KU LEUVEN

DEPARTMENT OF COMPUTER SCIENCE
CELESTIJNELAAN 200A
3001 HEVERLEE
BELGIUM

Prof. doc. Ing. Milan Polívska
Office for Science and Research
Faculty of Electrical Engineering
Czech Technical University in Prague

OUR REFERENCE
YOUR REFERENCE
HEVERLEE 2018-12-04

Evaluation PhD Manuscript Matej Pčolka

To whom it may concern,

Herewith you find my comments on the PhD thesis submitted by Mr. Matej Pčolka.

The thesis proposes several approaches to significantly improve the efficiency of solving optimal control problems within the framework of Model Predictive Control (MPC). The method for solving optimal control problems, which forms the starting point of the thesis, is the nonlinear gradient method, which corresponds to a gradient based search in the space of control inputs, where derivatives of the cost are obtained from solving adjoint equations (which falls within the class of sequential approaches towards optimal control).

After a general introduction and outline of the thesis in Chapter 2, a novel strategy for the step-length selection along the computed descent direction is proposed in Chapter 3. It is based on fitting a quadratic interpolant and outperforms approaches based on a fixed, respectively shrinking step-length. Chapter 4 address the choice of the prediction horizon and proposes the following improvements:

- Using a shrinking horizon (instead of a receding horizon), which is beneficial if the optimal control problem is formulated in terms of an objective defined on a time-interval with an a priori specified end-point.
- Adaptation towards problems where the length of the horizon makes part of the variables of the optimization problem. Such problems occur for instance in the context of maximizing the *average* production over a time-interval (time-efficiency), as done in the thesis, but also in the context of time-optimal control, e.g., moving an object from one position to another one in minimum time, while respecting the constraints. The final solution, which is based on a rescaling of time (leading to a problem with a fixed horizon and transforming the original horizon length into a conventional variable), is adequate.
- For the case-study of controlling a racing car, an interesting novel strategy is developed for the on-line adjustment of the prediction horizon.

Chapter 5 addresses several aspects related to discontinuities and hybrid dynamics in optimal control problems:

PROF. DR. IR. WIM MICHIELS
TEL. + 32 16 32 70 64
Wim.Michiels@cs.kuleuven.be
http://people.cs.kuleuven.be/wim.michiels

- Handling inputs restricted to a countable set. Instead of the conventional approaches of solving mixed-integer optimization problems (accurate but a (too) large computational burden) and of an a posteriori quantization of a computed real valued input sequence (fast but suboptimal and inducing high frequency perturbations), a novel method is proposed based on integration of quantization and filtering within the outer loop of the optimization problem, which has the property of ``taking the best of both worlds".
- Highly nonlinear systems with a large variety of the operating point. Here again an interesting compromise is proposed between optimization based on the full nonlinear model and on a linear approximation. The key ingredient is that each time an optimal control problem needs to be solved, another linear approximation is used, based on the latest state measurement.
- Discontinuities along solutions of the system (hybrid nature) and/or discontinuities in the cost functional, leading to possible switching between different "modes". Here an improvement is obtained over the classical a-priori switching (keeping the mode fixed over the prediction horizon), which is very natural in the context of the adopted adjoint differentiation technique. Every time when the system is simulated forward in time, to compute the cost, the switches are recorded, and when the adjoint system is subsequently integrated backwards, to compute derivatives, the adjoint system switches in a synchronized way, such that correct derivatives are obtained.

Chapter 6 presents novel strategies to solve optimal control problems, where both the initial conditions and the inputs are considered as variables. One of the key ingredients to handle the complexity is a reduction of the number of variables by a (re)parameterization. The thesis ends with general conclusions and suggestions for future research.

All methodological improvements are carefully validated by means of application case-studies: control of a cultivation process related to the production of penicillin, control of a racing car, and the climate control within a building.

From my reading of the thesis, it is clear that the candidate masters the topics very well. Adequate solutions are provided to challenging problems in numerical optimal control and MPC, which are well validated. As outlined in the chapter-by-chapter overview, the thesis contains distinctive original contributions.

The results obtained in the framework of the thesis already led to an impressive publication output, including 4 papers in high-impact journals, all of which Mr. Pčolka is the first author, as well as a large number of peer reviewed conference papers. His works already received a considerable number of citations.

In conclusion, the author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

I conclude with a few questions that could be addressed during the defense:

- How does the proposed line-search strategy in Section 3 compare to standard line-search based globalization techniques in numerical optimization, such as back-tracking until the Armijo or Wolfe conditions are satisfied?
- Several of the algorithmic improvement discussed above have been introduced and presented in conjunction with application case studies. To what extent are the conclusions generic in the context of solving optimal control problems (versus specific for the considered application)?
- After the first two stages of the JIPICO algorithm the variables to be optimized are contained in parameter vector P (which in turn parametrizes the initial condition and control inputs). The optimization of the cost as a function of P in Stage III is done on a surrogate model (a spline

approximation, obtained by interpolation in neighboring points obtained by perturbing P component-wise). Why, consistently with the approach in other chapters, not directly performing a gradient search in the P-space? It seems that with the adjoint differentiation technique also derivatives with respect to P can be obtained?

Wim Michiels