Technical Committee on Control Theory

第二十四届
中国控制会议论文集

PROCEEDINGS OF THE 24TH CHINESE CONTROL CONFERENCE

（上 册）

主　编　程代展　胥布工

副主编　胡跃明　郑大钟　王　龙　张纪峰
　　　　谢胜利　贾英民　刘智敏　黄　一

华南理工大学出版社

第二十四届中国控制会议论文集

Proceeding of the 24th Chinese Control Conference

(上　册)

主　编：程代展　胥布工

副主编：胡跃明　郑大钟　王　龙　张纪峰

谢胜利　贾英民　刘智敏　黄　一

华南理工大学出版社

·广州·

图书在版编目（CIP）数据

第二十四届中国控制会议论文集/程代展，胥布工主编；胡跃明等副主编.—广州：华南理工大学出版社，2005.7
ISBN 7-5623-2249-X

Ⅰ.第…
Ⅱ.①程… ②胥… ③胡…
Ⅲ.自动控制理论-学术会议
Ⅳ.TP13-53

中国版本图书馆 CIP 数据核字(2005)第075481号

总 发 行：华南理工大学出版社（广州五山华南理工大学17号楼，邮编 510640）
发行部电话：020-87113487 87111048（传真）
E-mail：scut202@scut.edu.cn **http**：//www.scutpress.com.cn
责任编辑：孙 莉 吴兆强
印 刷 者：广东省农垦总局印刷厂
开 本：890×1240 1/16 印张：122 字数：3780千
版 次：2005年7月第1版第1次印刷
印 数：1～550册
定 价：600.00元（上、下册）

第二十四届中国控制会议

The 24th Chinese Control Conference

时　　间：　2005年7月16日至18日
地　　点：　中国 广州

主办单位：中国自动化学会控制理论专业委员会
承办单位：华南理工大学自动化科学与工程学院

协办单位：IEEE 控制系统协会
日本仪器与控制工程师协会
韩国控制、自动化与系统工程学会
中国科学院数学与系统科学研究院系统科学研究所
广东省科学院自动化工程中心
广东省自动化学会
广州市自动化学会
桂林电子工业学院

会　议　机　构

顾问委员会

曹希仁	香港科技大学	戴汝为	中国科学院
冯纯伯	东南大学	B. Ghosh	Washington University
郭　雷	中国科学院	Y. C. Ho	Harvard University
黄　琳	北京大学	H. Kimura	Tokyo University
F. L. Lewis	University of Texas	李元元	华南理工大学
卢　强	清华大学	C. Martin	Texas Tech University
R. Ortega	CNR S, France	C. Park	Kyung Hee University, Korea
秦化淑	中国科学院	宋　健	中国工程院 中国科学院
M. W. Spong	University of Illinois	T. J. Tarn	Washington University
吴　捷	华南理工大学	吴宏鑫	中国航天科技集团
张嗣瀛	东北大学		

大会总主席（General Chairman）

陈翰馥 中国科学院

程序委员会

主　席：	程代展（中国科学院）	黄　捷（香港中文大学 华南理工大学）	
秘书长：	苏为洲（华南理工大学）	黄　一（中国科学院）	

程序委员会委员

毕大川	(中国技术创新有限公司)	曹希仁	(香港科技大学)
陈本美	(新加坡国立大学)	陈翰馥	(中国科学院)
陈　杰	(University of California, USA)	陈叔平	(浙江大学)
陈增强	(南开大学)	陈志炜	(香港大学)
陈宗基	(北京航空航天大学)	程代展	(中国科学院)
楚天广	(北京大学)	褚　健	(浙江大学)
丛　爽	(中国科学技术大学)	戴冠中	(西北工业大学)
邓飞其	(华南理工大学)	段广仁	(哈尔滨工业大学)
费树岷	(东南大学)	冯　刚	(香港城市大学)
耿志勇	(北京大学力学)	关新平	(燕山大学)
关治洪	(华中科技大学)	管晓宏	(西安交通大学)
郭　雷	(中国科学院)	韩京清	(中国科学院)
韩志刚	(黑龙江大学)	侯忠生	(北方交通大学)
胡德文	(国防科技大学)	胡跃明	(华南理工大学)
黄　捷	(香港中文大学)	黄　一	(中国科学院)
霍　伟	(北京航空航天大学)	贾英民	(北京航空航天大学)
姜钟平	(Polytechnic University, USA)	蒋昌俊	(同济大学)
康　伟	(Naval Postgraduate School, USA)	李春文	(清华大学)
李少远	(上海交通大学)	李泽湘	(香港科技大学)
林宗利	(University of Virginia)	潘　泉	(西北工业大学)
秦化淑	(中国科学院)	丘　立	(香港科技大学)
阮晓钢	(北京工业大学)	申铁龙	(Sophia University, Japan)
孙常胜	(北京理工大学)	谭　民	(中国科学院)
谭永红	(桂林电子工业学院)	田玉平	(东南大学)
涂菶生	(南开大学)	王　华	(Boston University, USA)
王　龙	(北京大学)	王　伟	(大连理工大学)
王庆林	(北京理工大学)	王诗宓	(清华大学)
王先来	(天津大学)	王行愚	(华东理工大学)

