Overnight glucose control in people with type 1 diabetes

This paper presents an individualized model predictive control (MPC) algorithm for overnight blood glucose stabilization in people with type 1 diabetes (T1D). The MPC formulation uses an asymmetric objective function that penalizes low glucose levels more heavily. We compute the model parameters in the MPC in a systematic way based on a priori available patient information. The model used by the MPC algorithm for filtering and prediction is an autoregressive integrated moving average with exogenous input (ARIMAX) model implemented as a linear state space model in innovation form. The control algorithm uses frequent glucose measurements from a continuous glucose monitor (CGM) and its decisions are implemented by a continuous subcutaneous insulin infusion (CSII) pump. We provide guidelines for tuning the control algorithm and computing the Kalman gain in the linear state space model in innovation form. We test the controller on a cohort of 100 randomly generated virtual patients with a representative inter-subject variability. We use the same control algorithm for a feasibility overnight study using 5 real patients. In this study, we compare the performance of this control algorithm with the patient’s usual pump setting. We discuss the results of the numerical simulations and the in vivo clinical study from a control engineering perspective. The results demonstrate that the proposed control strategy increases the time spent in euglycemia.
Evaluation of pharmacokinetic model designs for subcutaneous infusion of insulin aspart

Effective mathematical modelling of continuous subcutaneous infusion pharmacokinetics should aid understanding and control in insulin therapy. Thorough analysis of candidate model performance is important for selecting the appropriate models. Eight candidate models for insulin pharmacokinetics included a range of modelled behaviours, parameters and complexity. The models were compared using clinical data from subjects with type 1 diabetes with continuous subcutaneous insulin infusion. Performance of the models was compared through several analyses: $R^2$ for goodness of fit; the Akaike Information Criterion; a bootstrap analysis for practical identifiability; a simulation exercise for predictability. The simplest model fit poorly to the data ($R^2 = 0.53$), had the highest Akaike score, and worst prediction. Goodness of fit improved with increasing model complexity ($R^2 = 0.85-0.92$) but Akaike scores were similar for these models. Complexity increased practical non-identifiability, where small changes in the dataset caused large variation (CV > 10%) in identified parameters in the most complex models. Best prediction was achieved in a relatively simple model. Some model complexity was necessary to achieve good data fit but further complexity introduced practical non-identifiability and worsened prediction capability. The best model used two linear subcutaneous compartments, an interstitial and plasma compartment, and two identified variables for interstitial clearance and subcutaneous transfer rate. This model had optimal performance trade-off with reasonable fit ($R^2 = 0.85$) and parameterisation, and best prediction and practical identifiability (CV < 2%).

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Adaptive control in an artificial pancreas for people with type 1 diabetes

In this paper, we discuss overnight blood glucose stabilization in patients with type 1 diabetes using a Model Predictive Controller (MPC). We compute the model parameters in the MPC using a simple and systematic method based on a priori available patient information. We describe and compare 3 different model structures. The first model structure is an autoregressive integrated moving average with exogenous input (ARIMAX) structure. The second model structure is an autoregressive moving average with exogenous input (ARMAX) model, i.e. a model without an integrator. The third model structure is an adaptive ARMAX model in which we use a recursive extended least squares (RELS) method to estimate parameters of the stochastic part. In addition, we describe some safety layers in the control algorithm that improve the controller robustness and reduce the risk of hypoglycemia. We test and compare our control strategies using a virtual clinic of 100 randomly generated patients with a representative inter-subject variability. This virtual clinic is based on the Hovorka model. We consider the case where only half of the meal bolus is administered at mealtime, and the case where the insulin sensitivity increases during the night. The numerical results suggest that the use of an integrator leads to higher occurrence of hypoglycemia than for the controllers without the integrator. Compared to other control strategies, the adaptive MPC reduces both the time spent in hypoglycemia and the time spent in hyperglycemia.
A least squares approach for efficient and reliable short-term versus long-term optimization

The uncertainties related to long-term forecasts of oil prices impose significant financial risk on ventures of oil production. To minimize risk, oil companies are inclined to maximize profit over short-term horizons ranging from months to a few years. In contrast, conventional production optimization maximizes long-term profits over horizons that span more than a decade. To address this challenge, the oil literature has introduced short-term versus long-term optimization. Ideally, this problem is solved by a posteriori multi-objective optimization methods that generate an approximation to the Pareto front of optimal short-term and long-term trade-offs. However, such methods rely on a large number of reservoir simulations and scale poorly with the number of objectives subject to optimization. Consequently, the large-scale nature of production optimization severely limits applications to real-life scenarios. More practical alternatives include ad hoc hierarchical switching schemes. As a drawback, such methods lack robustness due to unclear convergence properties and do not naturally generalize to cases of more than two objectives. Also, as this paper shows, the hierarchical formulation may skew the balance between the objectives, leaving an unfulfilled potential to increase profits. To promote efficient and reliable short-term versus long-term optimization, this paper introduces a natural way to characterize desirable Pareto points and proposes a novel least squares (LS) method. Unlike hierarchical approaches, the method is guaranteed to converge to a Pareto optimal point. Also, the LS method is designed to properly balance multiple objectives, independently of Pareto front’s shape. As such, the method poses a practical alternative to a posteriori methods in situations where the frontier is intractable to generate.

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An Adaptive Nonlinear Basal-Bolus Calculator for Patients With Type 1 Diabetes

Background: Bolus calculators help patients with type 1 diabetes to mitigate the effect of meals on their blood glucose by administering a large amount of insulin at mealtime. Intraindividual changes in patients physiology and nonlinearity in insulin-glucose dynamics pose a challenge to the accuracy of such calculators.

Method: We propose a method based on a continuous-discrete unscented Kalman filter to continuously track the postprandial glucose dynamics and the insulin sensitivity. We augment the Medtronic Virtual Patient (MVP) model to simulate noise-corrupted data from a continuous glucose monitor (CGM). The basal rate is determined by calculating the steady state of the model and is adjusted once a day before breakfast. The bolus size is determined by optimizing the postprandial glucose values based on an estimate of the insulin sensitivity and states, as well as the announced meal size. Following meal announcements, the meal compartment and the meal time constant are estimated, otherwise insulin sensitivity is estimated.

Results: We compare the performance of a conventional linear bolus calculator with the proposed bolus calculator. The proposed basal-bolus calculator significantly improves the time spent in glucose target (P < .01) compared to the conventional bolus calculator.

Conclusion: An adaptive nonlinear basal-bolus calculator can efficiently compensate for physiological changes. Further clinical studies will be needed to validate the results.
An experimentally validated simulation model for a four-stage spray dryer

In this paper, we develop a dynamic model of an industrial type medium size four-stage spray dryer. The purpose of the model is to enable simulations of the spray dryer at different operating points, such that the model facilitates development and comparison of control strategies. The dryer is divided into four consecutive stages: a primary spray drying stage, two heated fluid bed stages, and a cooling fluid bed stage. Each of these stages in the model is assumed ideally mixed and the dynamics are described by mass- and energy balances. These balance equations are coupled with constitutive equations such as a thermodynamic model, the water evaporation rate, the heat transfer rates, and an equation for the stickiness of the powder (glass transition temperature). Laboratory data is used to model the equilibrium moisture content and the glass transition temperature of the powder. The resulting mathematical model is an index-1 differential algebraic equation (DAE) model with 12 states, 9 inputs, 8 disturbances, and 30 parameters. The parameters in the model are identified from well-excited experimental data obtained from the industrial type spray dryer. The simulated outputs of the model are validated using independent well-excited experimental data from the same spray dryer. The simulated temperatures, humidities, and residual moistures in the spray dryer compare well to the validation data. The model also provides the profit of operation, the production rate, the energy...
consumption, and the energy efficiency. In addition, it computes stickiness of the powder in different stages of the spray dryer. These facilities make the model well suited as a simulation model for comparison of the process economics associated to different control strategies.
C code generation applied to nonlinear model predictive control for an artificial pancreas

This paper presents a method to generate C code from MATLAB code applied to a nonlinear model predictive control (NMPC) algorithm. The C code generation uses the MATLAB Coder Toolbox. It can drastically reduce the time required for development compared to a manual porting of code from MATLAB to C, while ensuring a reliable and fairly optimized code. We present an application of code generation to the numerical solution of nonlinear optimal control problems (OCP). The OCP uses a sequential quadratic programming algorithm with multiple shooting and sensitivity computation. We consider the problem of glucose regulation for people with type 1 diabetes as a case study. The average computation time when using generated C code is 0.21 s (MATLAB: 1.5 s), and the maximum computation time when using generated C code is 0.97 s (MATLAB: 5.7 s). Compared to the MATLAB implementation, generated C code can run in average more than 7 times faster.

Comparison of three control strategies for optimization of spray dryer operation

Spray drying is the preferred process to reduce the water content of many chemicals, pharmaceuticals, and foodstuffs. A significant amount of energy is used in spray drying to remove water and produce a free flowing powder product. In this paper, we present and compare the performance of three controllers for operation of a four-stage spray dryer. The three controllers are a proportional-integral (PI) controller that is used in industrial practice for spray dryer operation, a linear model predictive controller with real-time optimization (MPC with RTO, MPC-RTO), and an economically optimizing nonlinear model predictive controller (E-NMPC). The MPC with RTO is based on the same linear state space model in the MPC and the RTO layer. The E-NMPC consists of a single optimization layer that uses a nonlinear system of ordinary differential equations for its predictions. The PI control strategy has a fixed target that is independent of the disturbances, while the MPC-RTO and the E-NMPC adapt the operating point to the disturbances. The goal of spray dryer operation is to optimize the profit of operation in the presence of feed composition and ambient air humidity variations; i.e. to maximize the production rate, while minimizing the energy consumption, keeping the residual moisture content of the powder below a maximum limit, and avoiding that the powder sticks to the chamber walls. We use an industrially recorded disturbance scenario in order to produce realistic simulations and conclusions. The key performance indicators such as the profit of operation, the product flow rate, the specific energy consumption, the energy efficiency, and the residual moisture content of the produced powder are computed and compared for the three controllers. In this simulation study, we find that the economic performance of the MPC with RTO as well as the E-NMPC is considerably improved compared to the PI control strategy used in industrial practice. The MPC with RTO improves the profit of operation by 8.61%, and the E-NMPC improve.
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Cross-Validation of a Glucose-Insulin-Glucagon Pharmacodynamics Model for Simulation using Data from Patients with Type 1 Diabetes

Background: Currently, no consensus exists on a model describing endogenous glucose production (EGP) as a function of glucagon concentrations. Reliable simulations to determine the glucagon dose preventing or treating hypoglycemia or to tune a dual-hormone artificial pancreas control algorithm need a validated glucoregulatory model including the effect of glucagon.

Methods: Eight type 1 diabetes (T1D) patients each received a subcutaneous (SC) bolus of insulin on four study days to induce mild hypoglycemia followed by a SC bolus of saline or 100, 200, or 300 µg of glucagon. Blood samples were analyzed for concentrations of glucagon, insulin, and glucose. We fitted pharmacokinetic (PK) models to insulin and glucagon data using maximum likelihood and maximum a posteriori estimation methods. Similarly, we fitted a pharmacodynamic (PD) model to glucose data. The PD model included multiplicative effects of insulin and glucagon on EGP. Bias and precision of PD model test fits were assessed by mean predictive error (MPE) and mean absolute predictive error (MAPE).

Results: Assuming constant variables in a subject across nonoutlier visits and using thresholds of ±15% MPE and 20% MAPE, we accepted at least one and at most three PD model test fits in each of the seven subjects. Thus, we successfully validated the PD model by leave-one-out cross-validation in seven out of eight T1D patients.

Conclusions: The PD model accurately simulates glucose excursions based on plasma insulin and glucagon concentrations. The reported PK/PD model including equations and fitted parameters allows for in silico experiments that may help improve diabetes treatment involving glucagon for prevention of hypoglycemia.
Design, economics and parameter uncertainty in dynamic operation of post-combustion CO$_2$ capture using piperazine (PZ) and MEA

Post-combustion capture is a promising solution to mitigate the anthropogenic CO$_2$ emission rate and reduce global warming. However, to make it economically attractive, the techno-economic performance of this process needs to be improved. This includes steady-state but also dynamic operation of the plant. Flexibility is particularly crucial from an economic and operational point of view since plants must balance the power production and the electricity demand on a daily basis.

This work shows the impact of design decisions and uncertainties on the dynamic operation and economics of a CO$_2$ capture plant using piperazine (PZ), compared to the benchmark MEA solvent. This is exemplified through dynamic model calculations. The results show that the capacity of the buffer tank is a key parameter for the flexibility of the plant. A small tank corresponds to lower capital cost but it leads to increased operation cost and also to flexibility/controllability issues. Both, the PZ and MEA plants present inverse response for small tanks. These plants are challenging to control.
Dynamic Optimization of UV Flash Processes

UV ash processes, also referred to as isoenergetic-isochoric ash processes, occur for dynamic simulation and optimization of vapor-liquid equilibrium processes. Dynamic optimization and nonlinear model predictive control of distillation columns, certain two-phase ow problems, as well as oil reservoirs with signi_cant compositional and thermal e_ects may be conducted as dynamic optimization of UV ash processes. The dynamic optimization problem involving a UV ash problem is formulated as a bilevel optimization problem. This problem is solved using a gradient based single-shooting method. The gradients are computed using the adjoint method and di_erent o-the-shelf optimization software (fmincon, IPOPT, KNITRO, NPSOL) are used for the numerical optimization. Computational results are reported for a ash process involving benzene, toluene and diphenyl. The computational experiments demonstrate that the optimization solver, the compiler, and high-performance linear algebra software are all important for e_cient dynamic optimization of UV ash processes.

Economic MPC based on LPV model for thermostatically controlled loads

Rapid increase of the renewable energy share in electricity production requires optimization and flexibility of the power consumption side. Thermostatically controlled loads (TCLs) have a large potential for regulation service provision. Economic model predictive control (MPC) is an advanced control method which can be used to synchronize the power consumption with undispatchable renewable electricity production. Thermal behavior of TCLs can be described by linear models based on energy balance of the system. In some cases, parameters of the model may be time-varying. In this work, we present a modi_ed economic MPC based on linear parameter-varying model. In particular, we provide an exact transformation from a standard economic MPC formulation to a linear program. We assume that the variables in uencing the model parameters are known (predictable) for the prediction horizon of the controller. As a case study, we present control system that minimizes operational cost of swimming pool heating system, where parameters of the model depend on the weather forecast. Simulation results demonstrate that the proposed method is able to deal with this kind of systems.

Fault and meal detection by redundant continuous glucose monitors and the unscented Kalman filter

The purpose of this study is to develop a method for detecting and compensating the anomalies of continuous glucose monitoring (CGM) sensors as well as detecting unannounced meals. Both features, sensor fault detection/correction and meal detection, are necessary to have a reliable artificial pancreas. The aim is to investigate the best detection results achievable with the proposed detection configuration in a perfect situation, and to have the results as a benchmark against which the imperfect scenarios of the proposed fault detection can be compared. The perfect situation that we set up here is in terms of a patient simulation model, where the model in the detector is the same as the patient simulation model used for evaluation of the detector. The detection module consists of two CGM sensors, two fault detectors, a fault isolator, and an adaptive unscented Kalman filter (UKF). Two types of sensor faults, i.e., drift and pressure induced sensor attenuation (PISA), are simulated by a Gaussian random walk model. Each of the fault detectors has a local UKF that receives the signal from the associated sensor, detects faults, and finally tunes the adaptive UKF. A fault isolator that accepts data from the two fault detectors differentiates between a sensor fault and an unannounced meal appearing as an anomaly in the CGM data. If the fault isolator indicates a sensor fault, a method based on the covariance matching technique tunes the covariance of the measurement noise associated with the faulty sensor. The main UKF uses the tuned noise covariances and fuses the CGM data from the two sensors. The drift detection sensitivity and specificity are 80.9% and 92.6%, respectively. The sensitivity and specificity of PISA detection are 78.1% and 82.7%, respectively. The fault detectors can detect 100 out of 100 simulated drifts and 485 out of 500 simulated PISA events. Compared to a nonadaptive UKF, the adaptive UKF reduces the deviation of the CGM measurements from their paired blood glucose concentrations from 72.0% to 12.5% when CGM is corrupted by drift, and from 10.7% to 6.8% when CGM is corrupted by PISA. The fault isolator can detect 199 out of 200 unannounced meals. The average change in the glucose concentrations between the meals and the detection time points is 46.3 mg/dL.
Implementation of advanced process control on the four tank pilot plant

The four tank process laboratory experiment is used as a relevant case to unfold problems that arise when implementing advanced process control such as model predictive control. The controller, which is executed on a computer, and the process equipment communicate using OPC to exchange process measurements and actuator set points. The process equipment is described along with the setup of the PLC and the OPC server in order to be able to access process variables on a dimensional scale. A process emulator in which a process simulator is embedded in an OPC interface has
been developed in Python. Using the detailed information of sensor and actuator calibration as well as PLC functionality, the emulator appears identical to the actual process and may be used to perform virtual tests of controllers prior to commissioning. Examples of how to interact with OPC servers are presented for both Matlab and Python. An MPC has been designed based on a linearized model of the process and tested using the emulator. This controller was then implemented on a realization of the process at the Technical University of Denmark, demonstrating MPC experimentally.

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**Modeling Pharmacokinetics and Pharmacodynamics of Glucagon for Simulation of the Glucoregulatory System in Patients with Type 1 Diabetes.**
The goal of this thesis was to develop a pharmacokinetics/pharmacodynamics (PK/PD) model for glucagon. The proposed PD model included multiplication of the stimulating glucagon effect and inhibiting insulin effect on the endogenous glucose production (EGP). Moreover, the concentration-response relationship of glucagon and EGP was characterized by a non-linear function, where the response saturated for high concentrations of glucagon. The novel EGP model extended Hovorka's glucoregulatory model to include the effect of glucagon. The PK/PD model described both regular glucagon and a novel glucagon analogue in healthy dogs. The extended glucoregulatory model translated to the human species and described glucose-insulin-glucagon dynamics in healthy subjects and patients with type 1 diabetes (T1D). The extended glucoregulatory model was successfully validated by leave-one-out cross-validation in seven T1D patients which justified its use for simulations. The final model parameters were estimated from three to four datasets from each patient. The validated extended glucoregulatory model was used for in silico studies. The model replicated a clinical study of the effect of glucagon at varying insulin levels. The simulations also suggested new glucagon doses to be tested in a similar in vivo study to provide new insight to the relationship between insulin, glucagon, and EGP. Finally, the model was used to conduct a large original simulation study investigating an insulin dependent glucagon dosing regimen for treatment of insulin-induced mild hypoglycemia.

