Application

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Information about applicant

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Information about application

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Keywords: Optimal design, Optimal control, Convex optimization, Energy management, Dynamic systems

Funds applied for

Year:	2016	2017	2018
Amount:	616,000	640,000	662,000

Descriptive data

Project info

Project title (Swedish)*

Kombinerad dimensionering och optimal styrning av energibuffertsystem

Project title (English)*

Combined design and control optimization of dynamic systems with energy buffers

Abstract (English)*

The emerging energy-clean and efficient systems, comprising several energy buffers and utilizing predictive information, are fundamental in the quest for sustainable economy and environment. However, the new technology introduced to these systems aggravates their price, compared to conventional solutions, thus limiting the level of penetration to the market. Therefore, significant effort is being invested in optimizing both design and operation that minimize cost and maximize efficiency, while satisfying performance requirements. This is a complex optimization problem of combined plant design and control that is not being adequately studied. Traditional approaches, such as dynamic programming, typically require severe modeling approximations, or high computational resources, which in practice limits their efficacy.
This project focuses on development of computationally efficient methods for combined design and control optimization of dynamic systems with energy buffers. The goal is to replace or augment traditional optimal control techniques with the novel technological improvements in convex optimization. Additionally, this project will investigate the synergy between convex optimization, mixed-integer programming, dynamic programming and optimal control theory. The second goal is adapting the optimization methods from the design phase to the real-time control in the final product. Investigations will be performed on functional architecture in the form of hierarchical, decentralized and distributed model predictive control and reference governor systems.

Popular scientific description (Swedish)*

Den tekniska utvecklingen mot högre energieffektivitet leder till allt mer komplexa system, såsom autonoma och hybrida fordon, energieffektiva byggnader, trådstyrda flygande vindkraftverk etc. De här systemen har ofta flera energibuffertar och kan använda prediktiv information till att förbättra energieffektiviteten. Att bättre utnyttja tillgängliga buffertsystemen blir således ett steg mot en hållbar ekonomi och miljö. Tekniken kräver viss investering i hårdvara, som vid jämförelse med konventionella lösningar måste kunna räknas hem i minskade energi- och driftkostnader. För att få nå ut till marknaden måste både design och funktion utformas så att den totala ägandekostnaden minimeras, samtidigt som prestandakraven uppfylls. Detta optimeringsproblem, med kombinerad dimensionering och styrning, är ett komplext problem som ännu inte studerats tillräckligt. Traditionella metoder, såsom dynamisk programmering, kräver vanligtvis stora modellapproximationer eller höga beräkningskrav, vilket i praktiken begränsar metodernas användbarhet.
Den här studien fokuserar på utveckling av beräkningsmässigt effektiva metoder för kombinerad dimensionering och optimal styrning av buffertsystem. Målet är att ersätta eller förbättra traditionella optimeringstekniker med de nya landvinningarna inom konvex optimering. Genom att använda konvex optimering är det för vissa problem möjligt att samtidigt optimera både dimensionering och styrning i polynomisk tid. Fokus kommer även vara på att utveckla metoder med samverkan mellan konvex optimering, mixed-integer programmering, dynamisk programmering och optimal styrning. De utvecklade metoderna kommer inte bara reducera beräkningsbördan jämfört med traditionella metoder, utan kommer också möjliggöra förbättrade modeller och inkludera dynamik som tidigare har utelämnats.
Det andra målet med den här studien är att anpassa optimeringsmetoderna till realtidsstyrning av dynamiska buffertsystem och därmed snabba upp utvecklingsprocessen genom att i huvudsak använda samma modeller och metoder både i förstudiestadiet som i den slutliga produkten. Med relativt begränsade beräkningsresurser blir den funktionella styrarkitekturen central för att möjliggöra modellprediktiv styrning av ett komplext system. Modellprediktiv styrning med hierarkisk, distribuerad och decentraliserad funktionell arkitektur kommer därför studeras inom projektet.

Project period

Number of project years*

3

Calculated project time*

2016-01-01 - 2018-12-31

Deductible time

Deductible time

Cause	Months
Career age: 34	

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*

1. Naturvetenskap > 101. Matematik > 10105. Beräkningsmatematik

1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804)

1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10205. Programvaruteknik

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

Keyword 1*

Optimal design

Keyword 2*

Optimal control

Keyword 3*

Convex optimization

Keyword 4

Energy management

Keyword 5

Dynamic systems

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*

This research does not raise any ethical issues.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

1. Motivation and background

The notion of sustainable economy and environment has motivated development of complex energy-clean and efficient systems. The development is also driven by governmental legislations. For example, the national energy plan of the Swedish parliament states that the specific energy use in residential and commercial buildings should be reduced by 20% until 2020 and halved until 2050 [5]. Similar goals have to be achieved in the transportation sector, where electrification of vehicles is being indicated as a possible solution. It has been projected that the use of electricity in the transportation sector has the potential of reducing energy consumption by 80% of the current level, by downsizing or even eliminating internal combustion engines, while facilitating renewable ways of generation in the power sector [4].

A common way of improving energy efficiency is to modify existing systems by appending energy buffers that increase the system degree of freedom. Examples of such systems are electrified vehicles [1], zero energy buildings [2], irrigations and drainage systems [3], etc. Additionally, the energy efficiency of the emerging dynamic systems depends on the way the plants are operated. The controller synthesis often includes predictive information, introducing the ability to recognize an entire or part of a fore coming trajectory based on user inputs, sensory information (e.g., radars, cameras, GPS), or previously collected measurements. The predictive information can be utilized to improve the system's energy efficiency, by deciding on distribution and arbitration of power among the energy buffers.

