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Control of Hybrid Systems Affected by Time Delay with Application in Haptic Rendering

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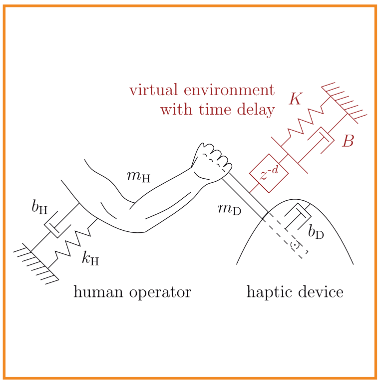

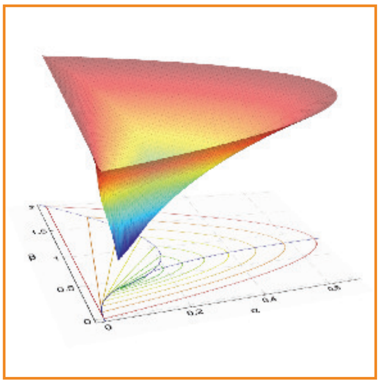

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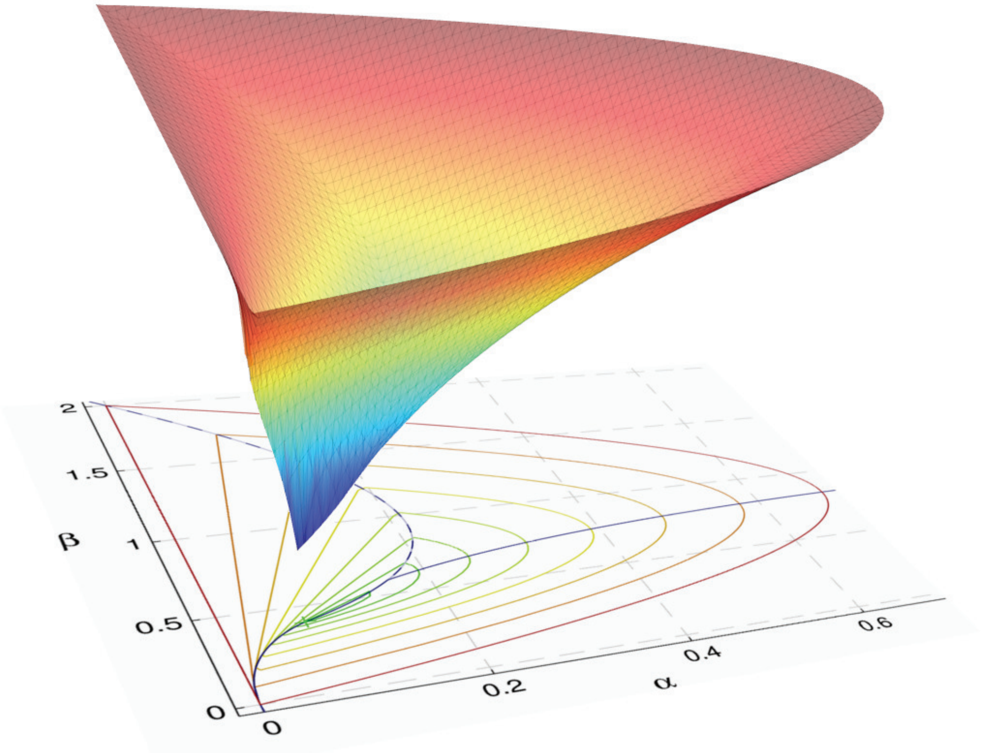
Control of Hybrid Systems Affected by Time Delay with Application in Haptic Rendering

Von der Fakultät für Maschinenbau
der Gottfried Wilhelm Leibniz Universität Hannover
zur Erlangung des akademischen Grades
Doktor-Ingenieur
genehmigte Dissertation

von

Dipl.-Ing. Thomas Hulin



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Preface

Interacting with a virtual environment without perceiving haptic feedback is like eating without smelling the delicious fragrance of the food or watching a movie without hearing its impressive sound effects. Researching on haptic feedback has been my main research interest in the past years, since I started my work as a young researcher at the Institute of Robotics and Mechatronics. This thesis summarizes important results of my research on haptic control carried out at the Institute of Robotics and Mechatronics at the DLR (German Aerospace Center). I have already published parts of this work within several conference and journal papers and the present thesis contains text passages from these publications. The introductory sections of the respective chapters contain appropriate references accordingly.

It is important to me to mention that the findings of my research do not only apply to haptic systems but in fact to a wide variety of physical systems. This is mainly due to electromechanical analogies [13] and the analytical representation of the investigated hybrid control system. Hence, I hope that my findings will also inspire and advance the research in domains other than haptics. To this end, I tried to present the results as clear as possible in an understandable language with numerous meaningful figures, and I want to motivate other researchers to also put emphasis on a clear and comprehensible form of presentation of their research activities.

