University of Freiburg

IMTEK – TEMPO Workshop on

Embedded Quadratic Programming (EQP 2014)

March 19, 2014, 9:00-17:00

Contents

I WELCOME

Dear Participants,

Welcome to Freiburg at the interactive IMTEK-TEMPO Workshop on Embedded Quadratic Programming!

Recent algorithmic progress made it possible that quadratic programming solvers can run on embedded platforms with kHz and MHz sampling rates. Aim of this small technical workshop is to bring together algorithm developers, with the aim to discuss recent algorithmic progress in a highly interactive format. The workshop has 17 participants and only 10 talks, and after each talk we reserved time for discussion. In the morning, we discuss mostly condensing based and dense QP solution algorithms, starting with an overview of QP solving approaches and and outline of the open source code qpOASES, new progress on condensing for sparsity exploitation, a new test suite for online QPs, and hardware and industrial implementation issues. Lunch will take place in the Solar Info Center just accross the street, at own cost. After lunch, we have a small demo of a balancing humanoid robot called Nao that uses qpOASES inside, and a lab tour to the HIGHWIND hangar 074. The three afternoon talks will focus completely on band structure exploiting QP solution approaches. A final panel discussion will have a focus on the input of the non-presenting participants and point out future directions for research. The scientific program of the workshop ends at 17:00. For those staying in Freiburg that want to join, we reserved a table in *Hausbrauerei Feierling* in the city center of Freiburg at 19:00.

The workshop is organized within the Department of Microsystems Engineering (IMTEK) at the University of Freiburg. Special thanks go to Christine Paasch for organizing all the arrangements of the workshop. Support by the Initial Training Network TEMPO (EU-FP7 Grant No 607957) and the ERC project HIGHWIND (EU-FP7 Grant No 259 166)) is gratefully acknowledged.

We wish all of you a pleasant day in Freiburg and we are looking forward to a hopefully exciting, interesting and inspiring workshop!

Moritz Diehl and Milan Vukov
Freiburg, March 2014

II Program overview

Program for Wednesday, March 19, 2014.

09:00	Introduction (**Moritz Diehl**)
09:10	qpOASES - Past, Present, and Future (**Hans Joachim Ferreau**)
09:40	Discussion
09:45	A Condensing and Factorization Algorithm with Quadratic Complexity (**Gianluca Frison**)
10:10	Discussion
10:15	The QP Solvers in the ACADO Code Generation Tool (**Milan Vukov**)
10:40	Discussion
10:45	Break
11:15	Proper Assessment of QP solvers for Model Predictive Control (**Dimitrios Kouzoupis**)
11:25	Discussion
11:30	Embedded MPC on a PLC Using a First-Order Method (**Giorgio Kufoalor**)
11:50	Discussion
11:55	Fast FPGA Prototyping for MPC Demo (**Andrea Suardi**)
12:15	Discussion
12:20	Status and Plans of EMBOTECH (**Juan Jerez**)
12:30	Discussion
12:45	Lunch in *Solar Info Center* (own cost)
14:00	Demo of Nao-Balancing Robot and Visit HIGHWIND Carousel (Building 074)
14:45	A sparse variant of qpOASES based on a symmetric indefinite factorization and Schur complement updates (**Christian Kirches**)
15:05	Discussion
15:10	A Parallel Quadratic Programming Method for Dynamic Optimization Problems (**Janick Frasch**)
15:35	Discussion
15:40	Break
16:10	Huge Quadratic Programming (**Ruediger Franke**)
16:35	Discussion
16:40	Wrap up panel discussion
17:00	End
19:00	Dinner at *Hausbrauerei Feierling* (own cost)

III ABSTRACTS

09:10-09:40	Hans Joachim Ferreau

qpOASES – Past, Present and Future

qpOASES is an open-source C/C++ software package which implements a parametric active-set method for use in model predictive control in a reliable and efficient way. Various interfaces to third-party software packages make it easy to use, even on embedded computer hardware. This talk briefly summarizes the development history of qpOASES, reviews past and current real-world applications of the code and sketches plans for future development.

