Research Self-Assessment

João Hespanha

June 21, 2019

This overview is not exhaustive and, for each topic, I only provide 1-2 representative references. A full list of publications with citations can be found at https://scholar.google.com/citations?user=NAwmHTEAAAAJ.

1 Computer Vision

My work in the area of computer vision mostly explores geometric aspects of image formation. One of my early works is based on the observation that when we regard a grey-level image as a vector in a high dimensional space (one dimension per pixel), all images of the same three-dimensional surface under different lighting conditions lie in a 3-dimensional space that is characteristic of the surface. This observation enabled the design of face recognition algorithms that are robust with respect to changes in illumination and the paper below became one of the highest cited papers on face recognition.

> P. Belhumeur, J. P. Hespanha, and D. Kriegman, "Eigenfaces vs. Fisherfaces: Recognition using class specific linear projection," *IEEE Trans. on Pattern Analysis and Machine Intelligence,* Special Theme Issue on Face and Gesture Recognition, vol. 19, pp. 711–720, July 1997
> http://www.ece.ucsb.edu/~hespanha/published/faces.pdf

My work has also explored the fact that a camera under perspective projection can be modeled as a sensor whose output is a 1-dimensional subspace of $\mathbb{R}^3$. This observation has been used, e.g., for camera calibration and matching point images between multiple cameras. My own contribution has been on exploiting this particular structure of vision sensors in estimation and feedback control. In this area, I highlight the following paper that provides a state estimator for systems with linear dynamics with perspective output maps that resembles an extended Kalman filter, but is globally convergent. This work was subsequently extended for rigid body dynamics, integration of vision with other sensing modalities (including IMU sensors), measurement delays, etc.

> A. P. Aguiar and J. P. Hespanha, "Minimum-energy state estimation for systems with perspective outputs," *IEEE Trans. on Automat. Contr.*, vol. 51, pp. 226–241, Feb. 2006
> http://www.ece.ucsb.edu/~hespanha/published/minenergy-journal05.pdf

More papers in this area can be found at
http://web.ece.ucsb.edu/~hespanha/published/#14Vision-basedControlandEstimation.

2 Switching Adaptive Control

Adaptation and learning in feedback control is another area of interest for me, in particular in the used of switching instead of continuous tuning. This line of work was inspired by pioneering work of B. Mårtenson in 1985 and had been followed up by several others in the context of linear systems (Miller, Davidson, Kulkarni, Ramadge, Morse, Narendra, Mosca, Prandini, Campi, Safonov, etc.). However, the extension to nonlinear systems proved difficult because of the possibility of finite escape time. This problem was resolved by introducing a form of hysteresis-like switching that rapidly switches out misbehaving controllers and naturally slows down switching when the controllers produced desirable behavior. The following was one of the first papers that proposed a switching adaptive controller for nonlinear systems without a global Lipschitz requirement (or any other growth-rate constraint) and could be used for several systems for which adaptive control techniques based on continuous tuning did not seem easily applicable, e.g., because the unknown parameters do not enter in a linear fashion and/or dynamics that cannot be linearized through integrator backstepping.

> J. P. Hespanha and A. S. Morse, "Certainty equivalence implies detectability," *Syst. & Contr. Lett.*, vol. 36, pp. 1–13, Jan. 1999
> http://www.ece.ucsb.edu/~hespanha/published/rr.pdf

We (and others) have later found out that the same form of hysteresis switching could bring benefits for the control of linear processes with unmodeled dynamics, time-varying dynamics, disturbances, and measurement noise. The following paper follows this line of research and addresses linear time-varying process dynamics.

