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# Design and Analysis of Control Systems

## Case Studies

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*To Carolina Pereira Gomes, my parents, and friends*

# Preface

> Bold ideas, unjustified anticipations, and speculative thought, are our only means for interpreting nature: our only organon, our only instrument, for grasping her. And we must hazard them to win our prize. Those among us who are unwilling to expose their ideas to the hazard of refutation do not take part in the scientific game.
>
> K. Popper, The Logic of Scientific Discover.

Over the years, technology and society have become more dependent on autonomous systems. In this book, two methodologies for the analysis and design of autonomous systems are considered: the interaction of two subsystems and controller design, i.e., the algorithm that will govern the behavior of these systems. In general, techniques for analysis and design of systems depend on the structure of the equation that describes the system dynamics which, in many cases, is nonlinear. Moreover, the presence of unknown terms such as disturbances or modeling errors may lead to a system lacking the appropriate structures.

The purpose of this book is to provide a methodology to merge different known techniques for the design and analysis of systems lacking those structures. This monograph has been written for readers varying from undergraduate students to Ph.D. candidates/researchers in the fields of sciences and engineering. Since another objective of this book is to be accessible to the largest variety of readers, I provide only sketches of proofs, making the idea behind the proofs accessible for the unfamiliar reader. In Chap. 2, the design and blending of two nonlinear controllers is presented. In Chap. 3, the analysis of two interconnected systems is considered. The Appendix A recalls fundamental results and concepts employed along the other chapters.

This monograph has mostly been adapted from my Ph.D. dissertation [1] and based on a few subsequent articles. The English translation of the title my Ph.D. manuscript is Stabilization under local and global constraints. This thesis was supervised by Christophe Prieur (senior researcher at the CNRS/GIPSA-lab, Grenoble) and co-supervised by Vincent Andrieu (junior researcher at the

CNRS/LAGEP, Lyon). I thank them for advising me in this project which made me one of the recipients of the GdR MACS best theses award. This is a French national prize awarded to up to four Ph.D. candidates every 2 years. I also thank the examiners and opponents: Antoine Chaillet, Andrew Teel, Andrea Bacciotti, Laurent Praly, Sophie Tarbouriech, and Luca Zaccarian. They enriched not only my thesis but also my work as a researcher with their comments.

Sydney, Australia
October 2016

Humberto Stein Shiromoto

## Reference

1. Stein Shiromoto H (2014) Stabilisation sous contraintes locales et globales. PhD thesis, Université Grenoble Alpes

# Contents

# Acronyms and Notations

| | |
|---|---|
| $\mathscr{C}^k$ | Denotes the class of $k$-times continuously differentiable functions; |
| $\mathscr{K}$ | Denotes the class of continuous strictly increasing functions; |
| $\mathscr{K}_\infty$ | Denotes class of functions belonging to $\mathscr{K}$ and that are unbounded; |
| $\mathscr{P}$ | Denotes the class of positive definite functions; |
| $\mathscr{L}^\infty_{\mathrm{loc}}$ | Denotes the class of locally essentially bounded functions; |
| $\mathbb{R}$ | Denotes the set of real values; |
| $\mathbb{R}_{>0}$ | Denotes the set of strictly positive real values; |
| $\mathbb{R}_{\geq 0}$ | Denotes the set of positive real values; |
| $\mathbf{B}_{<r}(\mathbf{K})$ | Denotes the open ball centered at the set $\mathbf{K}$ and with radius $r > 0$; |
| $\mathbf{B}_{\leq r}(\mathbf{K})$ | Denotes the closed ball centered at the set $\mathbf{K}$ and with radius $r > 0$; |
| $\mathbf{S}_{\neq 0}$ | Denotes the set $\mathbf{S}\backslash\{0\}$; |
| $\mathtt{cl}\{\mathbf{S}\}$ | Denotes the closure of the set $\mathbf{S}$; |
| $\mathrm{co}\{\mathbf{S}\}$ | Denotes the convex closure of the set $\mathbf{S}$; |
| $\mathscr{K}\mathscr{L}$ | Denotes the class of functions $\beta : \mathbb{R}_{\geq 0} \times \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ such that, for a fixed $t \geq 0$, the function $s \mapsto \beta(s,t)$ is of class $\mathscr{K}$ and, for a fixed $s \geq 0$, the function $t \mapsto \beta(s,t) \in \mathbb{R}_{\geq 0}$ is strictly decreasing and satisfies $\beta(s,t) \to 0$, as $t$ tends to infinity; |
| $\Omega(V)_{\diamond c}$ | Denotes the set $\{x \in \mathbb{R}^n : V(x) \diamond c\}$, where $\diamond$ is a binary comparison operator (i.e., $\diamond \in \{\geq, <, \neq$, etc$\}$; |
| $\mathtt{supp}(\mathtt{f})$ | Denotes the set $\{x \in \mathbb{R}^n : f(x) \neq 0\}$; |
| $D^+_v V$ | is the Dini derivative of a function $V : \mathbb{R}^n \to \mathbb{R}$ in along the vector $v \in \mathbb{R}^n$; |
| $L_h V$ | Lie derivative of $V$ in along the vector field $h$ |
| $M \succ 0$ | Stands for the matrix $M \in \mathbb{R}^{n\times n}$ being positive definite; |
| $M \succcurlyeq 0$ | Stands for the matrix $M \in \mathbb{R}^{n\times n}$ being positive semidefinite; |
| $x \cdot y$ | Denotes the inner product between the vectors $x$ and $y \in \mathbb{R}^n$; |
| UGAS | Uniformly Globally Asymptotically Stable |