Application

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2015-05563	Axehill, Daniel	NT-14

Information about applicant

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Information about application

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Descriptive data

Project info

Project title (Swedish)*

Optimerad kodgenerering för modellprediktiv reglering på parallella hårdvaruarkitekturer

Project title (English)*

Optimized code generation for model predictive control on parallel hardware architectures

Abstract (English)*

Model Predictive Control (MPC) is one of the most widespread modern control principles used in industry. MPC for linear systems requires solution of Quadratic Programming (QP) problems on-line, while MPC for more challenging hybrid system requires solution of NP-hard Mixed Integer Quadratic Programming (QP) problems. The focus of the proposed research is to develop high performance optimization algorithms for on-line MPC that combine recent state-of-the-art structure exploitation algorithms and parallel hardware, with the promising trend of code generation. The objective is to extend and combine the ideas of code generation for MPC in three so far unexplored directions: parallel hardware architectures, performance optimization for target platforms using theoretical complexity models in combination with automated empirical testing, and MIQP optimization for hybrid systems. Our previous research include high performance QP and MIQP optimization algorithms tailored for MPC problems both for non-parallel hardware as well as for parallel hardware. Furthermore, in recent work we have shown that it is possible to parameterize an entire family of optimization problem formulations of a given MPC problem. It is shown that this flexibility in the problem formulation can be used to significantly improve the performance of existing code generating optimization solvers with respect to a given target platform and the framework is highly suitable to be integrated in a code generation framework. Moreover, analogous ideas are expected to be useful for optimal, or close to optimal, distribution of the workload on parallel hardware. Performing this type of parameter optimization off-line with respect to on-line computational performance in a code generation phase for non-parallel as well as for parallel hardware is one objective with the proposed research. Another objective is to apply these results and extend the ideas to the challenging hybrid MPC control problem, where solution of MIQP problems are required in real-time. Since these directions appear to be unexplored in the field of MPC today, and the preliminary results are very promising, we believe that the outcome of research in these directions is of high relevance for academia as well as for industry. The research is planned to be performed during 4 years and will involve the applicant as project leader and a new Ph.D. student to be reqruited if the application is granted.

Popular scientific description (Swedish)*

Utveckling av automatiskt optimerade metoder för reglering av snabba och komplexa system

Inom reglertekniken är modellprediktiv reglering (MPC) en av de mest använda moderna reglerstrategierna. MPC är en tidsdiskret metod, vilket betyder att viktiga storheter i systemet mäts med vissa tidsintervall. Efter varje mätning löses ett optimeringsproblem för att kunna hitta det bästa sättet att påverka systemet fram till nästa mättidpunkt. Detta innebär att om systemet som ska regleras är komplext, eller om det som ska regleras ändrar sig snabbt, blir det en utmaning att lösa optimeringsproblemet på den ofta korta tid som finns tillgänglig mellan mättidpunkterna. Ett sätt att snabba upp beräkningarna som krävs för att lösa optimeringsproblemet är att låta algoritmer utifrån en högnivåbeskrivning av problemet i lugn och ro skapa källkod för en effektiv implementation innan reglersystemet tas i drift. Detta kallas för kodgenerering. Fördelarna är att koden som genereras kan vara mycket specialiserad och snabb, samt den kan genereras även av personer som inte har fullständig kunskap om numerisk optimering. Ytterligare ett sätt att kunna utföra snabbare beräkningar är att skapa algoritmer som kan utföra flera beräkningar parallellt vilket det ofta finns stöd för i modern datorhårdvara. Syftet med den föreslagna forskningen är att gå ytterligare ett steg längre med kodgenereringen. Tanken är att utnyttja att man ofta relativt sett har mycket gott om tid innan systemet tas i bruk för att skapa en effektiv implementation och att dessa implementationer kan göras ännu mer effektiva genom att utföra mer avancerad optimering av beräkningarnas struktur och beteende. T.ex. kan det vara så att beräkningstiden beror på vissa parametrar i algoritmerna som ska exekveras. Det är då naturligt att försöka göra ett val av dessa så att prestandan maximeras. I vissa fall kan detta göras på ett enkelt sätt, och i andra fall blir det mer komplext. En utökning av denna idé, som potentiellt just kan leda till att det blir lite mer komplext att göra bra val av parametrar är att försöka optimera hur beräkningarna distribueras i en parallell miljö. D.v.s. att bestämma vad och hur mycket som ska beräknas var. Slutligen har vi ambitionen att föra över existerande kunskaper inom kodgenerering och nyvunna kunskaper från det föreslagna projektet till MPC-reglering av system som även innehåller olika former av logiska beslut, sk. hybrida system. Reglering av dessa typer av system är ofta avsevärt mycket mer beräkningskrävande än reglering av linjära och icke-hybrida olinjära system. Av den anledning så är den typen av algoritmoptimeringar som det här projektet handlar om extra relevant för dessa typer av problem. Eftersom det finns många industriella tillämpningar där avancerade reglermetoder som MPC är intressanta om bara beräkningsprestandan hade varit tillräcklig, är vi övertygade om att resultatet av denna forskning potentiellt sett kommer att få stor praktisk betydelse inom många viktiga områden som till exempel autonoma fordon och reglering av elnät.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

	Cause	Months
1	Parental leave	2
	Total	2

Career age: 83

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes* 2. Teknik > 202. Elektroteknik och elektronik > 20202. Reglerteknik

Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

Model predictive control

Keyword 2*

Optimization

Keyword 3*

Numerical linear algebra

Keyword 4

Keyword 5

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

No ethical question are relevant for this research.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