> P. Tesi, G. Battistelli, J. P. Hespanha, and E. Mosca, "Model-free adaptive switching control of time-varying plants," *IEEE Trans. on Automat. Contr.*, vol. 58, pp. 1208–1220, May 2013
> http://www.ece.ucsb.edu/~hespanha/published/FP-11-356_01_MS.pdf

More papers in this area can be found at
http://web.ece.ucsb.edu/~hespanha/published/#3SupervisoryControl

3 Switched and Hybrid Systems

My initial contributions in switched and hybrid systems were motivated by the stability analysis of switching adaptive control algorithms, but my interest in this area greatly outgrew this initial application. Two important papers are worth highlighting in this area: The following paper[1] contains a collection of results that can be viewed as extensions of LaSalle's Invariance Principle to switched linear systems. Using these results one can deduce asymptotic stability using multiple Lyapunov functions whose Lie derivatives are only negative semi-definite. Depending on the regularity assumptions placed on the switching signals, one may be able to conclude just asymptotic stability or (uniform) exponential stability. It is important to emphasize that the results obtained are not valid for general time-varying linear system as they explicitly explore the switching nature of the systems under consideration. In particular, the fact that they are "piecewise time-invariant." This unexpected discovery underscored the importance of studying this type of systems and understanding the specific properties that they exhibit.

[1] 2006 George S. Axelby Outstanding Paper Award

J. P. Hespanha, "Uniform stability of switched linear systems: Extensions of LaSalle's invariance principle," *IEEE Trans. on Automat. Contr.*, vol. 49, pp. 470–482, Apr. 2004
http://www.ece.ucsb.edu/~hespanha/published/hespanha-slasalle.pdf

Since it is not always possible to design feedback controllers for complex systems that perform satisfactorily under every operating condition, control systems' designers often construct several alternative complementary controllers and then switch among them based on the current operating conditions. However, switching between alternative controllers can lead to system instability and the resulting transients may prove to be more damaging than using just one low-performance controller. The following paper[2] showed that it is always possible to realize controller transfer functions with a structure that enables the switching among alternative controllers without running the risk of system instability. The result was unexpected because (i) it can be used for any number of controller transfer functions (ii) it often requires non-minimal realizations, and (iii) it introduces degrees of freedom in controller realizations that can be used to improve the transients caused by controller switching. This work opened the door for the integration of many feedback controllers with significant performance improvement.

J. P. Hespanha and A. S. Morse, "Switching between stabilizing controllers," *Automatica*, vol. 38, pp. 1905–1917, Nov. 2002
http://www.ece.ucsb.edu/~hespanha/published/single-journal.pdf

More papers in this area can be found at
http://www.ece.ucsb.edu/~hespanha/published/#1SwitchedandHybridSystems

4 Networked Control Systems

My work on networked control systems has been focused on feedback loops in which the communication between sensors, controllers, and actuators is mediated by a general purpose communication network, which introduced challenges like variable delays, quantization, finite communication bandwidth, missing information, lack of time synchronization, etc. The following paper address fundamental limitations on the ability to stabilize unstable systems with a finite communication bit rate, specialized to the wireless medium. In particular, it explored the idea that not sending a measurement (which in a wireless medium saves energy) provides by itself useful information that a controller can use to compute the actuation signal. One of the consequences of the results in this paper is that any unstable system can be stabilized with an arbitrarily small number of transmission per unit of time. This does not contradict previous results on the minimal data rate to stabilize an unstable system, once we take into account that not transmitting a measurement still provides information.

J. Pearson, J. P. Hespanha, and D. Liberzon, "Control with minimal cost-per-symbol encoding and quasi-optimality of event-based encoders," *IEEE Trans. on Automat. Contr.*, vol. 62, pp. 2286–2301, May 2017
http://www.ece.ucsb.edu/~hespanha/published/minenergy_nondiagA_twocol.pdf

The following paper addresses the robustness of a networked control system with respect to the lack of synchronization between clocks at the sensors, controllers, actuators. A key result in this

[2] Automatica Theory/Methodology best paper prize for the 2002-2004 period.

paper is that linear systems with a scalar state space are intrinsically more fragile with respect to timing errors than systems with a vector state. In essence, this is because multiple eigenvalues in the system dynamics provide timing information that can be used to “calibrate” different clocks. However, we show that such calibration is impossible (regardless of the algorithm used) when the dynamics have a single eigenvalue.