吴　敏	(中南大学)	吴　臻	(山东大学)
吴宏鑫	(中国航天科技集团)	武玉强	(曲阜师范大学)
胥布工	(华南理工大学)	薛安克	(杭州电子工业学院)
杨晓松	(华中科技大学)	俞　立	(浙江工业大学)
郁文生	(中国科学院)	张　旭	(四川大学)
张纪峰	(中国科学院)	赵　军	(东北大学)
郑大钟	(清华大学)	郑德玲	(北京科技大学)
钟宜生	(清华大学)	周鸿兴	(山东大学)
周　彤	(清华大学)		

组织委员会

主　席：胡跃明（华南理工大学）

副主席：黄　一（中国科学院）

徐建闽（华南理工大学）

刘琪瑾（华南理工大学）

谭永红（桂林电子工业学院）

张纪峰（中国科学院）

刘智敏（中国科学院）

邓飞其（华南理工大学）

郭华芳（中科院广东分院）

编辑委员会

主编：程代展（中国科学院）

委员：胡跃明（华南理工大学）

王　龙（北京大学）

谢胜利（华南理工大学）

刘智敏（中国科学院）

胥布工（华南理工大学）

郑大钟（清华大学）

张纪峰（中国科学院）

贾英民（北京航空航天大学）

黄　一（中国科学院）

前　言

“中国控制会议”是由中国自动化学会控制理论专业委员会负责组织的学术会议，自 1979 年至今已举办了 24 届。该系列年会的目的是为海内外系统控制领域的专家、学者、研究生及控制系统的设计人员提供一个学术交流的机会，以推动控制科学的学科发展和控制技术的应用。第二十四届中国控制会议定于 2005 年 7 月 15—18 日在美丽的花城广州举行。会议由华南理工大学承办，协办单位包括：IEEE Control System Society，The Society of Instrument and Control Engineers (SICE) of Japan, The Institute of Control, Automation and System Engineers of Korea (KICASE)，中国科学院数学与系统科学研究院系统科学研究所，广东省科学院自动化工程中心，广东省自动化学会，广州市自动化学会以及桂林电子工业学院等单位。

本着开拓创新、与时俱进的精神，本届大会加强了组织协调，扩大了国际交流，得到海内外学者的热烈回应。中国控制会议正朝着国际化的目标稳步前进。

本届会议邀请 5 位知名学者做大会报告，他们分别是 Professor Hassan K. Khalil（Michigan State University），Professor Clyde Martin (Texas Tech University), Professor Jing Sun（University of Michigan），吴捷教授（华南理工大学），Professor Kemin Zhou（Louisiana State University）。

本次会议共收到投稿论文 549 篇，创造了新的记录。经程序委员会评审，论文集共收录 400 篇论文。论文作者来自中国大陆、香港、澳门、日本、美国、瑞典、瑞士、新加坡、加拿大、伊朗、波兰、澳大利亚、塞尔维亚，英国等国家和地区。论文内容包括线性系统、非线性系统、变结构控制、最优控制、优化方法、鲁棒控制、H^∞控制、预测控制、过程控制、随机控制、自适应控制、稳定性分析、分布参数系统、DEDS 与 CIMS、复杂系统、模糊系统与控制、神经网络、机器人控制、交通系统、故障检测与诊断、电力系统等领域的研究成果。本论文集可供从事自动控制理论及其应用研究的高等院校教师和研究生、科研单位的研究人员以及工业部门的工程技术人员参考。

本论文集的出版必将进一步促进系统科学的发展，推动先进控制理论与方法更好地为生产实践服务，促进控制技术产业化。

本届“关肇直奖”竞争激烈。它的评选促使一批优秀的中青年控制科学工作者脱颖而出，为控制科学的发展注入了新的血液。

我们诚挚感谢为中国控制会议的发展献策出力的海内外朋友们，为论文集的出版付出辛勤劳动和出色工作的各位论文作者，论文集主编、副主编，程序委员会专家和华南理工大学出版社的同志们。

