Final Report

Yutao Chen

September 28, 2017

Student Name: Yutao Chen

Cycle: XXX

Curriculum: Information and Communication Science and Technology (I.C.T)

Supervisor name: Alessandro Beghi

Thesis title (final): Efficient Nonlinearity Model Predictive Control: Algorithms and Applications

PART 1-COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

- Applied Linear Algebra
- Computational Inverse Problems
- Statistical Methods
- Applied Functional Analysis

Summer schools, short courses, tutorials

- Numerical Optimization Software Summer School, University of Freiburg, Germany, 07/2016
- International Graduate School on Control, M11, Padova, 03/2017

Seminars

- 23/03/2015: Walter Snoeys (*PH department, CERN, Geneva, Switzerland)*, "How chips helped discover the Higgs boson at CERN", Distinguish lecture
- 27/03/2015: Lorenzo Rosasco (*Universit di Genova, MIT)*, "Learning with Computational Regularization", DEI Seminars
- 20/04/2015: Keshav Pingali (*The University of Texas at Austin)*, "Kinetic Dependence Graphs", DEI Seminars

- 24/04/2015: Luigi Palopoli (*University of Trento)*, "When multimedia meets control: use of soft real–time techniques for control design", DEI Seminars
- 03/06/2015: Merouanne Debbah (*Huawei France R&D Center)*, "Mathematical Scientific Challenges of 5G", Distinguish lecture
- 17/06/2015: Michel Verhaegen (*University of Delft)*, "Nuclear Norm identification for lumped and distributed systems", DEI Seminars
- 18/06/2015: Rodolphe Sepulchre (*Dept. of Engineering, University of Cambridge, UK)*, "Do brains compute?", Distinguish lecture
- 07/07/2015: Davide Piovesan (*Gannon University (Pennsylvania, USA))*, "Human Arm Mechanics: from system identification to neural control ", DEI Seminars
- 17/07/2015: Nancy Amato (*Texas A&M University)*, "Hybrid Approaches for Synchrony and Memory for Parallel Graph Algorithms", DEI Seminars
- 25/09/2015: Pratap Pattnaik (*IBM)*, "BITCOIN, an attempt at a separation of money and state", Distinguish lecture
- 30/09/2015: Pierluigi Crescenzi (*Universita' di Firenze)*, "Fast and Simple Computation of Top-k Closeness Centralities", DEI Seminars
- 05/10/2015: Jun Miura (*Toyohashi University of Technology)*, "Autonomous Mobile Robot Research", DEI Seminars
- 22/10/2015: Ashraf Owis (*Universita' del Cairo)*, "Solving the Nonlinear Control Problem in Astrodynamics", Automatica Group Seminars
- 30/10/2015: Giulio Caravagna (*University of Edinburgh)*, "Algorithmic Methods to Infer the Evolutionary Trajectories in Cancer Progression", DEI Seminars
- 18/01/2016: Alessandro Abate (*University of Oxford)*, "Formal verification of complex control systems", DEI Seminars
- 31/03/16: Lucia Pallottino (*"E.Piaggio" Research Center and the Dipartimento di Ingegneria dell'Informazione)*, "The Walk-Man humanoid robot: whole-body loco-manipulation planning and control", DEI Seminars
- 13/04/16: Paolo Gargiulo (*Reykjavik University, Islanda)*, "The Integration of Computational Medical Modeling and 3D Rapid Prototyping with Pre-Surgical Planning",
- 27/04/16: Alexandr Aravkin (*University of Washington, Seattle)*, "Conjugate Interior Point Method for Large-Scale Problems",
- 02/05/16: Erica Bisesi (*University of Graz)*, "How does music expression depend on structure", DEI Seminars
- 18/05/16: Ujjwal Maulik (*Jadavpur University, Kolkata, India)*, "Single and Multiobjective clustering", Automatica Group Seminars
- 19/05/16: Domenico DAlessandro (*Iowa State University)*, "On Symmetries in Optimal Control: The KP problem and applications to Quantum Systems", DEI Seminars