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Modeling Pharmacokinetics and Pharmacodynamics of Glucagon for Simulation of the Glucoregulatory System in Patients with Type 1 Diabetes.
Multiple shooting applied to robust reservoir control optimization including output constraints on coherent risk measures

The production life of oil reservoirs starts under significant uncertainty regarding the actual economical return of the recovery process due to the lack of oil field data. Consequently, investors and operators make management decisions based on a limited and uncertain description of the reservoir. In this work, we propose a new formulation for robust optimization of reservoir well controls. It is inspired by the multiple shooting (MS) method which permits a broad range of parallelization opportunities and output constraint handling. This formulation exploits coherent risk measures, a concept traditionally used in finance, to bound the risk on constraint violation. We propose a reduced sequential quadratic programming (rSQP) algorithm to solve the underlying optimization problem. This algorithm exploits the structure of the coherent risk measures, thus a large set of constraints are solved within sub-problems. Moreover, a variable elimination procedure allows solving the optimization problem in a reduced space and an iterative active-set method helps to handle a large set of inequality constraints. Finally, we demonstrate the application of constraints to bound the risk of water production peaks rather than worst-case satisfaction.

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Simulating clinical studies of the glucoregulatory system: in vivo meets in silico

In this report we use a validated model of the glucoregulatory system including effects of insulin and glucagon for simulation studies in seven type 1 diabetes patients. Using simulations, we replicate the results from a clinical study investigating the effect of micro-doses of glucagon on glucose metabolism at varying ambient insulin levels. The report compares in vivo and in silico results head-to-head, and discusses similarities and differences. We design and simulate simple studies to emphasize the implications of some glucoregulatory dynamics which are ignored in most previous clinical studies: the effect of discontinuing insulin and glucose infusions prior to glucagon administration, the delayed effect of insulin, timing of data sampling, and carryover effects from multiple subcutaneous doses of glucagon. We also use simulations to discuss two hypotheses of how insulin and glucagon might interact in influencing the glucose response. Following the simulations we propose a study design that potentially could explore if the hypotheses are true or false.

Validation of a Simulation Model Describing the Glucose-Insulin-Glucagon Pharmacodynamics in Patients with Type 1 Diabetes

Currently, no consensus exists on a model describing endogenous glucose production (EGP) as a function of glucagon concentrations. Reliable simulations to determine the glucagon dose preventing or treating hypoglycemia or to tune a dual-hormone artificial pancreas control algorithm need a validated glucoregulatory model including the effect of glucagon.
A Hierarchical Algorithm for Integrated Scheduling and Control With Applications to Power Systems

The contribution of this paper is a hierarchical algorithm for integrated scheduling and control via model predictive control of hybrid systems. The controlled system is a linear system composed of continuous control, state, and output variables. Binary variables occur as scheduling decisions in the optimal control problem (OCP). The scheduling decisions are made on a slow time scale compared with the system dynamics. This gives rise to a temporal separation of the scheduling and control variables in the OCP. Accordingly, the proposed hierarchical algorithm consists of two optimization levels. The upper level (scheduling level) solves a mixed-integer linear program (MILP) with a low frequency. The lower level (control level) solves an LP with a high frequency. The main advantage of the proposed approach is that it requires online solution of an LP rather than an MILP. Simulations based on a power portfolio case study show that the hierarchical algorithm reduces the computation to solve the OCP by several orders of magnitude. The improvement in computation time is achieved without a significant increase in the overall cost of operation.

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Algorithms and Methods for High-Performance Model Predictive Control

The goal of this thesis is to investigate algorithms and methods to reduce the solution time of solvers for Model Predictive Control (MPC). The thesis is accompanied with an open-source toolbox for High-Performance implementation of solvers for MPC (HPMPC), that contains the source code of all routines employed in the numerical tests. The main focus of this thesis is on linear MPC problems.

In this thesis, both the algorithms and their implementation are equally important. About the implementation, a novel implementation strategy for the dense linear algebra routines in embedded optimization is proposed, aiming at improving the computational performance in case of small matrices. About the algorithms, they are built on top of the proposed linear algebra, and they are tailored to exploit the high-level structure of the MPC problems, with special care on reducing the computational complexity.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Copenhagen Center for Health Technology, Center for Energy Resources Engineering
Authors: Frison, G. (Intern), Jørgensen, J. B. (Intern)
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An Efficient Implementation of Partial Condensing for Nonlinear Model Predictive Control

Partial (or block) condensing is a recently proposed technique to reformulate a Model Predictive Control (MPC) problem into a form more suitable for structure-exploiting Quadratic Programming (QP) solvers. It trades off horizon length for input vector size, and this degree of freedom can be employed to find the best problem size for the QP solver at hand. This paper proposes a Hessian condensing algorithm particularly well suited for partial condensing, where a state component is retained as an optimization variable at each stage of the partially condensed MPC problem. The optimal input-horizon trade-off is investigated from a theoretical point of view (based on algorithms flop count) as well as by benchmarking (in practice, the performance of linear algebra routines for different matrix sizes plays a key role). Partial condensing can also be seen as a technique to replace many operations on small matrices with fewer operations on larger matrices, where linear algebra routines perform better. Therefore, in case of small-scale MPC problems, partial condensing can greatly improve performance beyond the flop count reduction.

General information
State: Published
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2016

An Efficient UD-Based Algorithm for the Computation of Maximum Likelihood Sensitivity of Continuous-Discrete Systems

This paper addresses maximum likelihood parameter estimation of continuous-time nonlinear systems with discrete-time measurements. We derive an efficient algorithm for the computation of the log-likelihood function and its gradient, which can be used in gradient-based optimization algorithms. This algorithm uses UD decomposition of symmetric matrices and the array algorithm for covariance update and gradient computation. We test our algorithm on the Lotka-Volterra equations. Compared to the maximum likelihood estimation based on finite difference gradient computation, we get a significant speedup without compromising the numerical accuracy.

General information
State: Published
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An Ensemble Nonlinear Model Predictive Control Algorithm in an Artificial Pancreas for People with Type 1 Diabetes
This paper presents a novel ensemble nonlinear model predictive control (NMPC) algorithm for glucose regulation in type 1 diabetes. In this approach, we consider a number of scenarios describing different uncertainties, for instance meals or metabolic variations. We simulate a population of 9 patients with different physiological parameters and a time-varying insulin sensitivity using the Medtronic Virtual Patient (MVP) model. We augment the MVP model with stochastic diffusion terms, time-varying insulin sensitivity and noise-corrupted CGM measurements. We consider meal challenges where the uncertainty in meal size is ±50%. Numerical results show that the ensemble NMPC reduces the risk of hypoglycemia compared to standard NMPC in the case where the meal size is overestimated or correctly estimated at the expense of a slightly increased number of hyperglycemia. Therefore, ensemble MPC-based algorithms can improve the safety of the AP compared to the classical MPC-based algorithms.

General information
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Organisations: Department of Applied Mathematics and Computer Science , Scientific Computing, Dynamical Systems
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An open-source thermodynamic software library
This is a technical report which accompanies the article "An open-source thermodynamic software library" which describes an efficient Matlab and C implementation for evaluation of thermodynamic properties. In this technical report we present the model equations, that are also presented in the paper, together with a full set of first and second order derivatives with respect to temperature and pressure, and in cases where applicable, also with respect to mole numbers. The library is based on parameters and correlations from the DIPPR database and the Peng-Robinson and the Soave-Redlich-Kwong equations of state.

General information
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Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science , Scientific Computing
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Application of Economic MPC to Frequency Control in a Single-Area
This paper presents a novel model predictive control scheme for frequency control in a single-area power system. The proposed controller provides set-point corrections to the system power generators, based on the solution to an optimal control problem. The optimal control problem directly incorporates the cost of operation into its objective function. A trade-
off parameter is used to balance set-point tracking and cost minimization. Simulations based on a Faroe Islands case study show that the proposed approach reduces cost of operation by almost an order of magnitude, compared to both set-point based model predictive control as well as conventional frequency-based PI-control.

General information
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Application of the Continuous-Discrete Extended Kalman Filter for Fault Detection in Continuous Glucose Monitors for Type 1 Diabetes
The purpose of this study is the online detection of faults and anomalies of a continuous glucose monitor (CGM). We simulated a type 1 diabetes patient using the Medtronic virtual patient model. The model is a system of stochastic differential equations and includes insulin pharmacokinetics, insulin-glucose interaction, and carbohydrate absorption. We simulated and detected two types of CGM faults, i.e., spike and drift. A fault was defined as a CGM value in any of the zones C, D, and E of the Clarke error grid analysis classification. Spike was modelled by a binomial distribution, and drift was modelled by a Gaussian random walk. We used a continuous-discrete extended Kalman filter for the fault detection, based on the statistical tests of the filter innovation and the 90-min prediction residuals of the sensor measurements. The spike detection had a sensitivity of 93% and a specificity of 100%. Also, the drift detection had a sensitivity of 80% and a specificity of 85%. Furthermore, with 100% sensitivity the proposed method was able to detect if the drift overestimates or underestimates the interstitial glucose concentration.

General information
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Comparison of Three Nonlinear Filters for Fault Detection in Continuous Glucose Monitors
The purpose of this study is to compare the performance of three nonlinear filters in online drift detection of continuous glucose monitors. The nonlinear filters are the extended Kalman filter (EKF), the unscented Kalman filter (UKF), and the particle filter (PF). They are all based on a nonlinear model of the glucose-insulin dynamics in people with type 1 diabetes. Drift is modelled by a Gaussian random walk and is detected based on the statistical tests of the 90-min prediction
residuals of the filters. The unscented Kalman filter had the highest average F score of 85.9%, and the smallest average detection delay of 84.1%, with the average detection sensitivity of 82.6%, and average specificity of 91.0%.

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**Controllability and flexibility analysis of CO2 post-combustion capture using piperazine and MEA**

In this study, we developed a decentralized control scheme and investigate the performance of the piperazine (PZ) and monoethanolamine (MEA) CO2 capture process for industrially-relevant operation scenarios. The base for the design of the control schemes is Relative Gain Array (RGA) analysis combined with open-loop dynamic sensitivity analysis.

This study suggests that controllers with smaller time integrals and larger gains are required to maintain the PZ plant within reasonable short closed-loop settling times when compared to MEA. It also shows that the offset from the designated set-points in the presence of disturbances in the flue gas flow and heat duty is larger using PZ compared to MEA. The settling time for the PZ plant is generally larger than for MEA. However, the PZ plant rejects the disturbances faster and with less variability in the load of the power plant. Furthermore, this study indicates that the proposed PI-based control structure can handle large changes in the load provided that the manipulated variables, i.e. lean solvent flow or reboiler duty, do not reach their saturation limit. Additionally, we observed that shortage in the steam supply (reboiler duty) may represent a critical operational bottleneck for PZ plant operation while the CO2 capture rate performance of the PZ plant reduces drastically in the presence of constraints in the availability of steam. These findings suggest the need for advanced control structures, e.g. MPC, which can explicitly account for constraints in the process variables.

**General information**

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Scopus rating (2015): SJR 1.515 SNIP 1.537 CiteScore 4.37
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CO₂ Capture Dynamic and Steady-State Model Development, Optimization and Control: Applied to Piperazine and Enzyme Promoted MEA/MDEA

Despite the efforts and recent advances in renewable energy sources, the energy infrastructure is not yet ready to replace the fossil-fuel fired power plants with renewables. Thermal power plants represent the main energy supply and especially in developing countries, they are expected to dominate the market in the coming decades. However, the growing focus on mitigation of anthropogenic CO₂ requires integration of fossil-fuel fired power plant with CO₂ capture units. Post-combustion capture is the most mature capture technology and it is suitable for various processes in power plants, steel industry, cement production, and bio-chemical industry. However, to make CO₂ capture economically attractive, design of innovative solvents, optimization of operation conditions/process configuration and operational flexibility are of crucial importance.

This thesis aims to contribute to the development of efficient CO₂ post-combustion capture technology using alkanolamine solvents. Amine based CO₂ post-combustion capture is a reactive absorption process which implies complex mechanism of simultaneously occurring reaction and mass transport phenomena. Accordingly, first a simplified and easy to implement but general valid mass transfer model is developed and applied to single and parallel reactions systems, i.e. MEA, PZ and CA/MDEA. This mass transfer model uses existing correlations for mass and hydraulic characteristic and an enhancement factor to describe the acceleration of the mass transfer rate due to the reaction between CO₂ and amines. Afterwards, this sub-model together with the extended UNIQUAC thermodynamic model and correlations for physical properties is incorporated in a rate-based model for CO₂ absorption and desorption. The developed model is applied to MEA, PZ, PZ/K₂CO₃ and CA/MDEA and it is benchmarked against experimental pilot plant data and various models from independent research groups.

The validated steady-state model is used to determine set of optimal operation parameters for CO₂ capture post-combustion capture using PZ. This study accounts for the solubility window of PZ when determining the optimal and feasible operating conditions. The results are created in Aspen Plus using the hybrid CAPCO₂ rate-based user model. This model considers slurry formation in the calculation of CO₂ mass transfer rate. The results show how the capture process needs to be operated up to 14% above the minimum achievable heat duty, to avoid clogging from solid formation. 5 molal PZ is the most promising trade-off between energy efficiency and solid-free operation with a specific reboiler duty of 3.22 GJ/t CO₂ at 0.34 lean loading.

Furthermore, this thesis presents a dynamic rate-based model for CO₂ absorption and desorption using MEA and PZ as solvent. This dynamic model is an extension of the steady-state model as it uses the same thermodynamic-, mass transfer-, kinetic- and physical property- modules. These modules are implemented in Fortran and interfaced with the dynamic model which is implemented in Matlab. The developed model is used to investigate the transient behavior of a post-combustion plant using MEA and PZ. Moreover, a proportional-integral control structure is developed to investigate...
the controllability of the PZ based post-combustion plant compared to the MEA plant. The results reveal that PZ may be a better solvent than MEA as it can accommodate disturbances with less variability in the manipulated variables. However, control design alternatives and/or model-based control structure should be developed to reduce the long settling time of the PZ plant compared to the MEA plant.

**General information**

State: Published  
Organisations: Department of Chemical and Biochemical Engineering, CERE – Center for Energy Resources Engineering  
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CO₂ Capture Dynamic and Steady-State Model Development, Optimization and Control: Applied to Piperazine and Enzyme Promoted MEA/MDEA

**Distributed Model Predictive Control for Smart Energy Systems**

Integration of a large number of flexible consumers in a smart grid requires a scalable power balancing strategy. We formulate the control problem as an optimization problem to be solved repeatedly by the aggregator in a model predictive control framework. To solve the large-scale control problem in real-time requires decomposition methods. We propose a decomposition method based on Douglas–Rachford splitting to solve this large-scale control problem. The method decomposes the problem into smaller subproblems that can be solved in parallel, e.g., locally by each unit connected to an aggregator. The total power consumption is controlled through a negotiation procedure between all cooperating units and an aggregator that coordinates the overall objective. For large-scale systems, this method is faster than solving the original problem and can be distributed to include an arbitrary number of units. We show how different aggregator objectives are implemented and provide simulations of the controller including the computational performance.

**General information**

State: Published  
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Scopus rating (2015): SJR 3.785 SNIP 3.424 CiteScore 8.48  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 1
Dynamic Operation and Simulation of Post-Combustion CO2 Capture

Thermal power need to operate, on a daily basis, with frequent and fast load changes to balance the large variations of intermittent energy sources, such as wind and solar energy. To make the integration of carbon capture to power plants economically and technically feasible, the carbon capture process has to be able to follow these fast and large load changes without decreasing the overall performance of the carbon capture plant. Therefore, dynamic models for simulation, optimization and control system design are essential. In this work, we compare the transient behavior of the model against dynamic pilot data for CO2 absorption and desorption for step-changes in the flue gas flow rate. In addition we investigate the dynamic behavior of a full-scale post-combustion capture plant using monoethanolamine (MEA) and piperazine (PZ). This analysis demonstrates the good agreement between the developed model (dCAPCO2) and the pilot measurements at both, transient and steady-state conditions. It outlines how the time needed to reach a new steady-state varies with respect to amine type and concentration. The simulation study reveals that it is essential to control the lean solvent flow to avoid sudden changes in the CO2 removal rate and to avoid increased heat demand of solvent regeneration. In addition, it shows how storage tanks (liquid hold-up of the system) can be designed to accommodate significant upstream changes in the power plant management. This flexibility is especially needed for operation in future mixed green energy market. [All rights reserved Elsevier].
Dynamic simulation and analysis of a pilot-scale CO₂ post-combustion capture unit using piperazine and MEA

Post-combustion capture is a promising technology for developing CO₂ neutral power plants. However, to make it economically and technically feasible, capture plants must follow the fast and large load changes of the power plants without decreasing the overall performance of the plant. Dynamic modeling and simulation is therefore needed to evaluate the performance of this plant under critical operation.

In this work, we evaluate the transient response of an absorber and a desorber for step changes of key process parameters, e.g. flue gas flow and composition, lean and rich CO₂ loading, etc. We show the results for the baseline 30 wt% MEA and the low energy piperazine (PZ) solutions. This analysis reveals that the absorber reaches steady-state faster using MEA compared to PZ. This is related to the shift of the mass transfer zone due to changes in temperature. The transient operation in the regeneration unit is somewhat similar while using both solvents: an initial fast decrease of the lean loading is followed by a slow transient period as the system approaches steady-state conditions. We show the presence of inverse response in the stripper column when the rich loading decreases or the feed's temperature reduces using PZ solvent. Thus, we demonstrate that the dynamics of the MEA system cannot be extrapolated to other solvents.

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The main challenge in cost optimal operation of a spray dryer, is to maximize the production rate while minimizing the energy consumption, keeping the residual moisture content of the powder below a maximum limit and avoiding that the powder sticks to the chamber walls. The conventional PI control strategy is simple, but known to be insufficient at providing optimal operation in the presence of variations in the feed and the ambient air humidity. This motivates our investigation of Model Predictive Control (MPC) strategies.

