University of California
Santa Barbara

Control under energy and time constraints

A dissertation submitted in partial satisfaction
of the requirements for the degree

Doctor of Philosophy
in
Electrical and Computer Engineering

by

Justin Payne Pearson

Committee in charge:

Professor João P. Hespanha, Chair
Professor Andrew R. Teel
Professor Jason R. Marden
Professor Amr El Abbadi

March 2018

The Dissertation of Justin Payne Pearson is approved.

Professor Andrew R. Teel

Professor Jason R. Marden

Professor Amr El Abbadi

Professor João P. Hespanha, Committee Chair

January 2018

Control under energy and time constraints

by

Justin Payne Pearson

To Jen.

Note: Joao gave me the following advice:

"Regarding the thesis, my main suggestion if to write a nice introduction that talks about state of the art and summarizes the key results. This allows the reader to easily pick and choose the chapter that he/she may find more interesting to explore further."

Acknowledgements

I'm very thankful to have met so many nice people during my graduate school career at UC Santa Barbara.

João Hespanha

João is the best

Andy Teel

Andy is so cool

Jason Marden

Jason is a neat guy

Amr El Abbadi

Professor El Abbadi is awesome

Funding Agencies

CCDC

Colleagues

Teachers

Staff

Family and Friends

Curriculum Vitæ
Justin Payne Pearson

Education

2018	Ph.D. in Electrical and Computer Engineering (Expected), University of California, Santa Barbara
2007	M.S. in Mechanical Engineering, Stanford University
2006	B.S. in Mechanical Engineering, University of California, Santa Barbara

Experience

2012 – 2017	Graduate Student Researcher, University of California, Santa Barbara
2008 – 2012	Controls Engineer, AeroVironment
2016	Instructor of Record, *COMP 150: Introduction to Object Oriented Programming*, California State University at Channel Islands
2015	Certificate in College and University Teaching, UCSB
2015	Mentor, Robotics internship, Institute for Collaborative Biotechnology, UCSB
2015	Instructor of Record, *ENGR 3: Introduction to Programming*, UCSB
2015	Mentor, School of Scientific Thought, Center for Science and Engineering Partnerships, UCSB
2014	Teaching Assistant, *ENGR 3: Introduction to Programming*, UCSB
2014	Teaching Assistant, *ECE 147C: Control System Design Project*, UCSB

Publications

A. Alanwar, F. M. Anwar, Y. Zhang, J. Pearson, J. Hespanha, M. B. Srivastava. "Cyclops: PRU Programming Framework for Precise Timing Applications." *Proc. of the 2017 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS)*, Aug. 2017.

J. Pearson, J. Hespanha, D. Liberzon. "Control with minimal cost-per-symbol encoding and quasi-optimality of event-based encoders." *IEEE Transactions on Automatic Control*, May 2017.

J. Pearson, J. Hespanha, D. Liberzon. "Quasi-optimality of event-based encoders." *Proc. of the 54th Conference on Decision and Control*, Dec. 2015.

J. Pearson, J. Hespanha, D. Liberzon. "Control with Minimum Communication Cost per Symbol." *Proc. of the 53nd Conference on Decision and Control*, Dec. 2014.

Abstract

Control under energy and time constraints

by

Justin Payne Pearson

The performance of a control system is often limited by constraints on timing, bandwidth, and energy. This dissertation explores the trade-offs between constraints on these resources, the control system performance, and the system to be controlled.

In this work we solve every problem ever.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Control systems are frequently hampered by constraints on resources like limits on bandwidth, energy, and processor speed.

This work explores the theoretical and practical trade-offs between these resources and control system performance. It consists of three chapters, each summarized next.

Control with Minimum Energy Per Symbol (Chapter 2)

Chapter 2 considers the problem of stabilizing a continuous-time linear time-invariant process subject to communication constraints. The basic setup is shown in Figure 1.1, in which a finite capacity communication channel connects the process sensors to the controller/actuator. An encoder at the sensor sends a symbol through the channel once per sampling time, and the controller determines the actuation signal based on the incoming stream of symbols. The question arises: what is the smallest channel average bit-rate for which a given process can be stabilized?