The additional degree of freedom, however, conveys an additional complexity in how these systems are designed and operated. The traditional approach which aimed at pursuing a feasible solution has now shifted focus to optimality. It is a *quest for the best* approach where both the operational and component cost within the system's lifetime are minimized. Hence, to be price-competitive, emerging dynamic systems often employ tools from mathematical optimization.

The optimal control of dynamic systems is a mature and thoroughly studied topic. However, the problem of combined plant design and control optimization merits further investigations. The survey of the field is deferred to Section 3, while the detailed problem description and examples of the two most common applications are provided in the reminder of this section.

Combined design and control optimization of dynamic systems with energy buffers

To obtain a cost effective solution that minimizes energy consumption while keeping total cost down, both the operational and component costs within the system's lifetime have to be minimized. These two objectives are strongly coupled, since a non-optimal controller may lead to non-optimal sizes of system's components, and vice versa [6]. The best approach is to simultaneously optimize the combined cost, also known as *total cost of ownership* (TCO). The optimization is subject to constraints derived from laws of physics, system's dynamics, limitations, performance requirements, etc. Without going into a detailed mathematical description, the problem is verbally formulated in Table 1.

The optimization results are twofold:

- Optimal sizes of components, e.g., power limits and energy capacity.
- Optimal control based on predictive information.

However, there is a layer on top of these results, which requires investigations that typically translate to: 1) interface and interplay among the system and infrastructures, such as electric

Table 1: Optimization problem for simultaneous component sizing and power-split control of a dynamic system.

Minimize:
Operational + component cost
Subject to:
Reference trajectory tracking and environmental constraints,
Energy conversion and balance constraints,
Performance requirements,
Physical limitations,
System dynamics,
…
For all time instances within a time-horizon

grid, weather satellites, telecommunication, navigation and traffic infrastructures; 2) configuration and choice of components; 3) selection of appropriate technology (e.g., electric capacitors, lithium-ion batteries); 4) reference and disturbance patterns (e.g., driving cycles for vehicles, weather forecast for buildings) upon which system's design and performance is to be optimized; 5) varying and future-projected prices for energy and components. As a consequence, the TCO problem in Table 1 has to be solved many times, in the order of thousands, which puts harsh requirements on computational efficiency.

A clearer picture of the problem of TCO minimization is provided by the following two real-world examples.

Example 1: Design and control of a hybrid electric vehicle (HEV)

An HEV is a vehicle with at least two sources of energy from which one is electric [7]. The HEV has an electric buffer (typically a battery and/or a supercapacitor) and one or more electric machines that may also generate electricity, e.g., while braking. The other energy source is typically petroleum or hydrogen. Compared to conventional vehicles, HEVs must also possess an additional controller, a power-split controller, which for a given level of requested power originating from the driver pressing the gas pedal, decides how big fraction of this power will be delivered by the fuel tank (e.g., via combustion engine) and the electric buffer.

Minimizing HEV's TCO requires careful consideration of the choice of powertrain topology (e.g., series, parallel, series-parallel), choice of powertrain components (e.g., battery, supercapacitor, flywheel, air tank, internal combustion engine. fuel cell system, continuously variable transmission, fixed-gearing transmission) and choice of typical driving patterns (described by, e.g., speed and slope vs. time). A plug-in HEV may also require additional considerations for a charging infrastructure that may have to be designed at the same time as the vehicle. (This is more relevant for public transportation, where decisions have to be taken about electrification of roads, distribution of chargers, charging durations and magnitude of charging power.) The problem of combined component sizing and control has to be solved for all these choices, where the operational cost includes cost for consumed fuel, electricity, and air pollutants. This cost will strongly depend on the HEV ability to recognize the receding horizon [1]. For example, information that a downhill driving is soon approaching can be exploited to run the vehicle on electric power, thus depleting the battery and making room for recuperation of the braking energy at the downhill segment.

Example 2: Design and control of an energy efficient building

The energy efficiency of buildings could be increased by 1) improving the building's thermal insulation and replacing the lightning and equipment/appliances with more efficient equivalents, and 2) by improving the ability to store energy for a later use [2]. Energy can be stored by using the building's structure as a thermal buffer. However, to improve efficiency even further, emerging buildings are augmented with additional thermal and electric buffers in order to store energy generated by, e.g., solar/photovoltaic panels, or wind turbines.

To minimize TCO, decisions have to be taken over many possible choices of components. This includes units that capture renewable energy (such as thermal solar collector, photovoltaics and wind turbine), diesel-electric generator, battery, heat storage tanks, waste water tank, cooling systems, electric or water heaters, etc. The number of combinations to configure these components is even greater than with HEVs, as every building may have a unique configuration. Then, the optimal component sizes that maintain desired level of heating, ventilation, air conditioning and humidity, can be obtained by solving the optimization problem described in Table 1. The operational cost may include electricity from the grid, diesel, fresh and hot water consumption, and emissions that pollute the environment. This cost will strongly depend on predictive information [2], e.g., thermal and electric loads of the building, electricity cost, weather forecast, rooms' occupancy, etc.

2. Purpose and aims

The overall objective of this project is to develop mathematical modeling and optimization methods for combined design and control of dynamic systems with energy buffers. The key ingredient is to study modeling steps that allow convex optimization techniques to be applied in order to exploit the computational efficiency of convex solvers [9].