A: Research Program

Introduction

Model Predictive Control (MPC) is a class of control algorithms that compute a sequence of control signals that optimizes the predicted behavior of a system. It has its origin in Dynamic Matrix Control (DMC) which was invented by engineers at Shell Oil in the early 1970's and presented in [18]. "DMC had a tremendous impact on industry.", [38]. How DMC evolved to become what today is called MPC together with the current status of research in MPC is described in numerous surveys, e.g., [38, 1, 35]. MPC is traditionally used in an intermediate level between low-level control loops and the planning level of production. Today, it is possible to use MPC also in fast low-level control loops thanks to the introduction of explicit MPC, where the computational effort is shifted from on-line to off-line using parametric optimization, [12, 44, 14], but also thanks to the recent developments in specialized on-line optimization algorithms for MPC, e.g., [2, 22, 31, 54, 47, 20, 43]. Unfortunately, the off-line computational complexity for explicit MPC is rather high which makes this strategy tractable only for small systems. For larger systems, on-line optimization is still the only tractable solution. Over the years, the range of application of MPC has been broadened from linear systems to nonlinear and hybrid systems.

The possibility of automatically generating source code implementing the optimization algorithms used for on-line MPC has recently received lots of attention. Code generation has more generally been used quite long in different fields [31]. However, the attention for its usefulness in MPC was presented in [31, 33], where it was shown how extremely fast optimization routines for embedded optimization like MPC can be generated from a high-level description of the problem. The concept also makes it possible to perform advanced preprocessing off-line where the processing time is less critical.

Modern computer architectures are developed in the direction of (sometimes several) processors containing several cores that can work concurrently and share memory. This is often called a parallel system. Beyond parallel computations on a single computer, computational resources that are composed of many computers connected over a network, so-called clusters, can be considered. This more loosely coupled architecture is called a distributed system. When we discuss systems that are able to perform operations simultaneously, without specifying exactly if it is done in a parallel or in a distributed fashion, we denote this a concurrent system. Concurrent computations for MPC is considered in, e.g., [17, 29, 6, 49, 7, 55, 46, 42, 50, 40, 41].

In the late 1990's MPC was developed for control of hybrid systems (hybrid MPC), i.e., systems which can switch between several operating modes, where each mode is governed by its own characteristic dynamics. This development opened up for the possibility to incorporate the planning level into the optimization, [37, 16], a need which has been recognized in, e.g., pulp and paper industry and petroleum industry, [53, 36]. Furthermore, on/off-inputs to the system can be readily incorporated in the hybrid framework. Unfortunately, the computational effort is significantly higher for control of hybrid systems compared to linear systems which currently makes applications to large-scale systems intractable.

The objective of the research to be proposed is to develop high performance optimization algorithms for on-line MPC that combine recent state-of-the-art structure exploitation algorithms and parallel hardware, with the new promising trend of code generation. The research focus is to extend and combine the ideas of code generation for MPC in three so far unexplored directions: parallel hardware architectures, performance optimization for target platforms using theoretical complexity models in combination with automated empirical testing, and global optimization for hybrid systems. We believe that these focus areas combine our expertise, the promising trends in the area, as well as the need from industry in a promising way.

Purpose and aims

The purpose with this research is to develop faster and more reliable optimization routines for on-line MPC. The need for increased performance of these algorithms is a natural consequence of that MPC becomes increasingly popular in industry for control of faster and larger processes. The aim with the proposed project is to further develop existing results on code generation for embedded Quadratic Programming (QP) optimization toward more efficient use of parallel hardware, to off-line algebraically and empirically perform explicit algorithmic performance optimization for the target platform including and extending the ideas recently presented in [3], and to apply these new results to challenging Mixed Integer Quadratic Programming (MIQP) optimization problems that have to be solved in real-time in hybrid MPC applications.

Survey of the field

The on-line computational effort in MPC can be reduced using several techniques. Since a large part of the computational effort on-line is spent in the numerical linear algebra a popular focus in this research has been to develop interior point and active-set optimization algorithms that use tailored numerical linear algebra for the specific application MPC, see e.g., [26, 45, 23, 13, 51, 27, 8, 2, 5]. Furthermore, other ideas have, e.g., been variants of active-set methods [22, 5].

Another recent way of reducing the computational effort for on-line MPC is to automatically generate specialized source code, often shortly called “code generation”, from a higher level problem description. The concept is rather old and dates back to at least the 1970s when the parser-generator Yacc was introduced [25]. Code generators commonly used in engineering applications today are, e.g., Matlab Coder and Simulink Coder, that are used to generate C-code from Matlab code and Simulink models, respectively [30, 48]. The idea of using code generation for on-line optimization routines for MPC was introduced in [31, 33] where the authors show the benefits of automatically generating C-code for high-performance QP solvers for various real-time convex optimization applications, such as MPC. The initial results were later packaged in a code generator called CVXGEN [32]. The result is fast, portable and predicable code [31, 33, 34, 32]. The ideas have been been further developed by other researchers. In [20] a tailored interior point method that is available as a code generated solver is presented and it is shown to be even faster than CVXGEN. Apart from code generated interior point QP (and QCQP) methods, it is also shown in [24] the benefits of code generated active-set methods for MPC.