- 20/05/16: Kim Listmann (*ABB, Ladenburg)*, "Interactive Control & Learning for Robots - What we need and why!", DEI Seminars
- 23/05/16: Luca Zaccarian (*LAAS-CNRS, Toulouse (France))*, "Static input allocation for reaction wheels desaturation using magnetorquers", DEI Seminars
- 06/06/16: Eli Upfal (*Brown University)*, "When is Big Data Sufficiently Big? When is it Too Big? Sample Complexity, Uniform Convergence, and Generalization Error", DEI Seminars
- 14/06/16: Oscar Pozzobon (*Qascom S.r.l., Italy)*, "Galileo Satellite Navigation System: Current status and research opportunities", DEI Seminars
- 21/06/16: Michael I. Jordan (*University of Berkeley)*, "Computational Thinking, Inferential Thinking and Data Science", DEI Seminars
- 01/07/16: Simone Montangero (*Ulm University)*, "Simulation and Control of Complex Quantum Systems", DEI Seminars
- 20/07/16: Subhrakanti Dey (*Uppsala University, Sweden)*, "Sensor Scheduling in Variance Based Event Triggered Estimation with Packet Drops", DEI Seminars
- 21/07/16: Enrico Lovisari (*Volvo Cars, Goteborg)*, "Traffic networks: modelling and control", DEI Seminars
- 13/09/16: Ralph Kennel (*TUM Technische Universität, München)*, "Predictive Control: the Poweful Method to Control Power coverters and Drives for the Future", DEI Seminars
- 29/09/16: Maurizio Corbetta (*Washington University School of Medicine St.Louis)*, "Networks: Brain, Health, and Society", DEI Seminars
- 19/10/2016: Pietro Andreani (*University of Lund)*, "Integrated Harmonic Oscillators", D EI SeminarsDEI Seminars
- 15/11/2016: Andrea Romanoni (*Politecnico di Milano)*, "Incremental Large-Scale Dense 3D Reconstruction", DEI Seminars
- 25/11/2016: Andrea Bisoffi (*University of Trento)*, "Global asymptotic stability of a PID control system with Coulomb friction", DEI Seminars
- 31/01/2017: Ana Garca Armada (*Universidad Carlos III de Madrid)*, "Non-coherent massive MIMO", DEI Seminars
- 28/02/2017: Sandro Zampieri (*University of Padova)*, "Information transmission in balanced neuronal networks: the role of matrix non-normality", DEI Seminars
- 02/03/2017: Carlo Cannistraci (*Technical University Dresden)*, "Machine learning and complex networks for precision and systems biomedicine", DEI Seminars
- 24/03/2017: Paris Koutris (*University of Wisconsin-Madison)*, "Pricing Relational Data with Formal Guarantees", DEI Seminars
- 05/04/2017: Simone Zaccaria (*Universit degli studi di Milano)*, "The Copy-Number Tree Mixture Deconvolution Problem", DEI Seminars

- 07/04/2017: Salvatore Anzalone (*Paris 8 University in Saint Denis)*, "Socially intelligent robots", DEI Seminars
- 13/04/2017: Paolo Baracca (*Nokia Bell Labs)*, "Interference mitigation and resource scheduling for mixed traffic types in dynamic TDD systems", DEI Seminars
- 03/05/2017: John Hauser (*University of Colorado at Boulder)*, "Trajectory Exploration for Aggressive Maneuvering", DEI Seminars
- 12/05/2017: Alberto Sangiovanni Vincentelli (*University of Berkeley)*, "Is Technology Transfer a Dream or a Reality?", Distinguish lecture
- 16/05/2017: Basilio Gentile (*ETH Zurich)*, "Distributed dynamics to achieve a location equilibrium", DEI Seminars
- 18/05/2017: Giulio Tononi (*University of Wisconsin, Madison)*, "Consciousness: From Theory to Practice", Distinguished Lecture
- 09/06/2017: Francesca Boem (*Laboratoire d'Automatique, EPFL, Switzerland)*, "Scalable Methods for Fault-tolerant Control of Large-Scale Systems", DEI Seminars
- 16/06/2017: Mattia Zorzi (*University of Padova)*, "The Harmonic Analysis of Kernel Functions", DEI Seminars
- 23/06/2017: Marco Todescato (*University of Padova)*, "Efficient Space/Time Learning: Gaussian Regression meets Kalman Filtering", DEI Seminars
- 17/07/2017: Marco Tognon (*Laboratory for Analysis and Architecture of Systems (LAAS), Tolouse)*, "Aerial Physical Interaction by Means of Cables or Bars: Modeling and Control of Tethered Aerial Vehicles ", DEI Seminars
- 21/07/2017: Reza Arghandeh (*Florida State University)*, "Fromm Data Mining to Knowledge Mining in Smart Infrastructure", DEI Seminars
- 22/09/2017: Chris Van Hoof (*Holts Centre/ IMEC, The Netherlands)*, "Personal Behavioral Technology-Wearables Can Become an Active Contributor to Your Wellbeing", Distinguished Lecture
- 28/09/2017: Jrgen Janek (*Institute of Physical Chemistry & Center for Materials Research (LaMa))*, "Energy Storage and the Rise of Electric Vehicles", DEI Seminars