The proposed study builds upon Nikolce's previous research [8] in the field of dimensioning and control of HEV powertrains. It has been shown, by Nikolce et al [10] (being the first to show this) that, although non-convex in its original form, the combined HEV design and control problem can be reformulated as a convex optimization problem. The strategy employs mathematical steps of disciplined convex programming, model approximations/linearization and reformulations, constraints relaxations, transformation from time to space domain, and projections from one search space to another. To give an example, consider the problem of optimal sizing and power control of a capacitor represented as a voltage source in series with a resistor. This model has been used in decades, but only recently has been proved, by Nikolce et al [11], that the problem can be remodeled as convex for both dimensioning and control purposes, and without any loss of modeling accuracy. As various buffer dynamics can be represented by equivalent resistor-capacitor (RC) circuits [12], the convexity of the capacitor, and thereby the RC circuits, will be exploited to extend the convex modeling steps to other energy buffers.

Based on these assertions, the following research goals are formulated, which will be detailed later, in Section 4:

- Convex modeling. The dynamic models for fluid tanks, fluid pumps, fans, battery aging, engine exhaust system, catalytic converters, cooling systems, and thermal modeling will be studied in terms of convexity, for efficient use in optimal dimensioning and control.
- Optimization methods development. The development of optimization methods will focus on employing the computational efficiency of convex solvers. The synergy

between convex optimization, optimal control theory and mixed-integer optimization will be studied in order to deal with integer variables that infringe convexity.

- Adaptation to real-time control. Development of dedicated convex solvers, and adaptation to real-time control of the methods used for TCO optimization will be investigated. This is a crucial ingredient for the autonomous operation of many systems. Hierarchical, distributed and decentralized optimization [26] will be also studied.
- Robust system design. The sensitivity of the optimal system design to uncertainties in reference and disturbance trajectories, energy and component prices, and non-optimal control due to limited or no access to predictive information will be investigated.
- Optimization tools and libraries. The developed optimization methods will be packed in publically accessible tools, in order to disseminate results and ease researchers share and reuse system models and optimization tools.

3. Survey of the field

Techniques for optimal control of dynamic systems, such as the famous dynamic programming [16], have been known for more than 50 years ago. However, the problem of combined plant design and control optimization has not been adequately studied. Existing approaches handle the problem by decoupling the plant and controller, and then optimizing them sequentially or iteratively [30]-[32]. This approach is currently state of the art in optimization of energy efficient buildings, where the system is first designed by engineering decisions and then the controller is optimized for the pre-defined system [2][13]. Sequential and iterative strategies, however, generally fail to achieve global optimality [31].

For the problem of dimensioning and control of HEVs attempts have been undertaken to optimize these two objectives simultaneously. There are two main approaches; the first approach relies on heuristic algorithms [14][15], while the second approach employs optimal control theory. Heuristic methods could be computationally efficient in obtaining a solution, but they do not provide a mechanism to qualify the optimality of the solution. Hence, such solutions are pursued by decision makers only when optimal control methods are not available.

From the optimal control methods, dynamic programming (DP) is the most commonly used. The solution is typically sought in a nested optimization strategy, where an outer loop optimizes system’s objective over the set of feasible plants, and an inner loop generates optimal control for plants chosen by the outer loop [31]. This approach delivers the globally optimal solution, but it may induce heavy computational burden, if e.g., DP is used for the optimal control, or may require substantial modeling approximations. A serious limitation of DP is that the computational time increases exponentially with the number of states and design variables [16]. As a consequence, the models are typically limited to only one, or possibly two states [17][18], which may not be sufficient to correctly describe the actual system dynamics.

Another well-known strategy for optimal control of HEVs is the Equivalence Consumption Minimization Strategy (ECMS) [1]. The strategy is based on the Pontryagin’s maximum principle [25], and could essentially be used for combined plant design and control in a nested optimization fashion, as described above. However, ECMS is only an approximate procedure in control problems where state constraints are activated. This is typically the case in most control applications.

In terms of computational efficiency a more promising approach has been recently presented by Nikolce et al [19], where convex optimization has been proposed for dimensioning and control of HEVs with either a series, or a parallel powertrain topology. The method is based on splitting the optimization into two nested levels, which allow the problem to be broken down into several convex sub-problems. Integer control variables, such as engine on/off and gear, are decided in the outer level, using Pontryagin's maximum principle [24][33] or DP [34]. The optimal component sizes and optimal control and state trajectories of the real-valued signals are obtained in the inner level, by using direct optimal control techniques, such as convex optimization. For given values of the integer variables, the convex optimization guarantees optimality (and provides a certificate for optimality). By decoupling the integer and control variables, the proposed method provides solutions in few minutes (very often in seconds, or milliseconds) on a standard PC. Moreover, the computational time does not increase exponentially with the number of states, which allows enhancing the models with essential dynamics that have been omitted in previous studies.

4. Project description

Detailed description of the proposed research studies can be described by the following tasks:

T1. Convex modeling and simulation environment:

T1.1. Enhanced battery model: This task investigates convex modeling of battery cells including thermal and aging phenomena [20]. The goal is to address the dynamics of fast charging and discharging impulses which may significantly influence battery aging and losses.

T1.2. Energy storage units: The convex modeling of fluid storage tanks, fuel cells, flywheels and thermal buffers will be investigated. The key step is to employ our most recent findings [11] about convexity of RC circuits, and the analogous electric RC description of different energy buffers. For a mobile system, such as a vehicle, the system itself could be considered a buffer that stores kinetic and potential energy. We have already shown initial results on the convex modeling of buffers for storing potential and kinetic energy [35].

T1.3. Enhanced models of actuators and other components: This task investigates convex modeling of fluid pumps, fans, condensers, retarders, catalytic converter[1], cooling units, room/passenger compartment. The possibility to augment the existing convex models of internal combustion engine and electric machine [8] with boost pressure and thermal dynamics will also be investigated.

