

# Finite Spectrum Assignment Controller for Teleoperation Systems with Time delay

ANAS FATTOUH

Laboratoire d'Automatique de Grenoble  
ENSIEG - BP 46  
38402 Saint Martin d'Hères Cedex, FRANCE  
Tel. +33.4.76.82.64.37 - FAX: +33.4.76.82.63.88

Anas.Fattouh@inpg.fr

Olivier SENAME<sup>†</sup>

INRIA Rhône-Alpes  
655 avenue de l'Europe, Monthonnnet  
38334 Saint Ismier Cedex, FRANCE  
Tel. +33.4.76.61.52.46 - FAX: +33.4.76.61.54.77

Olivier.Sename@inrialpes.fr

## Abstract

In this paper, two controllers are proposed for bilateral teleoperation systems with communication time delay. The first one guarantees the tracking of slave-master outputs, while the second one guarantees the transparency. Communication time delay appears in the control loop of the second controller, and finite spectrum assignment method is used to design this controller such that the resulting closed loop system have a desirable finite spectrum. Numerical example shows that both tracking and transparency can be guaranteed using the proposed method.

**Keywords:** Bilateral teleoperation systems, Time delay systems, Finite spectrum assignment (FSA).

## 1 Bilateral teleoperation system

In bilateral teleoperation system, the slave (remote) manipulator is controlled by an operator through the master (local) manipulator, while the contact force of the slave manipulator with the environment is reflected back to the operator through the master manipulator as shown in Figure 1.

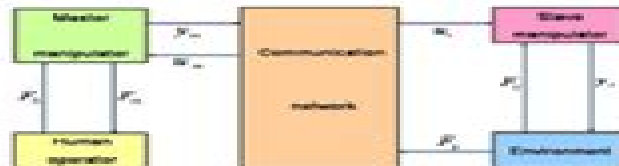


Figure 1: Bilateral teleoperation system.

In this configuration, the operator applies a force  $F_o$  on the master manipulator in order to drive it to the desired position or velocity  $y_m$ . The master manipulator assumes to work in a free space, i.e. there is no reaction force from the manipulator to the operator, or in other words, the operator can drive the master manipulator to any desired position or velocity. The output of the master manipulator is sent forward to the remote manipulator through the communication network and is considered as a reference for the slave manipulator (desired position or velocity). This reference is used to generate a torque (or a force)  $u_s$  which drives the slave manipulator to certain position or velocity  $y_s$ . Assuming that the slave manipulator acts in a non-free environment, there will be a reaction torque (or force)  $F_e$ . This force sensed at the environment  $F_e$ , or a function of this force  $F_e$ , is sent back to the master manipulator and used to generate a feedback torque (or force)  $F_m$  which is applied to the master manipulator in order to give the operator a sense of what is happening in the remote side.

A controller should be designed for the previous scheme in order to guarantee:

1. *The tracking: the slave manipulator's output  $y_s$  has to track the master manipulator's output  $y_m$ , i.e.  $\lim_{t \rightarrow \infty} (y_s(t) - y_m(t)) = 0$ .*
2. *The transparency: the feedback force  $F_m$  has to track the contact force  $F_e$ , or a function of this force  $F_e$ , i.e.  $\lim_{t \rightarrow \infty} (F_m(t) - F_e(t)) = 0$ .*

In the case where there is a time delay in the communication network, it should be incorporated in the designing method such that the previous objectives still maintain.

An approach used to solve the above problem is based on the passivity and scattering theory [1]: if the input power flow does not exceed the output power flow for

<sup>†</sup>Corresponding author, author is also with Laboratoire d'Automatique de Grenoble, FRANCE.