Participation to International Conferences and Workshops

- The 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM 2017), July 3-7, 2017, Munich, Germany

Other learning activities

None

Mobility periods

None

PART 2-RESEARCH ACTIVITY

Efficient algorithms for fast NMPC using long prediction horizon

Only recently, fast implementations of NMPC are becoming necessary and popular, from benchmark systems like the Pendubot, to industry relevant systems like combustion engines, tethered airfoils, and electrical motor drives. Fast implementations of NMPC are particularly relevant when addressing real-time control of systems exhibiting features like fast dynamics, large dimension, and long prediction horizon, as in such situations the computational burden of the NMPC may limit the achievable control bandwidth. Intuitively, applying in real-time an NMPC controller with a long prediction horizon would lead to a better control performance. However, this comes at a cost of significantly increased on-line computational load, since the dimension of the on-line optimization problem and its complexity scales more than linearly with the prediction horizon.

Therefore, we particularly addresses fast NMPC algorithms for controlling continuous-time dynamic systems using a long prediction horizon. The starting point is to build a bridge between linear and nonlinear MPC using partial linearizations. The idea is that, within the prediction window, the predicted trajectories of the control systems can be partial linearized, i.e. being linearized only when it is considered highly nonlinear. As a result, a partial sensitivity updating scheme for RTI-based NMPC algorithms has been proposed in order to reduce computational cost for sensitivity evaluation. This scheme exploits the multi-stage feature of the optimization problem due to multiple shooting and performs a block-wise update of the constraint Jacobian, which contains linearizations of state trajectories in each shooting interval. We have defined a novel Curvature-like Measure of Nonlinearity (CMoN) and apply it to access the degree of nonlinearity of each shooting interval. Based on the CMoN, two updating logic have been developed that result in different numerical and control performance. The first logic updates a fixed number of sensitivities with largest CMoN values. The second one introduces a constant threshold for CMoN to distinguish linear and nonlinear shooting intervals. The proposed scheme is shown to be able to reduce computational cost while maintain numerical and control performance as close as possible to that of the standard RTI scheme.

The optimality and local convergence properties have been investigated using theories in parametric programming. The partial updated, inexact Jacobian is considered as a perturbation parameter and its effects on the optimality of the solution has been quantified. As a consequence, an advanced tuning strategy is developed which converts the tuning of the threshold to that of the distance to optimum, i.e. the distance between the solutions of inexact and exact Jacobian QP problems. When considered in the full SQP scenario, the local convergence of this advanced strategy has also been proved with a tunable convergence rate. Simulations studies and numerical examples have demonstrated the correctness of the theory.

In addition, partial condensing algorithms for QP problems subject to partial sensitivity update have been developed. These algorithms overcome the shortcoming that full condensing need to be re-performed after partial sensitivity update and are capable of reducing the computational cost for condensing. In particular, an algorithm called LPC-RTI is proposed which has a linear computational complexity in prediction horizon length. Numerical examples show that a speedup by a factor of 10

is possible.

Alternatively, the QP problems can be solved directly in sparse form. The famous alternating direction method of multipliers (ADMM) is employed for time-varying QP problems in the scenario of RTI. We show that the KKT system for computing the primal variable can be partly updated thanks to partial sensitivity updating. Computational cost reduction has been proved by comparing floating point operations (flops) with classical interior point methods.

Development of NMPC software

After decades of development, many open source MPC software or packages are available for simulation and experiment purposes. The most popular packages include MATLAB Model Predictive Control Toolbox and MPT3. However, there are not many nonlinear MPC software that on the one hand, is easy to use and debug, and on the other hand, is computationally efficient. The difficulty of upgrading MPC implementations to NMPC ones rises considerably mainly due to the difficulty of efficient linearization and the complexity of non-convex optimization. Among the available NMPC software, ACADO automatically generates optimized c codes for the RTI scheme, using a user-friendly symbolic interface in MATLAB and C++. All types of objectives and constraints are supported in ACADO. VIATOC also generates c codes for box constrained problems using gradient projection methods to solve NLPs on-line. In addition to the code generation tools, other software exploit general NLP solvers to solve online optimization problems. For example, CasADi is mainly a symbolic differentiation tool and embeds many NLP and QP solvers such as IPOPT and SNOPT. Forces Pro is freely available for academic users, which employs CasADi for efficient derivative computations and generates state-of-the-art interior point methods to solve multi-stage NLPs that are usually observed in NMPC.