The recent development of parallel computer hardware has created a need for parallel algorithms for solving MPC problems, and much effort in research has been spent on this topic [17]. In [49] an extended Parallel Cyclic Reduction algorithm is used to reduce the computation of the original problem to smaller systems of equations that are solved in parallel. The computational complexity of this algorithm is reported to be $\mathcal{O}(\log N)$, where N is the prediction horizon. In [29] and [46] a time-splitting approach to split the prediction horizon into blocks is adopted. In [42] a splitting method based on Alternating Direction Method of Multipliers (ADMM) is used. In [50] an iterative three-set splitting QP solver is developed. The method splits the original problem into subproblems which can be computed in parallel and a consensus step using ADMM is performed to obtain the final solution. In [40, 41] parallel structure exploiting numerical linear algebra for MPC is presented where it is shown that the Newton step for these applications can be computed in $\mathcal{O}(\log N)$, which is verified in numerical experiments on a cluster. Furthermore, in [41] it is proposed that the distribution of the workload can be optimized for the MPC application using the ideas in our recent article [3], where the possibility to perform off-line performance optimizations before the system is launched for real-time operation is exploited. It is also observed that in high performance applications such as real-time MPC, communication times in a distributed setup cannot be neglected when aiming at distributing the computations for optimal performance. Moreover, the concept in [3] was applied to the existing state-of-the-art code generated QP solver FORCES [19] with convincing results which illustrates the potential of the ideas presented in [3].

The interest of hybrid systems in control began in the 1960's, [52]. In the late 1990's, it was discovered that discrete-time hybrid systems in Mixed Logical Dynamical (MLD) form can be controlled using MPC [15]. From a computational point of view, the major difference compared to the linear case is that an $\mathcal{NP}$-hard MIQP problem instead of a QP problem has to be solved in each sample. In our research in [4, 5], new tailored on-line optimization algorithms for hybrid MPC problems were developed. It was shown that the computational performance can be significantly improved using these new algorithms compared to using algorithms implemented in existing off-the-shelf software. Furthermore, the targeted platforms were single core platforms, and neither concurrent computations or code generation were explicitly taken into consideration. Ideas how parallelism can be used to improve the performance of hybrid MPC is presented in [6, 7], which we are partly working on realizing in our currently ongoing research project. The benefits from code generation for optimization grows with the number of problems from the same problem family (parameterization) to be solved. In global optimization via Branch and Bound (BnB), which is commonly used to solve hybrid MPC problems, sometimes a significant number of subproblems of MPC type is required to be solved in each sample [2] which indicates that this application would very likely benefit from code generation of the solvers for these subproblems.

Project description

This project contains three different sub-tasks; code generation for parallel hardware architectures, code generation using performance optimization for target platforms using theoretical complexity models in combination with automated empirical testing, and code generation for global optimization for hybrid systems. It might seem overambitious to consider three such challenging tasks, but the results in previous tasks can be reused in later tasks. The choice of these tasks are also based on our current research and expertise. We are currently performing research on real-time MPC as well as on parallel optimization for linear and hybrid MPC. During that research we have collected several ideas in the proposed directions. Furthermore, parallel hardware is now locally available and there exists an established collaboration with the National Supercomputer Centre (NSC) in Linköping, where even more relevant hardware and expertise in parallel programming can be found. During our parallel computation research is has become clear that it would be very beneficial to be able to do advanced a priori optimization of how the computations and communications in a parallel computation environment is setup. Moreover, our recent progress in optimizing tailored numerical linear algebra for MPC that was accepted as the journal article in [3] furthermore convinced us about continuing in this direction and that it seems very promising to embed the ideas of parallel computations and optimized linear algebra into the concept of code generation. While parallel computations admits more freedom for tuning on one hand, on the other hand it also requires a more sophisticated framework to perform the tuning with optimal, or close to optimal, performance. This is to be more deeply considered in the proposed project.

The proposed research in these three tasks will now be described in detail. In all tasks it is exploited that the MPC problem has the property that the optimization problem to be solved on-line is usually known in advance apart from some relatively few degrees of freedom which correspond to the current measured state of the system to be controlled. Code generation makes it possible to off-line perform optimization of the solver code off-line using information known a priori in the same spirit as for explicit MPC. However, in the code generation approach the optimization problems are still solved in real-time on-line, but it is performed using highly specialized code.

Task 1: Code generation using tailored numerical linear algebra optimized for the target platform; In our previous work on on-line linear and hybrid MPC in [4, 5, 10, 8, 11, 39], the causality structure of the MPC problem was used. The main focus was to reduce the computational time of the part of the optimization routine that consumes most of the computational effort, which is the numerical linear algebra. In the proposed research in Task 1 the intension is to maintain that focus. In [40, 41] we presented algorithms that are able to both utilize the causality structure of the problem as well the capabilities of parallel hardware. In the recent article [3] by the applicant it was shown that instead of selecting between the two traditional formulations of MPC problems on the dense or sparse form [2], the selection should be performed among instances in an entire parameterized family of MPC formulations where the two traditional ones are two special cases. As described in [3], freedom in the problem formulation can be exploited in either of two ways or using a combination of them. Firstly, the performance can be optimized based on theoretical expressions (models) for the computational complexity in terms of flops and can be performed using algebraic or numerical optimization. Secondly, structured off-line empirical tests on the target platform can be used to select the formulation that in reality produces the fastest code on the target platform. Our experience from [3] shows that it in order to obtained practically useful results, it is necessary to take the performance of the hardware in practice on the target platform into account. Theoretical flop counts tend to be increasingly less useful on modern hardware. To better capture the performance in practice also when performing the proposed non-empirical performance optimization, the theoretical flop counts can be replaced by models of the computational time estimated from empirical studies containing smaller units of operations that later can be composed into a complete model of how the computational time varies as a function of the tuning paramters. However, it might be harder to properly include effects of the processor cache if the algorithm is divided during the benchmarking. This a topic for further investigation.