> K. Okano, M. Wakaiki, G. Yang, and J. P. Hespanha, “Stabilization of networked control systems under clock offsets and quantization,” *IEEE Trans. on Automat. Contr.*, vol. 63, pp. 1618–1633, June 2018
> `http://www.ece.ucsb.edu/~hespanha/published/root_final2.pdf`

More papers in this area can be found at
`http://www.ece.ucsb.edu/~hespanha/published/#4EmbeddedandNetworkedControlSystems`

5 Vehicle Navigation and Distributed Control

My initial interest on vehicle control was motivated by the use of switching control to address parametric model uncertainty, especially for vehicles with nonholonomic underactuated dynamics, and feedback based on vision sensors. However, to avoid repetition, I highlight here contributions unrelated to adaptive control and computer vision. Fundamental performance limitation in *reference tracking* associated with non-minimum phase zeros have been quantified with classical Bode integrals and later connected to cheap LQ optimal control. *Path following* appears to be a small variation to reference tracking in that one asks the vehicle to follow a given spatial path with a prescribed velocity, but without a timing law that specifies a precise map between points in space and time. The following paper was the first to show that path following does not share the LQ performance limitations of trajectory tracking. The solutions is constructive and the controller used in the paper uses switching to adjust the vehicle’s velocity.

> A. P. Aguiar, J. P. Hespanha, and P. V. Kokotović, “Performance limitations in reference-tracking and path-following for nonlinear systems,” *Automatica*, vol. 44, pp. 598–610, Mar. 2008
> `http://www.ece.ucsb.edu/~hespanha/published/autom05-limits.pdf`

The following is part of a series of papers that explores the connection between problems in distributed control and estimation and the analysis of electrical networks. In this line of work, we introduced the notion of a matrix-valued electrical resistance, that would arise in electrical circuits that satisfy the usual Kirckhoff laws, but with vector-valued currents and voltages. This notion of resistance is closely related to error covariance in several problems in estimation and stochastic control and its electrical interpretation provides a novel approach for analysis. This paper uses this approach in an estimation problem associated with a graph in which nodes are associated with the variables to estimate and edges with noisy “relative” measurements between variables. It shows that the estimation error grows with the size of the graph according to a scaling law that depends greatly on the geometric structure of the graph: for graphs that “resemble” 1D, 2D, or 3D lattices, the error grows linear, logarithm, or is bounded (respectively) with respect to the size of the graph.

> P. Barooah and J. P. Hespanha, “Error scaling laws for linear optimal estimation from relative measurements,” *IEEE Trans. on Inform. Theory*, vol. 55, pp. 5661–5673, Dec. 2009
> `http://www.ece.ucsb.edu/~hespanha/published/scaling08.pdf`

More papers in this area can be found at
http://www.ece.ucsb.edu/~hespanha/published/#8DistributedControlandMulti-agentSystems and
http://www.ece.ucsb.edu/~hespanha/published/#10VehicleControlandUnderactuatedSystems.

6 Game Theory

My work related to Game Theory has been motivated by two application areas: distributed control of multi-agent systems and computer/network security. The first paper that I highlight addresses the computational complexity of computing mixed Nash equilibrium in large-scale zero-sum games. The key contribution is a procedure by which a player can compute policies that, with a high confidence, are security policies against an adversary using randomized methods to explore the possible outcomes of the game. The paper provides surprisingly simple bounds on how many samples are needed to guarantee a desired level of confidence.

> S. D. Bopardikar, A. Borri, , J. P. Hespanha, M. Prandini, and M. D. D. Benedetto, "Randomized sampling for large zero-sum games," *Automatica*, vol. 49, May 2013
> http://www.ece.ucsb.edu/~hespanha/published/SSPFinal_v3.pdf

The following paper is motivated by problems in computer security and addresses the estimation of a random variable based on measurements that may have been corrupted by an opponent that wants to maximize our estimation error. The optimal estimator turns out to be a mixed policy and involves randomizing between two distinct voting-like policies, which is significantly different than what one would get from (non-adversarial) Bayesian inference.

> K. G. Vamvoudakis, J. P. Hespanha, B. Sinopoli, and Y. Mo, "Detection in adversarial environments," *IEEE Trans. on Automatic Control,* Special Issue on the Control of Cyber-Physical Systems, vol. 59, pp. 3209–3223, Dec. 2014
> http://www.ece.ucsb.edu/~hespanha/published/Sym6.pdf

More papers in this area can be found at http://www.ece.ucsb.edu/~hespanha/published/#12GameTheory