The problems of aforementioned software are manifold:

1. The NMPC algorithms are automatically generated which can not be modified or investigated.
2. It is difficult to debug software and algorithms without a professional knowledge in computer programming.
3. The type of supported algorithms and functions are limited.

The reason for these problems is that, the available software aim at providing ready-to-use interfaces for engineers who know little about mathematical algorithms. The task of users is to tune model and software parameters to make algorithms work. There are few things that an algorithm developer can do to improve or augment the software unless he/she participates in the developing team.

Therefor, it is necessary to develop a NMPC package that aims at helping algorithm developer. This package should be fully open-source and commented at the level of algorithms. One of the contribution of my Ph.D study is that a MATLAB-based NMPC package MATMPC has been developed that can be used to implement algorithms presented above. MATMPC is designed for the purpose of algorithm development hence it has two working modes. In MATLAB mode, all algorithms are implemented completely in MATLAB language hence it is quite easy for modification and debugging. Algorithm developers can focus only on mathematics and relieve themselves from professional coding. In MEX mode, we provide MEX functions for popular algorithms such as SQP, multiple shooting and (partial) condensing. MATLAB Coder can also be used to automatically

generate C or MEX codes from M files. MEX mode enables MATMPC to achieve high performance when applied to real-time applications.

NMPC applications for dynamic driving simulator

The use of dynamic driving simulator has been increasingly popular in the automotive community, both in the research and industrial fields. Simulator platforms with different mechanical structures have been designed to target particular applications and markets. Such platforms are responsible for reproducing the driver sensations faithfully within their limited working space, while the mechanical constraints have to be satisfied to avoid hazardous situations. The strategy for the motion control of platforms are hence called *moting cueing algorithms* (MCA).

MCAs based on linear MPC techniques are well developed for the control of a linear actuated six DOF platforms. Human vestibular models and platform constraints are explicitly taken into account, and optimal control techniques are employed so that the tuning of the MCA is intuitive. Comparing with classical schemes based on washout filters, MPC-based MCAs allow for a better exploitation of the working space and a straightforward implementation of tilt coordination.

However, nonlinearities can be introduced by using more complex actuators and exploiting more DOFs. Therefore, NMPC-based MCAs are good candidates for providing faithful driver perceptions while considering nonlinear dynamics and constraints. A nine DOF driving simulator platform DiM 150 has been described in our previous papers. The mechanical structure of the simulator consists of a hexapod mounted on a tripod, which moves on a flat, stiff surface sliding on airpads. Such a structure allows for both low and high frequency of movements. The tripod is able to produce most of the low frequency longitudinal, lateral and yaw movements within a relatively large working space, while the hexapod provides high frequency longitudinal, lateral and yaw movements as well as pitch and roll rotations.

During my Ph.D study, we use MATMPC deveolped by ourselves for the application of a nine degree of freedom dynamic driving simulator. Real-time performance is achieved considering highly nonlinear dynamics and constraints using the standard RTI scheme. Therefore, algorithms are ready for real experiments on embedded platforms. A Multi-Sensory motion cueing algorithm is also tested using MATMPC running the adjoint RTI scheme and the ADMM solver. The real-time availability of the algorithm has been proved.

PART 3-PUBLICATIONS

List of publications on international journals

Y. Chen, M. Bruschetta, D. Cuccato and A. Beghi, "An Adaptive Sensitivity Updating Scheme for Fast Nonlinear Model Predictive Control", Submitted to Automatic Control, IEEE Transactions on, 2017

List of publications on conference proceedings

Y. Chen, D. Cuccato, M. Bruschetta and A. Beghi, "A fast Nonlinear Model Predictive Control strategy for real-time motion control of mechanical systems", Advanced Intelligent Mechatronics

(AIM), 2017 IEEE International Conference on, 1780–1785, 2017. DOI: 10.1109/AIM.2017.8014276

M. Bruschetta, D. Cunico, Y. Chen, A. Beghi and D. Minen, "An MPC based Multi-Sensory Cueing Algorithm (MSCA) for a high performance driving simulator with active seat", Accepted for publication in Driving Simulation Conference, September 6-8, 2017.

Y. Chen, D. Cuccato, M. Bruschetta and A. Beghi, "An Inexact Sensitivity Updating scheme for fast Nonlinear Model Predictive Control based on a Curvature-based Measure of Nonlinearity", Accepted for publication in Decision and Control, IEEE Conference on, 2017.

Date: 28/09/2017

Student signature

Chen Yutao

Supervisor signature