T2. Optimization method development: This task follows our initial research in [24] [33][34], investigating the synergy between convex optimization, mixed-integer optimization and optimal control methods such as Pontryagin's maximum principles and DP.

T3. Adaptation to real-time control:

T3.1. Hierarchical and distributed optimization: The state of the art solvers allow convex problems to be solved in a distributed fashion [26], and additional research is needed to remodel the studied problem as a distributed convex program. Distributed optimization may enable different sub-systems co-optimize their own objective, while negotiating on values of shared signals (similar to trading, where parties negotiate over a commonly acceptable price). In the process of manufacturing a dynamic buffer

[1]The influence of the catalytic converter on the optimal system's design has been very little studied. The catalytic converter is a device that filters out pollutants such as carbon monoxide, hydrocarbon and nitrogen oxides. Therefore, with the goal of sustainable environment, it is vital to include a model of this device within the system's design phase.

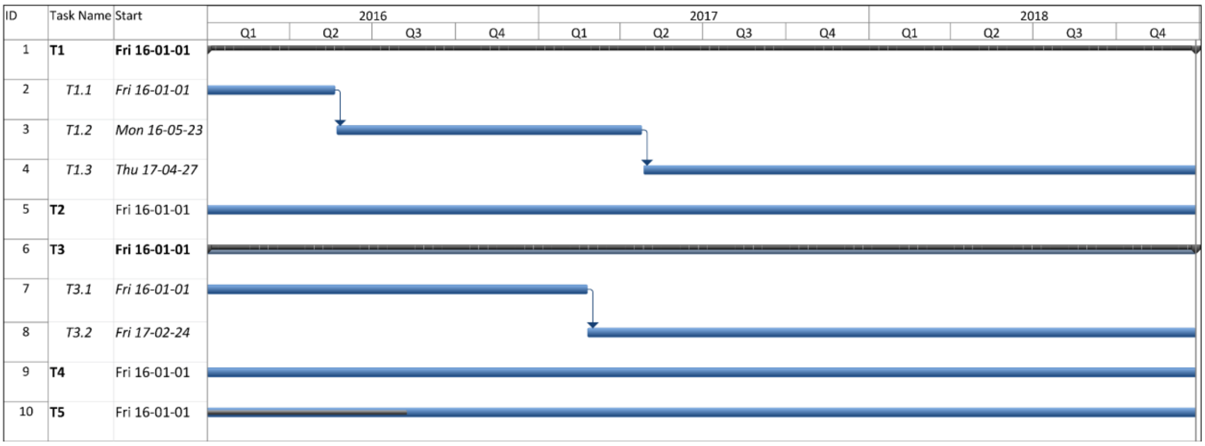

Figure 1: Timetable for the research tasks. Teaching activities are intermittent throughout the entire study period.

system, this will allow different departments optimize the sub-system they are specialized on, where models are built upon a signal that is shared by the sub-systems. Thus, very complex systems can be simplified into sub-systems that are easier to deal with.

T3.2. Dedicated convex solvers: This task focuses on adapting the TCO optimization methods, to methods for real-time model predictive control [28]. The goal is to design a functional architecture, and exploit problem sparsity, in order to decrease computational time and memory requirements, and to fit and run the code on existing embedded control units.

T4. Robustness: This task investigates the dependence of the optimal design to uncertainties in reference/disturbance trajectories, e.g., driving behaviors and climate changes. Uncertainties in projected future energy and component prices, and non-optimal control due to limited or no access to predictive information will also be studied.

T5. Optimization tools and libraries: The developed optimization methods are being packed in tools that are publically accessible by other researcher. Several examples of convex optimization in electromobility studies are already published [13]. Our goal is to continuously add new tools and examples, following the increased research interest by the research community.

The project's timetable, including the tasks listed above, is given in Figure 2.

5. Significance

The emerging complex energy-clean and efficient systems come with an increased cost. The technology introduced to these systems, especially electric batteries and supercapacitors, influence price the most. Furthermore, if not operated properly, the life expectancy of batteries may significantly suffer. Hence, to improve the market penetration of the emerging dynamic systems, solutions are sought that minimize the system's TCO, i.e. operational and component cost. Optimization tools are required that not only provide the optimal solution, but they do so with low computational demands. This is necessary for a detailed investigation of system's dependencies triggered by the paradigm change of the new technology. One of the goals of this study is to provide a tool that addresses the problem of TCO minimization. The tool is being built by using techniques from convex optimization, which has recently reached hype in the research community, and has already been regarded as the most promising technology [9].

The second goal of this study is to adapt the TCO optimization methods to real-time control of dynamic buffer systems and thus speed up the development process, by essentially using the same models and methods both in the pre-design phase and in the final product. The automated, real-time control of emerging dynamic systems is fundamental now and will be necessary in near future. Increased usage of automatic control in houses can be expected [2], while autonomous driving is on the horizon. The requirements on performance of these systems is not only being feasible, but also optimal in all respects. Hence, many optimization algorithms will run in real-time, under limited physical resources. It has been shown that convex optimization is the most promising technology to meet these requirements [9][21]-[23][27]. This study will investigate the real-time implementation of convex solvers. Furthermore, state of the art techniques will be investigated, such as distributed optimization [26], and decentralized hierarchical control.