第 24 届中国控制会议程序委员会主席
程代展　中国科学院
黄　捷　香港中文大学

Preface

Chinese Control Conference (CCC) is an annual technical conference sponsored and organized by the Technical Committee on Control Theory, Chinese Association of Automation. The first conference was held in 1979. This is the 24th conference. The purpose of this conference is to provide a forum for both practitioners and theorists in the area of systems and control to report their latest research results, exchange their ideas and experience, and promote collaborative research activities. Participants from both China and abroad gather together to advance the development of science of systems and control and the applications of control theory. The 24th CCC will be held on Jul. 15-18, 2005 in the beautiful flower city—Guangzhou. South China University of Technology is the local sponsor. The conference is also co-sponsored by IEEE Control System Society, The Society of Instrument and Control Engineer (SICE) of Japan, The Institute of Control, Automation and System Engineers of Korea (KICASE), and Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Automation Engineering Research and Manufacture Center (AEC) of Guangdong Provincial Academy of Sciences, The Automation Society of Guangdong Province, The Automation Society of Guangzhou, Guilin University of Electronic Technology.

In the spirit of reform, openness, and internationalization, this conference has strengthened its cooperation with various international organizations, and is now well received from both China and abroad. CCC is now building its reputation as a true international conference.

Five prominent scholars over the world are invited to deliver the plenary speeches. They are Professor Hassan K. Khalil from Michigan State University, Professor Clyde Martin from Texas Tech University, Professor Jing Sun from University of Michigan, Professor Wu Jie from South China University of Technology, and Professor Kemin Zhou from Louisiana State University.

This year, we have received record high submissions of a total of 549 papers. After a rigorous review process by the Conference Program Committee, 400 papers are accepted for presentation in the Conference. All accepted papers will be in the Conference Proceedings. The authors of the papers are from various countries and regions including Mainland China, Hong Kong, Macau, Japan, USA, Sweden, Switzerland, Singapore, Canada, Iran, Poland, Australia, Serbia and Montenegro and UK. The topics of the Conference include but not are limited to Linear Systems, Nonlinear Systems, Sliding-Mode Control, Optimal Control, Optimization, Robust Control, H-infinity Control, Predictive Control, Process Control, Stochastic Control, Adaptive Control, Stability Analysis, Distributed Parameter System, DEDS, CIMS, Complex Systems and Complexity, Fuzzy Systems and Control, Neural Networks, Robot Control, Transportation Systems, Error Detection and Diagnosis, Power Systems. The proceedings will be a current and comprehensive collection of the latest research papers of the conference contributors, and will serve an excellent reference for both university professors and graduate students in the field of automation and control as well as for experts working in research institutions and engineers in industry.

The publication of the Conference Proceedings will further enhance the development of systems and control, and foster the applications of advanced control theory and technologies to practical systems.

This year, we have also received a record-breaking number of papers for competing Guan Zhaozhi Best Paper Award. This is an indication that outstanding young researchers in the area of systems and control are mushrooming. They are rapidly moving up to the forefront of the Chinese system and control community.

We would like to express our sincere thanks to our domestic and overseas friends for their constant support of CCC. We are also greatly appreciative to all contributors of the papers, members of organizing committee, program committee, and editorial board of the conference proceedings.

Chair of 24th Chinese Control Conference
Daizhan Cheng
Chinese Academy of Sciences
Jie Huang
Chinese University of Hong Kong

第二十四届中国控制会议大会报告

The 24th Chinese Control Conference Plenary Lectures

Plenary Lecture 1

Splines and Control Theory: Past, Present and Future

Prof. Clyde Martin, Texas Tech University

Plenary Lecture 2

High Performance Robust and Fault Tolerant Control

Prof. Kemin Zhou, Louisiana State University

Plenary Lecture 3

Conditional Integral Action in Nonlinear Control

Prof. Hassan K. Khalil, Michigan State University

Plenary Lecture 4

Integrated Powerplants for Advanced Transportation Systems: Challenges and Opportunities for Controls

Prof. Jing Sun, University of Michigan

Plenary Lecture 5

Control of Renewable Energy Source and Power Electronics

Prof. Wu Jie, South China University of Technology

Plenary Speakers at the 24th Chinese Control Conference

Clyde F. Martin received his Ph D from University of Wyoming in 1971. He is currently a Professor with Dept. of Mathematics and Statistics, Texas Tech University.