# Finite Spectrum Abignment For Timedelay Systems

**Wim Michiels, Silviu-Iulian Niculescu**



## **Finite Spectrum Abignment For Timedelay Systems:**

**Finite-Spectrum Assignment for Time-Delay Systems** Qing-Guo Wang, Tong H. Lee, Kok K. Tan, 2014-03-12 The presence of considerable time delays in many industrial processes is well recognized and achievable performances of conventional unity feedback control systems are degraded if a process has a relatively large time delay compared to its time constants In this case dead time compensation is necessary in order to enhance the performances The most popular scheme for such compensation is the Smith Predictor but it is unsuitable for unstable or lightly damped processes because the compensated closed loop system always contains the process poles themselves An alternative scheme for delay elimination from the closed loop is the finite spectrum assignment FSA strategy and it can arbitrarily assign the closed loop spectrum One may note that the Smith Predictor Control can be found in delay systems control books and many process control books but the FSA control is rarely included in these books It is therefore timely and desirable to fill this gap by writing a book which gives a comprehensive treatment of the FSA approach This is useful and worthwhile since the FSA provides not only an alternative way but also certain advantages over the Smith Predictor The book presents the state of the art of the finite spectrum assignment for time delay systems in frequency domain It mainly contains those works carried out recently by the authors in this field Most of them have been published and others are awaiting publication They are assembled together and reorganized in such a way that the presentation is logical smooth and systematic *Stability, Control and Application of Time-Delay Systems* Qingbin Gao, Hamid Reza Karimi, 2019-06-27 *Stability Control and Application of Time Delay Systems* gives a systematic description of these systems It includes adequate designs of integrated modeling and control and frequency characterizations Common themes revolve around creating certain synergies of modeling analysis control computing and applications of time delay systems that achieve robust stability while retaining desired performance quality The book provides innovative insights into the state of the art of time delay systems in both theory and practical aspects It has been edited with an emphasis on presenting constructive theoretical and practical methodological approaches and techniques Unifies existing and emerging concepts concerning time delay dynamical systems Provides a series of the latest results in large delay analysis and multi agent and thermal systems with delays Gives in each chapter numerical and simulation results in order to reflect the engineering practice *Topics in Time Delay Systems* Jean Jacques Loiseau, Wim Michiels, Silviu-Iulian Niculescu, Rifat Sipahi, 2009-08-26 Time delays are present in many physical processes due to the period of time it takes for the events to occur Delays are particularly more pronounced in networks of interconnected systems such as supply chains and systems controlled over communication networks In these control problems taking the delays into account is particularly important for performance evaluation and control system s design It has been shown indeed that delays in a controlled system for instance a communication delay for data acquisition may have an ambiguous nature they may stabilize the system or in the contrary they may lead to deterioration of the closed loop performance or even

instability depending on the delay value and the system parameters. It is a fact that delays have stabilizing effects but this is clearly conflicting with human intuition. Therefore specific analysis techniques and design methods are to be developed to satisfactorily take into account the presence of delays at the design stage of the control system. The research on time delay systems stretches back to 1960s and it has been very active during the last twenty years. During this period the results have been presented at the main control conferences CDC ACC IFAC in specialized workshops IFAC TDS series and published in the leading journals of control engineering systems and control theory applied and numerical mathematics.

Advances in Time-Delay Systems Silviu-Iulian Niculescu, Keqin Gu, 2012-12-06 In the mathematical description of a physical or biological process it is a common practice to assume that the future behavior of the process considered depends only on the present state and therefore can be described by a finite set of ordinary differential equations. This is satisfactory for a large class of practical systems. However the existence of time delay elements such as material or information transport of the system renders such description unsatisfactory in accounting for important behaviors of many practical systems. Indeed due largely to the current lack of effective methodology for analysis and control design for such systems the time delay elements are often either neglected or poorly approximated which frequently results in analysis and simulation of insufficient accuracy which in turn leads to poor performance of the systems designed. Indeed it has been demonstrated in the area of automatic control that a relatively small delay may lead to instability or significantly deteriorated performances for the corresponding closed loop systems.

**Robust Control of Time-delay Systems** Qing-Chang Zhong, 2006-05-28 Recently there have been significant developments in robust control of time delay systems. This volume presents a systematic treatment of robust control for such systems in the frequency domain. The emphasis is on systems with a single input or output delay although the delay free part of the plant can be multi input multi output in which case the delays in different channels should be the same. The author covers the whole range of  $H_\infty$  control of time delay systems from controller parameterization implementation from the Nehari problem to the four block problem from theoretical developments to practical issues. The major tools used are similarity transformation the chain scattering approach and  $J$  spectral factorization. Self contained Robust Control of Time delay Systems will interest control theorists and mathematicians working with time delay systems. Its methodical approach will be of value to graduates studying general robust control theory or its applications in time delay systems.