In this thesis, we consider the development and application of new models and MPC strategies to optimize the operation of four-stage spray dryers. The models are first-principle dynamic models with parameters identified from dryer specific experiments and powder properties identified from laboratory tests. A simulation model is used for detailed closed-loop simulations and a complexity reduced control model is used for state estimation and prediction in the controllers. These models facilitate development and comparison of control strategies. We develop two MPC strategies; a linear tracking MPC with a Real-Time Optimization layer (MPC with RTO) and an Economic Nonlinear MPC (E-MPC). We tailor these for the spray drying process to optimize the cost of operation by adjustments to the inputs of the dryer according to the present disturbances and process constraints. Simulations show that MPC strategies improve the profit of operation by up to 9.69%, the production of powder by up to 9.6%, the residual moisture content by up to 0.114 p.p. and the energy efficiency by up to 6.06% while the produced powder is within the given quality specifications and sticky powder on the walls of the chamber is avoided. Thus, we are able to improve the cost of operation significantly compared to the conventional PI control strategy.

The proposed MPC strategies are based on a feedback control algorithm that explicitly handles constrained control inputs and uses a model to predict and optimize the future behavior of the dryer. The solution of the control problem results in a sequence of inputs for a finite horizon, out of which only the first input is applied to the dryer. This procedure is repeated at each sample instant and is solved numerically in real-time. The MPC with RTO tracks a target that optimizes the cost of operation at steady-state. The E-MPC optimizes the cost of operation directly by having this objective directly in the controller. The need for the RTO layer is then eliminated.

We demonstrate the application of the proposed MPC with RTO to control an industrial GEA MSDTM-1250 spray dryer, which produces approximately 7500 kg/hr of enriched milk powder. Compared to the conventional PI controller, our first results shows that the MPC improves the profit of operation by approximately 228,000 €/year, the product rate by 322 kg/hr, the residual moisture content by 0.166 p.p. and the energy efficiency by 1% at comparable ambient air humidity conditions. The demonstrated MPC with RTO is fully integrated in the daily operation of the spray dryer today.

Our primary objectives in the thesis are: 1) Spray dryer modeling of a smallscale four-stage spray dryer. The purpose of the models are to enable simulations of the spray drying process at different operating points, such that the models facilitate development and comparison of control strategies; 2) Development of MPC strategies that automatically adjust the dryer to variations in the feed and the ambient air humidity, such that the energy consumption is minimized, the residual moisture content in the powder is controlled within the specifications and sticky powder is avoided from building up on the dryer walls; 3) Demonstrate the industrial application of an MPC strategy to a full-scale industrial four-stage spray dryer.

The main scientific contributions can be summarized to:

- Modeling of a four-stage spray dryer. We develop new first-principles engineering models for simulation of a four-stage spray dryer. These models enables simulations of the spray dryer at different operating points with high accuracy.
- Development and simulation of control strategies. We develop two control strategies, the MPC with RTO and the E-MPC strategy. The performance of the controllers is studied and evaluated by simulation.
- Industrial application of MPC to a spray dryer. We demonstrate that our proposed MPC with RTO is applicable to an industrial GEA MSDTM-1250 spray dryer, that produces enriched milk powder.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Copenhagen Center for Health Technology, Dynamical Systems
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Economic MPC for a linear stochastic system of energy units

This paper summarizes comprehensively the work in four recent PhD theses from the Technical University of Denmark related to Economic MPC of future power systems. Future power systems will consist of a large number of decentralized power producers and a large number of controllable power consumers in addition to stochastic power producers such as wind turbines and solar power plants. Control of such large scale systems requires new control algorithms. In this paper, we formulate the control of such a system as an Economic Model Predictive Control (MPC) problem. When the power producers and controllable power consumers have linear dynamics, the Economic MPC may be expressed as a linear program. We provide linear models for a number of energy units in an energy system, formulate an Economic MPC for coordination of such a system. We indicate how advances in computational MPC makes the solutions of such large-scale models feasible in real-time. The system presented may serve as a benchmark for simulation and control of smart energy systems and we indicate how advances in computational MPC.

Industrial application of model predictive control to a milk powder spray drying plant

In this paper, we present our first results from an industrial application of model predictive control (MPC) with real-time steady-state target optimization (RTO) for control of an industrial spray dryer that produces enriched milk powder. The MPC algorithm is based on a continuous-time transfer function model identified from data and states estimated by a time-varying Kalman filter. The RTO layer utilizes the same linear model and a nonlinear economic objective function for calculation of the economically optimized targets. We demonstrate, by industrial application of the MPC, that this method provides significantly better control of the residual moisture content, increases the throughput and decreases the energy consumption compared to conventional PI-control. The MPC operates the spray dryer closer to the residual moisture constraint of the powder product. Thus, the same amount of feed produces more powder product by increasing the average water content. The value of this is 186,000 €/year. In addition, the energy savings account to 6,900 €/year.
Methods and Algorithms for Economic MPC in Power Production Planning

This thesis concerns methods and algorithms for power production planning in contemporary and future power systems. Power production planning is a task that involves decisions across different time scales and planning horizons. Hours-ahead to days-ahead planning is handled by solving a mixed-integer linear program for unit commitment and economic dispatch of the system power generators. We focus on a minutes-ahead planning horizon, where unit commitment decisions are fixed. Economic model predictive control (EMPC) is employed to determine an optimal dispatch for a portfolio of power generators in real-time. A generator can represent a producer of electricity, a consumer of electricity, or possibly both. Examples of generators are heat pumps, electric vehicles, wind turbines, virtual power plants, solar cells, and conventional fuel-fired thermal power plants. Although this thesis is mainly concerned with EMPC for minutes-ahead production planning, we show that the proposed EMPC scheme can be extended to days-ahead planning (including unit commitment) as well.

The power generation from renewable energy sources such as wind and solar power is inherently uncertain and variable. A portfolio with a high penetration of renewable energy is therefore a stochastic system. To accommodate the need for EMPC of stochastic systems, we generalize certainty-equivalent EMPC (CEEMPC) to mean-variance EMPC (MV-EMPC). In MV-EMPC, the objective function is a trade-off between the expected cost and the cost variance. Simulations show that MV-EMPC reduces cost and risk compared to CE-EMPC. The simulations also show that the economic performance of CE-EMPC can be much improved using a constraint back-off heuristic.

Efficient solution of the optimal control problems (OCPs) that arise in EMPC is important, as the OCPs are solved online. We present special-purpose algorithms for EMPC of linear systems that exploit the high degree of structure in the OCPs. A Riccati-based homogeneous and self-dual interior-point method is developed for the special case, where the OCP objective function is a linear function. We design an algorithm based on the alternating direction method of multipliers (ADMM) to solve input-constrained OCPs with convex objective functions. The OCPs that occur in EMPC of dynamically decoupled subsystems, e.g. power generators, have a block-angular structure.Subsystem decomposition algorithms based on ADMM and Dantzig-Wolfe decomposition are proposed to solve these OCPs. Subproblems that arise in the decomposition algorithms are solved using structure-exploiting algorithms. To reduce computation time of the EMPC algorithms further, warm-start and early-termination strategies are employed. Benchmarks show that the special-purpose algorithms are significantly faster than current state-of-the-art solvers.

As a potential application area of EMPC, we study power production planning in small isolated power systems. A critical part of power production planning in small isolated power systems is operational reserve planning. The operational reserves are activated to balance production and consumption in real-time. An EMPC scheme is presented for activation of operational reserves. Simulations based on a Faroe Islands case study show that significant cost savings can be achieved using this strategy. For efficient planning of the operational reserves, we present an optimal reserve planning problem (ORPP). The ORPP is a contingency-constrained unit commitment problem that addresses low inertia challenges in small isolated power systems.

In summary, the main contributions of this thesis are:
- A mean-variance optimization strategy for EMPC of linear stochastic systems.
- Tailored algorithms for solution of the OCPs that arise in EMPC of linear stochastic systems.
- Methods for power production planning in small isolated power; the ORPP for unit commitment and economic dispatch, and an EMPC scheme for activation of operational reserves.
Model Identification using Continuous Glucose Monitoring Data for Type 1 Diabetes

This paper addresses model identification of continuous-discrete nonlinear models for people with type 1 diabetes using sampled data from a continuous glucose monitor (CGM). We compare five identification techniques: least squares, weighted least squares, Huber regression, maximum likelihood with extended Kalman filter and maximum likelihood with unscented Kalman filter. We perform the identification on a 24-hour simulation of a stochastic differential equation (SDE) version of the Medtronic Virtual Patient (MVP) model including process and output noise. We compare the fits with the actual CGM signal, as well as the short- and long-term predictions for each identified model. The numerical results show that the maximum likelihood-based identification techniques offer the best performance in terms of fitting and prediction. Moreover, they have other advantages compared to ODE-based modeling, such as parameter tracking, population modeling and handling of outliers.
Modeling and Control for Price Responsive Electricity Loads

This thesis deals with the development of model-based control architectures to facilitate renewable sources integration in the power system, focusing on residential buildings. Energy use in buildings in developed countries is increasing rapidly, and advanced model based techniques for control of thermal storages are becoming popular due to the high demand for solutions that improve energy efficiency and reduce operating costs.

This presents new challenges on how to integrate uncertain and intermittent energy sources. This work proposes methods for control of price responsive electricity loads in future energy systems and methods for handling stochasticity of, e.g., wind and solar power production. Hierarchies of aggregators and predictive controllers, in flexible demand side response, are implemented to achieve a balance with the non-dispatchable energy production.

Particular focus is given on producing models for control that facilitate better planning for an efficient integration of renewable energy into the power generation. Combining both data and statistical expertise, opens up new possibilities for designing models that describe thermal storages flexibility.

Finally, focus is also put on the problem of managing a virtual power plant equipped with stochastic energy sources and flexible consumers. Two distinct control approaches are described: direct control of the load consumption and indirect control by broadcasting a price signal. The advantages and challenges of these two approaches are discussed providing examples for suggested techniques.

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Modeling and Prediction Using Stochastic Differential Equations
Pharmacokinetic/pharmakodynamic (PK/PD) modeling for a single subject is most often performed using nonlinear models based on deterministic ordinary differential equations (ODEs), and the variation between subjects in a population of subjects is described using a population (mixed effects) setup that describes the variation between subjects. The ODE setup implies that the variation for a single subject is described by a single parameter (or vector), namely the variance (covariance) of the residuals. Furthermore the prediction of the states is given as the solution to the ODEs and hence assumed deterministic and can predict the future perfectly. A more realistic approach would be to allow for randomness in the model due to e.g., the model be too simple or errors in input. We describe a modeling and prediction setup which better reflects reality and suggests stochastic differential equations (SDEs) for modeling and forecasting. It is argued that this gives models and predictions which better reflect reality. The SDE approach also offers a more adequate framework for modeling and a number of efficient tools for model building. A software package (CTSM-R) for SDE-based modeling is briefly described.

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Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Copenhagen Center for Health Technology, Center for Energy Resources Engineering, Scientific Computing
Modelling of glucose-insulin-glucagon pharmacodynamics in man
The purpose is to build a simulation model of the glucoregulatory system in man. We estimate individual human parameters of a physiological glucose-insulin-glucagon model. We report posterior probability distributions and correlations of model parameters.

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Authors: Wendt, S. L. (Intern), Møller, J. K. (Intern), Haidar, A. (Ekstern), Knudsen, C. B. (Ekstern), Madsen, H. (Intern), Jørgensen, J. B. (Intern)
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Modelling the glucose-insulin-glucagon dynamics after subcutaneous administration of native glucagon and a novel glucagon analogue in dogs
Zealand Pharma has invented a glucagon analogue, ZP-GA-1, with increased stability in liquid formulation for treatment of hypoglycemia. A pharmacodynamic (PD) model is needed to compare ZP-GA-1 with marketed glucagon. We aim to develop a model of the complex glucose-insulin-glucagon dynamics based on physiology and data.

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Authors: Wendt, S. L. (Intern), Boye Knudsen, C. (Ekstern), Jørgensen, J. B. (Intern), Madsen, H. (Intern), Haidar, A. (Ekstern)
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Model of the Glucose-Insulin-Glucagon Dynamics after Subcutaneous Administration of a Glucagon Rescue Bolus in Healthy Humans

In healthy individuals, insulin and glucagon work in a complex fashion to maintain blood glucose levels within a narrow range. This regulation is distorted in patients with diabetes. The hepatic glucose response due to an elevated glucagon level depends on the current insulin concentration and thus endogenous glucose production (EGP) cannot be modelled without knowledge of the concentration of both hormones in plasma. Furthermore, literature suggests an upper limit to EGP irrespective of glucagon levels. We build a simulation model of the glucose-insulin-glucagon dynamics in man including saturation effect of EGP.

Ten healthy subjects received a 1 mg subcutaneous (SC) glucagon bolus (GlucaGen®). Plasma samples were collected until 300 minutes post dose and analyzed for glucagon, insulin, and glucose concentrations. All observations were used to fit a physiological model of the glucose-insulin-glucagon dynamics using the Hovorka model with a novel multiplicative description of the effects of insulin and of glucagon on EGP.

Bayesian estimation by Maximum a Posteriori using prior knowledge reported in literature was used to estimate the model parameters for each subject. Profile likelihood plots were used to investigate parameter identifiability. Unidentifiable parameters were fixed at their prior mean values.

The new model enables simulations of the glucose-insulin-glucagon dynamics in humans at both low and high glucagon concentrations (180-8000 pg/mL) and physiologic insulin concentrations (1.2-81.9 mIU/L). The model can be used for simulation of glucagon bolus strategies for treatment of hypoglycemia and for in silico simulation of dual-hormone artificial pancreas algorithms.
Model of the Glucose-Insulin-Glucagon Dynamics after Subcutaneous Administration of a Glucagon Rescue Bolus in Healthy Humans

In healthy individuals, insulin and glucagon work in a complex fashion to maintain blood glucose levels within a narrow range. This regulation is distorted in patients with diabetes. The hepatic glucose response due to an elevated glucagon level depends on the current insulin concentration and thus endogenous glucose production (EGP) cannot be modelled without knowledge of the concentration of both hormones in plasma. Furthermore, literature suggests an upper limit to EGP irrespective of glucagon levels. We build a simulation model of the glucose-insulin-glucagon dynamics in man including saturation effect of EGP.

Ten healthy subjects received a 1 mg subcutaneous (SC) glucagon bolus (GlucaGen®). Plasma samples were collected until 300 minutes post dose and analyzed for glucagon, insulin, and glucose concentrations. All observations were used to fit a physiological model of the glucose-insulin-glucagon dynamics using the Hovorka model with a novel multiplicative description of the effects of insulin and of glucagon on EGP.

Bayesian estimation by Maximum a Posteriori using prior knowledge reported in literature was used to estimate the model parameters for each subject. Profile likelihood plots were used to investigate parameter identifiability. Unidentifiable parameters were fixed at their prior mean values.

The new model enables simulations of the glucose-insulin-glucagon dynamics in humans at both low and high glucagon concentrations (180-8000 pg/mL) and physiologic insulin concentrations (1.2-81.9 mIU/L). The model can be used for simulation of glucagon bolus strategies for treatment of hypoglycemia and for in silico simulation of dual-hormone artificial pancreas algorithms.

On the significance of the noise model for the performance of a linear MPC in closed-loop operation

This paper discusses the significance of the noise model for the performance of a Model Predictive Controller when operating in closed-loop. The process model is parametrized as a continuous-time (CT) model and the relevant sampled-data filtering and control algorithms are developed. Using CT models typically means less parameters to identify. Systematic tuning of such controllers is discussed. Simulation studies are conducted for linear time-invariant systems showing that choosing a noise model of low order is beneficial for closed-loop performance. (C) 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
PK/PD modelling of glucose-insulin-glucagon dynamics in healthy dogs after a subcutaneous bolus administration of native glucagon or a novel glucagon analogue

Objective We aim to develop a simulation model of the complex glucose-insulin-glucagon dynamics based on physiology and data. Furthermore, we compare pharmacokinetic (PK) and pharmacodynamic (PD) characteristics of marketed reconstituted glucagon with a stable liquid glucagon analogue invented by Zealand Pharma A/S.

Research Design and Methods We expanded a physiological model of endogenous glucose production with multiplicative effects of insulin and glucagon and combined it with the Hovorka glucoregulatory model. We used a Bayesian framework to perform multidimensional MAP estimation of model parameters given priors reported in the literature. We used profile likelihood analysis to investigate parameter identifiability and reduce the number of model variables. We estimated model parameters in pre-clinical data from one cross-over study with a total of 20 experiments in five dogs. The dogs received two subcutaneous (SC) bolus injections of low and high doses of glucagon and ZP-GA-1 (20 and 120 nmol/kg).

Results We report posterior probability distributions and correlations for all identifiable model parameters. Based on visual inspection and residual analysis, the PD model described data satisfactorily for both glucagon and the analogue. Parameter estimates of the PD model were not significantly different between the two compounds.

Conclusions The new PK/PD model enables simulations of the glucose-insulin-glucagon dynamics after a SC bolus of glucagon or glucagon analogue. The novel glucagon analogue by Zealand Pharma A/S shows PK and PD characteristics similar to marketed glucagon.
**Prediction Methods for Blood Glucose Concentration: Design, Use and Evaluation**

Standard diabetes insulin therapy for type 1 diabetes and late stages of type 2 is based on the expected development of blood glucose (BG) both as a consequence of the metabolic glucose consumption as well as of meals and exogenous insulin intake. Traditionally, this is not done explicitly, but the insulin amount is chosen using factors that account for this expectation.

The increasing availability of more accurate continuous blood glucose measurement (CGM) systems is attracting much interest to the possibilities of explicit prediction of future BG values. Against this background, in 2014 a two-day workshop on the design, use and evaluation of prediction methods for blood glucose concentration was held at the Johannes Kepler University Linz, Austria. One intention of the workshop was to bring together experts working in various fields on the same topic, in order to shed light from different angles on the underlying problem of modeling the glucose insulin dynamics of type 1 diabetes patients. Among the international participants were continuous glucose monitoring developers, diabetologists, mathematicians and control engineers, both, from academia and industry. In total 18 talks were given followed by panel discussions which allowed to receive direct feedback from the point of view of different disciplines.