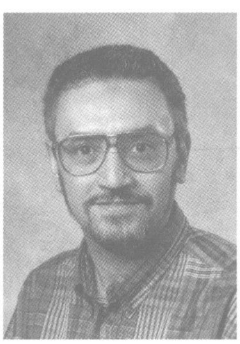
In 1983 he was appointed the Ex-Students Association Distinguished Visiting Professor of Mathematics at Texas Tech University, in 1988 he was appointed as the Ex-Students Association Distinguished Professor of Mathematics and in 1991 was appointed as the Paul Whitfield Horn Professor by the Board of Regents of Texas Tech University. He is a member of the American Mathematical Society, Institute of Electrical and Electronic Engineers, and the Institute of Mathematical Statistics and has served on numerous committees within these organizations. He is a Fellow of the Institute of Electrical and Electronic Engineers. Professor Martin has published more than 300 technical books and papers in a wide variety of areas. He has directed the theses and dissertations of more than 60 students at Texas Tech University, the University of Texas School of Public Health, Case Western Reserve University (1978-1983), The Royal Institute of Technology in Stockholm Sweden and Utah State University (1973-1975). Many of these students wrote in the area of public health and in bioengineering.

Professor Martin has received distinguished Alumni awards at both his undergraduate institution (Emporia State University) and his graduate institution (University of Wyoming). In 2001 he was awarded an honorary doctoral degree from the Royal Institute of Technology in Stockholm for his work in control theory.

Kemin Zhou was born in Wuhu in 1962. He received the B.S. degree from BUAA in 1982, the M.S.E.E. and the Ph.D. degrees from University of Minnesota in 1986 and 1988, respectively.

Since 1990, he has been with Louisiana State University where he is currently the Chair and the Voorhies Distinguished Professorship in Electrical Engineering. He is also an adjunct professor of Harbin Institute of Technology Shen Zhen Graduate School.

He is the leading author of two popular books in the field: Robust and Optimal Control (Prentice Hall, 1995), which has been used worldwide as graduate textbook and research references and has been translated into Japanese (1997) and Chinese (2002), and Essentials of Robust Control (Prentice Hall, 1997). He is/was an Associate Editor of Automatica, IEEE Transactions on Automatic Control, SIAM Journal on Control and Optimization, Systems and Control Letters, Journal of System Sciences and Complexity, and Journal of Control Theory and Applications. He was named the Oskar R. Menton Endowed Professor in 1998, given a special congressional recognition in 2003, recognized for outstanding accomplishments and contributions to LSU by the House of Representatives of the Louisiana Legislature in 2004, and received outstanding young investigator award from Natural Science Foundation of China in 2004. He was also selected as 2005 Chang Jiang Jiang Zuo Professor. He is one of the five professors selected by and representing LSU to be featured on the national TV during the 2005 LSU college football games. He was elected to IEEE Fellow in 2003. His work has been cited more than 2,300 times according to Science Citation Index.

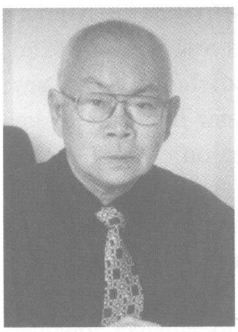


Hassan K. Khalil received electrical engineering degrees from Cairo University (BS 1973; MS 1975) and the University of Illinois (PhD 1978). Since 1978 he has been with Michigan State University, where he is currently University Distinguished Professor of Electrical and Computer Engineering. He has consulted for General Motors and Delco Products, and published several papers on singular perturbation methods and nonlinear control. He is author of Nonlinear Systems (Macmillan 1992; Prentice Hall 1996 & 2002) and coauthor, with P. Kokotovic and J. O'Reilly, of Singular Perturbation Methods in Control: Analysis and Design (Academic Press 1986; SIAM 1999). He was named IEEE Fellow in 1989 and received the 1989 IEEE-CSS George S. Axelby Outstanding Paper

Award, the 2000 AACC Ragazzini Education Award, the 2002 IFAC Control Engineering Textbook Prize, and the 2005 AACC O. Hugo Schuck Best Paper Award. He served as Associate Editor of IEEE Transactions on Automatic Control, Automatica and Neural Networks, and is currently Editor of Automatica for nonlinear systems and control. He was Registration Chair of the 1984 CDC, Finance Chair of the 1987 ACC, Program Chair of the 1988 ACC, and General Chair of the 1994 ACC.