Stability, Control, and Computation for Time-Delay Systems Wim Michiels, Silviu-Iulian Niculescu, 2014-12-11 Time delays are important components of many systems in for instance engineering physics economics and the life sciences because the transfer of material energy and information is usually not instantaneous. Time delays may appear as computation and communication lags they model transport phenomena and heredity and they arise as feedback delays in control loops. This monograph addresses the problem of stability analysis stabilization and robust fixed order control of dynamical systems subject to delays including both retarded and neutral type systems. Within the eigenvalue based framework an overall

solution is given to the stability analysis stabilization and robust control design problem using both analytical methods and numerical algorithms and applicable to a broad class of linear time delay systems In this revised edition the authors make the leap from stabilization to the design of robust and optimal controllers and from retarded type to neutral type delay systems thus enlarging the scope of the book within control include new state of the art material on numerical methods and algorithms to broaden the book's focus and to reach additional research communities in particular numerical linear algebra and numerical optimization and increase the number and range of applications to better illustrate the effectiveness and generality of their approach

**Semi-Discretization for Time-Delay Systems** Tamás Insperger, Gábor Stépán, 2011-07-15 This book presents the recently introduced and already widely referred semi discretization method for the stability analysis of delayed dynamical systems Delay differential equations often come up in different fields of engineering like feedback control systems machine tool vibrations balancing stabilization with reflex delay The behavior of such systems is often counter intuitive and closed form analytical formulas can rarely be given even for the linear stability conditions If parametric excitation is coupled with the delay effect then the governing equation is a delay differential equation with time periodic coefficients and the stability properties are even more intriguing The semi discretization method is a simple but efficient method that is based on the discretization with respect to the delayed term and the periodic coefficients only The method can effectively be used to construct stability diagrams in the space of system parameters

**Stability and Stabilization of Time-Delay Systems** Wim Michiels, Silviu-Iulian Niculescu, 2007-01-01 An overall solution to the robust stability analysis and stabilisation problem of linear time delay systems

Truncated Predictor Feedback for Time-Delay Systems Bin Zhou, 2014-05-29 This book provides a systematic approach to the design of predictor based controllers for time varying linear systems with either time varying input or state delays Differently from those traditional predictor based controllers which are infinite dimensional static feedback laws and may cause difficulties in their practical implementation this book develops a truncated predictor feedback TPF which involves only finite dimensional static state feedback Features and topics A novel approach referred to as truncated predictor feedback for the stabilization of time varying time delay systems in both the continuous time setting and the discrete time setting is built systematically Semi global and global stabilization problems of linear time delay systems subject to either magnitude saturation or energy constraints are solved in a systematic manner Both stabilization of a single system and consensus of a group of systems multi agent systems are treated in a unified manner by applying the truncated predictor feedback and predictor feedback The properties of the solutions to a class of parametric differential and difference Lyapunov matrix equations are presented in detail Detailed numerical examples and applications to the spacecraft rendezvous and formation flying problems are provided to demonstrate the usefulness of the presented theoretical results This book can be a useful resource for the researchers engineers and graduate students in the fields of control applied mathematics mechanical engineering electrical engineering and aerospace engineering