It is noted in [3] that these ideas would fit very well into a code generation framework and that it is very promising to also perform analogous algorithmic optimization for the more challenging concurrent setup.

Task 2: **Concurrent architectures;** This task is intended to utilize results from Task 1. For concurrent architectures, and distributed ones in particular, it is important to split the workload wisely among the processing units. Since the problem structure, and in particular problem dimensions, is known a priori, time off-line can be used to optimize the workload distribution among the cores available. Similarly to Task 1, models of the computational complexity of the operations to be performed can be used and also the amount of communication necessary to be performed as a function of the selected communication and distribution topology can be used in order to minimize the computational time. From our experience in [41], we know that in a distributed system, there also exist pure delays in the communication channel between the computational nodes that are not necessarily negligible in a high-performing real-time system as MPC. This is hence also something that has to be considered in order to obtain maximum performance. Since the parallel setup includes more parameters to tune and also delays that have to be taken into account, more advanced numerical optimization methods need most likely to be considered in order to extend the results from Task 1. However, the frameworks in [3] and in [41] share important similarities, which indicate, e.g., that performance optimization based theoretical flop counts can be easily performed also in the case of parallel hardware in simplified scenarios where, e.g., delays are disregarded. More degrees of freedom also make empirical tests more challenging, which introduces a need to develop algorithms that perform this testing in an automized structured way. One possibility would be to develop problem specific BnB algorithms that make certain tests of the hardware and combine those results with knowledge from the theoretical computational time in order to upper and lower bound the computational necessary for BnB to make progress.

Task 3: **Code generation for hybrid MPC;** This task is intended to utilize results from Task 1 and 2. MPC for hybrid systems on MLD form requires the solution of an MIQP in each sample, which usually are solved using BnB [2]. The computations in an MIQP BnB method can be split into three levels. At the top level, the integer nature of the problem is handled by formulating QP relaxations of the original integer problem which are ordered in a tree structure. At the intermediate level, these QP relaxations are solved using a QP method and the result is returned to the top level where the result is used to explore the search tree in an efficient way. The lowest level consists of subproblems solved inside the QP solver, which basically boil down to numerical linear algebra.

Firstly, it would be possible to utilize the structure from the branching-process to perform code generation for the relaxations and use the code generated solver as a part of the BnB framework. These are known to have linear MPC structure, with some additional equality constraints corresponding to variables that are fixed to 0 and 1 [2]. Hence, it would be possible to solve these using a code generated solver. Judging from the results for code generation for linear MPC reported in [31, 33, 34, 32, 20, 24], it is clear that such a setup would significantly improve the performance of MPC for hybrid systems. Since the main computational effort is spent in solving these relaxations (the time for branching itself can be considered negligible) and since the number of relaxations would be unaffected of if they are solved using a code generated solver or not, the relative performance gain would be roughly the same as reported in the references above for linear MPC. Hence, the speed-up is expected to be significant and the resulting solver would easily outperform generic commercial state-of-the-art-solver such as CPLEX and GUROBI.

Secondly, more advanced performance optimization for hybrid systems could perhaps be performed in line with the work we performed in [9], where it was shown how BnB for a parametric problem like MPC can be analyzed a priori in order to bound the on-line computational time. This result is the first one where the behavior of BnB applied to specific instances is analyzed with this level of details. Apart from being a tool for analysis, the same framework can potentially also be used to off-line a priori optimize the tuning (branch strategies, branch variable selection,...) of BnB. This idea can be combined with code generation in a natural way.

Summarizing, based on our recent advances in a priori performance optimization for MPC reported in [3] and our recent advances in parallel computations for MPC reported in [40, 41], we are highly confident that we are able to deliver useful results from the research proposed above. That the goals are realistic is confirmed by the already obtained results in [3]. Furthermore, the selected research focus is supported by the discussion about cases where code generation can be potentially useful in [31].

The research is planned to be performed during a total time of 4 years and will involve the applicant as project leader and a new Ph.D. student to be reqruited if the application is granted. Out of the total project time, 3 years are planned to be spent on the two first tasks presented above (including start-up-time for a new Ph.D. student). On the third task, we plan to spend the remaining 1 year.

This is clearly a very ambitious project that we propose. We consider that it contains a sound mix of tasks that are more straightforward and those that are more challenging. However, based on the fact that we know where to start and that we have a clear picture already at this stage how to proceed in the core parts of the project, we feel confident that we will succeed in realizing this research.

Significance

The expected outcome of the resulting algorithms from this research is that larger linear and hybrid MPC problems can be solved, and that it can performed at speeds that is simply impossible using today's methods. This implies that the area of applications where MPC is applicable today can be broadened toward faster and more complicated systems. Furthermore, the proposed research also aims at better utilizing the parallel hardware architectures that becomes increasingly popular in modern hardware. As shown in a numerical example with practical relevance in [3], the foundation to the research that is proposed is already today able to significantly speed-up current state-of-the-art code generated solvers with as much as $44\,\%$ in the example considered. Theoretical investigations in the same work show that the number of flops can be reduced up to a factor of 30 for certain combinations of number of states and control signals in the range 1 to 100. Practically this implies that, e.g., more advanced control problems in relevant fast applications such as automotive, aerospace and electrical grids can be controlled. For example, to solve problems with long horizons is relevant in planning problems for autonomous vehicles.

Furthermore, the applicability to hybrid systems opens up for applications such as large planning and scheduling problems involving dynamical systems in areas as transportation, logistics and economy can be solved. In other applications, the hybrid nature of the problem stems from, e.g., the physics of the problem. There are many important such problems in, e.g., the process industry and in communication systems where either the dynamics has a hybrid nature, or the inputs to the systems only can be taken from a finite alphabet. We believe that every improvement of the computational performance of computational methods for hybrid MPC is highly relevant, because if any MPC application need massive computational power, it is the hybrid MPC application.

