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Dear Ladies and Gentlemen,

Dear members of the Ph.D. examination committee,

it is my pleasure to provide the requested short review about the submitted doctoral thesis "Optimal Control of Multibody Systems Using an Efficient, Parallelizable Adjoint Method" by Pawed Wojciech Maciag. The chosen topic is very interesting and relevant. Frequently one has to compute sensitivity information besides the plain simulation. These sensitivities can be used in control, but are also required in optimization, neural networks, uncertainties and many more fields of research. Naïve numerical schemes give very unprecise and unreliable results. On the other hand, the so called direct methods give precise results but scale unfortunately with the number of input variables. Adjoint methods have the advantage that their runtime is nearly independent from the number of inputs but this comes at a price, namely that there must be a forward and a reverse sweep through the simulation process. Mr. Maciag investigates that for multibody dynamics in a Hamiltonian framework. This is an interesting contribution which has scientific depth and practical importance. It is appropriate for a doctoral thesis. The thesis consists of 145 + 14 pages which are distributed to 8 chapters and some appendices and lists. The thesis is written in English language and is formally in good shape.

About the contents:

Chapter 1 gives a very brief introduction to the topic and provides the structure of the thesis.

Chapter 2 provides an overview about the state-of-the-art and sensitivity analysis. For me techniques like numerical differentiation are missing and also the view to other areas of science are not included. Gradients are not just used in multibody dynamics but are required in many, many other areas as well. I will come back to this critics later.

Chapter 3 contains a nice description of MBS in a Hamiltonian framework. This is well written and the basis for the later sensitivity analysis.

Chapter 4 is for me the central chapter of the thesis. I am not aware of other works which did the sensitivity analysis for this kind of Hamiltonian structure. It is of course not surprising that adjoint equations can be derived but this needs great care.

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In **Chapter 5** some examples are demonstrated and it is shown that the derived theory is correct and the implementation fine. The examples are for quite simple academic systems but the results are convincing.

The following two chapters are a bit disappointing for me. In **Chapter 6** a parallel implementation is shown. However, it is only available for a simple system, a kinematic chain, where the parallel implementation is very simple and the results are predictable. It would have been much more convincing to apply this for a complex general MBS. There are many investigations for parallelization of adjoint equations in Automatic Differentiation (AD) literature but Mr. Maciag seems not to be aware of these.

Chapter 7 is a bit strange and it remains unclear why it is added to the thesis. Some simple control examples are given but nothing new or innovative is visible for me. Gradients are used (and it was shown before that the mechanical modeling is fine and that the computed gradients are correct) but there is nothing new visible for me.

Chapter 8 closes the thesis with a nice summary.

About the evaluation:

The thesis has strong and weak points. Among the strong points are the high formal quality and the deep mechanical understanding of the MBS parts. Also, the usage of adjoint equations for the described Hamiltonian framework was never described before to my knowledge. Mr. Maciag knows his mechanical field and deserves a positive evaluation of his thesis.

However, there are also weak points. Mr. Maciag seems not to be familiar with the Automatic Differentiation literature and its various investigations about the forward and reverse mode as well as optimal parallelization, check pointing, ... It is not a miracle that adjoint equations can be derived for a simulation process if once is familiar with AD and code transformation or overloading of operations. Also new contributions from machine learning, e.g. back propagation in neural networks are missing. Not convincing for me is the mentioning of control in the thesis. There is no content about advanced control in the thesis but just a usage of the correctly computed gradients in some control application.

To summarize: I recommend to continue the process and without doubts Mr. Maciag deserves the Ph.D. title for his thesis. However, due to the mentioned shortcomings I want to propose a mark in between

good to very good.

I am looking forward to the oral exam and the discussions.

With best regards,

Prof. Dr.-Ing. Prof. E.h. Peter Eberhard

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