Control of port-Hamiltonian systems

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Control of Port-Hamiltonian Systems: Observer Design and Alternate Passive Input-Output Pairs

The research described in this thesis was undertaken at the Johann Bernoulli Institute for Mathematics and Computer Science, University of Groningen, The Netherlands.

university of groningen

The research reported in this thesis is part of the research program of the Dutch Institute of Systems and Control (DISC). The author has successfully completed the educational program of the Graduate School DISC.

Printed by GrafiMedia, University of Groningen, The Netherlands.
The summary in dutch was done by Prof Arjan van der Schaft

ISBN (Book version): 978-90-367-4279-5
ISBN (Digital Version): 978-90-367-4280-1

RIJKSUNIVERSITEIT GRONINGEN

Control of Port-Hamiltonian systems: Observer Design and Alternate Passive Input-Output Pairs

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. F. Zwarts,
in het openbaar te verdedigen op
vrijdag 23 april 2010
om 16:15 uur

door

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geboren op 9 mei 1982
te Tiruchi, India

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ISBN: 978-90-367-4279-5

Acknowledgements

It has been (approximately with limit tending from the left hand side) four years of eventful grad life and I have reasons to be both happy and sad about its completion. However, let me keep my feelings aside and spend some time to thank all those people who have contributed in making my stay memorable and this thesis possible.

I would start by saying a few words about my advisor who is also one amongst the most pleasant and down-to-earth persons that I have come across. Dear Arjan, it has been a great pleasure to work under your supervision. I have been extremely benefitted by your in-depth knowledge on a broad spectrum of different topics related to systems theory and have always looked forward to those hourly insightful discussions with you. I should admit that I initially found your mentorship style of not pushing the PhD student too hard and giving him complete freedom and time to slowly explore his research interests, as a concept that is *too good to be true*! But, I did come to realize that (perhaps) there could be no better way to make the student become an independent researcher and I thank you whole heartedly for my current self. Research collaborations are always a unique experience *per se* for a PhD student and I thank you for allowing me to collaborate and publish papers with different research groups. Finally, a note of thanks for taking care of the Dutch summary of my thesis.

Paris has been my second home city during PhD and here I would like to acknowledge Prof Romeo Ortega and his PhD student Ioannis Sarras. I still have vivid memories of my first visit to Supelec in the September of 2007 when I was desperately on the lookout for a research breakthrough. The observer design problem got all three of us interested and then followed four to five months of interesting and fruitful discussions over the email which finally culminated in the IEEE paper. Dear Romeo, I thank you for your prompt responses over the emails which kept the momentum going and I admire your *killer instinct* approach towards solving a research problem. It was great working with you and a good learning experience for me. Dear Ioannis, you deserve a special mention in my thesis because the initial ideas came from our discussions on the inverted pendulum on cart example which was precisely the beginning. I thoroughly enjoyed the kind hospitality of yourself and Anna. Thanks to Dhruv, Fernando, Wissam, Michael and many others for the nice company at Supelec. I am surely going to miss those two hour long French lunch breaks (occasionally also supplemented by wine) and the informal talks we had on different topics.

London has always remained a dream city for many people from a tourist perspective and also to work / study there. I got a chance to visit London in January 2009 when Prof Alessandro Astolfi agreed to host me at the Imperial College. Then followed three intense weeks of hard work with 10-15 minutes of effective meeting every day. Dear Astolfi, apart from those crisp research discussions we had, working with you has helped me improve on two key aspects: efficiency and time management. My sincere thanks once again for all your time and guidance.

I would next like to acknowledge the members of my PhD reading committee, Prof Henk Nijmeijer, Prof Jacquelien Scherpen and Prof Romeo Ortega. My special thanks to Henk and Jacquelien for carefully spending time to read my thesis and providing detailed comments and suggestions for improvement.