This book is based on the contributions of that workshop and is intended to convey an overview of the different aspects involved in the prediction. The individual chapters are based on the presentations given by the authors at the workshop but were written afterward which allowed to include the findings and conclusions of the various discussions and of course updates.

The chapter "Alternative Frameworks for Personalized Insulin-Glucose Models" by Harald Kirchsteiger et al. asks the question whether more and more detailed physiological descriptions of the glucose metabolism with an ever-increasing degree of sophistication and number of modeled phenomena are really what is needed for pushing the boundaries in glucose prediction for control. As an alternative, the chapter introduces two data-based approaches that focus not on the prediction of exact future blood glucose values, but rather on the prediction of changes in the patients' blood glucose range.

The chapter "Accuracy of BG Meters and CGM Systems: Possible Influence Factors for the Glucose Prediction Based on Tissue Glucose Concentrations" by Guido Freckmann et al. discusses performance metrics used to characterize the accuracy of continuous glucose measurement devices. This topic is highly relevant for prediction models since many of them rely on the data given by the continuous sensors which are previously calibrated with blood glucose meter measurements which are also subject to measurement errors. Inaccurate measurements will directly affect the performance of the corresponding predictions.

The chapter “CGM — How Good Is Good Enough?” by Michael Schoemaker and Christopher G. Parkin also tackles the problem of continuous glucose monitor performance evaluation. Several performance metrics used in different published studies are compared and their individual characteristics analyzed. The chapter reveals why the comparison of a sensor evaluated in two different clinical studies is not always straightforward.

The chapter "Can We Use Measurements to Classify Patients Suffering from Type 1 Diabetes into Subcategories and Does It Make Sense?" by Florian Reiterer et al. makes use of continuous time prediction models to describe the interaction between ingested carbohydrates, subcutaneously injected insulin, and continuously measured glucose concentration. The identified model parameters of 12 subjects were analyzed and statistically significant correlations between the parameters and patient characteristics such as weight and age could be found.

The chapter “Prevention of Severe Hypoglycemia by Continuous EEG Monitoring” by Claus Borg Juhl et al. shows how to use EEG signals to predict upcoming hypoglycemic situations in real-time by employing artificial neural networks. The results of a 30-day long clinical study with the implanted device and the developed algorithm are presented.

The chapter “Meta-Learning Based Blood Glucose Predictor for DiabeticSmartphone App” by Valeriya Naumova et al. demonstrates how a highly sophisticated glucose prediction model can be ported from a development language running on a PC to a format such that it can be used conveniently by the patients. A unique feature of the algorithm is its independence of any user input other than historic CGM data which is automatically transmitted from a CGM device. No parameter estimation nor prediction model individualization is required.

The chapter "Predicting Glycemia in Type 1 Diabetes Mellitus with Subspace-Based Linear Multistep Predictors" by Marzia Cescon et al. uses data-based methods to develop individualized prediction models. The model can be considered as a combination of physiological models to precompute the rate of appearance of injected insulin and ingested carbohydrates in the bloodstream and of data-based models to combine this information and compute predictions up to 120 min in the future. The results show the performance on data from 14 type 1 diabetes patients in a clinical trial.

The chapter “Empirical Representation of Blood Glucose Variability in a Compartmental Model” by Stephen D. Patek et al. shows a modeling technique designed to extract the information on the net effect of meals on the blood glucose
By assuming that all major unexplained glycemic excursions can be attributed to oral glucose ingestion, a meal vector is estimated which significantly improves the mathematical model. Results are shown on three patients during a clinical trial and on virtual patients where it is shown how the method can be used for adjustments of the basal insulin rate.

The chapter "Physiology-Based Interval Models: A Framework for Glucose Prediction Under Intra-patient Variability" by Jorge Bondia and Josep Vehi tries to cope with the large intra-subject variability by using the concept of interval predictions. Instead of predicting a single blood glucose value in the future, a whole solution envelope is determined. With the presented theory it can be guaranteed that the real value is always inside of the envelope and moreover the envelope is not conservative. The method is evaluated on a physiological diabetes model.

The chapter "Modeling and Prediction Using Stochastic Differential Equations" by Rune Juhl et al. considers uncertainty in the dynamics between different patients as well as within a patient by making use of stochastic differential equations. It is shown how the mixed effects modeling methodology can be applied such that the underlying information of several datasets from different patients is extracted to form the model.

The chapter "Uncertainties and Modeling Errors of Type 1 Diabetes Models" by Levente Kovacs and Peter Szalay analyzes the effect of prediction model uncertainties on the control system during a design procedure involving the steps model reduction by elimination of state variables, state estimation using extended Kalman Filters and Sigma Point filters and linear parameter-varying control synthesis.

The chapter "Recent Results on Glucose–Insulin Predictions by Means of a State Observer for Time-Delay Systems" by Pasquale Palumbo et al. introduces a prediction model which in real time predicts the insulin concentration in blood which in turn is used in a control system. The method is tested in simulation on a time-delay system representing the glucose–insulin system.

The chapter "Performance Assessment of Model-Based Artificial Pancreas Control Systems" by Jianyuan Feng et al. makes use of prediction models to compute treatment advices. The novelty of the proposed algorithm consists in explicitly considering (among others) the model prediction error and model error elimination speed. A retuning of the advisory system is done in case the prediction model does not perform well. Results on 30 virtual patients show the performance of the control system.

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Time-explicit methods for joint economical and geological risk mitigation in production optimization
Real-life applications of production optimization face challenges of risks related to unpredictable fluctuations in oil prices and sparse geological data. Consequently, operating companies are reluctant to adopt model-based production optimization into their operations. Conventional production optimization methods focus on mitigation of geological risks related to the long-term net present value (NPV). A major drawback of such methods is that the time-dependent and exceedingly growing uncertainty of oil prices implies that long-term predictions become highly unreliable. Conventional
methods therefore leave the oil production subject to substantial economical risk. To address this challenge, this paper introduces a novel set of time-explicit (TE) methods, which combine ideas of multi-objective optimization and ensemble-based risk mitigation into a computationally tractable joint effort of mitigating economical and geological risks. As opposed to conventional strategies that focus on a single long-term objective, TE methods seek to reduce risks and promote returns over the entire reservoir life by optimization of a given ensemble-based geological risk measure over time. By explicit involvement of time, economical risks are implicitly addressed by balancing short-term and long-term objectives throughout the reservoir life. Open-loop simulations of a two-phase synthetic reservoir demonstrate that TE methods may significantly improve short-term risk measures such as expected return, standard deviation and conditional value-at-risk compared to nominal, robust and mean-variance optimization. The gains in short-term objectives are obtained with none or only slight deterioration of long-term objectives.

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BFI (2012): BFI-level 1
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A Bolus Calculator Based on Continuous-Discrete Unscented Kalman Filtering for Type 1 Diabetics

In patients with type 1 diabetes, the effects of meals intake on blood glucose level are usually mitigated by administering a large amount of insulin (bolus) at mealtime or even slightly before. This strategy assumes, among other things, a prior knowledge of the meal size and the postprandial glucose dynamics. On the other hand, administering the meal bolus during or after mealtime could benefit from the information provided by the postprandial meal dynamics at the expense of a delayed meal bolus. The present paper investigates different bolus administration strategies (at mealtime, 15 minutes after or 30 minutes after the beginning of the meal). We implement a continuous-discrete unscented Kalman filter to estimate the states and insulin sensitivity. These estimates are used in a bolus calculator. The numerical results demonstrate that administering the meal bolus 15 minutes after mealtime both reduces the risk of hypoglycemia in case of an overestimated meal and the time spent in hyperglycemia if the meal size is underestimated. Faster insulin and the use of glucagon will have the potential to encourage postprandial meal bolus administration and hence will not require to accurately estimate the meal size.

General information

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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems, Copenhagen Center for Health Technology, Center for Energy Resources Engineering, Technical University of Denmark
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A Continuous-Discrete Extended Kalman Filter for State and Parameter Estimation In People with Type 1 Diabetes

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A dynamic mathematical model for packed columns in carbon capture plants
In this paper, we present a dynamic mathematical model for the absorption and desorption columns in a carbon capture plant. Carbon capture plants must be operated in synchronization with the operation of thermal power plants. Dynamic and flexible operation of the carbon capture plant is important as thermal plants must be operated very flexibly to accommodate large shares of intermittent energy sources such as wind and solar in the energy system. To facilitate such operation, dynamic models for simulation, optimization and control system design are crucial. The dynamic model developed in this paper is suitable for gas-liquid packed columns, e.g. for CO2 absorption and desorption. The model is based on rigorous thermodynamic and conservation principles and it is set up to preserve these properties upon numerical integration in time. The developed model is applied for CO2 absorption and desorption simulation using monoethanolamine (MEA) and piperazine (PZ) as solvent. MEA is considered as the base-case solvent in the carbon capture business. The effect of changes in the flue gas flow rate and changes in the available steam are investigated to determine their influence on the performance of the capture process. The response of the model is shown in terms of capture efficiency and purity of the CO2 product stream. The model is aimed for rigorous dynamic simulation in the context
of optimization and control strategy development.

A Homogeneous and Self-Dual Interior-Point Linear Programming Algorithm for Economic Model Predictive Control
We develop an efficient homogeneous and self-dual interior-point method (IPM) for the linear programs arising in economic model predictive control of constrained linear systems with linear objective functions. The algorithm is based on a Riccati iteration procedure, which is adapted to the linear system of equations solved in homogeneous and self-dual IPMs. Fast convergence is further achieved using a warm-start strategy. We implement the algorithm in MATLAB and C. Its performance is tested using a conceptual power management case study. Closed loop simulations show that 1) the proposed algorithm is significantly faster than several state-of-the-art IPMs based on sparse linear algebra, and 2) warm-start reduces the average number of iterations by 35-40%.

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An artificial pancreas for automated blood glucose control in patients with Type 1 diabetes

Automated glucose control in patients with Type 1 diabetes is much-coveted by patients, relatives and healthcare professionals. It is the expectation that a system for automated control, also known as an artificial pancreas, will improve glucose control, reduce the risk of diabetes complications and markedly improve patient quality of life. An artificial pancreas consists of portable devices for glucose sensing and insulin delivery which are controlled by an algorithm residing on a computer. The technology is still under development and currently no artificial pancreas is commercially available. This review gives an introduction to recent progress, challenges and future prospects within the field of artificial pancreas research.

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A novel tuning approach for offset-free MPC
Since the beginnings in the chemical and process industry, model based predictive control strategies have become widely accepted. Often mentioned success factors for MPC are the use of optimization based on a plant model, the consideration of constraints, and an intuitive tuning. Indeed, if a nominal plant and overall objective are known, the tuning can become straightforward. However, as soon as disturbances have to be taken into account, the tuning effort increases and becomes less intuitive. Against this background, a novel strategy to address the issues with unknown disturbances is proposed. The idea is to separate the nominal tuning process and extend the control by an outer loop, which ensures offset-free control. The inner, nominal loop decouples the system and essentially leads to a first order response. This inner loop addresses the performance targets in the nominal case, and the outer loop provides offset-free control in case of unknown disturbances. The outer loop consists of feedback controllers adapting the reference, which due to the decoupling can be tuned by known guidelines. The proposed strategy is presented and evaluated using a simulated case study.
Bihormonal control of blood glucose in people with type 1 diabetes

This paper presents a bihormonal artificial pancreas (AP) for people with type 1 diabetes (T1D) designed to provide a safe blood glucose control with minimal use of glucagon. The control algorithm uses insulin as well as glucagon to prevent hyper- and hypoglycemia. We employ a novel prediction-based activation of glucagon administration. The control algorithm consists of a Kalman filter, an insulin infusion model predictive controller (MPC), a proportional-derivative (PD) controller for glucagon infusion, and a meal time insulin bolus calculator. The PD controller is activated if the Kalman filter predicts hypoglycemia. Predictions utilize an ARMAX model describing glucose-insulin and glucose-glucagon dynamics. The model parameters are estimated from basic patient-specific data. A continuous glucose monitor provides feedback. We test the control algorithm using a simulation model with time-varying parameters available for 3 patients. We consider a simulation scenario where meals are estimated correctly as well as overestimated by 30%. The simulation results demonstrate that during normal operation, the controller only needs insulin and does not need glucagon. During unexpected events, such as insulin overdose due to an overestimated meal, the control algorithm uses glucagon efficiently to avoid severe hypoglycemia.

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Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Scientific Computing, Copenhagen Center for Health Technology, Slovak University of Technology, Copenhagen University Hospital
Comparison of Linear and Nonlinear Model Predictive Control for Optimization of Spray Dryer Operation

In this paper, we compare the performance of an economically optimizing Nonlinear Model Predictive Controller (E-NMPC) to a linear tracking Model Predictive Controller (MPC) for a spray drying plant. We find in this simulation study, that the economic performance of the two controllers are almost equal. We evaluate the economic performance with an industrially recorded disturbance scenario, where unmeasured disturbances and model mismatch are present. The state of the spray dryer, used in the E-NMPC and MPC, is estimated using Kalman Filters with noise covariances estimated by a maximum likelihood (ML) method.

Comparison of Prediction Models for a Dual-Hormone Artificial Pancreas

In this paper we compare the performance of five different continuous time transfer function models used in closed-loop model predictive control (MPC). These models describe the glucose-insulin and glucose-glucagon dynamics. They are discretized into a state-space description and used as prediction models in the MPC algorithm. We simulate a scenario including meals and daily variations in the model parameters. The numerical results do not show significant changes in the glucose traces for any of the models, excepted for the first order model. From the present study, we can conclude that the second order model without delay should provide the best trade-off between sensitivity to uncertainties and practical usability for in vivo clinical studies.
This paper presents a mixed-integer linear optimization problem for unit commitment and economic dispatch of power generators in a meshed isolated power system. The optimization problem is referred to as the optimal reserve planning problem (ORPP). The ORPP guarantees that the system frequency is kept above a predefined limit in the event of a contingency. The minimum frequency constraints are formulated using novel sufficient conditions that take into account the system inertia and the dynamics of the power generators. The proposed sufficient conditions are attractive from both a computational and a modelling point of view. We compare the ORPP to a unit commitment problem that only considers the stationary behavior of the frequency. Simulations based on a Faroe Islands case study show that, without being overly conservative, potential blackouts and power outages can be avoided using the ORPP. In the particular case study, the cost increase associated with the additional security provided by the ORPP is less than 3%.
Dynamic and flexible operation of a carbon capture plant is important as thermal power plants must be operated very flexibly to accommodate large shares of intermittent energy sources such as wind and solar energy. To facilitate such operation, dynamic models for simulation, optimization and control system design are crucial. In this paper, we present a dynamic mathematical model for the absorption and desorption columns in a carbon capture plant. Moreover, we implement a decentralized proportional-integral (PI) based control scheme and we evaluate the performance of the control structure for various operational procedures, e.g. start-up, load changes, noise on the flue gas flow rate and composition. Note that the carbon capture plant is based on the solvent storage configuration. To the authors' knowledge, this is the first paper addressing the issue of start-up operation and control of carbon capture. The study demonstrates that the implemented control structure keeps the carbon capture process at 90% CO2 removal rate with a deviation up to 8% during load variations. In addition, it reveals that the control structure brings the process to the desired set point in approximately 10 min during process start-up.
Control of Electricity Load in Future Smart Cities

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Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Scientific Computing
Authors: Madsen, H. (Intern), Parvizi, J. (Intern), Halvgaard, R. (Intern), Jørgensen, J. B. (Intern)
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Control of Electricity Loads in Future Electric Energy Systems

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Chapter: 24
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Economic Model Predictive Control for Large-Scale and Distributed Energy Systems

In this thesis, we consider control strategies for large and distributed energy systems that are important for the implementation of smart grid technologies. An electrical grid has to ensure reliability and avoid long-term interruptions in the power supply. Moreover, the share of Renewable Energy Sources (RESs) in the smart grids is increasing. These energy sources bring uncertainty to the production due to their fluctuations. Hence, smart grids need suitable control systems that are able to continuously balance power production and consumption. We apply the Economic Model Predictive Control (EMPC) strategy to optimise the economic performances of the energy systems and to balance the power production and consumption. In the case of large-scale energy systems, the electrical grid connects a high number of power units. Because of this, the related control problem involves a high number of variables and constraints and its solution requires high computational times. Energy systems have a hierarchical control framework and the controllers have to work in the time-scale required by their hierarchy level. Dedicated optimisation techniques efficiently solve the control problem and reduce computational time. We implement the Dantzig-Wolfe decomposition technique to efficiently solve the EMPC problem.

The contributions of this thesis are primarily on:

**Large-scale energy system**

Smart-grids connect a high number of energy units. In such a large-scale scenario the energy units are independent and dynamically decoupled. The mathematical model of the large-scale energy system embodies the decoupled dynamics of each power unit. Moreover, all units of the grid contribute to the overall power production.

**Economic Model Predictive Control (EMPC)**

This control strategy is an extension of the Model Predictive Control (MPC) strategy. Energy systems often involve stochastic variables due to the share of fluctuating Renewable Energy Sources (RESs). Moreover, the related control problems are multi variables and they are hard, or impossible, to split into single-input-single-output control systems. MPC strategy can handle multi variables control problems and it can embody stochastic variables. The Economic MPC (EMPC) policy optimises the economic performances of the process. In this work, we apply the EMPC to energy systems and it computes the control trajectory for each energy unit. This control policy minimises production costs and ensures that the power production satisfies the customers’ demand. The EMPC designs a linear control problem that has a block-angular constraints matrix and it has two sets of constraints. The independent dynamics of the energy units define the decoupling constraints sited on the diagonal. The coupling constraints represent the common goal of all power units in the energy system and this is to satisfy the customers’ demand. The Dantzig-Wolfe optimisation technique applies to this structure of the constraints matrix in the view of fastening the control algorithm and increase its applicability.

**Dantzig-Wolfe decomposition**

The Dantzig-Wolfe decomposition solves the EMPC problem through a distributed optimisation technique. The EMPC problem via Dantzig-Wolfe decomposition algorithm computes the optimal input trajectory for each energy unit and reduces the computation times. Moreover, such a control algorithm applies to large-scale energy systems and the number of energy units does not affect the performances of the controller. In this thesis, we also investigate suboptimal solutions of the EMPC problem via modified versions of the Dantzig-Wolfe decomposition algorithms. The feasibility of the suboptimal solutions suffices for stability. The goal of these modified Dantzig-Wolfe decomposition algorithms is to reduce computation time in the solution of the EMPC problem.