Jing Sun received her Ph. D degree from University of Southern California in 1989, and her B. S. and M. S. degrees from University of Science and Technology of China in 1982 and 1984 respectively, all in Electrical Engineering.

From 1989-1993, she was on the faculty of the Electrical and Computer Engineering Department, Wayne State University. She joined Ford Research Laboratory in 1993 where she worked, first as a technical specialist then a project leader, in the Powertrain Control Systems Department on engine emission control and fuel economy optimization projects. After spending almost 10 years in industry, she came back to academia and joined the Naval Architecture and Marine Engineering Department and Electrical Engineering and Computer Science Department at the University of Michigan in September 2003. Her research interests include adaptive control, nonlinear control, system theory and their applications to marine and automotive propulsion systems. She holds 34 US patents, has co-authored a textbook, Robust Adaptive Control (Prentice Hall, 1996), and published many journal and conference papers. She is an IEEE fellow and one of the recipients of the 2003 IEEE Control System Technology Award.



Wu Jie graduated from Dept. of Automation, Harbin Institute of Technology. Currently, he is a Professor, Doctorial Advisor, Receiver of Government Special Honorarium with Dept. of EE, South China University of Technology. He is also the Deputy Director of Guangdong Energy Research Association, Deputy Director of Micro-computer Application Committee, China Instrument and Control Society, Director of the New Energy Research Center, South China University of Technology, Chief Editor of the journal: "Control Theory and Applications". As a principle investigator or major participant, he carried and completed over 40 projects including projects of national natural science foundation, national 863 project, sub-project of national key fundamental research project (973), projects of Guangdong natural science foundation, and some industrial projects. He has published three books and over 200 papers on the fields of adaptive control, control of structure-varying systems, control of dissipative systems, intelligent control etc. Among the projects he completed, the key project of Guangdong tenth Five Year Plan "distributed wind-sun mixed power generators" (A1050401, 2002-), the Guangdong-Hong Kong join key project "large-scale wind power generator and the nationalization of the design technique and parts (2004A10506003-Z01, 2004-2006), and the project "design of real-time detection and system analysis of wind electric field based on CAN general line" have received the swards from Chinese Ministry of Science and Technology, Chinese Academy of Sciences, Chinese Ministry of Education, and Guangdong Dept. of Science and Technology.

SPLINES AND CONTROL THEORY: PAST, PRESENT AND FUTURE

CLYDE MARTIN*, MAGNUS EGERSTEDT**, YISHAO ZHOU***, AND SHAN SUN*

* Department of Mathematics and Statistics. Texas Tech University. P.O. Box 41042. Lubbock, Texas,USA

** Magnus Egerstedt, Electrical and Computer Engineering Georgia Institute of Technology. 432 TSRB Atlanta, GA 30332

*** Department of Mathematics, Stockholm University, SE-10691, Stockholm, Sweden

1. The past

Spline functions are those functions that have a certain degree of differentiability at a set of times, called the nodes, and are infinitely differentiable every where else. Mathematical splines were first defined in the 1940s as solution to a certain optimization problem and there it was shown that there was an optimal function that interpolated a finite set of data and was twice continuously differentiable at the nodes and consisted of cubic polynomials between the nodes. Now it is an elementary part of every numerical analysis course to construct this "cubic spline" using elementary linear algebra. However in the 1940s there was not any real way to use the concept because of the lack of computers.

In the late 1960s computing power dramatically increased and the construction and use of splines of the polynomial type were in use everywhere. Some new directions were established with the concept of torsion splines and even a theory of L-splines. However control theory never entered the picture. It wasn't until Peter Crouch noted that trajectory planning problems could be interpreted as interpolation problems did control enter the world of splines. At about the same time Robert Hermann suggested that the first author look at the problem of creating fonts using control theoretic methods. This let to a series of papers by Martin, Egerstedt and Sun on general classes of interpolating splines with various constraints. This was motivated by the fact that in many cases interpolation was not necessary or even desirable. Often it was known that the true data lay in an interval and not at a know point. These problems were of interest mathematically because they reduced to quadratic programming problems.

2. The present

However, it wasn't until Professor Fritz Ruymgaart suggested that interpolating splines were of little use in statistics that the work began to focus on splines that didn't interpolate data but rather smoothed data. As work began it was discovered that the guru of polynomial smoothing splines was Professor Grace Wahba of the University of Wisconsin. She is the motivation of much of the work that has been done in the last decade. Finally a suitable formulation was put into place to construct a very large variety of smoothing splines. The formulation was pure control theory.