One example of an applied research project that the applicant is involved in which would benefit from the proposed research is the development of an autonomous truck within the large research project iQMatic [21] managed by the truck manufacturer Scania and involving other partners such as the Royal Institute of Technology, Autoliv and SAAB. The applicant together with co-workers are responsible for the local path planner of the vehicle, which is today built on a framework developed at MIT called Rapidly-exploring Random Trees (RRT) [28] which is one alternative of attacking the advanced optimization problems that have to be solved on-line in order to avoid obstacles and in order to short term plan the movements of the vehicle. In RRT a significant number of random closed loop trajectories are randomly generated and the best one is returned as the one to execute. In this project, a need for closing the loop using MPC controllers has arisen, and this is today not considered tractable since it would be too computationally demanding to simulate the system in closed loop for each random trajectory in the RRT framework with existing on-line MPC controllers. In the scope of the iQMatic project, it would be very interesting to investigate how well a code generated tailored solver using the available parallel hardware would work in this application.

In general, it is clear that there exist numerous of very relevant applications for both linear MPC as well as for hybrid MPC which are simply not tractable with today's optimization algorithms and we are convinced that many of these would significantly benefit from the proposed research.

Preliminary results

The proposed research is based on our results in [9, 40, 41, 3]. The result in [9] shows that it is possible to off-line perform preprocessing with the purpose of analyzing and potentially improving the performance also in advanced on-line algorithms such as BnB for real-time global optimization. The result shows that it is possible to a priori bound the size of the binary search tree in BnB for MIQP problems with a parametric structure as the MPC problem. In [40, 41] it is shown that it is possible to compute tailored Newton steps concurrently for the MPC application. In [3] a parameterized family of formulations of a given MPC problem is introduced. By optimizing with respect to the introduced parameter it is shown that significant performance improvement can be achieved. It is also shown that this can be performed using theoretical flop counts, empirically at the numerical linear algebra level, as well as empirically for the entire optimization routine. The results include that the performance of the existing state-of-the-art code generated solver FORCES could be improved by $44\,\%$ on an example of practical relevance. On the numerical linear algebra level it was shown in numerical examples that for certain problems the computational time can be reduced with an order of magnitude.

Independent line of research

The applicant's ongoing VR-project is as a natural continuation of research that partly was conducted during the main-applicant's Ph.D. studies, and partly during his two-year post-doc at ETH Zürich. Most of the research performed during his post-doc is not directly connected to what was done during the time as a Ph.D. student, and hence, these projects are not connected to the research of the former supervisor Prof. Hansson. The ongoing VR-project has been an important piece in order to build up a research group. If the new application is granted, the development of that group can continue and it would secure the applicant's possibilities to continue to perform independent research. The applicant has recently submitted an application for becoming a Docent, which will ensure that he is able to become the main supervisor of the Ph.D. student to be recruited if the proposed project is granted.

Form of employment

The applicant is currently holding a permanent position as an Assoc. Prof. at the division of Automatic Control at Linköping University.

International and national collaboration

Dr. Daniel Axehill is currently collaborating on the topic hybrid MPC with Prof. Manfred Morari and his staff at the Hybrid Systems Group, ETH Zürich. Other current collaborators on the MPC topic are Asst. Prof. Davide Raimondo (University of Pavia), Dr. Thomas Besselmann (ABB Corporate Research Switzerland), Asst. Prof. C. Jones (EPFL Lausanne), and Dr. Johan Löfberg (Linköping University). The collaboration with his former colleagues from his time as post-doc at ETH Zürich is ongoing and is planned to continue in various projects with the common topic MPC. Furthermore, Daniel has built up important collaborations within the autonomous vehicle area in Sweden. This is a result of his engagement in the iQMatic project, but also his engagement as project leader for the LiU team in heavy duty vehicle platooning as well as some minor projects within the active vehicle safety area. The primary collaboration partners in this area are Dr. Marco Trincavelli (Scania CV AB), Assoc. Prof. Petter Ögren (Royal Institute of Technology), Asst. Prof. John Folkesson (Royal Institute of Technology), Prof. Lars Nielsen (Linköping University), Assoc. Prof. Erik Frisk (Linköping University), Assoc. Prof. Paolo Falcone (Chalmers), and Assoc. Prof. Jonas Mårtensson (Royal Institute of Technology).

Other grants

No other grant has been applied for this project. However, the proposed research is a natural continuation of the ongoing VR project "Distributed optimization for hybrid MPC" for which financing ends in the end of year 2015. However, the research within that project will continue for at least one more year which is very timely since we feel that we now have obtained momentum and the required hardware is in place. The proposed research will, if it is granted, directly take over where the previous one ends in the direction of the ideas described in this application. If this application is granted we believe that the new project will get a warm start since knowledge transfer from Ph.D. student to Ph.D. student would be possible for some time.

References

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Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Preliminary scientific report for VR project "Distributed Optimization for hybrid MPC"

Agreement ID: B0598501
Amount: 3 MSEK, distributed over 4 years.
Grant period: 2012-01-01 -- 2015-12-31

Scientific results
The research within this project has so far been focused on two areas; concurrent numerical linear algebra for linear and hybrid Model Predictive Control (MPC), and suboptimal explicit MPC for hybrid systems using branch and bound.