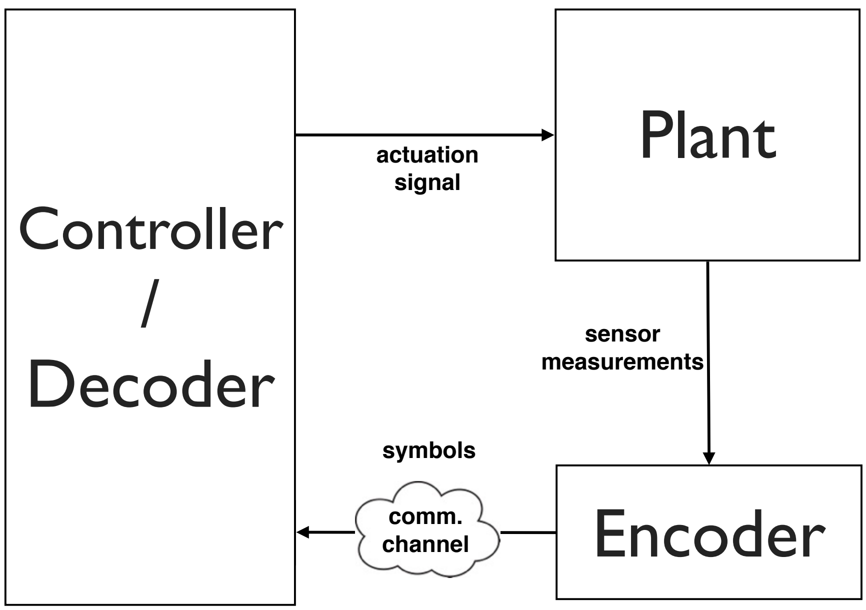

Figure 1.1: The limited-communication control setup. At sampling times, the encoder measures the process state and selects symbols from a finite alphabet to send to the decoder/controller. The decoder/controller constructs the actuation signal for the plant.

Prior work

Variants of the limited-communication environment in Figure 1.1 were also considered in [3, 4, 8, 11, 7, 6] and many other works.

...

Contributions

A starting point for the present work is the observation that an encoder can effectively save communication resources by occasionally not transmitting information — the absence of an explicitly transmitted symbol nevertheless conveys information. We formulate a framework to capture this by supposing that each symbol's transmission costs one unit of communication resources, except for one special free symbol that represents the absence of a transmission.

...

Quasi-optimality of Event-based control (Chapter 3)

In Chapter 3, we use the framework from Chapter 2 to analyze a family of event-based controllers.

...

Prior work

Recent results in event-based control [2, 1, 5, 10] indicate that an encoder can conserve communication resources by transmitting only on a “need-to-know” basis.

...

Contributions

In contrast to the optimal encoders introduced in Chapter 2, the proposed event-based encoders are easy to implement but not optimal. However, they are only slightly sub-optimal. Specifically, ...

Preemption-resistant control on a non-real-time operating system (Chapter 4)

The previous chapters indicate that networked control systems can benefit from precise timing by embedding information in the timing of messages. In Chapter 4, we turn our attention away from networked control systems and explore how precise timing can benefit a controller running (locally) on a non-real-time operating system.

...

Background and prior work

A program may execute nondeterministically for several reasons.

...

Contributions

The specific contribution of this chapter is a controller architecture that enables a controller to run on a non-real-time OS like Linux, yet maintain precise timing of the sensing and actuation despite OS preemption. This is achieved by performing the sensing and actuation on a dedicated “bare metal” microcontroller that in essence serves as a real-time I/O coprocessor; we refer to this as the “Real-Time Unit” (RTU).

...

Chapter 2

Control with Minimum Energy Per Symbol

Parts of this chapter come from [9]:

2017 IEEE. Reprinted, with permission, from J. Pearson, J. Hespanha, D. Liberzon. Control with minimal cost-per-symbol encoding and quasi-optimality of event-based encoders. IEEE Trans. on Automat. Contr., 62(5):2286–2301, May 2017.

In this chapter we consider the problem of stabilizing a continuous-time linear time-invariant process subject to communication constraints. We develop a framework for exploring the notion that the absence of communication nevertheless conveys information, yet it consumes no communication resources. We model the absence of a communication by appending a special “free” symbol to the set of symbols offered by the communications channel. Transmitting a normal symbol costs one unit of communications resources, but transmitting the free symbol costs no resources. This yields the notion of an encoder’s *average cost per symbol* — essentially the average fraction of non-free symbols sent by the encoder. We then develop a condition under which a stabilizing encoder with the smallest average cost per symbol may be designed.

This chapter is organized as follows.

...

2.1 Problem Statement

Consider a stabilizable linear time-invariant process

$$\dot{x} = Ax + Bu, \qquad x \in \mathbb{R}^n, u \in \mathbb{R}^m, \tag{2.1}$$

for which it is known that $x(0)$ belongs to a known bounded set $\mathcal{X}_0 \subset \mathbb{R}^n$.

2.2 Conclusion

In this chapter, we considered the problem of bounding the state of a continuous-time linear process under communication constraints. We considered constraints on both the channel average bit-rate and the encoding scheme's average cost per symbol. Our main contribution was a necessary and sufficient condition on the process and constraints for which a bounding encoder/decoder/controller exists.