Let $D = \{(t_i, \alpha_i) : \ i = 1, \cdots, N\}$ and let the spline generator be given by a controllable and observable linear system

$$\begin{aligned} \dot{x} &= Ax + bu, \ x(0) = x_0 \\ y &= cx, \ x \in \mathbb{R}^n \end{aligned}$$

where we assume that

$$cb = cAb = \cdots = cA^k b$$

where $0 \geq k \leq n-2$. We then define a cost function of the form

$$J(u, x_0) = \lambda \int_0^T u^2(t)dt + x_0' Q x_0 + \sum_{i=1}^{N} w_i (y(t_i) - \alpha_i)^2.$$

The problem then becomes a simple optimization problem

$$\min_{u \in L_2[0,T],\ x_0 \in \mathbb{R}^n} J(u, x_0)$$

subject to various linear constraints–periodicity, boundary values, integral constraint, etc. Martin, Egerstedt and Zhou have been able to convert this problem to the problem of finding the point of minimum norm in a linear variety in a certain Hilbert space. Any spline problem with additional linear constraints can be so formulated. The algorithm is very straight forward to apply and several papers have prepared and published.

3. THE FUTURE

The future is application. Research is underway to apply control theoretic to problems in the analysis of longitudinal duty in statistics. We are attempting to use control theoretic splines in the analysis of microarray data in genetics. There are problems in the extension of splines to higher dimensional problems. Recursive algorithms to construct splines and the list of applications and new theoretical results is seemingly without end. The future is bright and requires new ideas and new problems. However most of all it requires the best solutions to good problems. The field will generate such problems.

High Performance Robust and Fault Tolerant Control

Kemin Zhou

Department of Electrical and Computer Engineering, Louisiana State University, Baton Rouge, LA 70803, USA

哈尔滨工业大学深圳研究生院

kemin@ece.lsu.edu

Keywords: Robust control, Fault Tolerant Control, Performance

Extended Abstract

It is commonly known in the control community that there are intrinsic tradeoffs between achievable performance and robustness for a given control architecture. In other words, in order to achieve certain performance, one must sacrifices some robustness properties of the control systems and vise versa once the control architecture is chosen. For example, a high performance controller designed for a nominal model may have very little robustness against the model uncertainties and external disturbances. For this reason, various robust control design techniques have gained popularity in the last twenty years or so. Unfortunately, it is well recognized in the robust control community that the robustness of a closed-loop system is usually achieved at the expense of performance. In particular, it is well known that robust control design techniques such as H_∞ optimization, L_1 optimization, and μ synthesis may result in controllers that have very poor nominal performance. This is not hard to understand since most robust control design techniques are based on the worst possible scenarios that may never occur in a particular control system. Thus such controllers are not desirable in many applications. Nevertheless, the ability to maintain some minimum performance of the system under the worst-case scenario is also very important in many applications and hence it is desirable to have design techniques that can achieve the same level of robustness when there are model uncertainties and external disturbances while at the same time perform well when there is no or little model uncertainties and external disturbances. The control architecture proposed in [1] seems to be a good candidate for achieving this objective.

Consider a standard feedback configuration shown in Figure 1 where $\tilde{G}$ is a linear time invariant plant and K is a linear time invariant controller. It is well understood that the model $\tilde{G}$ is in general not perfectly known. What one actually knows is a nominal model G. Now assume that K_0 is a stabilizing controller for the nominal plant G and assume G and K_0 have the following stable coprime factorizations

$$K_0 = \tilde{V}^{-1}\tilde{U}, \quad G = \tilde{M}^{-1}\tilde{N}.$$

Then it is well known that every stabilizing controller for G can be written in the following form:

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

for some stable transfer matrix Q.

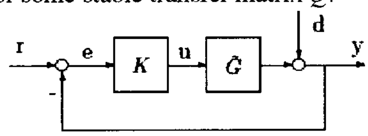


Figure 1: Standard Feedback Configuration

It is proposed in [1] that this controller can be implemented as shown in Figure 2. Note that the feedback diagram in Figure 2 is not equivalent to the diagram in Figure 1 since the reference signal r enters into the system from a different location. Nevertheless, the internal stability of the system is not changed since the transfer function from y to u is $-K$ and is not changed. Thus this controller implementation also stabilizes internally the feedback system.