**General information**

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**Organisations:** Department of Applied Mathematics and Computer Science, Scientific Computing, Center for Energy Resources Engineering, Dynamical Systems, Centre for IT-Intelligent Energy Systems in Cities  
**Authors:** Standardi, L. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern)  
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Economic Optimization of Spray Dryer Operation using Nonlinear Model Predictive Control with State Estimation

In this paper, we develop an economically optimizing Nonlinear Model Predictive Controller (E-NMPC) for a complete spray drying plant with multiple stages. In the E-NMPC the initial state is estimated by an extended Kalman Filter (EKF) with noise covariances estimated by an autocovariance least squares method (ALS). We present a model for the spray
drying plant and use this model for simulation as well as for prediction in the E-NMPC. The open-loop optimal control problem in the E-NMPC is solved using the single-shooting method combined with a quasi-Newton Sequential Quadratic programming (SQP) algorithm and the adjoint method for computation of gradients. We evaluate the economic performance when unmeasured disturbances are present. By simulation, we demonstrate that the E-NMPC improves the profit of spray drying by 17% compared to conventional PI control.

Efficient solvers for soft-constrained MPC
In this work, integrated design and control of reactive distillation processes is presented. Simple graphical design methods that are similar in concept to non-reactive distillation processes are used, such as reactive McCabe-Thiele method and driving force approach. The methods are based on the element concept, which is used to translate a system of compounds into elements. The operation of the reactive distillation column at the highest driving force and other candidate points is analyzed through analytical solution as well as rigorous open-loop and closed-loop simulations. By application of this approach, it is shown that designing the reactive distillation process at the maximum driving force results in an optimal design in terms of controllability and operability. It is verified that the reactive distillation design option is less sensitive to the disturbances in the feed at the highest driving force and has the inherent ability to reject disturbances.

High-Performance Small-Scale Solvers for Moving Horizon Estimation
In this paper we present a moving horizon estimation (MHE) formulation suitable to easily describe the quadratic programs (QPs) arising in constrained and nonlinear MHE. We propose algorithms for factorization and solution of the underlying Karush-Kuhn-Tucker (KKT) system, as well as thecient implementation techniques focusing on small-scale problems. The proposed MHE solver is implemented using custom linear algebra routines and is compared against implementations using BLAS libraries. Additionally, the MHE solver is interfaced to a code generation tool for nonlinear model predictive control (NMPC) and nonlinear MHE (NMHE). On an example problem with 33 states, 6 inputs and 15 estimation intervals execution times below 500 microseconds are reported for the QP underlying the NMHE.
Modeling and Simulation of a Modified Quadruple Tank System

Quadruple tank process is a non-linear system, have multiple manipulated and controlled variables and have significant cross binding parameters. Furthermore, the modified system is affected by some unknown measurement noise and stochastic disturbance variables which make it more complicated to model and control. In this paper, a modified quadruple-tank system has been described, all the important variables has been outlined and a mathematical model has been presented. We developed deterministic and stochastic models using differential equations and simulate the models using Matlab. Subsequently, steady state analysis is included to determine the operating window for the set points. The purpose to have an operating window for the system is to distinguish the range of feasible region to select the set points for optimum operations. Therefore, in this paper a virtual process plant is created, we investigate the operating window and construct the model in an appropriate form for future controller design.

Model predictive control for wind power gradients

We consider the operation of a wind turbine and a connected local battery or other electrical storage device, taking into account varying wind speed, with the goal of maximizing the total energy generated while respecting limits on the time derivative (gradient) of power delivered to the grid. We use the turbine inertia as an additional energy storage device, by varying its speed over time, and coordinate the flows of energy to achieve the goal. The control variables are turbine pitch, generator torque and charge/discharge rates for the storage device, each of which can be varied over given ranges. The system dynamics are quite non-linear, and the constraints and objectives are not convex functions of the control inputs, so the resulting optimal control problem is difficult to solve globally. In this paper, we show that by a novel change of variables, which focuses on power flows, we can transform the problem to one with linear dynamics and convex constraints. Thus, the problem can be globally solved, using robust, fast solvers tailored for embedded control applications. We implement the optimal control problem in a receding horizon manner and provide extensive closed-loop
tests with real wind data and modern wind forecasting methods. The simulation results using real wind data demonstrate
the ability to reject the disturbances from fast changes in wind speed, ensuring certain power gradients, with an
insignificant loss in energy production.

General information
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Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing, Vestas Technology R&D, Stanford University
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Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.124 SNIP 1.448
Web of Science (2009): Indexed yes
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Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.053 SNIP 1.453
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.637 SNIP 1.689
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.287 SNIP 0.9
Web of Science (2005): Indexed yes
MPC Related Computational Capabilities of ARMv7A Processors

In recent years, the mass market of mobile devices has pushed the demand for increasingly fast but cheap processors. ARM, the world leader in this sector, has developed the Cortex-A series of processors with focus on computationally intensive applications. If properly programmed, these processors are powerful enough to solve the complex optimization problems arising in MPC in real-time, while keeping the traditional low-cost and low-power consumption. This makes these processors ideal candidates for use in embedded MPC. In this paper, we investigate the floating-point capabilities of Cortex A7, A9 and A15 and show how to exploit the unique features of each processor to obtain the best performance, in the context of a novel implementation method for the linear-algebra routines used in MPC solvers. This method adapts high-performance computing techniques to the needs of embedded MPC. In particular, we investigate the performance of matrix-matrix and matrix-vector multiplications, which are the backbones of second- and first-order methods for convex optimization. Finally, we test the performance of MPC solvers implemented using these optimized linear-algebra routines.

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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Center for Energy Resources Engineering
Authors: Frison, G. (Intern), Jørgensen, J. B. (Intern)
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Pharmacokinetics Modeling of Glucagon and a Novel Glucagon Analogue after Subcutaneous Administration in Dogs

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems, Zealand Pharma A/S
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Number of pages: 1
Publication date: 2015
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Main Research Area: Technical/natural sciences
Electronic versions: Eposter_final2_comp.pdf
Real-time nonlinear MPC and MHE for a large-scale mechatronic application

Progress in optimization algorithms and in computational hardware made deployment of Nonlinear Model Predictive Control (NMPC) and Moving Horizon Estimation (MHE) possible to mechatronic applications. This paper aims to assess the computational performance of NMPC and MHE for rotational start-up of Airborne Wind Energy systems. The capabilities offered by an automatic code generation tool are experimentally verified on a real physical system, using a model comprising 27 states and 4 inputs at a sampling frequency of 25 Hz. The results show the feedback times less than 5 ms for the NMPC with more than 1500 variables.
Remarks on models for estimating the carbohydrate to insulin ratio and insulin sensitivity in T1DM

In this paper we estimate linear models for prediction of the interstitial glucose concentration in response to meals and bolus insulin. Parameters of these models can be directly used in simple bolus calculation rules. In contrast to models proposed in the literature, we present a model without an integrator. This model maintains the benefits of the existing empirical models and allows simulation of a longer time period than the post-prandial period, i.e. the couple of hours following a meal. Furthermore, the new model proposed in this paper does not require any re-initialization before meals.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Slovak University of Technology
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The contribution of glucagon in an Artificial Pancreas for people with type 1 diabetes

The risk of hypoglycemia is one of the main concerns in treatment of type 1 diabetes (T1D). In this paper we present a head-to-head comparison of a currently used insulin-only controller and a prospective bihormonal controller for blood glucose in people with T1D. The bihormonal strategy uses insulin to treat hyperglycemia as well as glucagon to ensure fast recovery from hypoglycemic episodes. Two separate model predictive controllers (MPC) based on patient-specific models handle insulin and glucagon infusion. In addition, the control algorithm consists of a Kalman filter and a meal time insulin bolus calculator. The feedback is obtained from a continuous glucose monitor (CGM). We implement a bihormonal simulation model with time-varying parameters available for 3 subjects to compare the strategies. We consider a protocol with 3 events - a correct mealtime insulin bolus, a missed bolus and a bolus overestimated by 60%. During normal operation both strategies provide similar results. The contribution of glucagon becomes evident after administration of the overestimated insulin bolus. In a 10h period following an overbolused meal, the bihormonal strategy reduces time spent in hypoglycemia in the most severe case by almost 15% (1.5h), outperforming the insulin-only control. Therefore, glucagon contributes to the safety of an Artificial Pancreas.

General information
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A Dantzig-Wolfe decomposition algorithm for linear economic model predictive control of dynamically decoupled subsystems

This paper presents a warm-started Dantzig–Wolfe decomposition algorithm tailored to economic model predictive control of dynamically decoupled subsystems. We formulate the constrained optimal control problem solved at each sampling instant as a linear program with state space constraints, input limits, input rate limits, and soft output limits. The objective function of the linear program is related directly to the cost of operating the subsystems, and the cost of violating the soft output constraints. Simulations for large-scale economic power dispatch problems show that the proposed algorithm is significantly faster than both state-of-the-art linear programming solvers, and a structure exploiting implementation of the alternating direction method of multipliers. It is also demonstrated that the control strategy presented in this paper can be tuned using a weighted ℓ₁-regularization term. In the presence of process and measurement noise, such a regularization term is critical for achieving a well-behaved closed-loop performance.

General information

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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems, Center for Energy Resources Engineering, DONG Energy A/S
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Scopus rating (2015): SJR 1.338 SNIP 2.028 CiteScore 3.35
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Scopus rating (2014): SJR 1.521 SNIP 2.735 CiteScore 3.92
Web of Science (2014): Indexed yes
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Scopus rating (2013): SJR 1.507 SNIP 2.607 CiteScore 3.47
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BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.563 SNIP 2.954 CiteScore 3.39
A Decomposition Algorithm for Mean-Variance Economic Model Predictive Control of Stochastic Linear Systems

This paper presents a decomposition algorithm for solving the optimal control problem (OCP) that arises in Mean-Variance Economic Model Predictive Control of stochastic linear systems. The algorithm applies the alternating direction method of multipliers to a reformulation of the OCP that decomposes into small independent subproblems. We test the decomposition algorithm using a simple power management case study, in which the OCP is formulated as a convex quadratic program. Simulations show that the decomposition algorithm scales linearly in the number of uncertainty scenarios. Moreover, a parallel implementation of the algorithm is several orders of magnitude faster than state-of-the-art convex quadratic programming algorithms, provided that the number of uncertainty scenarios is large.
A Family of High-Performance Solvers for Linear Model Predictive Control

In Model Predictive Control (MPC), an optimization problem has to be solved at each sampling time, and this has traditionally limited the use of MPC to systems with slow dynamic. In this paper, we propose an efficient solution strategy for the unconstrained sub-problems that give the search-direction in Interior-Point (IP) methods for MPC, and that usually are the computational bottle-neck. This strategy combines a Riccati-like solver with the use of high-performance computing techniques: in particular, in this paper we explore the performance boost given by the use of single precision computation, and techniques such as inexact search direction and mixed precision computation. Finally, we test our HPMPC toolbox, a family of high-performance solvers tailored for MPC and implemented using these techniques, that is shown to be several times faster than current state-of-the-art solvers for linear MPC.

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A Mean-Variance Criterion for Economic Model Predictive Control of Stochastic Linear Systems

Stochastic linear systems arise in a large number of control applications. This paper presents a mean-variance criterion for economic model predictive control (EMPC) of such systems. The system operating cost and its variance is approximated based on a Monte-Carlo approach. Using convex relaxation, the tractability of the resulting optimal control problem is addressed. We use a power management case study to compare different variations of the mean-variance strategy with EMPC based on the certainty equivalence principle. The certainty equivalence strategy is much more computationally efficient than the mean-variance strategies, but it does not account for the variance of the uncertain parameters. Openloop simulations suggest that a single-stage mean-variance approach yields a significantly lower operating cost than the certainty equivalence strategy. In closed-loop, the single-stage formulation is overly conservative, which results in a high operating cost. For this case, a two-stage extension of the mean-variance approach provides the best trade-off between the expected cost and its variance. It is demonstrated that by using a constraint back-off technique in the specific case study, certainty equivalence EMPC can be modified to perform almost as well as the two-stage mean-variance formulation. Nevertheless, we argue that the mean-variance approach can be used both as a strategy for evaluating less computational demanding methods such as the certainty equivalence method, and as an individual control strategy when heuristics such as constraint back-off do not perform well.

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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems, Center for Energy Resources Engineering, Centre for IT-Intelligent Energy Systems in Cities
Authors: Sokoler, L. E. (Intern), Dammann, B. (Intern), Madsen, H. (Intern), Jørgensen, J. B. (Intern)
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A mean–variance objective for robust production optimization in uncertain geological scenarios

In this paper, we introduce a mean–variance criterion for production optimization of oil reservoirs and suggest the Sharpe ratio as a systematic procedure to optimally trade-off risk and return. We demonstrate by open-loop simulations of a two-phase synthetic oil field that the mean–variance criterion is able to mitigate the significant inherent geological uncertainties better than the alternative certainty equivalence and robust optimization strategies that have been suggested for production optimization. In production optimization, the optimal water injection profiles and the production borehole pressures are computed by solution of an optimal control problem that maximizes a financial measure such as the Net Present Value (NPV). The NPV is a stochastic variable as the reservoir parameters, such as the permeability field, are stochastic. In certainty equivalence optimization, the mean value of the permeability field is used in the maximization of the NPV of the reservoir over its lifetime. This approach neglects the significant uncertainty in the NPV. Robust optimization maximizes the expected NPV over an ensemble of permeability fields to overcome this shortcoming of certainty equivalence optimization. Robust optimization reduces the risk compared to certainty equivalence optimization because it considers an ensemble of permeability fields instead of just the mean permeability field. This is an indirect mechanism for risk mitigation as the risk does not enter the objective function directly. In the mean–variance bi-criterion objective function, risk appears directly, it also considers an ensemble of reservoir models, and has robust optimization as a special extreme case. The mean–variance objective is common for portfolio optimization problems in finance. The Markowitz portfolio optimization problem is the original and simplest example of a mean–variance criterion for mitigating risk. Risk is mitigated in oil production by including both the expected NPV (mean of NPV) and the risk (variance of NPV) for the ensemble of possible reservoir models. With the inclusion of the risk in the objective function, the Sharpe ratio can be used to compute the optimal water injection and production borehole pressure trajectories that give the optimal return–risk ratio. By simulation, we investigate and compare the performance of production optimization by mean–variance optimization, robust optimization, certainty equivalence optimization, and the reactive strategy. The optimization strategies are simulated in open-loop without feedback while the reactive strategy is based on feedback. The simulations demonstrate that certainty equivalence optimization and robust optimization are risky strategies. At the same computational effort as robust optimization, mean–variance optimization is able to reduce risk significantly at the cost of slightly smaller return. In this way, mean–variance optimization is a powerful tool for risk management and uncertainty mitigation in production optimization.

General information
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Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing, Norwegian University of Science and Technology
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Scopus rating (2016): SJR 0.764 SNIP 1.631 CiteScore 2.56
Web of Science (2016): Indexed yes
  BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.801 SNIP 1.652 CiteScore 2.38
Web of Science (2015): Indexed yes
  BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.692 SNIP 1.751 CiteScore 1.95
Application of Constrained Linear MPC to a Spray Dryer

In this paper we develop a linear model predictive control (MPC) algorithm for control of a two stage spray dryer. The states are estimated by a stationary Kalman filter. A non-linear first-principle engineering model is developed to simulate the spray drying process. The model is validated against experimental data and able to precisely predict the temperatures, the air humidity and the residual moisture in the dryer. The MPC controls these variables to the target and reject disturbances. Spray drying is a cost-effective method to evaporate water from liquid foods and produces a free flowing powder. The main challenge of spray drying is to meet the residual moisture specification and prevent powder from sticking to the chamber walls. By simulation we compare the performance of the MPC against the conventional PID control strategy. During an industrially recorded disturbance scenario, the MPC increases the production rate by 7.9%, profit of production by 8.2% and the energy efficiency by 4.1% on average.
A Realistic Process Example for MIMO MPC based on Autoregressive Models

Advanced controllers such as model predictive control are in use for a wide range of applications in the process industry. The potential utilization of such advanced predictive controllers is far from exhausted. One barrier for more widespread implementation is the lack of simple methodologies for advanced control design development which may be used by non-experts in control theory. This paper presents and illustrates the use of a simple methodology to design an offset-free MPC based on ARX models. Hence a mechanistic process model is not required. The forced circulation evaporator by Newell and Lee is used to illustrate the offset-free MPC based on ARX models for a nonlinear multivariate process.

General information
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A Reduced Dantzig-Wolfe Decomposition for a Suboptimal Linear MPC

Linear Model Predictive Control (MPC) is an efficient control technique that repeatedly solves online constrained linear programs. In this work we propose an economic linear MPC strategy for operation of energy systems consisting of multiple and independent power units. These systems cooperate to meet the supply of power demand by minimizing production costs. The control problem can be formulated as a linear program with block-angular structure. To speed-up the solution of the optimization control problem, we propose a reduced Dantzig-Wolfe decomposition. This decomposition algorithm computes a suboptimal solution to the economic linear MPC control problem and guarantees feasibility and stability. Finally, six scenarios are performed to show the decrease in computation time in comparison with the classic Dantzig-Wolfe algorithm.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems, Department of Chemical and Biochemical Engineering, Center for Energy Resources Engineering, Centre for IT-Intelligent Energy Systems in Cities
Authors: Standardi, L. (Intern), Poulsen, N. K. (Intern), Jørgensen, J. B. (Intern)
Assessment of Model Predictive and Adaptive Glucose Control Strategies for People with Type 1 Diabetes

This paper addresses overnight blood glucose stabilization in people with type 1 diabetes using a Model Predictive Controller (MPC). We use a control strategy based on an adaptive ARMAX model in which we use a Recursive Extended Least Squares (RELS) method to estimate parameters of the stochastic part. We compare this model structure with an autoregressive integrated moving average with exogenous input (ARIMAX) structure, and with an autoregressive moving average with exogenous input (ARMAX) model, i.e. without an integrator. Additionally, safety layers improve the controller robustness and reduce the risk of hypoglycemia. We test our control strategies on a virtual clinic of 100 randomly generated patients with a representative inter-subject variability. This virtual clinic is based on the Hovorka model. We consider the case where only half of the meal bolus is administered at mealtime, and the case where the insulin sensitivity varies during the night. The simulation results demonstrate that the adaptive control strategy can reduce the risks of hypoglycemia and hyperglycemia during the night.