A lot of people supported me in conducting my research and made this thesis possible. In particular, I would like to express my gratitude to the following people for their valuable and constructive support. First of all, I would like to thank Professor Gerhard Hirzinger, the former head of the institute, who largely founded this great institute and who managed to create an amazingly inspiring working atmosphere. My particular thanks go also to Professor Alin Albu-Schäffer, the head of the DLR's Institute of Robotics and Mechatronics, who understands well how to motivate his colleagues in publishing their research activities and writing doctoral theses. Christian Ott, the head of the department for Analysis and Control of Advanced Robotic Systems, created the freedom for me to work on my research topics and to finalize the thesis. It is a great privilege to work in this institute and in this research department.

I want to thank Professor Jürgen Ackermann and Naim Bajcinca, who introduced me into the fascinating field of parameter space control design during my diploma thesis under their supervision. I have learned a lot during these few months of work and, more importantly, the interest in this topic has never left me since. Professor Tobias Ortmaier deserves my special thanks for supervising my doctoral studies and providing valuable advices for improving the thesis.

I want to express my particular gratitude to Carsten Preusche for establishing the research group for telepresence and virtual reality, of which I have been a member since I started working at DLR. He inspired my work with a remarkable number of various ideas. My special thanks go also to the whole research group for telepresence and virtual reality, and all the colleagues that were involved in building the amazing robotic systems that I could use for conducting my research work.

I gratefully acknowledge the fruitful and constructive collaboration with Bernhard Vodermayer in the international research project STAMAS. My sincere thanks also go to my office mates Joseph Reill, Andreas Tobergte, and Phillip Schmidt, who often had to listen to my desperation and who encouraged me in finalizing my thesis. I also thank all my students in supporting me in my research activities. The reviewers and editors of my scientific publications also deserve my gratitude, as they provided valuable input and excellent suggestions for improvements.

My special thanks go to Jorge Juan Gil, who shared with me his extensive experience and knowledge in the field of stable haptic control and who get never tired to discuss on control issues. I have learned a lot from him during the six months that he was visiting our institute as a guest scientist, and also afterwards during numerous short visits and intense discussions.

There are three persons to whom I want to express my sincerest gratitude: Philipp Kremer, Katharina Hertkorn, and Mikel Sagardia, who proofread this thesis and also motivated and pushed me to finalize it. They had invested hours of their time and I sincerely appreciate their excellent ideas and comments. Also, my grateful thanks go to Anja Hellings and Phillip Schmidt for proofreading parts of this thesis.

I want to express my gratitude to the VR-Lab of the Volkswagen AG, which funded a research project on haptic assembly simulations. I also acknowledge the support from the EU for funding three research projects that I have worked on, in particular ENACTIVE (IST-2004-002114), SKILLS (FP6-IST-035005), and STAMAS (Project reference: 312815). Finally, I would like to thank the reader in advance for taking the time to read this thesis and I am convinced that the time spent is a worthwhile investment.

Oberpfaffenhofen, January 2017 Thomas Hulin

The pictures on the cover page show (i) the haptic device HUG that was used for the experiments (photo: DLR, CC-BY 3.0), (ii) the investigated model, and (iii) a three-dimensional illustration of the left contour plot of Fig. 5.2. The lower tip of this three dimensional-shape is the optimum point with respect to the pole-based settling time.

Abstract

Haptic rendering denotes the process of computing and displaying forces from a virtual environment to a human operator via a haptic device. From the control point of view, the haptic system comprising virtual environment, haptic device, and human operator is a hybrid control system that contains both discrete- and continuous-time elements. Discrete-time sampling as well as time delay that is typically present in such haptic systems may lead to unstable behavior.

This thesis investigates stability, passivity, and control design of such hybrid system. Its primary goal is to close some of the existing lacks in the current state of research, in particular to analyze the influence of the human operator on a haptic system behavior, to investigate the precise effect of delay and discrete-time sampling, and to introduce optimal control methods to the field of haptic rendering. A unique characteristic of the presented approach is the exact combination of discrete- and continuous-time elements, while taking into account time delay and user dynamics.

A linear stability analysis is presented to determine the stability boundaries of the haptic system and to investigate the influence of both delay and human operator. This analysis leads to the definition of normalized dimensionless parameters greatly simplifying calculations and presentation of results. The analysis reveals that the human operator modeled as mass-spring-damper system has a stabilizing effect, which is mainly constituted by its mass contribution. For small parameter values of the virtual environment, the relationship between the parameters may be approximated by a linear stability condition.

Passivity is analyzed by enhancing an existing passivity approach towards delayed haptic systems. The influence of the system parameters on passivity is completely different than for stability. For realistic parameter values, passive regions result as small subregions of the stable regions, which emphasizes the fact that passivity is highly conservative with regard to stability. This is because passivity admits human arm stiffnesses that are orders of magnitudes higher than realistically feasible.