...

Chapter 3

Quasi-optimality of Event-based control

Parts of this chapter come from [9]:

2017 IEEE. Reprinted, with permission, from J. Pearson, J. Hespanha, D. Liberzon. Control with minimal cost-per-symbol encoding and quasi-optimality of event-based encoders. IEEE Trans. on Automat. Contr., 62(5):2286–2301, May 2017.

In the last chapter we constructed an N-of-M encoding scheme that stabilizes process (2.1) provided that the bit-rate and average cost condition (**??**) holds. This scheme may be difficult to implement in practice if the encoder/decoder pair use a large number of codewords. In this section we present an *event-based* encoding scheme that is easy to implement and does not require storing a large set of codewords. Instead, it uses a library of only three symbols $\{-1, 0, 1\}$ and does not group them into codewords. The basic idea is to monitor in parallel each one-dimensional component of the error system, and as long as it stays inside a fixed interval, send the free symbol 0.

...

3.1 Definition of the event-based scheme

Unlike the scheme from Section **??**, this scheme differs in what symbols are sent and how the state estimate $\hat{x}$ is updated:

...

3.2 Conclusion

In this chapter examined an event-based controller based on the framework from Chapter 2. We proved its average bit-rate requirements were order-optimal with respect to the necessary and sufficient condition for stabilizability from Chapter 2. This supports the use of event-based controllers in limited-communication control schemes.

...

Chapter 4

Preemption-resistant control on a non-real-time operating system

In this chapter we consider the problem of stabilizing a system with unpredictable timing due to the controller running on a non-real-time operating system. We propose a method of implementing a discrete-time control algorithm on a non-real-time operating system so that the sensing and actuation occur at precise times, even if the OS preempts the control task.

4.1 Real-time I/O coprocessor concept

We first describe the architecture of our control and sensing/actuation scheme. Figure **??** illustrates the basic idea, which is that the controller and sensor/actuator execute on two separate processors.

...

4.2 Conclusion

In this chapter, we presented a controls architecture that pairs a real-time I/O coprocessor with a controller on a non-real-time operating system. The RTU enables sampling and actuation at precise times, even when the controller is preempted by the OS. This enables control designers to reap the benefits of an OS with minimal concern for the timing uncertainties associated with the OS task scheduler.

Appendix A

Proofs of lemmas

...

Bibliography

[1] K.J. Aström. Event based control. In *Analysis and Design of Nonlinear Control Systems: In Honor of Alberto Isidori*, page 127. Springer Verlag, 2007.

[2] K.J. Aström and B.M. Bernhardsson. Comparison of Riemann and Lebesgue sampling for first order stochastic systems. In *Decision and Control, 2002, Proceedings of the 41st IEEE Conference on*, volume 2, pages 2011 – 2016, dec. 2002.

[3] R.W. Brockett and D. Liberzon. Quantized feedback stabilization of linear systems. *Automatic Control, IEEE Transactions on*, 45(7):1279–1289, Jul 2000.

[4] João Pedro Hespanha, Antonio Ortega, and Lavanya Vasudevan. Towards the control of linear systems with minimum bit-rate. In *Proc. of the Int. Symp. on the Mathematical Theory of Networks and Syst.*, Aug. 2002.

[5] Jan Lunze and Daniel Lehmann. A state-feedback approach to event-based control. *Automatica*, 46(1):211 – 215, 2010.

[6] A. Matveev and A. Savkin. Multirate stabilization of linear multiple sensor systems via limited capacity communication channels. *SIAM Journal on Control and Optimization*, 44(2):584–617, 2005.

[7] Girish N. Nair and Robin J. Evans. Exponential stabilisability of finite-dimensional linear systems with limited data rates. *Automatica*, 39(4):585 – 593, 2003.

[8] G.N. Nair and R.J. Evans. Communication-limited stabilization of linear systems. In *Decision and Control, 2000. Proceedings of the 39th IEEE Conference on*, volume 1, pages 1005 –1010, 2000.

[9] Justin Pearson, João Pedro Hespanha, and Daniel Liberzon. Control with minimal cost-per-symbol encoding and quasi-optimality of event-based encoders. *IEEE Trans. on Automat. Contr.*, 62(5):2286–2301, May 2017.

[10] P. Tabuada. Event-triggered real-time scheduling of stabilizing control tasks. *Automatic Control, IEEE Transactions on*, 52(9):1680 –1685, sept. 2007.

[11] S. Tatikonda and S. Mitter. Control under communication constraints. *Automatic Control, IEEE Transactions on*, 49(7):1056 – 1068, july 2004.