In optimization algorithms used for on-line MPC, linear systems of equations are often solved in each iteration. The main computational effort is spent while solving these linear systems of equations, and hence, it is of greatest interest to solve them efficiently. In the project, effort has been spent to develop algorithms that are able to combine problem structure exploitation and parallel computations. Since commonly used structure exploiting algorithms rely on the causality of the problem it is not obvious how to split the problem in time efficiently. The result today is that we have found two alternative ways of non-iteratively decoupling the problem in time. The first alternative is presented in [5] and is inspired by parametric programming where firstly batches along the horizon can be (efficiently) solved independently parametrically and secondly the resulting batch-wise explicit solutions are combined into a new less complicated artificial problem again in MPC form. This implies that the procedure can be repeated over and over again producing a tree-like structure. The overall computational complexity of this approach grows as O(log N), compared to state-of-the-art serial structure exploiting algorithms for which the computational complexity grows as O(N). The second alternative which is presented in [4] shares similarities with the work in [5], however here the batch problems along the horizon are solved independently while treating the final penalty as a parameter. It is shown that the degrees of freedom in the solution introduced by this parameter is usually relatively small, which basically means that a large portion of the computations can be performed without explicitly knowing the value of these parameters. Also this second algorithm is executed in a tree-like fashion starting with the original batches in the leaves and working one pass upward and one pass downward, without the need for any iterations in order to achieve consensus. Also this algorithm obtains an overall computational complexity of O(log N).

Project time has also been invested in building up a hardware testbed for performing numerical tests. For that end, a cluster consisting of 18 quad-core PCs has been setup for the project. The initial idea was to use Matlab's Parallel Computing Toolbox and Distributed Computing Server as rapid prototyping environments, but it was discovered that this setup was not suitable for the type of low-latency concurrency that is requested in real-time MPC. As a result, the developed algorithms were C-coded during fall 2014. Furthermore, the project is also granted time at the National Supercomputer Centre (NSC), where larger experiments can be performed. The collaboration with NSC is also useful since they have valuable insight in how to write efficient code for clusters.

As the hardware and software infrastructure now is in place, upcoming research includes considering how to parallelize the branch and bound level of the algorithm for hybrid MPC problems. It has been realized in the project that there is no universal answer to how to distribute the workload at for example the numerical linear algebra level and the branch and bound level. For that reason, ideas have arisen that there seems to be a need for developing automated tools that off-line analyze the problem and computes an optimal, or close to optimal, distribution of the workload. Our introductory work in this direction is presented for the serial case in our recent work [2]. Extensive off-line algorithmic optimization is in principle possible in the MPC application since large parts of the structure of the problem is fixed on-line from sample to sample. Since this is planned to be done at the preprocessing step off-line, these ideas combines very well with the recent ideas of code generation.

Within the second focus area, explicit MPC for hybrid systems, our work on suboptimal explicit hybrid MPC using branch and bound has been finalized and resulted in the journal publication [3]. The relation to the VR project is that the choice of branch and bound enables the use of parallel computations. Upcoming research within the current VR project is to distribute the explicit hybrid algorithm and to implement it on our now functional hardware testbed. Another recent work within hybrid MPC that can be said to partially be a result of the VR project is [1], where it is shown how computed explicit solutions from the algorithm in [3] can be stored efficiently. The main result in [1] is that it is shown that it is possible to represent the explicit solution to a hybrid MPC problem also with quadratic norm in a single polyhedral partition. Practically this removes the need for comparing several parametric solutions on-line, and the on-line computational complexity becomes in parity with the one for problems with linear norms.

Moreover, our ideas for how to proceed in the area of parallel computations for hybrid MPC has been presented in [6].

Except for the project leader Daniel Axehill, the Ph.D. student Isak Nielsen has been working within the project. Isak is planning to present his Licentiate's thesis during early fall 2015.

Relation between the current project and the proposed one

The idea with the proposed project is to continue on the most promising parts of the ongoing VR project. It has been realized that there is much more left to be done in parallel numerical linear algebra for MPC (relevant for linear, nonlinear and hybrid MPC). Due to recent advances in code generation, it is now also reasonable to believe that code generation of parts of the algorithms can improve the performance drastically. To even further improve the performance, we suggest to consider more explicit algorithm performance optimization off-line where the computational time is not critical. The time spent off-line pays-off as better performance during potentially many years of on-line operation. As mention above, in the old VR project we have realized the need for more complex off-line algorithmic optimization for the case of parallel hardware. This is one topic where the proposed new project is intended to advance beyond the results in the old project.

The project has been completely supported by the VR grant.

Publications entirely or partially based on work from the VR project "Distributed Optimization for hybrid MPC"

[1] Alexander Fuchs, Daniel Axehill, and Manfred Morari. Lifted evaluation of mp-MIQP solutions. Accepted for publication in IEEE Trans. Autom. Control, 2015.

[2] Daniel Axehill. Controlling the level of sparsity in MPC. Syst. Control Lett., 76:1-7, 2015.

[3] Daniel Axehill, Thomas Besselmann, Davide Martino Raimondo, and Manfred Morari. A parametric branch and bound approach to suboptimal explicit hybrid MPC. Automatica, 50(1):240-246, January 2014.

[4] Isak Nielsen and Daniel Axehill. A parallel structure-exploiting factorization algorithm with applications to model predictive control. Submitted for possible publication at the 54th IEEE CDC, March 2015.

[5] Isak Nielsen and Daniel Axehill. An O(log N) parallel algorithm for Newton step computation in model predictive control. In Proc. 19th IFAC WC, pages 10505-10511, Cape Town, South Africa, August 2014.