To analyze the performance of a haptic system, various optimization criteria are investigated that are either based on the system poles or on the transient response. Each of these criteria is based on a dimensionless performance measure resulting in cost maps and in optimal points that hold for any positive mass and sampling rate. A polynomial approximation function is found to predict the optimal performance of the haptic system in these optimal points under the influence of delay. This function leads to the formulation of an easy-to-remember rule of thumb for the optimal settling time.

The theoretical investigations are accompanied by a series of experiments on two different devices, a Novint Falcon and a DLR/KUKA light-weight robot. They exhibit a remarkable accordance to the theoretical results. The practical impact of this thesis on haptic rendering applications was already demonstrated in haptic assembly simulations and haptically supported training. In addition, the theoretical results lead to design guidelines of haptic devices and provide the theoretical basis for future psychophysical studies.

Keywords: haptic rendering, time delay, stabililty analysis, passivity analysis, optimal control

Kurzfassung

Titel der Arbeit: Regelung totzeitbehafteter hybrider Systeme mit Anwendung für haptisches Rendern

Haptisches Rendern beschreibt die Berechnung von Kräften aus der virtuellen Welt und deren Darstellung an den Menschen über ein haptisches Gerät. Aus regelungstechnischer Sicht ist das haptische System bestehend aus virtueller Umgebung, haptischem Gerät und dem Menschen ein hybrides System, das sowohl zeitdiskrete als auch zeitkontinuierliche Elemente enthält. Die zeitdiskrete Abtastung sowie eine zusätzliche Totzeit, die typischerweise in solchen haptischen Systemen vorhanden ist, können zu einem instabilen Systemverhalten führen.

Diese Dissertationsschrift untersucht Stabilität, Passivität und den Reglerentwurf für solche hybriden Systeme. Das primäre Ziel dieser Arbeit ist es einige grundlegende Lücken im Stand der Forschung auf diesem Gebiet zu schließen. Im einzelnen wird der Einfluss des Menschen auf das Verhalten haptischer Systeme analysiert, die genaue Auswirkung von Totzeit und zeitdiskreter Abtastung untersucht und Methoden der optimalen Regelung in das Gebiet des haptischen Renderns eingeführt. Ein Alleinstellungsmerkmal des vorgestellten Ansatzes ist die exakte Kombination von zeitdiskreten und -kontinuierlichen Elementen unter gleichzeitiger Berücksichtigung von Totzeit und der Dynamik des Benutzers.

In einer linearen Stabilitätsanalyse werden die Stabilitätsgrenzen des haptischen Systems bestimmt und untersucht, wie sie sich durch die Totzeit und den Benutzer verändern. Die Analyse führt zu normierten, dimensionslosen Parametern, mit denen sich die Berechnungen stark vereinfachen lassen und die eine klare Präsentation der Ergebnisse ermöglichen. Sie offenbart auch, dass der Mensch, als Masse-Feder-Dämpfer System modelliert, stabilisierend auf das haptische System wirkt, was hauptsächlich an der zusätzlich eingebrachten Trägheit liegt. Für kleine Parameterwerte der virtuellen Wand kann das Verhältnis zwischen den Parametern durch eine lineare Stabilitätsbedingung angenähert werden.

Passivität wird unter Verwendung eines existierenden Passivitätsansatzes für haptische Systeme analysiert, der dazu bezüglich Totzeiten verallgemeinert wird. Es zeigt sich, dass sich der Einfluss der Systemparameter auf Passivität strukturell von dem für Stabilität unterscheidet. Für realistische Parameterwerte resultieren darüber hinaus die passiven Parametergebiete als Teile der stabilen Gebiete. Dies unterstreicht die Tatsache, dass Passivität stark konservativ bezüglich Stabilität ist. Der Grund dafür liegt in dem von der Passivitätsanalyse betrachteten Steifigkeitsbereich des menschlichen

Arms, der realistische Werte um Größenordnungen übersteigt.

Die Performanz haptischer Systeme wird anhand verschiedenartiger Optimierungskriterien untersucht, die entweder auf der Lage der Systempole oder auf dem Einschwingverhalten basieren. Für jedes dieser Kriterien wird ein dimensionsloses Performanzmaß eingeführt, mit welchem Kostenkarten und optimale Punkte berechnet werden können, die unabhängig von der Masse und der Abtastrate sind. Mit Hilfe einer polynomischen Approximationsfunktion lässt sich die optimale Performanz des haptischen Systems unter dem Einfluss der Totzeit vorhersagen. Diese Funktion führt außerdem zu einer leicht zu merkenden Faustregel für die optimale Einschwingzeit.