09:45-10:10	Gianluca Frison

A Condensing and Factorization Algorithm with Quadratic Complexity

In this talk, we want to present an algorithm for condensing and factorization of the Hessian of the Linear-Quadratic Control Problem (LQCP). The algorithm exploits the special structure of the LQCP, to build and factorize the Hessian on-the-fly. The cost of the algorithm is quadratic in both the horizon length N and the number of states n_x, and while the cost of the classical Cholesky factorization of the condensed Hessian is cubic in N, and the cost of another recent condensing algorithm is cubic in n_x (2012, Axehill et. al.). Our algorithm shows a good performance for a wide range of problems sizes, a high-performance implementation of the algorithm can attain a large fraction of the peak performance on modern CPUs.

10:15-10:40	Milan Vukov

The QP Solvers in the ACADO Code Generation Tool

The ACADO code generation tool is a software framework within the ACADO toolkit (`www.acadotoolkit.org`) which allows export of customized and optimized C-code for optimal control problems (OCPs) solvers. Those solvers can be used in the context of nonlinear model predictive control (NMPC) and moving horizon estimation (MHE). An OCP is solved by means of the real-time iteration (RTI) scheme, where at each step a single SQP iteration is performed with full Newton step. At this stage, one quadratic problem QP is solved. This talk will give an overview of the QP solvers that can be coupled to the generated OCP solvers. Moreover, some synthetic benchmark results will be presented as well as experimental results coming from real-world applications.

11:15-11:25	Dimitrios Kouzoupis

Proper Assessment of QP solvers for Model Predictive Control

With model predictive control becoming a viable approach for advanced feedback control at very fast sampling times, a plethora of methods for solving quadratic programming problems on embedded computing hardware has been proposed. While most of these methods seem to be useful and superior to competing approaches on particular problem instances, very little effort has been put into a proper benchmarking on a non-trivial number of MPC problems.This talk presents a benchmarking suite that aims to fill in this gap by properly assessing state-of-the-art QP solvers on academic and real-world examples.

11:30-11:50	Giorgio Kufoalor

Embedded MPC on a PLC Using a First-Order Method

An embedded MPC based on the linear MPC module in SEPTIC (Statoil Estimation and Prediction Tool for Identification and Control) is developed and implemented on the ABB AC500 PLC. We used custom ANSI C code generation, problem size reduction methods, MPC structure preserving transformations, embedded real-time considerations, and a primal-dual first-order method that provides a fast and light QP solver obtained from the FiOrdOs code generator toolbox. Since the primal-dual first-order method proposed in this work is new in the control community, a comparison study with other state-of-the-art first-order methods is conducted to underline its potential. The embedded MPC performance was tested using hardware-in-the-loop simulation of Statoil's newly patented sub-sea compact separation process. The results show that a warm-start variant of the proposed first-order method outperforms a tailored interior-point method by a factor of 4 while occupying 40% less memory.

11:55-12:15	Andrea Suardi

Fast FPGA Prototyping for MPC Demo

Computation-intensive optimization algorithm have for a long time been carried out on CPU-based machines primarily because of their ease of use at the expense of compute speed and energy consumption. Today, new tools exist to make the designer's effort comparable for both CPU and FPGA based algorithm implementations. This hands-on tutorial aims to show how to use these new tools and will include step-by-step instructions on how to design and verify an FPGA-based Fast Gradient Algorithm.

12:20-12:30	Juan Jerez

Status and Plans of EMBOTECH

The choice of the most appropriate optimization algorithm for a particular optimal controller implementation depends on the problem structure, the type of constraints, and the computing platform that will implement the controller. Unfortunately, developing and testing different high-performance optimization codes is a highly time consuming process. We will introduce the new version of the code generation system FORCES, which automatically selects the most appropriate method and generates customized code for a range of target embedded platforms, including ARM, x86, AURIX and FPGAs.