A tuning approach for offset-free MPC with conditional reference adaptation

Model predictive control has become a widely accepted strategy in industrial applications in the recent years. Often mentioned reasons for the success are the optimization based on a system model, consideration of constraints and an intuitive tuning process. However, as soon as unknown disturbances or model plant mismatch have to be taken into account the tuning effort to achieve offset-free tracking increases. In this work a novel approach for offset-free MPC is presented, which divides the tuning in two steps, the setup of a nominal MPC loop and an external reference adaptation. The inner nominal loop addresses the performance targets in the nominal case, decouples the system and essentially leads to a first order response. The second outer loop enables offset-free tracking in case of unknown disturbances and consists of feedback controllers adapting the reference. Due to the mentioned properties these controllers can be tuned separate and by known guidelines. To address conditions with active input constraints, additionally a conditional reference adaptation scheme is introduced. The tuning strategy is evaluated on a simulated linear Wood-Berry binary distillation column example.
A Tuning Approach for Offset-free MPC with Conditional Reference Adaptation.

Model predictive control has become a widely accepted strategy in industrial applications in the recent years. Often mentioned reasons for the success are the optimization based on a system model, consideration of constraints and an intuitive tuning process. However, as soon as unknown disturbances or model plant mismatch have to be taken into account the tuning effort to achieve offset-free tracking increases. In this work a novel approach for offset-free MPC is presented, which divides the tuning in two steps, the setup of a nominal MPC loop and an external reference adaptation. The inner nominal loop addresses the performance targets in the nominal case, decouples the system and essentially leads to a first order response. The second outer loop enables offset-free tracking in case of unknown disturbances and consists of feedback controllers adapting the reference. Due to the mentioned properties these controllers can be tuned separate and by known guidelines. To address conditions with active input constraints, additionally a conditional reference adaptation scheme is introduced. The tuning strategy is evaluated on a simulated linear Wood-Berry binary distillation column example.

Bihormonal model predictive control of blood glucose in people with type 1 diabetes

In this paper we present a bihormonal control system that controls blood glucose in people with type 1 diabetes (T1D). We use insulin together with glucagon to mitigate the negative effects of hyper- and hypoglycemia. The system consists of a Kalman filter, a micro-bolus insulin and glucagon infusion MPC, a mealtime bolus calculator and a CGM providing feedback to the controller. The controller employs a patient data-based prediction model with ARMAX structure. We test the controller using a bihormonal model with time-varying parameters for 3 subjects and compare its performance to a system with an identical insulin MPC, but a glucagon PD controller. The key contribution of the bihormonal MPC is the efficiency of glucagon use. We consider scenarios where the meals are estimated correctly or overestimated and where the insulin sensitivity increases. Both solutions provide tight glucose control. According to the simulations, the bihormonal MPC requires on average 30% less glucagon than the system with a PD controller.
Conditional Reference Adaptation for Offset-free MPC

Model predictive control has become a widely accepted strategy in industrial applications in the recent years. Often mentioned reasons for the success are the optimization based on a system model, consideration of constraints and an intuitive tuning process. However, as soon as unknown disturbances or model plant mismatch have to be taken into account the tuning effort to achieve offset-free tracking increases. In this work a novel approach for offset-free MPC is presented, which divides the tuning in two steps, the setup of a nominal MPC loop and an external reference adaptation. The inner nominal loop addresses the performance targets in the nominal case, decouples the system and essentially leads to a first order response. The second outer loop enables offset-free tracking in case of unknown disturbances and consists of feedback controllers adapting the reference. Due to the mentioned properties these controllers can be tuned separate and by known guidelines. To address conditions with active input constraints, additionally a conditional reference adaptation scheme is introduced. The tuning strategy is evaluated on a simulated linear Wood-Berry binary distillation column example.

Economic Optimization of Spray Dryer Operation using Nonlinear Model Predictive Control

In this paper we investigate an economically optimizing Nonlinear Model Predictive Control (E-NMPC) for a spray drying process. By simulation we evaluate the economic potential of this E-NMPC compared to a conventional PID based control strategy. Spray drying is the preferred process to reduce the water content for many liquid foodstuffs and produces a free flowing powder. The main challenge in controlling the spray drying process is to meet the residual moisture specifications.
and avoid that the powder sticks to the chamber walls of the spray dryer. We present a model for a spray dryer that has been validated on experimental data from a pilot plant. We use this model for simulation as well as for prediction in the E-NMPC. The E-NMPC is designed with hard input constraints and soft output constraints. The open-loop optimal control problem in the E-NMPC is solved using the single-shooting method combined with a quasi-Newton Sequential Quadratic Programming (SQP) algorithm and the adjoint method for computation of gradients. The E-NMPC improves the cost of spray drying by 26.7% compared to conventional PI control in our simulations.

**Efficient Implementation of Solvers for Linear Model Predictive Control on Embedded Devices**

This paper proposes a novel approach for the efficient implementation of solvers for linear MPC on embedded devices. The main focus is to explain in detail the approach used to optimize the linear algebra for selected low-power embedded devices, and to show how the high-performance implementation of a single routine (the matrix-matrix multiplication gemm) can speed-up an interior-point method for linear MPC. The results show that the high-performance MPC obtained using the proposed approach is several times faster than the current state-of-the-art IP method for linear MPC on embedded devices.
area of fast small-scale solvers for linear MPC, with the two main research areas of explicit MPC and tailored on-line MPC. State-of-the-art solvers in this second class can outperform optimized linear-algebra libraries (BLAS) only for very small problems, and do not explicitly exploit the hardware capabilities, relying on compilers for that. This approach can attain only a small fraction of the peak performance on modern processors. In our paper, we combine high-performance computing techniques with tailored solvers for MPC, and use the specific instruction sets of the target architectures. The resulting software (called HPMPC) can solve linear MPC problems 2 to 8 times faster than the current state-of-the-art solver for this class of problems, and the high-performance is maintained for MPC problems with up to a few hundred states.

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**Input-constrained model predictive control via the alternating direction method of multipliers**
This paper presents an algorithm, based on the alternating direction method of multipliers, for the convex optimal control problem arising in input-constrained model predictive control. We develop an efficient implementation of the algorithm for the extended linear quadratic control problem (LQCP) with input and input-rate limits. The algorithm alternates between solving an extended LQCP and a highly structured quadratic program. These quadratic programs are solved using a Riccati iteration procedure, and a structure-exploiting interior-point method, respectively. The computational cost per iteration is quadratic in the dimensions of the controlled system, and linear in the length of the prediction horizon. Simulations show that the approach proposed in this paper is more than an order of magnitude faster than several state-of-the-art quadratic programming algorithms, and that the difference in computation time grows with the problem size. We improve the method further using a warm-start procedure.

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Interior Point Methods on GPU with application to Model Predictive Control

The goal of this thesis is to investigate the application of interior point methods to solve dynamical optimization problems, using a graphical processing unit (GPU) with a focus on problems arising in Model Predictive Control (MPC). Multi-core processors have been available for over ten years now, and manycore processors, such as GPUs, have also become a standard component in any consumer computer. The GPU offers faster floating point operations and higher memory bandwidth than the CPU, but requires algorithms to be redesigned and implemented, to match the underlying architecture. A large number of different optimization algorithms are available for solving optimization problems. Some of the most common method are the simplex method and interior point methods. We focus on interior point methods in this thesis, due to its polynomial complexity, and since the use of the simplex method with GPUs have been investigated by several other authors already. The main computational task in interior point methods is the solution of a linear system to compute the Newton direction in each iteration. Direct interior point methods use a direct method such as Cholesky factorization to factorize the normal equations of the Hessian matrix. The use of a GPU has been shown to be very efficient in the factorization of dense matrices, and several numeric libraries, which utilize the GPU, have become available during the course of this thesis. We have developed a direct interior point method, which utilizes the GPU, and demonstrate that our implementation can reduce the solution time substantially.

There are multiple software packages available for solving optimization problems with interior point methods, such as GLPK, IPOPT, MOSEK and many more. However, none of these support the GPU yet. With this thesis, we include a new software package called GPUOPT, available under the non-restrictive MIT license. GPUOPT includes includes a primal-dual interior-point method, which supports both the CPU and the GPU. It is implemented as multiple components, where the matrix operations and solver for the Newton directions is separated from the core interior point method. This makes it possible to replace the matrix operations and solver with alternative, and potentially problem-specific, implementations. In this thesis, we include different implementations of the matrix operations, including general dense, general sparse and problem-specific implementation of a test problem from model predictive control. Multiple solvers are implemented as well, including a direct solver based on CHOLMOD, and an iterative solver which uses preconditioned conjugate gradient. The iterative solver is based on the matrix-free iterative interior point method.

Model Predictive Control for Smart Energy Systems

In this thesis, we consider control strategies for flexible distributed energy resources in the future intelligent energy system – the Smart Grid. The energy system is a large-scale complex network with many actors and objectives in different hierarchical layers. Specifically the power system must supply electricity reliably to both residential and industrial consumers around the clock. More and more fluctuating renewable energy sources, like wind and solar, are integrated in the power system. Consequently, uncertainty in production starts to affect an otherwise controllable power production significantly. A Smart Grid calls for flexible consumers that can adjust their consumption based on the amount of green energy in the grid. This requires coordination through new large-scale control and optimization algorithms. Trading of flexibility is key to drive power consumption in a sustainable direction. In Denmark, we expect that distributed energy resources such as heat pumps, and batteries in electric vehicles will mobilize part of the needed flexibility.

Our primary objectives in the thesis were threefold:

1. Simulate the components in the power system based on simple models from literature (e.g. heat pumps, heat tanks,
electrical vehicle battery charging/discharging, wind farms, power plants).

2. Embed forecasting methodologies for the weather (e.g. temperature, solar radiation), the electricity consumption, and the electricity price in a predictive control system.

3. Develop optimization algorithms for large-scale dynamic systems. This includes decentralized optimization and simulation on realistic large-scale dynamic systems.

Chapter 1 introduces the power system, the markets, and the main actors. The objectives and control hierarchy is outlined while Aggregators are introduced as new actors.

Chapter 2 provides linear dynamical models of Smart Grid units: Electric Vehicles, buildings with heat pumps, refrigeration systems, solar collectors, heat storage tanks, power plants, and wind farms. The models can be realized as discrete time state space models that fit into a predictive control system.

Chapter 3 introduces Model Predictive Control (MPC) including state estimation, filtering and prediction for linear models.

Chapter 4 simulates the models from Chapter 2 with the certainty equivalent MPC from Chapter 3. An economic MPC minimizes the costs of consumption based on real electricity prices that determined the flexibility of the units. A predictive control system easily handles constraints, e.g. limitations in power consumption, and predicts the future behavior of a unit by integrating predictions of electricity prices, consumption, and weather variables. The simulations demonstrate the expected load shifting capabilities of the units that adapts to the given price predictions. We furthermore evaluated control performance in terms of economic savings for different control strategies and forecasts.

Chapter 5 describes and compares the proposed large-scale Aggregator control strategies. Aggregators are assumed to play an important role in the future Smart Grid and coordinate a large portfolio of units. The developed economic MPC controllers interfaces each unit directly to an Aggregator. We developed several MPC-based aggregation strategies that coordinates the global behavior of a portfolio of units by solving a large-scale optimization and control problem. We applied decomposition methods based on convex optimization, such as dual decomposition and operator splitting, and developed price-based aggregator strategies.

Chapter 6 provides conclusions, contributions and future work.

The main scientific contributions can be summarized to:

- Linear dynamical models of flexible Smart Grid units: heat pumps in buildings, heat storage tanks, and electric vehicle batteries.
- Economic MPC that integrates forecasts in the control of these flexible units.
- Large-scale distributed control strategies based on economic MPC, convex optimization, and decomposition methods.
- A Matlab toolbox including the modeled units for simulating a Smart Energy System with MPC.

**General information**

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**Predicting Plasma Glucose From Interstitial Glucose Observations Using Bayesian Methods**

One way of constructing a control algorithm for an artificial pancreas is to identify a model capable of predicting plasma glucose (PG) from interstitial glucose (IG) observations. Stochastic differential equations (SDES) make it possible to account both for the unknown influence of the continuous glucose monitor (CGM) and for unknown physiological
influences. Combined with prior knowledge about the measurement devices, this approach can be used to obtain a robust predictive model. A stochastic-differential-equation-based gray box (SDE-GB) model is formulated on the basis of an identifiable physiological model of the glucoregulatory system for type 1 diabetes mellitus (T1DM) patients. A Bayesian method is used to estimate robust parameters from clinical data. The models are then used to predict PG from IG observations from 2 separate study occasions on the same patient. First, all statistically significant diffusion terms of the model are identified using likelihood ratio tests, yielding inclusion of $\sigma_{Isc}$, $\sigma_{GP}$, and $\sigma_{Gsc}$. Second, estimates using maximum likelihood are obtained, but prediction capability is poor. Finally, a Bayesian method is implemented. Using this method the identified models are able to predict PG using only IG observations. These predictions are assessed visually. We are also able to validate these estimates on a separate data set from the same patient. This study shows that SDE-GBs and a Bayesian method can be used to identify a reliable model for prediction of PG using IG observations obtained with a CGM. The model could eventually be used in an artificial pancreas.

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Real-time economic optimization for a fermentation process using Model Predictive Control
Fermentation is a widely used process in production of many foods, beverages, and pharmaceuticals. The main goal of the control system is to maximize profit of the fermentation process, and thus this is also the main goal of this paper. We present a simple dynamic model for a fermentation process and demonstrate its usefulness in economic optimization. The model is formulated as an index-1 differential algebraic equation (DAE), which guarantees conservation of mass and energy in discrete form. The optimization is based on recent advances within Economic Nonlinear Model Predictive Control (E-NMPC), and also utilizes the index-1 DAE model. The E-NMPC uses the single-shooting method and the adjoint method for computation of the optimization gradients. The process constraints are relaxed to soft-constraints on the outputs. Finally we derive the analytical solution to the economic optimization problem and compare it with the numerically determined solution.

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A Dantzig-Wolfe Decomposition Algorithm for Economic MPC of Distributed Energy Systems
In economic model predictive control of distributed energy systems, the constrained optimal control problem can be expressed as a linear program with a block-angular structure. In this paper, we present an efficient Dantzig-Wolfe decomposition algorithm specifically tailored to problems of this type. Simulations show that a MATLAB implementation of the algorithm is significantly faster than several state-of-the-art linear programming solvers and that it scales in a favorable way.

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A Decomposition Algorithm for Optimal Control of Distributed Energy System
In economic model predictive control of distributed energy systems, the constrained optimal control problem can be expressed as a linear program with a block-angular structure. In this paper, we present an efficient Dantzig-Wolfe decomposition algorithm specifically tailored to problems of this type. Simulations show that a MATLAB implementation of the algorithm is significantly faster than several state-of-the-art linear programming solvers and that it scales in a favorable way.

General information
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A Fast Condensing Method for Solution of Linear-Quadratic Control Problems

In both Active-Set (AS) and Interior-Point (IP) algorithms for Model Predictive Control (MPC), sub-problems in the form of linear-quadratic (LQ) control problems need to be solved at each iteration. The solution of these sub-problems is usually the main computational effort. In this paper we consider a condensing (or state elimination) method to solve an extended version of the LQ control problem, and we show how to exploit the structure of this problem to both factorize the dense Hessian matrix and solve the system. Furthermore, we present two efficient implementations. The first implementation is formally identical to the Riccati recursion based solver and has a computational complexity that is linear in the control horizon length and cubic in the number of states. The second implementation has a computational complexity that is quadratic in the control horizon length as well as the number of states. When the state dimension is high, this implementation is faster than the Riccati recursion based implementation.

A Grey-Box Model for Spray Drying Plants

Multi-stage spray drying is an important and widely used unit operation in the production of food powders. In this paper we develop and present a dynamic model of the complete drying process in a multi-stage spray dryer. The dryer is divided into three stages: The spray stage and two fluid bed stages. Each stage is assumed ideally mixed and described by mass- and energy balances. The model is able to predict the temperature, the residual moisture and the particle size in each stage. Process constraints are also proposed to predict deposits due to stickiness of the powder. The model predictions are compared to datasets gathered at GEA Process Engineering's test facility. The identified grey-box model parameters are identified from data and the resulting model fits the data well. The complexity of the model has been selected such that it is suitable for development of real-time optimization algorithms in an economic optimizing MPC framework.
A Riccati Based Homogeneous and Self-Dual Interior-Point Method for Linear Economic Model Predictive Control

In this paper, we develop an efficient interior-point method (IPM) for the linear programs arising in economic model predictive control of linear systems. The novelty of our algorithm is that it combines a homogeneous and self-dual model, and a specialized Riccati iteration procedure. We test the algorithm in a conceptual study of power systems management. Simulations show that in comparison to state of the art software implementation of IPMs, our method is significantly faster and scales in a favourable way.

A Tuning Procedure for ARX-based MPC

We present an optimization based tuning procedure with certain robustness properties for an offset free Model Predictive Controller (MPC). The MPC is designed for univariate processes that can be represented by an ARX model. The advantage of ARX model representations is that standard system identification techniques using convex optimization can be used for identification of such models from input-output data. The stochastic model of the ARX model identified from input-output data is modified with an ARMA model designed as part of the MPC-design procedure to ensure offset-free control. The ARMAX model description resulting from the extension can be realized as a state space model in innovation form. The MPC is designed and implemented based on this state space model in innovation form. Expressions for the closed-loop dynamics of the unconstrained system is used to derive the sensitivity function of this system. The closed-loop expressions are also used to numerically evaluate absolute integral performance measures. Due to the closed-loop expressions, these evaluations can be done relative quickly. Consequently, the tuning may be performed by numerical minimization of the integrated absolute error subject to the a constraint on the maximum of the sensitivity function. The latter constraint provides a robustness measure that is essential for the procedure.
A Tuning Procedure for ARX-based MPC of Multivariate Processes

We present an optimization based tuning procedure with certain robustness properties for an offset free Model Predictive Controller (MPC). The MPC is designed for multivariate processes that can be represented by an ARX model. The stochastic model of the ARX model identified from input-output data is modified with an ARMA model designed as part of the MPC-design procedure to ensure offset-free control. The MPC is designed and implemented based on a state space model in innovation form. Expressions for the closed-loop dynamics of the unconstrained system is used to derive the sensitivity function of this system. The closed-loop expressions are also used to numerically evaluate absolute integral performance measures. Due to the closed-loop expressions these evaluations can be done relatively quickly. Consequently, the tuning may be performed by numerical minimization of the integrated absolute error subject to a constraint on the maximum of the sensitivity function. The latter constraint provides a robustness measure that is essential for the procedure. The method is demonstrated for two simulated examples: A Wood-Berry distillation column example and a cement mill example.