[6] Daniel Axehill and Anders Hansson. Parallel implementation of hybrid MPC. In Jose M. Maestre and Rudy R. Negenborn, editors, Distributed Model Predictive Control Made Easy, volume 69 of Intelligent Systems, Control and Automation: Science and Engineering, pages 375-392. Springer Verlag, 2014.

Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project*

	Role in the project	Name	Percent of full time
1	PhD Student	To be reqruited	80
2	Applicant	Daniel Axehill	40

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Daniel Axehill	40	350,000	360,000	370,000	381,000	1,461,000
2	Participating researcher	Ph.D. student to be recruited	80	427,000	440,000	453,000	467,000	1,787,000
	Total			777,000	800,000	823,000	848,000	3,248,000

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Office space	36,000	36,000	36,000	36,000	144,000
	Total	36,000	36,000	36,000	36,000	144,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travel expenses	Expenses for travels to conferences etc.	30,000	50,000	50,000	50,000	180,000
2	IT subscription		20,000	20,000	20,000	20,000	80,000
	Total		50,000	70,000	70,000	70,000	260,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	777,000	800,000	823,000	848,000	3,248,000		3,248,000
Running costs	50,000	70,000	70,000	70,000	260,000		260,000
Depreciation costs					0		0
Premises	36,000	36,000	36,000	36,000	144,000		144,000
Subtotal	863,000	906,000	929,000	954,000	3,652,000	0	3,652,000
Indirect costs	221,000	227,000	232,000	239,000	919,000		919,000
Total project cost	1,084,000	1,133,000	1,161,000	1,193,000	4,571,000	0	4,571,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The budget includes salaries for the project leader and a Ph.D. student to be recruited if the project is granted. Furthermore, it covers costs for offices spaces for the Ph.D. student as well as costs for travels for the project leader and the Ph.D. student. The university IT subscription for the Ph.D. student costs 20 000 kr per year. Finally, indirect costs of 25% are added.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV and publications

CV

B: CURRICULUM VITAE

Daniel Axehill

Address:	Division of Automatic Control Linköpings universitet SE–581 83 Linköping	**Phone:** **Fax:** **E-mail:**	013–28 40 42 013–14 94 03 `daniel@isy.liu.se`

1. Higher education qualification

2003	Master of Science	Applied Physics & Electrical Engineering, Linköping University

2. Doctoral degree

2008	Doctor of Philosophy, Automatic Control, Supervisor: Anders Hansson	Integer Quadratic Programming for Control and Communication, Linköping University

3. Postdoctoral positions

Jan 2009 – Oct 2010	Postdoctoral fellow	ETH Zürich, Switzerland
Feb 2008 – Sep 2014	Assistant professor (forskarassistent)	Linköping University, Sweden

4. Qualification required for appointments as a docent

Applied for a Docent in Automatic Control at Linköping University 2015-03-23.

5. Current position

Oct 2014 –	Associate professor (universitetslektor)	Linköping University, Sweden (80 % research)

6. Previous positions and periods of appointment

Feb 2008 – Sep 2014	Assistant professor, Linköping University, Sweden
Jan 2009 – Oct 2010	Postdoctoral fellow, ETH Zürich, Switzerland
Feb 2003 – Feb 2008	Doctoral student, Linköping University, Sweden

7. Interruption in research

Jan 2015 – Aug 2015 Paternal leave 80%

8. Supervised doctoral students

Not applicable.

9. Collaboration partners

2014 –	Dr. Marco Trincavelli, Scania CV AB, Sweden
2013 –	M. Sc. Jon Andersson, Scania CV AB, Sweden
2013 –	M. Sc. Lars Hjorth, Scania CV AB, Sweden
2013 –	Assoc. Prof. Petter Ögren, Royal Institute of Technology, Sweden
2013 –	Asst. Prof. John Folkesson, Royal Institute of Technology, Sweden
2012 –	Prof. Lars Nielsen, Linköping University, Sweden
2012 –	Assoc. Prof. Erik Frisk, Linköping University, Sweden
2012 –	Assoc. Prof. Paolo Falcone, Chalmers, Sweden
2012 –	Assoc. Prof. Jonas Mårtensson, Royal Institute of Technology, Sweden
2011 – 2012	Dr. Peter Hessling, SP Technical Research Institute of Sweden, Sweden
2010 – 2012	M. Sc. Jan Široký, University of West Bohemia, Czech Republic
2010 –	Asst. Prof. Raimondo, University of Pavia, Italy
2009 – 2010	Dr. C. Verhelst, K. U. Leuven, Belgium
2009 – 2010	Prof. L. Helsen, K. U. Leuven, Belgium
2009 –	Dr. A. Fuchs, ETH Zürich, Switzerland
2009 – 2010	Dr. S. Mariéthoz, ETH Zürich, Switzerland
2009 –	Asst. Prof. C. Jones, EPFL Lausanne, Switzerland
2009 –	Dr. T. Besselmann, ABB Corporate research, Switzerland
2009 – 2010	Dr. S. Almér, ETH Zürich, Switzerland
2009 –	Prof. M. Morari, ETH Zürich, Switzerland
2008 –	Assoc. Prof. J. Löfberg, Linköping University, Sweden
2005 – 2008	Dr. F. Gunnarsson, Linköping University, Sweden
2006 –	Prof. L. Vandenberghe, UCLA, USA
2003 –	Prof. A. Hansson, Linköping University, Sweden

Publication list

C: Publications

1. Peer-reviewed original articles

[1] Alexander Fuchs, Daniel Axehill, and Manfred Morari. Lifted evaluation of mp-MIQP solutions. Accepted for publication in IEEE Transactions on Automatic Control, 2015.