6. Preliminary results

After the principal methods for combined design and control via convex optimization have been provided by Nikolce et al [10], they have been significantly improved and successfully implemented by researchers and engineers. A major reason for the success of these methods is in the performed transformations that exactly reformulate the problem to a form that is easier to solve. Typical examples of such contributions are our papers N. Murgovski et al, *Convex modeling of energy buffers in power control applications* [11] and N. Murgovski et al. *Convex relaxations in the optimal control of electrified vehicles* [35]. In these papers we have shown that two well-studied control problems that were known to be exceptionally difficult to solve, can be formulated as convex programs that not only solve the problems much faster (reduced computation time by a factor 100, or more), but are also very elegant in its simplicity.

The most notable preliminary results with industrial partners are those with AB Volvo, 2012-2014. The tools developed during Nikolce's PhD studies have been used to investigate the potential of alternative powertrain technologies to be introduced to the market in the following 3-10 years. This collaboration has been featured in the Chalmers News as a success story: *The researchers who can predict the future of transportation* [29]. Thanks to these results, a new project on the development of a hybrid electric vehicle platform within AB Volvo has been initiated. Nikolce's involvement in this, following project has been in the development of optimal energy management controllers in the form of reference governor systems that run in a hierarchical decentralized fashion and in real-time, on-board the vehicle. One of the goals has been to optimize the charge/discharge trajectories of energy buffers by using predictive road information. Already at the start of the project we had several breakthroughs. A patent application has been submitted, and an article has been written and submitted to Control Engineering Practice. By considering the vehicle as a buffer for kinetic and potential energy, the innovation permits convex optimization to be used for a real-time decision on the optimal speed trajectory in a succeeding horizon, allowing a semi-autonomous driving. The result of this project, together with our recent findings [37], have influenced the initiation of the FFI project on Multivariable engine control methods for improved energy efficiency, which is about to start.

A major goal of this project is to disseminate results and notify research community that our proposed methodology is an efficient tool that is valuable for researchers and engineers in the area of optimal design and control of dynamic systems. First steps have been taken by publishing open source Matlab code [13] that demonstrates the effectiveness and the computational advantage of the convex programming methodology. Collaboration with other researchers has also been initiated. As for example, two papers have been recently published together with researchers from ETH, Switzerland [33][36]. A journal article has been submitted with researchers from University of California, Berkeley, and Cranfield University, UK. Two conference papers have been submitted, and Nikolce is currently working on additional three journal articles with researcher from Eindhoven University, The Netherlands. Within the department of Signals and System at Chalmers University, Nikolce has established collaboration with the groups of Mechatronics, Automatic Control and Signal Processing. Nikolce has also actively participated in several projects, such as the Green Car[2,3], FUEREX[4], OPTIMORE[5], Plug-in bus, IVDC[6].

7. Independent line of research

The applicant works in a research group with solid experience in both fundamental and applied research in the field of optimal control, intelligent transportation and system's design. The ideas outlined in this project originate from the applicant's research activities and are not related with the research performed by his former advisor.

The applicant's research has been strongly intertwined with industrial collaborations. However, to preserve the quality of contributions it is crucial to obtain individual funding, in order to alleviate the strong dependence on industrial aspirations.

8. Form of employment

The applicant is applying for 50% of full time costs for an Assistant Professor, for a period of three years within 2016-2018. As of January 2015, the applicant is an Assistant Professor at the department of Signals and Systems, Chalmers University.

9. International and national collaboration

The applicant current collaborates with researchers from Eindhoven University, The Netherlands. Research is being conducted on three topics: 1) Optimal control of complex engine systems with after-treatment and waste heat recovery; 2) Optimal dimensioning and control of a novel engine concept with electric supercharger; and 3) Optimization strategies for system-level design in hybrid electric vehicles.

The applicant will visit The Ohio State University, for the period of two months, July-August, 2015. Collaboration is planned on the utilization of convex optimization in electromobility and autonomous driving.

The applicant has also envisaged a visit to the University of Michigan and Berkeley University, although a detailed plan has not yet been established.

[2] Green Car 1, http://www.vinnova.se/sv/ffi/Om-FFI/Tidigare-forskning---PFF/Grona-bilen-1/
[3] Green Car 2, http://www.vinnova.se/sv/ffi/Om-FFI/Tidigare-forskning---PFF/Grona-bilen-2/
[4] FUEREX, http://www.fuerex.eu/
[5] OPTIMORE, http://www.optimore-project.eu/
[6] IVDC (Integrated Vehicle Design and Control), https://www.viktoria.se/projects/ivdc

References

[1] A. Sciarretta, L. Guzzella. Control of hybrid electric vehicles. IEEE Control Systems Magazine, vol. 27, no. 2, pp. 60-70, 2007.

[2] Y. Ma, A. Kelman, A. Daly, F. Borrelli. Predictive control for energy efficient buildings with thermal storage: modeling, simulation, and experiments. IEEE Control Systems Magazine, vol. 32, no. 1, pp. 44-64, 2012.

[3] J.M. Lemos. Distributed linear-quadratic control of serially chained systems: application to a water delivery canal [Applications of control]. IEEE Control Systems, vol. 32, no. 6, pp. 26-38, 2012.

[4] D. MacKay. Sustainable Energy: Without the Hot Air. Cambridge: UIT Cambridge, 2009.

[5] Swedish energy agency. Energy in Sweden. Eskilstuna, 2008.

[6] T. C. Moore. HEV control strategy: Implications of performance criteria, system configuration and design, and component selection. Proceedings of the American Control Conference, Albuquerque, New Mexico, June 1997.

[7] L. Guzzella and A. Sciarretta. Vehicle propulsion systems, introduction to modeling and optimization. 2nd ed. Berlin, Heidelberg: Springer, 2007.

[8] N. Murgovski. Optimal powertrain dimensioning and potential assessment of hybrid electric vehicles. Ph.D. thesis, Chalmers University of Technology, Sweden, 2012.

