Scientific Report

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I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

After a short period of vocational adjustment, the fellow and the scientific coordinator decide to change the topic of the fellowship from fault-tolerance-control to methods for embedded nonlinear Model predictive control.

The mid-term goal was to develop a prototype NMPC infrastructure on a programmable logic controller (PLC). The basis of this NMPC implementation is the direct single shooting method for optimal control of continuous models.

For online applications, robust solution of the moving optimal control problems is indispensable. One important source of failure in numerical optimization is the presence inconsistent derivative information of the objective functions and the constraints. Since the NMPC model is continuous, sensitivity analysis or parametric ordinary differential equations (ODE) is required.

In the first project, we provide this sensitivity information by means of the full algorithmic differentiation (AD), also referred to as first-discretize-then-differentiate, of a stiffly accurate Rosenbrock-type method with variable step size and error control. In this context, full algorithmic differentiation means that the model equation and the numerical integrator, including the step control mechanism, are simultaneously processed by an AD tool. The fully differentiated Rosenbrock-type integrator is interfaced to the nonlinear programming (NLP) solver SNOPT. We compared the robustness of the fully algorithmically differentiated solver with the sensitivity integrator IDAS which represents the approach of first-differentiate-then-discretize.
With respect to the optimization by means of SNOPT (a sequential quadratic programming solver) the numerical experiments with a small nonlinear optimal control problem indicate that the first-discretize-then-differentiate approach is more robust and may reduce the overall computational costs. The results were presented at the 13th European Control Conference und published in the conference proceedings.

Full algorithmic differentiation of an error-controlled variable step-size integrator will give consistent derivatives for the optimizers. However, variable step-size integration will generate state vectors, that are in general neither differentiable nor continuous for specific parameter values, i.e, those parameter values for which the sequence of step acceptances/rejections changes. This issue was addressed in the second project.

In the second project, the Rosenbrock-type integrator was modified in a way that guarantees continuity and differentiability of the state vector of parametric ODEs with respect to small changes of the parameters. Essentially, the non-differentiability of variable step-size integration can be identified as if-else-statements in the algorithm. The basic idea of our modification of the Rosenbrock-type integrator is to record the active branch of the if-then-else-statements for the nominal parameter values and try to use the same sequence of active branches in subsequent integrations. In a numerical experiment we showed the practical applicability of this modification in the context of direct single shooting. During the phase of rapid convergence of the associated numerical optimizer, the parameter changes are small and the integrator stays differentiable for all parameter changes. The results are written down in the contribution (Hannemann-Tamás, Kufoalor

& Imsland; XXXXa) that is submitted for publication in a book project of the Society for Industrial and Applied Mathematics (SIAM).

We have implemented an NMPC prototype on the ABB AC500-592PM programmable logic controller. This prototype is based in direct single shooting for optimal control. We use an open-source SQP solver as numerical optimizer. The required sensitivity analysis is performed by the NMPC-tailored error-control integrator Rosi that provides a convenient interface to the algorithmic differentiation tool dcc of Uwe Naumann (RWTH Aachen University).

For hardware-in-the-loop simulations a TCP/IP client has been implemented on th PLC, while the PC that simulates the plant runs a TCP/IP client.
The numerical results of the case studies are encouraging, providing a proof-of-concept of our embedded NMPC implementation.
To this end, We offer most of the source code of our embedded NMPC application for download in the hope that other researchers might benefit from our work.

In the third and last project, a programmable logic controller (PLC), the ABB AC500-592PM, is used to run a prototype nonlinear model predictive control (NMPC) implementation. The NMPC implementation focuses on efficiency to take into account the limited software and hardware of the PLC, but keeps the applied programming interface as simple as possible.
Again, the NMPC model is provided as a time-continuous state-space model, allowing for economic NMPC. The numerical solution method is based on direct single shooting. The associated numerical optimization code is an adapted version of the open-source SQP-method SLSQP. This SQP-method uses BFGS-updates to build up the Hessian of the Lagrangian but requires the gradient and Jacobian of the objective function and the constraints, respectively. These first-order derivatives are provided by the further improved Rosenbrock-type sensitivity integrator Rosi from the second project. To test the NMPC implementation, we performed hardware-in-the-loop-kind experiments by establishing a TCP/IP connection of the PLC to a PC.
The PC provides the PLC with perturbed simulated measurements while the PLC performs the NMPC algorithm. The numerical results are encouraging and indicate a proof-of-concept. The developed software is released under an open-source license, and can serve as a basis for future NMPC implementations. The results are meant to be published in the IFAC-Journal Control Engineering Practice (Hannemann-Tamás & Imsland; XXXXb).

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

Hannemann-Tamás, R. & Imsland, L. S. (2014), Full algorithmic differentiation of a Rosenbrock-type method for direct single shooting, *in* 'Control Conference (ECC), 2014 European', pp. 1242-1248. (published)

Hannemann-Tamás, R.; Kufoalor, K. M. & Imsland, L. S. (XXXXa), Smooth Adaptive Integration of Stiff Ordinary Differential Equations for Direct Single Shooting, *in* Uwe Naumann, ed., 'Algorithmic Differentiation in Computational Science, Engineering, and Finance. Introductory Case Studies', SIAM, 27 pages. (Pending. According to information from the editor, the status of the book project is on hold)

Hannemann-Tamás, R. & Imsland, L. S. (XXXXb), 'Algorithmic Differentiation for Nonlinear Model-Predictive Control on a Programmable Logic Controller', *Control Engineering Practice*. 33 pages. (Pending)

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

13th European Control Conference (2014) in Strasbourg. Presentation of ‘Full algorithmic differentiation of a Rosenbrock-type method for direct single shooting’

IV – RESEARCH EXCHANGE PROGRAMME (REP)

Not applicable.