Apart from research, the daily life of a PhD student revolves around the *much needed* coffee and tea breaks, lunch hours and the general social corners. In this regard, I would like to thank all my fellow PhD students for making *life outside research* interesting! The long list starts with my office mates Rosty and Florian with whom I have shared many a hearty laugh and the rest which includes Shaik, Harsh, Sijbo, Diego, Minh, Amit, Sasanka, Alef, Tudor, Thomas, Danny, Tano, Bas, Younas and many more. I would like to mention Prof Harry Trentelman, whose professional and competitive approach towards research has often been a good source of inspiration for me. On the other hand, his warm and friendly nature, together with his witty and humorous remarks and *not to forget* his great whistling tunes keeps the office very lively. Next, I would like to mention about a very socially interesting person, Kanat Camlibel who used to drop into our office at any given time of the day and engage us in a wide gamut of topics ranging from complicated mathematics to football to women! I would say that this person is a *connoisseur* of anything to everything. Dear Kanat, thanks for all the entertainment...$\ddot\smile$...I would thank Bayu for initiating the Journal club which has been a success on both, the research and social frontiers. I would thank Mijn Cao and Mirjam for useful discussions on optimization related problems. Dear Esmee, Ineke and Desiree, you have all been very helpful when it came to administrative tasks and paper work. Finally, the various conference trips (California, Mexico, Virginia, Budapest, Sienna) and the DISC summer schools are always going to be reminiscent.

Its now time to come to the real world, that is, *life outside the mathematics department*! I hardly knew any Indians when I arrived here in May 2006. It was then close to August and a small group of people enthusiastically pitched in to celebrate India's 60^{th} independence day in Groningen. That was my first acquaintance with the Indian group and in the same year, GISA (Groningen Indian Student Association) was formed which has since then been a big success. I would like to acknowledge all the people who were instrumental behind starting it and who have been involved in its various activities. The

GISA meetings were always great fun, a perfect ground for socialization and served as an appropriate starting point for me to make some good friends. The list goes this way.

Ranjeet and Subhadeep, the weekend get togethers with you guys along with roasted chicken and beer were just amazing! Shaik, you had been a good accommodative housemate despite of our occasional differences in opinions. And yes, I would give a $(10/10)$ for your culinary skills. Ratna and Kalyani, I always felt at home whenever I visited your place, mainly because of your warm and friendly nature. Hope our good friendship continues and I wish you all the best. Avinash, the one-on-one conversations we had on a couple of occasions including the night out at Sheffield were interesting and fun filled! I admire your endurance when faced with problems and would add that yourself and Shilpa are great hosts! Deepa and Anjli, it was fun to hang out with you people and the Barcelona trip will always remain memorable. Deepa, hats of to your dare devil nature towards life and big toast for all the wine, tea and coffee sessions we had together. Anjli, thanks for having been a good friend and, I enjoyed anchoring the Diwali game show with you. Thanks to Sriram, Raaj, Shirisha, Samta, Biswa, Kodanda, Madhuri, Divya, Ruchi, Tauqeer, Vinod, Das, Anil, Vinay, Hans, Chandra Mouli, Hari Subhramanium, Erusha, Prashant, Aradhana and many others. Additional thanks to Samta for proof reading the hindi summary of my thesis.

My mother has always been supportive on all the sane and insane decisions that I have made in life (including the decision of doing a PhD in mathematics..ॅ...) and I'm very lucky to have her. My sister Nithya and my bro-in-law Amit have guided me in many possible ways on both the personal and professional fronts. Thanks for all the pep talks we had..ॅ..It was great catching up with you guys in Atlanta and Boston.

My final word of thanks to all the people who have directly or indirectly played a role in making this thesis a possibility. I am not yet sure of my future coordinates in life but I am surely going to miss Groningen and the memoirs of my stay here will make me nostalgic for time to come.

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Notation

Symbol	Description	Page
∇	the partial differential operation	1
∇_x	the partial differential operation with respect to variable x	2
$\mathcal{C}$	a Casimir function	10
$\mathcal{L}$	the Lagrangian	18
C	matrix representing the Coriolis and centrifugal forces	18
H	the Hamiltonian	19
$\mathcal{X}$	the n-dimensional state space manifold	20
$T\mathcal{X}$	the tangent bundle	20
$T^*\mathcal{X}$	the co-tangent bundle	20
$\mathcal{F}$	the space of flow variables	22
$\mathcal{F}^*$	the space of effort variables	22
f	a flow vector	22
e	an effort vector	22
$\mathcal{D}$	a Dirac structure	22
$\mathcal{R}$	a Resistive structure	26
$\circ$	composition operator for Dirac and resistive structures	26
$[X, Y]$	standard Lie bracket of vector fields X and Y	35