[2] Daniel Axehill. Controlling the level of sparsity in MPC. *Systems & Control Letters*, 76:1–7, 2015. *

[3] Daniel Axehill, Thomas Besselmann, Davide Martino Raimondo, and Manfred Morari. A parametric branch and bound approach to suboptimal explicit hybrid MPC. *Automatica*, 50(1):240–246, January 2014.

[4] Daniel Axehill and Manfred Morari. An alternative use of the Riccati recursion for efficient optimization. *Systems & Control Letters*, 61(1):37–40, 2012. *

[5] Daniel Axehill, Lieven Vandenberghe, and Anders Hansson. Convex relaxations for mixed integer predictive control. *Automatica*, 46(9):1540 – 1545, September 2010.

[6] Daniel Axehill, Fredrik Gunnarsson, and Anders Hansson. A low-complexity high-performance preprocessing algorithm for multiuser detection using Gold sequences. *IEEE Transactions on Signal Processing*, 56(9):4377–4385, September 2008.

2. Peer-reviewed conference contributions

[1] Isak Nielsen and Daniel Axehill. An O(log N) parallel algorithm for Newton step computation in model predictive control. In *Proceedings of the 19th IFAC World Congress*, pages 10505–10511, Cape Town, South Africa, August 2014. *

[2] Isak Nielsen, Daniel Ankelhed, and Daniel Axehill. Low-rank modifications of Riccati factorizations with applications to model predictive control. In *Proceedings of the 52nd IEEE Conference on Decision and Control*, pages 3684–3690, Palazzo dei Congressi, Florence, Italy, December 2013.

[3] Jan Širokỳ, Miroslav Šimandl, Daniel Axehill, and Ivo Puncochár. An optimization approach to resolve the competing aims of active fault detection and control. In *Proceedings of the 50th IEEE Conference on Decision and Control*, pages 3712 – 3717, Hilton Orlando Bonnet Creek Hotel, Orlando, USA, December 2011.

[4] Daniel Axehill, Thomas Besselmann, Davide Martino Raimondo, and Manfred Morari. Suboptimal explicit hybrid MPC via branch and bound. In *Proceedings of the 18th IFAC World Congress*, pages 10281 – 10286, UCSC, Milano, Italy, August 2011.

[5] Daniel Axehill and Manfred Morari. Improved complexity analysis of branch and bound for hybrid MPC. In *Proceedings of the 49th IEEE Conference on Decision and Control*, pages 4216 – 4222, Hilton Atlanta, Atlanta, USA, December 2010.

[6] Alexander Fuchs, Daniel Axehill, and Manfred Morari. On the choice of the linear decision functions for point location in polytopic data sets - application to explicit MPC. In *Proceedings of the 49th IEEE Conference on Decision and Control*, pages 5283 – 5288, Hilton Atlanta, Atlanta, USA, December 2010.

[7] Clara Verhelst, Daniel Axehill, Colin Jones, and Lieve Helsen. Study of optimal control formulations for an air-to-water heat pump system. In *Proceedings of the 8th International Conference on System Simulation in Buildings*, December 2010.

[8] Martin Elfstadius, Daniel Gecer, Lars Nordström, and Daniel Axehill. Method to detect and measure potential market power on electricity markets using the concept of monopolistic energy. In *Proceedings of the Power Systems Conference and Exposition, 2009*, March 2009.

[9] Daniel Axehill and Anders Hansson. A dual gradient projection quadratic programming algorithm tailored for model predictive control. In *Proceedings of the 47th IEEE Conference on Decision and Control*, pages 3057–3064, Fiesta Americana Grand Coral Beach, Cancun, Mexico, December 2008. *

[10] Daniel Axehill, Anders Hansson, and Lieven Vandenberghe. Relaxations applicable to mixed integer predictive control – comparisons and efficient computations. In *Proceedings of the 46th IEEE Conference on Decision and Control*, pages 4103–4109, Hilton New Orleans Riverside, New Orleans, USA, December 2007.

[11] Daniel Axehill, Lieven Vandenberghe, and Anders Hansson. On relaxations applicable to model predictive control for systems with binary control signals. In *Preprints of the 7th IFAC Symposium on Nonlinear Control Systems*, pages 200–205, Pretoria, South Africa, August 2007.

5. Books and book chapters

[1] Daniel Axehill and Anders Hansson. Parallel implementation of hybrid MPC. In José M. Maestre and Rudy R. Negenborn, editors, *Distributed Model Predictive Control Made Easy*, volume 69 of *Intelligent Systems, Control and Automation: Science and Engineering*, pages 375–392. Springer Verlag, 2014.

[2] Daniel Axehill and Anders Hansson. Towards parallel implementation of hybrid MPC – a survey and directions for future research. In Rolf Johansson and Anders Rantzer, editors, *Distributed Decision Making and Control*, volume 417 of *Lecture Notes in Control and Information Sciences*, pages 313–338. Springer Verlag, 2012. *

CV

Name: Daniel Axehill	**Doctorial degree:** 2008-02-27
Birthdate: 19781204	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Research education

Dissertation title (swe)		
Integer quadratic programming for control and communication		

Dissertation title (swe)
Integer quadratic programming for control and communication

Dissertation title (en)
Integer quadratic programming for control and communication

Organisation	Unit	Supervisor
Linköpings universitet, Sweden Sweden - Higher education Institutes	Institutionen för systemteknik (ISY)	Anders Hansson

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20202. Reglerteknik	978-91-85523-03-0	2008-02-27

Publications

Name: Daniel Axehill	**Doctorial degree:** 2008-02-27
Birthdate: 19781204	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Axehill, Daniel has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.