A Warm-Started Homogeneous and Self-Dual Interior-Point Method for Linear Economic Model Predictive Control

In this paper, we present a warm-started homogenous and self-dual interior-point method (IPM) for the linear programs arising in economic model predictive control (MPC) of linear systems. To exploit the structure in the optimization problems, our algorithm utilizes a Riccati iteration procedure which is adapted to the non-standard system solved in homogenous and self-dual IPMs, and specifically tailored to economic MPC. Fast convergence is further achieved by means of a recent warm-starting strategy for homogenous and self-dual IPMs that has not previously been applied to MPC. We implement
our algorithm in MATLAB and its performance is analyzed based on a smart grid power management case study. Closed loop simulations show that 1) our algorithm is significantly faster than state-of-the-art IPMs based on sparse linear algebra routines, and 2) warm-starting reduces the number of iterations by approximately 15-35%.

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Computational Efficiency of Economic MPC for Power Systems Operation
In this work, we propose an Economic Model Predictive Control (MPC) strategy to operate power systems that consist of independent power units. The controller balances the power supply and demand, minimizing production costs. The control problem is formulated as a linear program that is solved by a computationally efficient implementation of the Dantzig-Wolfe decomposition. To make the controller suitable for realtime applications, we investigate a suboptimal MPC scheme, introducing an early termination strategy to the Dantzig-Wolfe algorithm. Simulations demonstrate that the early termination technique substantially reduces the computation time.

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Decentralized Large-Scale Power Balancing
A power balancing strategy based on Douglas-Rachford splitting is proposed as a control method for largescale integration of flexible consumers in a Smart Grid. The total power consumption is controlled through a negotiation procedure between all units and a coordinating system level. The balancing problem is formulated as a centralized large-scale optimization problem but is then decomposed into smaller subproblems that are solved locally by each unit connected to an aggregator. For large-scale systems the method is faster than solving the full problem and can be distributed to include an arbitrary number of units.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Dynamical Systems
Dual Decomposition for Large-Scale Power Balancing

Dual decomposition is applied to power balancing of flexible thermal storage units. The centralized large-scale problem is decomposed into smaller subproblems and solved locally by each unit in the Smart Grid. Convergence is achieved by coordinating the units consumption through a negotiation procedure with the dual variables.

Early Termination of Dantzig-Wolfe Algorithm for Economic MPC

In this paper we apply the Economic Model Predictive Control (MPC) for balancing the power supply and demand in the future power systems in the most economic way. The control problem is formulated as a linear program, having a block-angular structure solved by the implementation of the Dantzig-Wolfe decomposition. For real-time applications we introduce an early termination technique. Simulations demonstrate that the algorithm developed operates efficiently a power system, reducing significantly computational time.
Efficient Implementation of the Riccati Recursion for Solving Linear-Quadratic Control Problems

In both Active-Set (AS) and Interior-Point (IP) algorithms for Model Predictive Control (MPC), sub-problems in the form of linear-quadratic (LQ) control problems need to be solved at each iteration. The solution of these sub-problems is typically the main computational effort at each iteration. In this paper, we compare a number of solvers for an extended formulation of the LQ control problem: a Riccati recursion based solver can be considered the best choice for the general problem with dense matrices. Furthermore, we present a novel version of the Riccati solver, that makes use of the Cholesky factorization of the $P_n$ matrices to reduce the number of flops. When combined with regularization and mixed precision, this algorithm can solve large instances of the LQ control problem up to 3 times faster than the classical Riccati solver.

Exercise effects in a virtual type 1 diabetes patient: Using stochastic differential equations for model extension

The use of virtual patients for in silico testing of control algorithms for an artificial pancreas is growing. It is an easy, fast and low-cost alternative to pre-clinical testing. To simulate the everyday life of a type 1 diabetes (T1D) patient a simulator must be able to take into account physical activity. Exercise constitutes a substantial challenge to closed-loop control of T1D. The effects are many and depend on intensity and duration and may be delayed by several hours. In this study, we use a model for the glucoregulatory system based on the minimal model and a previously published extension incorporating exercise effects on insulin and glucose dynamics. Our model is constructed as a stochastic state space model consisting of a set of stochastic differential equations (SDEs). In a stochastic state space model, the residual error is split into random measurement error and misspecification noise. The latter of the two can be used to pinpoint model deficiencies or unknown influential factors during the development of the model. The model is thus built on the basis of physiological knowledge of the system combined with information from observed data. Model parameters are estimated on clinical data from a study including exercise bouts of 20 minutes performed on 12 T1D patients treated with continuous subcutaneous insulin infusion. The predictive abilities of the model are investigated. In conclusion, this study illustrates the advantages of using SDEs in the development of an extended glucoregulatory model including effects of exercise suited for in silico testing.
Background:
To improve type 1 diabetes mellitus (T1DM) management, we developed a model predictive control (MPC) algorithm for closed-loop (CL) glucose control based on a linear second-order deterministic-stochastic model. The deterministic part of the model is specified by three patient-specific parameters: insulin sensitivity factor, insulin action time, and basal insulin infusion rate. The stochastic part is identical for all patients but identified from data from a single patient. Results of the first clinical feasibility test of the algorithm are presented.

Methods:
We conducted two randomized crossover studies. Study 1 compared CL with open-loop (OL) control. Study 2 compared glucose control after CL initiation in the euglycemic (CL-Eu) and hyperglycemic (CL-Hyper) ranges, respectively. Patients were studied from 22:00–07:00 on two separate nights.

Results:
Each study included six T1DM patients (hemoglobin A1c 7.2% ± 0.4%). In study 1, hypoglycemic events (plasma glucose < 54 mg/dl) occurred on two OL and one CL nights. Average glucose from 22:00–07:00 was 90 mg/dl [74–146 mg/dl;
median (interquartile range) during OL and 108 mg/dl (101–128 mg/dl) during CL (determined by continuous glucose monitoring). However, median time spent in the range 70–144 mg/dl was 67.9% (3.0–73.3%) during OL and 80.8% (70.5–89.7%) during CL. In study 2, there was one episode of hypoglycemia with plasma glucose <54 mg/dl in a CL-Eu night. Mean glucose from 22:00–07:00 and time spent in the range 70–144 mg/dl were 121 mg/dl (117–133 mg/dl) and 69.0% (30.7–77.9%) in CL-Eu and 149 mg/dl (140–193 mg/dl) and 48.2% (34.9–72.5%) in CL-Hyper, respectively.

Conclusions:
This study suggests that our novel MPC algorithm can safely and effectively control glucose overnight, also when CL control is initiated during hyperglycemia.

Model Identification Using Stochastic Differential Equation Grey-Box Models in Diabetes
BACKGROUND:
The acceptance of virtual preclinical testing of control algorithms is growing and thus also the need for robust and reliable models. Models based on ordinary differential equations (ODEs) can rarely be validated with standard statistical tools. Stochastic differential equations (SDEs) offer the possibility of building models that can be validated statistically and that...
are capable of predicting not only a realistic trajectory, but also the uncertainty of the prediction. In an SDE, the prediction error is split into two noise terms. This separation ensures that the errors are uncorrelated and provides the possibility to pinpoint model deficiencies.

METHODS:
An identifiable model of the glucoregulatory system in a type 1 diabetes mellitus (T1DM) patient is used as the basis for development of a stochastic-differential-equation-based grey-box model (SDE-GB). The parameters are estimated on clinical data from four T1DM patients. The optimal SDE-GB is determined from likelihood-ratio tests. Finally, parameter tracking is used to track the variation in the "time to peak of meal response" parameter.

RESULTS:
We found that the transformation of the ODE model into an SDE-GB resulted in a significant improvement in the prediction and uncorrelated errors. Tracking of the "peak time of meal absorption" parameter showed that the absorption rate varied according to meal type.

CONCLUSION:
This study shows the potential of using SDE-GBs in diabetes modeling. Improved model predictions were obtained due to the separation of the prediction error. SDE-GBs offer a solid framework for using statistical tools for model validation and model development.
MPC for Wind Power Gradients - Utilizing Forecasts, Rotor Inertia, and Central Energy Storage

We consider the control of a wind power plant, possibly consisting of many individual wind turbines. The goal is to maximize the energy delivered to the power grid under very strict grid requirements to power quality. We define an extremely low power output gradient and demonstrate how decentralized energy storage in the turbines' inertia combined with a central storage unit or deferrable consumers can be utilized to achieve this goal at a minimum cost. We propose a variation on model predictive control to incorporate predictions of wind speed. Due to the aerodynamics of the turbines the model contains nonconvex terms. To handle this nonconvexity, we propose a sequential convex optimization method, which typically converges in fewer than 10 iterations. We demonstrate our method in simulations with various wind scenarios and prices for energy storage. These simulations show substantial improvements in terms of limiting the power ramp rates (disturbance rejection) at the cost of very little power. This capability is critical to help balance and stabilize the future power grid with a large penetration of intermittent renewable energy sources.

General information
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Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing, Vestas Technology R&D, Stanford University
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Nonconvex Model Predictive Control for Commercial Refrigeration

We consider the control of a commercial multi-zone refrigeration system, consisting of several cooling units that share a common compressor, and is used to cool multiple areas or rooms. In each time period we choose cooling capacity to each unit and a common evaporation temperature. The goal is to minimize the total energy cost, using real-time electricity prices, while obeying temperature constraints on the zones. We propose a variation on model predictive control to achieve this goal. When the right variables are used, the dynamics of the system are linear, and the constraints are convex. The cost function, however, is nonconvex due to the temperature dependence of thermodynamic efficiency. To handle this nonconvexity we propose a sequential convex optimization method, which typically converges in fewer than 5 or so iterations. We employ a fast convex quadratic programming solver to carry out the iterations, which is more than fast enough to run in real-time. We demonstrate our method on a realistic model, with a full year simulation and 15 minute time periods, using historical electricity prices and weather data, as well as random variations in thermal load. These simulations show substantial cost savings, on the order of 30%, compared to a standard thermostat-based control system. Perhaps more important, we see that the method exhibits sophisticated response to real-time variations in electricity prices. This demand response is critical to help balance real-time uncertainties in generation capacity associated with large penetration of intermittent renewable energy sources in a future smart grid.

General information
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Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Center for Energy Resources Engineering, Vestas Technology R&D, Stanford University
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Nonlinear Model Predictive Control for Oil Reservoirs Management

The current world average recovery factor from oil fields is widely agreed to be about 30-35%. An increase of 10% point of this recovery factor would bring about 500 billion of oil barrels, sufficient to meet 16 years of current global production. To realize this potential production increase, the research community is working on improving current feedback model-based optimal control technologies. The topic of this thesis is production optimization for water flooding in the secondary phase of oil recovery. We developed numerical methods for nonlinear model predictive control (NMPC) of an oil field. The controller
- A model based optimizer for maximizing some predicted financial measure of the reservoir (e.g. the net present value).
- A parameter and state estimator.
- Use of the moving horizon principle for data assimilation and implementation of the computed control input.

The optimizer uses gradient-based optimization and the required gradients are computed by the adjoint method. We propose the use of efficient high order implicit time integration methods for the solution of the forward and the adjoint equations of the dynamical model. The Ensemble Kalman filter is used for data assimilation. Further, we studied the use of robust control strategies in both open-loop, i.e. without measurement feedback, and closed-loop, i.e. with measurement feedback, configurations.

This thesis has three main original contributions:

The first contribution in this thesis is to improve the computationally expensive gradient computation by using high-order ESDIRK (Explicit Singly Diagonally Implicit Runge-Kutta) temporal integration methods and continuous adjoints. The high order integration scheme allows larger time steps and therefore faster solution times. We compare gradient computation by the continuous adjoint method to the discrete adjoint method and the finite-difference method. We demonstrate that the optimization algorithm can be accelerated by using the continuous time adjoint equations. This is the first time in the literature that the higher order continuous adjoint and higher order discrete adjoint methods have been investigated for oil production optimization.

The second contribution of this thesis is the application of the Robust Optimization strategy in both open-loop (i.e. without measurement feedback) and closed-loop (i.e. with measurement feedback). In the oil industry, Robust Optimization has been suggested to compensate for inherent geological uncertainties in an oil field. In robust optimization of an oil reservoir, the water injection and production borehole pressures are computed such that the predicted net present value of an ensemble of permeability field realizations is maximized. In our study, the permeability field is the uncertain parameters. We compare the performance of the RO strategy to a certainty equivalent optimization strategy, based on the ensemble mean of the permeability field realizations as its permeability field, and to a reactive strategy. In open-loop, for the case studied, the reactive strategy performed better than the open-loop RO strategy. These observations are nontrivial, as previous literature suggests that the open-loop RO strategy performs better than the reactive strategy. Simulations indicate that the inferior performance of the open-loop RO strategy compared to the reactive strategy is due to the inability of the RO strategy to efficiently encompass ensembles with very different and conflicting optimal control trajectories. Hence, we propose a modified RO strategy that allow shut in of uneconomical wells. The modified RO strategy performs significantly better than the other open-loop strategies and the reactive strategy. Finally, this is the first time in literature that the RO optimization has been investigated in closed-loop. Surprisingly, for the case studied, the closed-loop robust strategy yields a higher NPV than the closed-loop RO strategy. The uncertainty reduction of the permeability field estimate due to data assimilation explains the good performance of the closed-loop certainty equivalent optimization strategy. Consequently, in closed-loop, the increased computational effort of the RO strategy compared to the certainty equivalent strategy is not justified for the particular case studied in this paper.

The third contribution of this thesis is a mean-variance method for risk mitigation in production optimization of oil reservoirs. We introduce a return-risk bicriterion objective function for the profit-risk tradeoff. With this objective function we link the optimization problem in production optimization to the Markowitz portfolio optimization problem in finance or to the robust design problem in topology optimization. In this study we focus on open-loop configuration, i.e. without measurement feedback. We demonstrate that a return-risk bi-criterion objective function is a valuable tool for the profit-risk tradeoff. If combined with the previous contribution, this result trigger the necessity of comparing the closed-loop CE strategy with the closed-loop MV strategy.

The thesis consists of a summary report and a collection of five research papers written during the period May 2010 to August 2013. Three papers are published in conference proceedings, one paper is published in Computational Geosciences journal and another paper is submitted to Journal of Petroleum Science and Engineering.

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Authors: Capolei, A. (Intern), Jørgensen, J. B. (Intern)
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Parallel Implementation of Riccati Recursion for Solving Linear-Quadratic Control Problems

In both Active-Set (AS) and Interior-Point (IP) algorithms for Model Predictive Control (MPC), sub-problems in the form of linear-quadratic (LQ) control problems need to be solved at each iteration. The solution of these sub-problems is usually the main computational effort. In this paper an alternative version of the Riccati recursion solver for LQ control problems is presented. The performance of both the classical and the alternative version is analyzed from a theoretical as well as a numerical point of view, and the alternative version is found to be approximately 50% faster than the classical one, for systems with many states. A number of parallel implementations of the alternative version has been proposed and tested.

Power Management for Energy Systems

In this thesis, we consider the control of two different industrial applications that belong at either end of the electricity grid; a power consumer in the form of a commercial refrigeration system, and wind turbines for power production. Our primary studies deal with economic model predictive control of a commercial multi-zone refrigeration system, consisting of several cooling units that share a common compressor, and is used to cool multiple areas or rooms, e.g., in supermarkets. Substantial amounts of energy are consumed in refrigeration systems worldwide and there is a strong motivation for introducing more energy efficient as well as cost reducing control techniques. At the same time, the power grid is evolving from a centralized system with rather controllable production in the conventional power plants to a much more decentralized network of many independent power generators and a large penetration of renewable, fossil-free energy sources such as solar and wind power. To facilitate such intermittent power producers, we must not only control the production of electricity, but also the consumption, in an efficient and flexible manner. By enabling the use of thermal energy storage in supermarkets, we open up for flexible power consumption schemes with the possibility of reducing operational costs and we develop and demonstrate prototype control technology that creates completely new business opportunities for both power consumers and producers of renewable energy. Moreover, this enables a larger penetration of wind energy in the power production and increases the potential market size for wind power generators and other renewable energy sources. Thus, we aim at promoting the use of environmentally sustainable power production technologies while creating new business opportunities for both power consumers and producers of renewable energy.

The second application, wind turbines, takes us to the production side of the power grid. The key concern here is to improve the quality and integrability of power delivered to the grid from large parks of wind turbines. Our goal is to reduce the fluctuating nature of the power output and to meet tightened demands from the grid by enabling a more intelligent control at both the individual turbine level, at the park controller level, and in cooperation with exible power consumers or other means of energy storage. The possible interaction and synergies of the two applications are obvious reasons to consider both in this thesis, and as we will see, the similarities in our formulations of the different control problems allow us to apply almost identical techniques despite the lack of immediate similarity.

For control of the commercial refrigeration application as well as the wind turbine application, we propose an economic optimizing model predictive controller, economic MPC. MPC is a feedback control technique that is characterized by its explicit handling of constrained control problems in which a model is used to predict the future behavior of a system along with forecasts of future disturbances. At each time step the values of the control inputs are computed by solving an open-loop finite time optimal control problem over a dened prediction horizon. Only the rst step in this optimal open-loop
sequence is implemented as a control command. Feedback is obtained by solving the open-loop problem repeatedly, in a receding horizon fashion, as new predictions become available.

Our investigations are primarily concerned with: 1) modeling of the applications to suit the chosen control framework; 2) formulating the MPC controller laws to overcome challenges introduced by the industrial applications, and defining economic objectives that reflect the real physics of the systems as well as our control objectives; 3) solving the involved, non-trivial optimization problems efficiently in real-time; 4) demonstrating the feasibility and potential of the proposed methods by extensive simulation and comparison with existing control methods and evaluation of data from systems in actual operation.

