control	14
9.2.	Stabilizing sets	15
9.3.	Phase, signature, poles, zeros, and Bode plots	16
	Sketch of proof	17
10.	PID synthesis for delay free continuous-time systems	17
11.	PID controller synthesis for systems with delay	18
12.	Computer-aided design (Bhattacharyya et al., 2009)	19
13.	Achievable performance: gain and phase margin specifications	19
13.1.	Continuous-time controllers: constant gain and phase Loci	19
13.2.	PI controllers (Diaz-Rodriguez and Bhattacharyya (2016))	19
	PID controllers (Diaz-Rodriguez, Han, Lee, & Bhattacharyya, 2017)	21
14.	Discrete-time controllers: constant gain and phase loci	21
14.1.	PI controllers (Diaz-Rodriguez & Bhattacharyya, 2015)	21
14.2.	PID controllers (Diaz-Rodriguez et al., 2015)	22
15.	Achievable performance with PI and PID controllers	23
15.1.	Stabilizing set determination	23
15.2.	Gain-phase margin design curves	23
15.3.	Achievable performance	23
15.4.	Computation of the stabilizing set	24
15.5.	Achievable gain-phase margin design curves	24
15.6.	Achievable performance and final design	24
16.	Multi-input multi-output (MIMO) control using single-Input single-Output (SISO) methods	25
16.1.	MIMO feedback stability analysis via SISO feedback analysis (Keel & Bhattacharyya, 2015)	25
16.1.1.	Preliminaries	25
16.1.2.	Main result	26
16.1.3.	Stability margin calculations	26
16.1.4.	Gain margin calculation	26
16.1.5.	Phase margin calculation	26
16.1.6.	Time-delay margin calculation	26
16.2.	SISO control of MIMO systems using the Smith-McMillan form	26
16.2.1.	Main result	27
17.	Concluding remarks	32
	Acknowledgments	32
	References	32

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".

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