[9] S. Boyd and L. Vandenberghe. Convex Optimization. Cambridge University Press, 2004.

[10] N. Murgovski, L. Johannesson, J. Hellgren, B. Egardt, J. Sjöberg. Convex optimization of charging infrastructure design and component sizing of a plug-in series HEV powertrain. IFAC World Congress, Milano, Italy, 2011.

[11] N. Murgovski, L. Johannesson, J. Sjöberg. Convex modeling of energy buffers in power control applications. IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-CoSM), Rueil-Malmaison, Paris, France, October 23-25 2012.

[12] A. P. Ramallo-González, M. E. Eames, D. A. Coley. Lumped parameter models for building thermal modelling: An analytic approach to simplifying complex multi-layered constructions. Journal of Energy and Buildings, vol. 60, pp. 174-184, 2013.

[13] N. Murgovski. CONES: Matlab code for convex optimization in electromobility studies. Chalmers University of Technology, https://publications.lib.chalmers.se/publication/192858, January 2014.

[14] S. M. Lukic and A. Emadi. Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles. IEEE Transactions on Vehicular Technology, vol. 53, no. 2, pp. 385–389, 2004.

[15] S. Ebbesen, C. Dönitz, and L. Guzzella. Particle swarm optimization for hybrid electric drive-train sizing. Int. J. Vehicle Design, vol. 58, no. 58, pp. 181–199, 2012.

[16] R. Bellman. Dynamic Programming. New Jersey: Princeton Univ Pr, June 1957.

[17] U. Zoelch and D. Schroeder. Dynamic optimization method for design and rating of the components of a hybrid vehicle. International Journal of Vehicle Design, vol. 19, no. 1, pp. 1–13, 1998.

[18] O. Sundström, L. Guzzella, and P. Soltic. Torque-assist hybrid electric powertrain sizing: From optimal control towards a sizing law. IEEE Transactions on Control Systems Technology, vol. 18, no. 4, pp. 837-849, July 2010.

[19] N. Murgovski, L. Johannesson, J. Sjöberg, B. Egardt. Component sizing of a plug-in hybrid electric powertrain via convex optimization. Journal of Mechatronics, vol. 22, no. 1, pp. 106-120, 2012.

[20] S. B. Peterson, J. Apt, and J. Whitacre. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. Journal of Power Sources, vol. 195, no. 8, pp. 2385–2392, 2010.
[21] I. CVX Research. CVX: Matlab software for disciplined convex programming, version 2.0 beta. http://cvxr.com/cvx, Sep. 2012.
[22] J. Löfberg. YALMIP: A Toolbox for Modeling and Optimization in MATLAB. Proceedings of the CACSD Conference, Taipei, Taiwan, 2004.
[23] Y. Labit, D. Peaucelle, and D. Henrion. SeDuMi interface 1.02: a tool for solving LMI problems with SeDuMi. IEEE International Symposium on Computer Aided Control System Design Proceedings, pp. 272–277, September 2002.
[24] N. Murgovski, L. Johannesson, J. Sjöberg. Engine on/off control for dimensioning hybrid electric powertrains via convex optimization. IEEE Transactions on Vehicular Technology, vol. 62, no. 7, pp. 2949-2962, 2013.
[25] A. E. Bryson, Y.-C. Ho. Applied Optimal Control. Taylor & Francis Group, 1975.
[26] S. Boyd, N. Parikh, and E. Chu. Distributed Optimization and Statistical Learning via the Alternating Direction Method of Multipliers. Now Publishers Inc, 2011.
[27] J. Mattingley, S. Boyd. CVXGEN: A Code Generator for Embedded Convex Optimization. Optimization and Engineering, vol. 12, no. 1, pp. 1-27, 2012.
[28] C. E. García, D. M. Prett, M. Morari. Model predictive control: Theory and practice - A survey. Automatica, vol. 25, no. 3, pp. 335-348, 1989.
[29] The researchers who can predict the future of transportation. Chalmers University of Technology, 2013. http://www.chalmers.se/en/departments/s2/news/Pages/S2-researchers-help-Volvo-AB-understand-the-future-of-transportation.aspx.
[30] A. J. Conejo, E. Castillo, R. Mnguez, R. Garca-Bertrand. Decomposition Techniques in Mathematical Programming. Engineering and science applications. Berlin/Heidelberg/New York: Springer, 2006.
[31] H. Fathy, P. Papalambros, A. Ulsoy. On combined plant and control optimization. In 8th Cairo University International Conference on Mechanical Design and Production, Cairo University, 2004.
[32] D. L. Peters, P. Y. Papalambros, A. G. Ulsoy. “Sequential co-design of an artifact and its controller via control proxy functions. Mechatronics, 23(4):409–418, 2013.
[33] P. Elbert, T. Nüesch, A. Ritter, N. Murgovski, L. Guzzella. Engine on/off control for the energy management of a serial hybrid electric bus via convex optimization. IEEE Transactions on Vehicular Technology, vol. 63, no. 8, pp. 3549-3559, 2014.
[34] M. Pourabdollah, N. Murgovski, B. Egardt, A. Grauers. An iterative dynamic programming/convex optimization procedure for optimal sizing and energy management of PHEVs. IFAC World Congress, Cape Town, South Africa, 2014.
[35] N. Murgovski, L. Johannesson, X. Hu, B. Egardt, J. Sjöberg. Convex relaxations in the optimal control of electrified vehicles. American Control Conference, Chicago, USA, 2015, Accepted.
[36] L. Johannesson, N. Murgovski, S. Ebbessen, B. Egardt, E. Gelso, J. Hellgren. Including a battery state of health model in the HEV component sizing and optimal control problem. IFAC Symposium on Advances in Automotive Control, Tokyo, Japan, 2013.
[37] N. Murgovski, M. Grahn, L. Johannesson, T. McKelvey. Automated engine calibration of hybrid electric vehicles. IEEE Transactions on Control Systems Technology. DOI: 10.1109/TCST.2014.2360920.