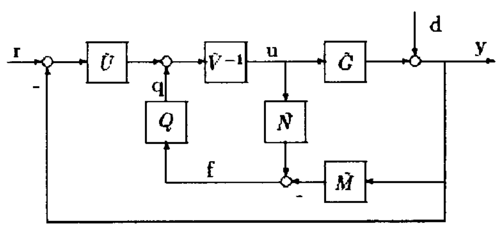


Figure 2: High performance robust controller

The distinct feature of this controller implementation is that the inner loop feedback signal f is always zero, i.e., $f = 0$, if there is no model uncertainties (i.e., $\tilde{G} = G$), external disturbances or faults and then the control system will be solely controlled by the high performance controller $K_0 = \tilde{V}^{-1}\tilde{U}$. On the other hand, the controller Q in the inner loop will only be active when $f \neq 0$, i.e., there are either model uncertainties or external disturbances or sensor/actuator faults. Moreover, the strength of the signal q depends on the size of the model uncertainties, the size of the disturbances, and the extents of the faults. Hence Q can be designed to robustify the feedback systems. Thus this controller design architecture has a clear separation between performance and robustness.

A problem closely related to the above tradeoff is to keep good performance in the event of sensor/actuator failures that are crucial in many applications. One way of synthesizing fault-tolerant controllers is by appealing to robust design techniques. Unfortunately, as we have discussed earlier, most robust control design techniques are based on the worst case scenario which may never occur and it is not surprising to see that such a control system does not perform very well even though it is robust to model uncertainties and sensor/actuator faults.

Nevertheless, the above control structure also provides a systematic method for fault tolerant control design. Note that $f = \tilde{N}(s)u - \tilde{M}(s)y$ is the filtered error between the estimated output and the true output of the system (residual signal). This signal contains valuable information in case of a system components/sensors/actuators failure. Consequently, in order to have the exact nominal performance in case of no-failure, f could be monitored to detect a sensor or actuator failure and then activate the robustness loop, i.e. switch on the signal q. Thus, the controller may also be implemented as shown in Figure 3. Note that in this case Q can be a set of controllers corresponding to specific situations. This will improve the performance of the overall control system, since there is no degradation of nominal performance in order to improve robustness. Possible extensions to nonlinear setting will also be explored.

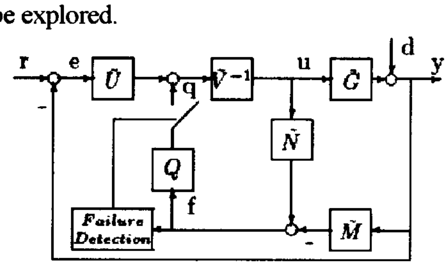


Figure 3: Controller architecture with failure detector

Figures 4-7 demonstrate how the new controller architecture maintains the robustness while improves the performance of the robust controller.

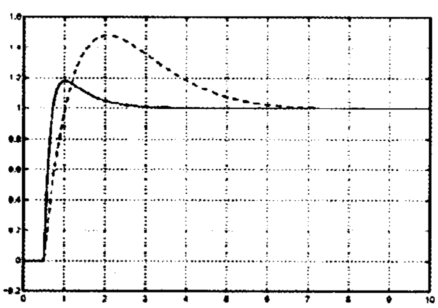


Figure 4: Responses to Nominal Plant: good performance controller K_0 (solid) and robust controller K (dashed), and the new controller implementation of K (solid)

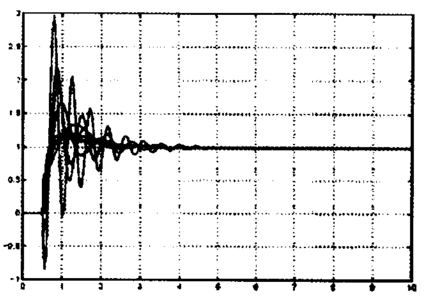


Figure 5: Responses to perturbed plants with K_0

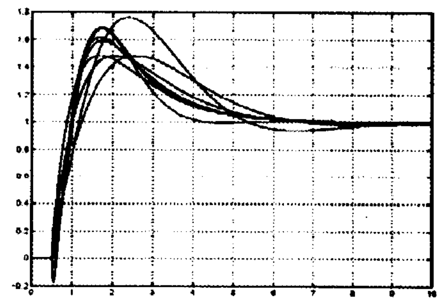


Figure 6: Responses to perturbed plants with robust controller K

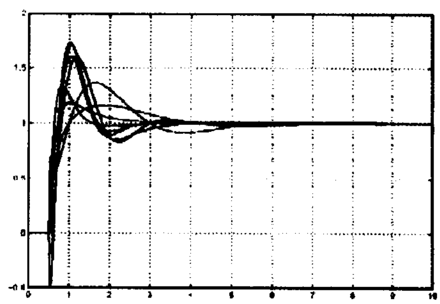


Figure 7: Responses to perturbed plants with new controller implementation of the robust controller K