14:45-15:05	Christian Kirches

A sparse variant of qpOASES based on a symmetric indefinite factorization and Schur complement updates

We present a recent extension of the popular active-set code for parametric quadratic programming qpOASES to QPs with sparse Hessian and constraint matrices. Our implementation is based on a symmetric indefinite factorization of an initial KKT matrix, provided by e.g. the MA27 solver. Schur complement updates are employed to efficiently update this factorization on active set exchanges. We give details on different linear algebra issues to be addressed within this approach, and report on computational experience with this new code when solving QPs from the CUTEr and Maros-Meszaros test sets.

15:10-15:35	Janick Frasch

A Parallel Quadratic Programming Method for Dynamic Optimization Problems

Quadratic programming problems (QPs) that arise from dynamic optimization problems typically exhibit a very particular structure. We address the ubiquitous case where these QPs are strictly convex and propose a dual Newton strategy that exploits the block-bandedness similarly to an interior-point method. Still, the proposed method features warmstarting capabilities of active-set methods. We give details for an efficient implementation, including tailored numerical linear algebra, step size computation, parallelization, and infeasibility handling. We prove convergence of the algorithm for the considered problem class. A numerical study based on the open-source implementation qpDUNES shows that the algorithm outperforms both well-established general purpose QP solvers as well as state-of-the-art tailored control QP solvers significantly on the considered benchmark problems.

16:10-16:35	Ruediger Franke

Huge Quadratic Programming

Huge Quadratic Programming (HQP) is a solver whose development started 20 years ago as a diploma thesis investigating the implementation of an Interior Point QP solver with sparse matrices. The software design as a framework in the C++ programming language allowed the continuous further development by adding new solver modules, for instance for the treatment of block-band structured problems arising in optimal control with vectors of dense matrices. Later on the solver was complemented with an interface to modeling and simulation languages, in particular to Modelica. This was crucial for industrial applications, enabling non-experts in mathematical programming to engineer optimization applications.

As of today HQP is running in the real-time control of many power plants all over the world. Exemplary applications include model predictive startup optimization, model predictive setpoint calculation and real-time optimization of the distribution of balancing power.

Further real-world applications of the software include the control of water canal systems and of boom cranes.

IV List of participants

Jonas Asprion, FPT Motorenforschung AG, Switzerland
Moritz Diehl, University of Freiburg – IMTEK, Germany
Hans Joachim Ferreau, ABB, Switzerland
Rüdiger Franke, ABB, Germany
Janick Frasch, University of Magdeburg, Germany
Gianluca Frison, Technical University of Denmark, Denmark
Dominic Gross, University of Kassel, Germany
Jean-Hubert Hours, EPFL, Switzerland
Juan Jerez, EMBOTECH & ETHZ, Switzerland
Christian Kirches, University of Heidelberg, Germany
Dimitrios Kouzoupis, ABB, Switzerland
Giorgio Kufoalor, Norwegian University of Science and Technology, Norway
Nikolce Murgovski, Chalmers University of Technology, Sweden
Magnus Nilsson, Chalmers University of Technology, Sweden
Giorgos Stathopoulos, EPFL, Switzerland
Andrea Suardi, Imperial College London, United Kingdom
Milan Vukov, KU Leuven, Belgium

V Space for notes

VI LOCATIONS AND PHONE NUMBERS

The workshop site is located at:

University of Freiburg
Georges-Koehler-Allee, Building 101
Room SR 02-016/18 (2^{nd} floor)

Phone numbers:

- Moritz Diehl: +49-152-22928584
- Christine Paasch: +49-176-98834570

Dinner Location (at 19:00):

Hausbrauerei Feierling
Gerberau 46
79098 Freiburg
Tel.: +49-761-243480