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

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	Applicant	Nikolce Murgovski	50

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	Total
1	Applicant	Nikolce Murgovski	50	398,000	412,000	426,000	1,236,000
	Total			398,000	412,000	426,000	1,236,000

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	Total
1	Office space	29,000	30,000	31,000	90,000
	Total	29,000	30,000	31,000	90,000

Running Costs

	Running Cost	Description	2016	2017	2018	Total
1	Conferences, literature, travel, IT	Conferences, literature, travel, IT	43,000	47,000	49,000	139,000
	Total		43,000	47,000	49,000	139,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018

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	Total, applied	Other costs	Total cost
Salaries including social fees	398,000	412,000	426,000	1,236,000		1,236,000
Running costs	43,000	47,000	49,000	139,000		139,000
Depreciation costs				0		0
Premises	29,000	30,000	31,000	90,000		90,000
Subtotal	470,000	489,000	506,000	1,465,000	0	1,465,000
Indirect costs	146,000	151,000	156,000	453,000		453,000
Total project cost	616,000	640,000	662,000	1,918,000	0	1,918,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The proposed budget considers 50% of full time costs for an Assistant Professor, for a period of three years within 2016-2018. The running costs include costs for IT, literature, conferences and travel.

	2016	2017	2018
IT	9000	9000	9000
Literature	2500	2500	3000
Conferences	6000	7000	7000
Travel	26000	28000	30000

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

CV and publications

CV

Nikolce Murgovski

Higher education qualifications

2005 – 2007 MSc in Complex Adaptive Systems, Applied Physics, Chalmers University of Technology, Gothenburg, Sweden.

Subjects: Evolutionary algorithms, Artificial neural networks, Humanoid robots, Autonomous agents, Simulation of complex systems, Computational biology, Dynamical systems, Information theory.

Thesis: Vehicle modeling and washout filter tuning for the Chalmers Vehicle Simulator.

2006 – 2007 MSc in Software Engineering, University West, Trollhättan, Sweden.

Subjects: Technical programming, Software development through modeling, Requirements engineering, Verification and validation in software, Component technologies, Theory and publication methodology in science, Software engineering.

Thesis: Optimization of chemical pulp bleaching process.

1999 – 2004 BSc in Computer Science, Information Technology & Automation, Faculty of Electrical Engineering, Skopje, Macedonia.

Doctoral degree

2007 – 2012 PhD in Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.

Thesis: Optimal powertrain dimensioning and potential assessment of hybrid electric vehicles.

Postdoctoral position

2012 –2014 Postdoc in Mechatronics, Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.

Current position

2015 –2018 Assistant Professor in Mechatronics, Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden.

Previous positions

2003 – 2005 Company: Macedonian Telecommunications AD, Skopje, Macedonia.
Position: Project manager / web & software developer.

Consultancy and outsourcing

2014 Company: Viktoria Swedish ICT, Gothenburg, Sweden.
Position: Consultant for development of real-time control architecture for AB Volvo.

2012-2013 Company: Viktoria Swedish ICT, Gothenburg, Sweden.
Position: Consultant for minimizing total cost of vehicle ownership for AB Volvo.
Info: "The researchers who can predict the future of transportation"
http://www.chalmers.se/en/departments/s2/news/Pages/S2-researchers-help-Volvo-AB-understand-the-future-of-transportation.aspx.

2007 Company: FindWise, Gothenburg, Sweden (project work).
Position: Software developer for visual presentation of relationships between information entities in enterprise search engines.

2007 Gothenburg University, Gothenburg, Sweden (project work).
Position: Software developer for spectral analyses of air pollutants.

2007 Company: EKA Chemicals, Gothenburg, Sweden (master thesis project).
Position: Optimization of chemical pulp bleaching.

2005 Company: Pexim, Serbia (project work).
Position: Software developer for bank administration.

Publication list

Publication List

Peer-reviewed articles

[1] *N. Murgovski, M. Grahn, L. Johannesson, T. McKelvey. Automated engine calibration of hybrid electric vehicles. IEEE Transactions on Control Systems Technology. DOI: 10.1109/TCST.2014.2360920.

[2] X. Hu, L. Johannesson, N. Murgovski, B. Egardt. Longevity-conscious dimensioning and power management of the hybrid energy storage system in a fuel cell hybrid electric bus. Applied Energy, vol. 137, pp. 913-924, 2015.

[3] X. Hu, N. Murgovski, L. Johannesson, B. Egardt. Optimal dimensioning and power management of a fuel cell/battery hybrid bus via convex programming. IEEE/ASME Transactions on Mechatronics, vol. 20, no. 1, pp. 457-468, 2015.

[4] P. Elbert, T. Nüesch, A. Ritter, N. Murgovski, L. Guzzella. Engine on/off control for the energy management of a serial hybrid electric bus via convex optimization. IEEE Transactions on Vehicular Technology, vol. 63, no. 8, pp. 3549-3559, 2014.

[5] X. Hu, N. Murgovski, L. Johannesson, B. Egardt. Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous optimal sizing and energy management. IEEE Transactions on Intelligent Transportation Systems, vol. 15, no. 3, pp. 1193-1205, 2014.