References

[1] K. Zhou and Z. Ren, "A New Controller Architecture for High Performance, Robust and Fault Tolerant Control," *IEEE Transactions on Automatic Control*, Vol. 46, No.10, pp. 1613-1618, 2001.

[2] D. U. Campos-Delgado and K. Zhou, "Reconfigurable Fault Tolerant Control Using GIMC Structure," *IEEE Transactions on Automatic Control*, Vol. 48, No. 5, May 2003, pp. 832-838.

[3] K. Zhou, "A New Approach to Robust and Fault Tolerant Control," *ACTA Automatica Sinca*, Vol. 31, No. 1, pp. 43-55, 2005.

[4] D. U. Campos-Delgado, S. Martinez Martinez, and K. Zhou, "Integrated Fault Tolerant Scheme for aDC Speed Drive," IEEE Trans. on Mechatronics to appear.

Conditional Integral Action in Nonlinear Control*

Hassan K. Khalil
Department of Electrical and Computer Engineering
Michigan State University
East Lansing, MI 48824-1226
(**E-mail:** khalil@msu.edu)

Abstract

Integral action is indispensable as a tool for achieving robust asymptotic regulation, but it degrades the transient response of the system. Recently, a new tool of conditional integral action was introduced as a way to achieve robust asymptotic regulation of a class of minimum phase nonlinear systems without degrading the transient performance. In this paper we review the main elements of this new tool. We start by developing the tool in a sliding-mode-control framework; then we extend it to other design techniques using Lyapunov redesign. We also demonstrate a connection between conditional integrators and commonly used integrator antiwindup schemes.

Keywords: High-gain observers; Integral control; Integrator antiwindup; Lyapunov redesign; Minimum-phase systems; Output regulation; Sliding-mode control

1 Introduction

Integral control, or integral action, is a classical tool for achieving asymptotic tracking and disturbance rejection of constant exogenous signals in the presence of uncertain parameters. The theory of integral control of nonlinear systems has developed considerably in the last fifteen years or so; c.f., [2], [5], [6], and [9]. The main advantage of integral action is the robustness of the asymptotic regulation property to all parameter perturbations that do not destroy the stability of the closed-loop system. Its main disadvantage is the degradation of the transient performance, compared with a design that does not include integral action. Such degradation takes the form of integrator windup when the control saturates [14]. Recently, a new tool of conditional integrators was introduced to implement integral action in nonlinear systems without degrading the transient performance. The main results are available in [10] and [12]. In this tutorial paper, we review the main idea of conditional integration and the analytical results that back it up. We focus attention on a class of single-input–single-output, minimum phase, input-output linearizable systems, even though the results of [10] and [12] deal with multi-input–multi-output systems. We also describe the connection between conditional integration and integrator antiwindup schemes.

*This work was supported in part by the National Science Foundation under grant numbers ECS-0114691 and ECS-0400470.

2 Integral Control

Consider the single-input–single-output system

$$\dot{x} = f(x, u, w) \quad (1)$$
$$y = h(x, w) \quad (2)$$

where $x \in R^n$ is the state vector, u is the control input, y is the measured regulation error (the difference between the plant output and a constant reference), and w is a vector of unknown constant parameters. The functions f and h are sufficiently smooth in their arguments over the domain of interest. The control objective is to asymptotically regulate y to zero for all values of w in a given compact set W. The regulation task can be achieved by stabilizing the system at an equilibrium point at which $y = 0$. Towards that end, we assume that for each $w \in W$ there is a unique pair (x_{ss}, u_{ss}) that depends continuously on w and satisfies the steady-state equations

$$0 = f(x_{ss}, u_{ss}, w) \quad (3)$$
$$0 = h(x_{ss}, w) \quad (4)$$

so that x_{ss} is the desired equilibrium point and u_{ss} is the steady-state control that is needed to maintain equilibrium at x_{ss}. Stabilizing the equilibrium point x_{ss} is complicated by the uncertainty of x_{ss} and u_{ss}. For example, we cannot simply shift the equilibrium point to the origin via the change of variables