Die theoretischen Untersuchungen werden von einer Reihe an Experimenten an zwei unterschiedlichen Geräten begleitet, einem Novint Falcon und einem DLR/KUKA Leichtbauroboter. Sie weisen bemerkenswerte Übereinstimmungen zu den theoretischen Ergebnissen auf. Der praktische Nutzen der in dieser Dissertationsschrift neu vorgestellten Erkenntnisse konnte bereits erfolgreich in zwei Anwendungen demonstriert werden, in einer haptischen Einbausimulation und in haptisch unterstütztem Training. Darüber hinaus führen die theoretischen Ergebnisse zu Gestaltungsrichtlinien für haptische Geräte und liefern die theoretische Grundlage für zukünftige psychophysische Studien.

Schlagworte: haptisches Rendern, Totzeit, Stabilitätsanalyse, Passivitätsanalyse, optimale Regelung

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Notations

List of Abbreviations

Table 1: Abbreviations

abbreviation	description
BIBO stability	bounded input-bounded output stability
CAD	computer-aided design
DLR	German Aerospace Center
DoF	degree of freedom
ISE	integral of the square of the error
ITSE	integral of time multiplied by the squared error
ISTSE	integral of squared time multiplied by the squared error
LWR	Light-Weight Robot
VR	virtual reality
ZOH	zero-order hold

List of Mathematical Abbreviations

Table 2: Mathematical abbreviations

operator	description
cos(.)	cosine function
deg(.)	degree of a polynomial
ln(.)	natural logarithm
max(.)	maximum of a set or function
min(.)	minimum of a set or function
sin(.)	sine function

Conventions

Throughout this dissertation, italic letters indicate scalars while vectors and matices are denoted by bold letters. Dots denote derivatives with respect to time t.

Table 3: Subscripts and superscripts

sub-/superscripts	description
x_D	parameter x associated with the haptic device
x_E	parameter x associated with an energy
x_F	parameter x associated with a force
x_H	parameter x associated with the human operator
x_k	parameter x at time instant $t = \mathrm{k} \cdot T$ with $\mathrm{k} \in \mathbb{N}_0$
x_max	maximum value of parameter x
x_obs	observed value of parameter x
x_opt	optimal value of parameter x
x_ov	parameter x associated with the relative overshoot
x_rot	parameter x for a rotational movement
x_settle	parameter x associated with system settling time
x_x	parameter x associated with a position
x_0	initial or specific value of parameter x
x_∞	abbreviation for $\lim_{t\to\infty} x(t)$
x^*	discrete-time sampled signal of a parameter x
O^step	optimization criterion based on the step response
O^impulse	optimization criterion based on the impulse response

List of Symbols

The following table summarizes the symbols that are used in this thesis. Their units are also given in the last column, where dashes (–) stand for dimensionless parameters and stars ($*$) marks ambiguous parameters units. The units for the rotational case are given in parentheses, if applicable.

Table 4: Symbols

symbol	description	unit
b	physical damping	Ns/m (Nms/rad)
B	virtual damping	Ns/m (Nms/rad)
c_i	substitution variable	–
C	cost function	–
d	delay factor	–
$\mathfrak{d}(.)$	Dirac delta function	–
e	Euler's number	–

E	energy	Nm
F	force	N
$\mathcal{F}(.)$	Fourier transform	*
g	slope of a function	–
$G_x(.)$	closed-loop transfer function with output parameter x	*
$H_x(.)$	open-loop transfer function with output parameter x	*
I	moment of inertia	$\mathrm{kg{\cdot}m^2}$
j	imaginary unit	–
k	physical stiffness	N/m (Nm/rad)
K	virtual stiffness	N/m (Nm/rad)
$l(.)$	function of a line	–
m	mass	kg
$n(.)$	polynomial in the numerator of a transfer function	*
O	optimization criterion	–
$p(.)$	characteristic polynomial of a transfer function	*
r	radius of a concentric circle in the complex z-plane	–
$\Re$	real part of a complex argument	*
s	Laplace variable	1/s
t	time	s
t_d	time delay	s
t_r	effective time delay	s
T	sampling period	s
$u(.)$	unit step function or Heaviside step function	–
w	weighting factor or exponent	–
x	position	m
z	Z-transform variable	–
$\mathcal{Z}$	Z-transform	*
α	normalized virtual stiffness	–
β	normalized virtual damping	–
γ	normalized physical stiffness	–
δ	normalized physical damping	–
ϵ	arbitrarily small positive quantity	*
ζ	system damping ratio	–
η	ratio of two parameters	–
Θ	joint angle	rad
κ	integer time index of discrete-time systems	–
ρ	relative error	–
τ	variable of integration representing time	s
$\boldsymbol{\tau}$	torque	Nm
χ	weighted position	N (Nm)
ω	angular frequency	rad/s
ω_{N}	Nyquist frequency	rad/s