[6] N. Murgovski, L. Johannesson, B. Egardt. Optimal battery dimensioning and control of a CVT PHEV powertrain. IEEE Transactions on Vehicular Technology, vol. 63, no. 5, pp. 2151-2161, 2014.

[7] *B. Egardt, N. Murgovski, M. Pourabdollah, L. Johannesson. Electromobility studies based on convex optimization: design and control issues regarding vehicle electrification. IEEE Control Systems Magazine, vol. 34, no. 2, pp. 32-49, 2014.

[8] X. Hu, N. Murgovski, L. Johannesson, B. Egardt. Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes. Applied Energy, vol. 111, pp. 1001-1009, 2013.

[9] N. Murgovski, L. Johannesson, J. Sjöberg. Engine on/off control for dimensioning hybrid electric powertrains via convex optimization. IEEE Transactions on Vehicular Technology, vol. 62, no. 7, pp. 2949-2962, 2013.

[10] M. Pourabdollah, N. Murgovski, A. Grauers, B. Egardt. Optimal sizing of a parallel PHEV powertrain. IEEE Transactions on Vehicular Technology, vol. 62, no. 6, pp. 2469-2480, 2013.

[11] *N. Murgovski, L. Johannesson, J. Sjöberg, B. Egardt. Component sizing of a plug-in hybrid electric powertrain via convex optimization. Mechatronics, vol. 22, no. 1, pp. 106-120, 2012.

[12] N. Murgovski, J. Sjöberg, J. Fredriksson. A methodology and a tool for evaluating hybrid electric powertrain configurations. Int. Journal of Electric and Hybrid Vehicles, vol. 3, no. 3, pp. 219-245, 2011.

Peer-reviewed conference papers

[1] *N. Murgovski, L. Johannesson, X. Hu, B. Egardt, J. Sjöberg. Convex relaxations in the optimal control of electrified vehicles. American Control Conference, Chicago, USA, 2015. Accepted for publication.

[2] N. Murgovski, X. Hu, B. Egardt. Computationally efficient energy management of a planetary gear hybrid electric vehicle. IFAC World Congress, Cape Town, South Africa, 2014.

[3] M. Pourabdollah, N. Murgovski, B. Egardt, A. Grauers. An iterative dynamic programming/convex optimization procedure for optimal sizing and energy management of PHEVs. IFAC World Congress, Cape Town, South Africa, 2014.

[4] L. Johannesson, N. Murgovski, S. Ebbessen, B. Egardt, E. Gelso, J. Hellgren. Including a battery state of health model in the HEV component sizing and optimal control problem. IFAC Symposium on Advances in Automotive Control, Tokyo, Japan, 2013.

[5] N. Murgovski, X. Hu, B. Egardt. Filtering driving cycles for assessment of electrified vehicles. Workshop for new energy vehicle dynamic system and control technology, Beijing, China, 2013.

[6] N. Murgovski, L. Johannesson, A. Grauers, J. Sjöberg. Dimensioning and control of a thermally constrained double buffer plug-in HEV powertrain. 51st IEEE Conference on Decision and Control, Maui, Hawaii, 2012.

[7] *N. Murgovski, L. Johannesson, J. Sjöberg. Convex modeling of energy buffers in power control applications. IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-CoSM), Rueil-Malmaison, Paris, France, 2012.

[8] N. Murgovski, L. Johannesson, J. Hellgren, B. Egardt, J. Sjöberg. Convex optimization of charging infrastructure design and component sizing of a plug-in series HEV powertrain. IFAC World Congress, Milano, Italy, 2011.

[9] N. Murgovski, J. Sjöberg, J. Fredriksson. Automatic simplification of hybrid powertrain models for use in optimization. International Symposium on Advanced Vehicle Control, Loughborough, UK, 2010.

[10] N. Murgovski, J. Sjöberg, J. Fredriksson. A tool for generating optimal control laws for hybrid electric powertrains. IFAC Symposium on Advances in Automotive Control, Munich, Germany, 2010.

[11] N. Murgovski, J. Sjöberg, J. Fredriksson. Hybrid powertrain concept evaluation using optimization. Electric Vehicle Symposium (EVS-25), Shenzhen, China, 2010.

[12] I. Jolevski, S. Loskovska, I. Chorbev, D. Mihajlov, N. Murgovski. Constraints Modeling of the High School Scheduling Problem. IEEE Conference on computer as a tool, EUROCON, 2005.

Book chapters

[1] N. Murgovski, X. Hu, L. Johannesson, B. Egardt. Combined design and control optimization of hybrid vehicles. Handbook of Clean Energy Systems. In press.

Open access computer programs

[1] N. Murgovski, "CONES: Matlab code for convex optimization in electromobility studies", Chalmers University of Technology, https://chalmersuniversity.app.box.com/cones, January 2014.

CV

Name: Nikolce Murgovski	**Doctorial degree:** 2012-05-29
Birthdate: 19800629	**Academic title:** Doktor
Gender: Male	**Employer:** Chalmers tekniska högskola

Research education

Dissertation title (swe)

Dissertation title (en)

Optimal powertrain dimensioning and potential assessment of hybrid electric vehicles

Organisation	Unit	Supervisor
Chalmers tekniska högskola, Sweden Sweden - Higher education Institutes	3206 - Reglerteknik, automation och mekatronik	Jonas Sjöberg

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804)	ISBN 978-91-7385-682-9	2012-05-29

Publications

Name: Nikolce Murgovski	**Doctorial degree:** 2012-05-29
Birthdate: 19800629	**Academic title:** Doktor
Gender: Male	**Employer:** Chalmers tekniska högskola

Murgovski, Nikolce 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.