Time Delay

Systems: Methods, Applications and New Trends Rifat Sipahi,Tomas Vyhlídal,Silviu-Iulian Niculescu,Pierdomenico Pepe,2012-02-24 This volume is concerned with the control and dynamics of time delay systems a research field with at least six decade long history that has been very active especially in the past two decades In parallel to the new challenges emerging from engineering physics mathematics and economics the volume covers several new directions including topology induced stability large scale interconnected systems roles of networks in stability and new trends in predictor based control and consensus dynamics The associated applications problems are described by highly complex models and require solving inverse problems as well as the development of new theories mathematical tools numerically tractable algorithms for real time control The volume which is targeted to present these developments in this rapidly evolving field captures a careful selection of the most recent papers contributed by experts and collected under five parts i Methodology From Retarded to Neutral Continuous Delay Models ii Systems Signals and Applications iii Numerical Methods iv Predictor based Control and Compensation and v Networked Control Systems and Multi agent Systems     Applications of Time Delay Systems John Chiasson,Jean Jacques Loiseau,2007-02-08 This book provides an update of the latest research in control of time delay systems and applications by world leading experts It will appeal to engineers researchers and students in Control     Control Strategy for Time-Delay Systems Mohammad-Hassan Khooban,Tomislav Dragicevic,2020-11-21 Control Strategy for Time Delay Systems Part I Concepts and Theories covers all the important features of real world practical applications which will be valuable to practicing engineers and specialists especially given that delays are present in 99% of industrial processes The book presents the views of the editors on promising research directions and future industrial applications in this area Although the fundamentals of time delay systems are discussed the book focuses on the advanced modeling and control of such systems and will provide the analysis and test or simulation results of nearly every technique described For this purpose highly complex models are introduced to describe the mentioned new applications which are characterized by time varying delays with intermittent and stochastic nature several types of nonlinearities and the presence of different time scales Researchers practitioners and PhD students will gain insights into the prevailing trends in design and operation of real time control systems reviewing the shortcomings and future developments concerning practical system issues such as standardization protection and design Presents an overview of the most recent trends for time delay systems Covers the important features of the real world practical applications that can be valuable to practicing engineers and specialists Provides analysis and simulations results of the techniques described in the book     **Time-delay Systems** Sun Yi,Patrick William Nelson,Ali Galip Ulsoy,2010 This book comprehensively presents a recently developed novel methodology for analysis and control of time delay systems Time delays frequently occurs in engineering and science Such time delays can cause problems e g instability and limit the achievable performance of control systems The concise and self contained volume uses the Lambert W function to obtain solutions to time delay systems represented by delay differential equations

Subsequently the solutions are used to analyze essential system properties and to design controllers precisely and effectively

*Nonlinear Control Under Nonconstant Delays* Nikolaos Bekiaris-Liberis, Miroslav Krstic, 2013-09-25 The authors have developed a methodology for control of nonlinear systems in the presence of long delays with large and rapid variation in the actuation or sensing path or in the presence of long delays affecting the internal state of a system In addition to control synthesis they introduce tools to quantify the performance and the robustness properties of the designs provided in the book The book is based on the concept of predictor feedback and infinite dimensional backstepping transformation for linear systems and the authors guide the reader from the basic ideas of the concept with constant delays only on the input all the way through to nonlinear systems with state dependent delays on the input as well as on system states Readers will find the book useful because the authors provide elegant and systematic treatments of long standing problems in delay systems such as systems with state dependent delays that arise in many applications In addition the authors give all control designs by explicit formulae making the book especially useful for engineers who have faced delay related challenges and are concerned with actual implementations and they accompany all control designs with Lyapunov based analysis for establishing stability and performance guarantees

Delay Compensation for Nonlinear, Adaptive, and PDE Systems Miroslav Krstic, 2010-01-23 Shedding light on new opportunities in predictor feedback this book significantly broadens the set of techniques available to a mathematician or engineer working on delay systems It is a collection of tools and techniques that make predictor feedback ideas applicable to nonlinear systems systems modeled by PDEs systems with highly uncertain or completely unknown input output delays and systems whose actuator or sensor dynamics are modeled by more general hyperbolic or parabolic PDEs rather than by pure delay Replete with examples Delay Compensation for Nonlinear Adaptive and PDE Systems is an excellent reference guide for graduate students researchers and professionals in mathematics systems control as well as chemical mechanical electrical computer aerospace and civil structural engineering Parts of the book may be used in graduate courses on general distributed parameter systems linear delay systems PDEs nonlinear control state estimator and observers adaptive control robust control or linear time varying systems

