Stephen Boyd

MURI Report 2009-10

Embedded Convex Optimization.

This work concerns the use of convex optimization in high speed, real-time embedded systems, such as those found for signal processing, automatic control, estimation, resource allocation and decision making. While convex optimization is widely used on time scales of seconds or minutes, typically with a skilled engineer 'in the loop' supervising the optimization solver, it is less commonly seen for real-time applications.

A primary concern in real-time or embedded applications is the solver speed. We have addressed this for a variety of applications, including using hand-coded solvers, including software for high-speed model predictive control (MPC). Taking this work further, we have created an automatic code generator, CVXGEN, which takes a high-level description of a convex optimization problem and automatically generates compilable, library-free C code for a high speed solver.

This enables extensive (automatic) customization for the problem at hand, and makes solution much faster than existing methods. While with a hand-written solver, even small changes in problem specification necessitated painstaking redesign, even a complete change only requires the use of CVXGEN to automatically generate new code. This, combined with extremely fast solvers that carry out convex optimization on millisecond or even microsecond time scales, means that many new applications are possible, particularly for embedded systems.

A parallel branch of work investigates high-speed control algorithms for use in linear stochastic control. Here we evaluate a control-Lyapunov policy at each time step. For small problems the associated QP can be solved explicitly, but for larger problems on-line optimization is required. This means the control-Lyapunov policy is often considered excessively computationally intensive for real-time or embedded systems. We have demonstrated several techniques for accelerating evaluation of control-Lyapunov policies, including the pre-computation of certain quantities, and the use of performance bounds that enable much faster approximate policies to be used instead. The performance bounds are computed offline using linear matrix inequalities and semidefinite programming.

Stanford personnel

1. Professor Stephen Boyd

2. Jacob Mattingley, Ph.D. Candidate

3. Yang Wang, Ph.D. Candidate

Publications

"Code Generation for Receding Horizon Control", J. Mattingley, Y. Wang and S. Boyd, manuscript, May 2010.

"Real-Time Convex Optimization in Signal Processing", J. Mattingley and S. Boyd, IEEE Signal Processing Magazine, 27(3):50-61, May 2010.

"Approximate Dynamic Programming via Iterated Bellman Inequalities", Y. Wang and S. Boyd, manuscript, April 2010.

"Fast Model Predictive Control Using Online Optimization", Y. Wang and S. Boyd, IEEE Transactions on Control Systems Technology, 18(2):267-278, March 2010.

"Automatic Code Generation for Real-Time Convex Optimization", J. Mattingley and S. Boyd, chapter in Convex Optimization in Signal Processing and Communications, Y. Eldar and D. Palomar, Eds., Cambridge University Press, 2009.

"Fast Evaluation of Quadratic Control-Lyapunov Policy", Y. Wang and S. Boyd, manuscript, July 2009.

"Performance Bounds and Suboptimal Policies for Linear Stochastic Control via LMIs", Y. Wang and S. Boyd, manuscript, May 2009.

"Performance Bounds for Linear Stochastic Control", Y. Wang and S. Boyd, Systems and Control Letters, 58(3):178-182, March 2009.

Talks:

Stephen Boyd gave many presentations on real-time convex optimization, embedded optimization, and related topics, including a plenary lecture at ISMP to an audience over 1000. Jacob Mattingley gave a detailed presentations on code generation at UC Berkeley, including members of Edward Lee's group.

- Jacob Mattingley: Talk on "Embedded Convex Optimization" at UC Berkeley,

March 2, 2010.

- Stephen Boyd: Many talks, including Plenary on "Real-Time Embedded Convex

Optimization" at the International Symposium on Mathematical Programming,

Chicago, August 23-28, 2009. More than 1000 people present.