**Predictor Feedback for Delay Systems: Implementations and Approximations** Iasson Karafyllis, Miroslav Krstic, 2017-03-06 This monograph bridges the gap between the nonlinear predictor as a concept and as a practical tool presenting a complete theory of the application of predictor feedback to time invariant uncertain systems with constant input delays and or measurement delays It supplies several methods for generating the necessary real time solutions to the systems nonlinear differential equations which the authors refer to as approximate predictors Predictor feedback for linear time invariant LTI systems is presented in Part I to provide a solid foundation on the necessary concepts as LTI systems pose fewer technical difficulties than nonlinear systems Part II extends all of the concepts to nonlinear time invariant systems Finally Part III explores extensions of predictor feedback to systems described by integral delay equations and to discrete time systems The book s core is the design of

control and observer algorithms with which global stabilization guaranteed in the previous literature with idealized but non implementable predictors is preserved with approximate predictors developed in the book An applications driven engineer will find a large number of explicit formulae which are given throughout the book to assist in the application of the theory to a variety of control problems A mathematician will find sophisticated new proof techniques which are developed for the purpose of providing global stability guarantees for the nonlinear infinite dimensional delay system under feedback laws employing practically implementable approximate predictors Researchers working on global stabilization problems for time delay systems will find this monograph to be a helpful summary of the state of the art while graduate students in the broad field of systems and control will advance their skills in nonlinear control design and the analysis of nonlinear delay systems

**Nonlinear Systems** Nathan van de Wouw,Erjen Lefeber,Ines Lopez Arteaga,2016-07-07 This treatment of modern topics related to the control of nonlinear systems is a collection of contributions celebrating the work of Professor Henk Nijmeijer and honoring his 60th birthday It addresses several topics that have been the core of Professor Nijmeijer s work namely the control of nonlinear systems geometric control theory synchronization coordinated control convergent systems and the control of underactuated systems The book presents recent advances in these areas contributed by leading international researchers in systems and control In addition to the theoretical questions treated in the text particular attention is paid to a number of applications including mobile robotics marine vehicles neural dynamics and mechanical systems generally This volume provides a broad picture of the analysis and control of nonlinear systems for scientists and engineers with an interest in the interdisciplinary field of systems and control theory The reader will benefit from the expert participants ideas on important open problems with contributions that represent the state of the art in nonlinear control **Limits of Stability**

**and Stabilization of Time-Delay Systems** Jing Zhu,Tian Qi,Dan Ma,Jie Chen,2018-02-05 This authored monograph presents a study on fundamental limits and robustness of stability and stabilization of time delay systems with an emphasis on time varying delay robust stabilization and newly emerged areas such as networked control and multi agent systems The authors systematically develop an operator theoretic approach that departs from both the traditional algebraic approach and the currently pervasive LMI solution methods This approach is built on the classical small gain theorem which enables the author to draw upon powerful tools and techniques from robust control theory The book contains motivating examples and presents mathematical key facts that are required in the subsequent sections The target audience primarily comprises researchers and professionals in the field of control theory but the book may also be beneficial for graduate students alike

**Introduction to Time-Delay Systems** Emilia Fridman,2014-09-02 The beginning of the 21st century can be characterized as the time delay boom leading to numerous important results The purpose of this book is two fold to familiarize the non expert reader with time delay systems and to provide a systematic treatment of modern ideas and techniques for experts This book is based on the course Introduction to time delay systems for graduate students in



Engineering and Applied Mathematics that the author taught in Tel Aviv University in 2011 2012 and 2012 2013 academic years The sufficient background to follow most of the material are the undergraduate courses in mathematics and an introduction to control The book leads the reader from some basic classical results on time delay systems to recent developments on Lyapunov based analysis and design with applications to the hot topics of sampled data and network based control The objective is to provide useful tools that will allow the reader not only to apply the existing methods but also to develop new ones It should be of interest for researchers working in the field for graduate students in engineering and applied mathematics and for practicing engineers It may also be used as a textbook for a graduate course on time delay systems

**Recent Results on Nonlinear Delay Control Systems** Iasson Karafyllis, Michael Malisoff, Frederic Mazenc, Pepe Pierdomenico, 2015-07-15 This volume collects recent advances in nonlinear delay systems with an emphasis on constructive generalized Lyapunov and predictive approaches that certify stability properties The book is written by experts in the field and includes two chapters by Miroslav Krstic to whom this volume is dedicated This volume is suitable for all researchers in mathematics and engineering who deal with nonlinear delay control problems and students who would like to understand the current state of the art in the control of nonlinear delay systems

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