We present contributions on:

Economic MPC for commercial refrigeration systems, including
-Linear economic MPC formulations that utilize the flexibility in refrigeration systems to counteract fluctuations in the balance between power consumption and production.
-Nonlinear economic MPC, reflecting the nonconvexity in the realistic description of temperature dependent efficiencies in the refrigeration cycle.
-Nonlinear economic MPC with uncertain predictions and the implementation of very simple predictors that use entirely historical data of, e.g., electricity prices and outdoor temperatures.

Economic MPC for wind turbines, including
-Optimal steady-state calculation for wind farms.
-Nonlinear economic MPC for individual turbines.

Tractable optimization methods for the MPC problems, including
-Sequential convex programming (SCP) for specific nonconvex problems originating from our studies of commercial refrigeration as well as from our studies concerning wind power.
-Successful demonstration of the SCP approach on three different problems the commercial refrigeration system with linear dynamics and constraints and a nonconvex objective, the individual wind turbine with nonlinear dynamics and constraints, and the static optimization of the wind farm with a black-box model.

The major contribution is the formulation of these problems and the demonstrations to show that the SCP method can be used for their solution.

We demonstrate, i.a., substantial cost savings, on the order of 30 %, compared to a standard thermostat-based supermarket refrigeration system and show how our methods exhibit sophisticated demand response to real-time variations in electricity prices. Violations of the temperature ranges can be kept at a very low frequency of occurrence in spite of the presence of uncertainty. For the power output from wind turbines, ramp rates, as low as 3 % of the rated power per minute, can be effectively ensured with the use of energy storage and we show how the active use of rotor inertia as an additional energy storage can reduce the needed storage capacity by up to 30 % without reducing the power output.

**General information**

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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Center for Energy Resources Engineering, Department of Electrical Engineering, Automation and Control, VESTAS Wind Systems A/S
Authors: Hovgaard, T. G. (Intern), Jørgensen, J. B. (Intern), Blanke, M. (Intern), Larsen, L. F. S. (Ekstern)
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**Practical Implementations of Advanced Process Control for Linear Systems**

This paper describes some practical problems encountered, when implementing Advanced Process Control, APC, schemes on linear processes. The implemented APC controllers discussed will be LQR, Riccati MPC and Condensed MPC controllers illustrated by simulation of the Four Tank Process and a linearised CSTR. Advantages and disadvantages of these controllers will be discussed. All three controller types show a set of common undesirable characteristics, which
must be accounted for. At the end of the evaluation horizon the "optimal" solution has an unstable characteristics, which can be suppressed by selecting different control and evaluation horizon. Depending of the degrees of freedom, offset-free control of a number of the controlled variables can be achieved by integration of the innovation errors and introduction of noise models. If the measured or unmeasured disturbances increases, offset-free control cannot be achieved without violation of process constraints. A target calculation function can be used to calculate the optimal achievable target for the process. The use of hard and soft constraints for process input constraints in the MPC controllers, ensures feasible solutions. The computational load as function of controllers type, Model dimension and constraint type will be discussed. Finally the special requirements set by processes including a pure integration dynamics will be illustrated by a linearised CSTR process. The simulated results presented, will later on be implemented on and demonstrated on pilot plant equipment on the department of Chemical Engineering DTU Lyngby.

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Practical Implementations of Advanced Process Control for Linear Systems

Most advanced process control systems are based on Model Predictive Control (MPC). In this paper we discuss three critical issues for the practical implementation of linear MPC for process control applications. The first issue is related to offset free control and disturbance models; the second issue is related to the use of soft output constraints in MPC; and the third issue is related to the computationally efficient solution of the quadratic program in the dynamic regulator of the MPC. We have implemented MPC in .Net using C# and the MPCMath library. The implemented MPC is based on the target-regulator structure.

It enables offset free control; it can be computed efficiently on-line using several optimization algorithms; and accommodates soft constraint for the outputs and for shaping the set-point tracking penalty function. We report selected observations using this implementation and discuss their practical implications for process control. If the control and evaluation intervals are chosen too short, the predicted behaviour of the controllers may have unstable characteristics. Depending of the degrees of freedom, offset-free control of a number of the controlled variables can be achieved by introduction of noise models and integration of the innovation errors. If the disturbances increases, offset-free control cannot be achieved without violation of process constraints. A target calculation function is used to calculate the optimal achievable target for the process. The use of soft constraints for process output constraints in the MPC controllers, ensures feasible solutions. The computational load as function of controllers type, model dimension and constraint type are shown.

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The Homogeneous Interior-Point Algorithm: Nonsymmetric Cones, Warmstarting, and Applications

The overall topic of this thesis is convex conic optimization, a sub-field of mathematical optimization that attacks optimization problem with a certain geometric structure. These problems allow for modelling of an extremely wide range of real-world problems, but the availability of solution algorithms for these problems is still limited.
The goal of this thesis is to investigate and shed light on two computational aspects of homogeneous interior-point algorithms for convex conic optimization:

The first part studies the possibility of devising a homogeneous interior-point method aimed at solving problems involving constraints that require nonsymmetric cones in their formulation. The second part studies the possibility of warmstarting the homogeneous interior-point algorithm for conic problems. The main outcome of the first part is the introduction of a completely new homogeneous interior-point algorithm designed to solve nonsymmetric convex conic optimization problems. The algorithm is presented in detail and then analyzed. We prove its convergence and complexity. From a theoretical viewpoint, it is fully competitive with other algorithms and from a practical viewpoint, we show that it holds lots of potential, in several cases being superior to other solution methods.

The main outcome of the second part of the thesis is two new warmstarting schemes for the homogeneous interior-point algorithm for conic problems. Again, we first motivate and present the schemes and then analyze them. It is proved that they, under certain circumstances, result in an improved worst-case complexity as compared to a normal coldstart. We then move on to present an extensive series of computational results substantiating the practical usefulness of these warmstarting schemes. These experiments include standard benchmarking problem test sets as well as an application from smart energy systems.

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The Potential of Economic Model Predictive Control for Spray Drying Plants
In 2015 the milk quota system in the European Union will be completely liberalized. As a result, analysts expect production of skimmed and whole milk powder to increase by 5-6% while its price will decline by about 6-7%. Multi-stage spray drying is the prime process for the production of food powders. The process is highly energy consuming and capacity depends among other factors on correct control of the dryer. Consequently efficient control and optimization of the spray drying process has become increasingly important to accommodate the future market challenges.

The goal of the presentation is to present our results regarding modeling of the process and how the efficiency and probability can be lifted by introducing an economic optimizing MPC scheme.

Firstly, we develop a first-principle engineering model that can be used to simulate spray drying processes with high accuracy. The model can be adjusted to describe drying of various products and describes the complete drying process of a multi-stage spray dryer. The dryer is divided into three stages, the spray stage and two uid bed stages. Each stage is assumed ideally mixed and described by mass- and energy balances. The model is able to predict outlet temperatures, the residual moisture and particle size of the product. We also give a novel approach to predict deposits due to stickiness of the powder. The model predictions are compared to datasets gathered at GEA Process Engineering's test facility. The identified model parameters are identified from data and the resulting model is the data well.

Secondly, the effect of disturbances, ambient air humidity and solids content in the feed, is studied by simulation. We show that conventional control is insufficient at controlling the product quality as well as driving the plant to the most economic conditions. Furthermore, we show that the efficiency can be increased by correct adjustment of heat and inlet air ow at each stage.

The recent focus in research has shifted from reference tracking MPC to optimization of economic objective functions. We will discuss how this optimization can be performed by advanced process control techniques, such as Economic Model Predictive Control (E-MPC). We suggest adding an E-MPC based supervisory control layer on top of the contemporary PI-controllers. The strong interconnection between drying stages and process onstraints are well suited for MPC.
Thermal Storage Power Balancing with Model Predictive Control

The method described in this paper balances power production and consumption with a large number of thermal loads. Linear controllers are used for the loads to track a temperature set point, while Model Predictive Control (MPC) and model estimation of the load behavior are used for coordination. The total power consumption of all loads is controlled indirectly through a real-time price. The MPC incorporates forecasts of the power production and disturbances that influence the loads, e.g. time-varying weather forecasts, in order to react ahead of time. A simulation scenario demonstrates that the method allows for the integration of flexible thermal loads in a smart energy system in which consumption follows the changing production.

Waterflooding optimization in uncertain geological scenarios

In conventional waterflooding of an oil field, feedback based optimal control technologies may enable higher oil recovery than with a conventional reactive strategy in which producers are closed based on water breakthrough. To compensate for the inherent geological uncertainties in an oil field, robust optimization has been suggested to improve and robustify optimal control strategies. In robust optimization of an oil reservoir, the water injection and production borehole pressures (bhp) are computed such that the predicted net present value (NPV) of an ensemble of permeability field realizations is maximized. In this paper, we both consider an open-loop optimization scenario, with no feedback, and a closed-loop optimization scenario. The closed-loop scenario is implemented in a moving horizon manner and feedback is obtained using an ensemble Kalman filter for estimation of the permeability field from the production data. For open-loop implementations, previous test case studies presented in the literature, show that a traditional robust optimization strategy (RO) gives a higher expected NPV with lower NPV standard deviation than a conventional reactive strategy. We present and study a test case where the opposite happen: The reactive strategy gives a higher expected NPV with a lower NPV standard deviation than the RO strategy. To improve the RO strategy, we propose a modified robust optimization strategy (modified RO) that can shut in uneconomical producer wells. This strategy inherits the features of both the reactive and the RO strategy. Simulations reveal that the modified RO strategy results in operations with larger returns and less risk than the reactive strategy, the RO strategy, and the certainty equivalent strategy. The returns are measured by the
expected NPV and the risk is measured by the standard deviation of the NPV. In closed-loop optimization, we investigate and compare the performance of the RO strategy, the reactive strategy, and the certainty equivalent strategy. The certainty equivalent strategy is based on a single realization of the permeability field. It uses the mean of the ensemble as its permeability field. Simulations reveal that the RO strategy and the certainty equivalent strategy give a higher NPV compared to the reactive strategy. Surprisingly, the RO strategy and the certainty equivalent strategy give similar NPVs. Consequently, the certainty equivalent strategy is preferable in the closed-loop situation as it requires significantly less computational resources than the robust optimization strategy. The similarity of the certainty equivalent and the robust optimization based strategies for the closed-loop situation challenges the intuition of most reservoir engineers. Feedback reduces the uncertainty and this is the reason for the similar performance of the two strategies.

**General information**
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Web of Science (2007): Indexed yes
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Scopus rating (2005): SJR 0.807 SNIP 1.376
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A Dantzig-Wolfe Decomposition Algorithm for Linear Economic MPC of a Power Plant Portfolio

Recently, the interest in renewable energy sources is increasing. In the short future, their penetration in the power systems will be significantly higher than today. Denmark is working on achieving its goal by 2020 of having 30% of the energy production provided by renewable sources. 50% of the total power consumption is expected to stem from wind turbines. Due to the inherent stochasticity in renewable energy systems (RES), their energy production is usually complicated to forecast and control. The aim of the smart grid in which consumers as well as producers are controlled is to allow for larger variation in the power production due to the significant amount of renewable energy. The multiple power generators and consumers must be coordinated to balance the supply and demand for power at all times. The aim of this study is to examine a control technique for large scale distributed energy systems (DES), where a significant amount of renewable energy sources are present. Economic Model Predictive Control (MPC) is applied to control the power generators, minimizing the cost and producing the amount of energy required. We examine the large scale scenario, where multiple power generators and consumers such as e.g. electrical vehicles, heat pumps for domestic heating, and refrigeration and cooling systems must be controlled to balance the supply and demand for power. The system is very large scale. To address the large scale of the system and be able to compute the control decisions within a sample period, Dantzig-Wolfe decomposition is used for solution of the resulting linear program describing the Economic MPC of such systems. The controller obtained has been tested by simulations of a power portfolio system.

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A Dantzig-Wolfe Decomposition Algorithm for Linear Economic MPC of a Power Plant Portfolio

Future power systems will consist of a large number of decentralized power producers and a large number of controllable power consumers in addition to stochastic power producers such as wind turbines and solar power plants. Control of such large scale systems requires new control algorithms. In this paper, we formulate the control of such a system as an Economic Model Predictive Control (MPC) problem. When the power producers and controllable power consumers have linear dynamics, the Economic MPC may be expressed as a linear program and we apply Dantzig-Wolfe decomposition for solution of this linear program. The Dantzig-Wolfe decomposition algorithm for Economic MPC is tested on a simulated case study with a large number of power producers. The Dantzig-Wolfe algorithm is compared to a standard linear programming (LP) solver for the Economic MPC. Simulation results reveal that the Dantzig-Wolfe algorithm is faster than
the standard LP solver and enables solution of larger problems.

Analyzing Control Challenges for Thermal Energy Storage in Foodstuffs

We consider two important challenges that arise when thermal energy is to be stored in foodstuffs. We have previously introduced economic optimizing MPC schemes that both reduce operating costs and offer flexible power consumption in a future Smart Grid. The goal is to utilize the thermal capacity of refrigerated goods in a supermarket to shift the load of the system in time without deteriorating the quality of the foodstuffs. The analyses in this paper go before closing any control loops. In the first part, we introduce and validate a new model with which we can estimate the actual temperatures of refrigerated goods from available air temperature measurements. This is based on data obtained from a dedicated experiment. Since limits are specified for food temperatures, the estimate is essential for full exploitation of the thermal potential. Secondly, the thermal properties, shapes and sizes of different foodstuffs make them behave differently when exposed to changes in air temperature. We present a novel analysis based on Biot and Fourier numbers for the different foodstuffs. This provides a valuable tool for determining how different items can be utilized in load-shifting schemes on different timescales and for estimating maximum energy storage time. The results are shown for a large range of parameters, and with specific calculations for selected foodstuff items.
Control of Blood Glucose for People with Type 1 Diabetes: an In Vivo Study

Since continuous glucose monitoring (CGM) technology and insulin pumps have improved recent years, a strong interest in a closed-loop artificial pancreas for people with type 1 diabetes has arisen. Presently, a fully automated controller of blood glucose must face many challenges, such as daily variations of patient's physiology and lack of accuracy of glucose sensors. In this paper we design and discuss an algorithm for overnight closed-loop control of blood glucose in people with type 1 diabetes. The algorithm is based on Model Predictive Control (MPC). We use an offset-free autoregressive model with exogenous input and moving average (ARMAX) to model the patient. Observer design and a time-varying glucose reference signal improve robustness of the algorithm. We test the algorithm in two clinical studies conducted at Hvidovre Hospital. The first study took place overnight, and the second one took place during daytime. These trials demonstrate the importance of observer design in ARMAX models and show the possibility of stabilizing blood glucose during the night.
Economic Model Predictive Control for Building Climate Control in a Smart Grid

Model Predictive Control (MPC) can be used to control a system of energy producers and consumers in a Smart Grid. In this paper, we use heat pumps for heating residential buildings with a floor heating system. We use the thermal capacity of the building to shift the electricity consumptions to periods with low energy prices. In this way the heating system of the house becomes a flexible power consumer in the Smart Grid. This scenario is relevant for systems with a significant share of stochastic energy producers, e.g. wind turbines, where the ability to shift power consumption according to production is crucial. We present a model for a house with a heat pump used for supplying thermal energy to a floor heating system. The model is a linear state space model and the resulting controller is an Economic MPC formulated as a linear program. The model includes forecasts of both weather and electricity price. Simulation studies demonstrate the capabilities of the proposed model and algorithm. Compared to traditional operation of heat pumps with constant electricity prices, the optimized operating strategy saves 25-33% of the electricity cost.

Effects of Everyday Life Events on Glucose, Insulin, and Glucagon Dynamics in Continuous Subcutaneous Insulin Infusion–Treated Type 1 Diabetes: Collection of Clinical Data for Glucose Modeling

Background: In the development of glucose control algorithms, mathematical models of glucose metabolism are useful for conducting simulation studies and making real-time predictions upon which control calculations can be based. To obtain type 1 diabetes (T1D) data for the modeling of glucose metabolism, we designed and conducted a clinical study. Methods: Patients with insulin pump–treated T1D were recruited to perform everyday life events on two separate days. During the study, patients wore their insulin pumps and, in addition, a continuous glucose monitor and an activity monitor to estimate energy expenditure. The sequence of everyday life events was predetermined and included carbohydrate intake, insulin boluses, and bouts of exercise; the events were introduced, temporally separated, in different orders and in different
Throughout the study day, 10-min plasma glucose measurements were taken, and samples for plasma insulin and glucagon analyses were obtained every 10 min for the first 30 min after an event and subsequently every 30 min. Results: We included 12 patients with T1D (75% female, 34.3±9.1 years old [mean±SD], hemoglobin A1c 6.7±0.4%). During the 24 study days we collected information-rich, high-quality data during fast and slow changes in plasma glucose following carbohydrate intake, exercise, and insulin boluses. Conclusions: This study has generated T1D data suitable for glucose modeling, which will be used in the development of glucose control strategies. Furthermore, the study has given new physiologic insight into the metabolic effects of carbohydrate intake, insulin boluses, and exercise in continuous subcutaneous insulin infusion–treated patients with T1D.
Electric vehicle charge planning using Economic Model Predictive Control

Economic Model Predictive Control (MPC) is very well suited for controlling smart energy systems since electricity price and demand forecasts are easily integrated in the controller. Electric vehicles (EVs) are expected to play a large role in the future Smart Grid. They are expected to provide grid services, both for peak reduction and for ancillary services, by absorbing short term variations in the electricity production. In this paper the Economic MPC minimizes the cost of electricity consumption for a single EV. Simulations show savings of 50–60% of the electricity costs compared to uncontrolled charging from load shifting based on driving pattern predictions. The future energy system in Denmark will most likely be based on renewable energy sources e.g. wind and solar power. These green energy sources introduce stochastic fluctuations in the electricity production. Therefore, energy should be consumed as soon as it is produced to avoid the need for energy storage as this is expensive, limited and introduces efficiency losses. The Economic MPC for EVs described in this paper may contribute to facilitating transition to a fossil free energy system.

Fast Nonconvex Model Predictive Control for Commercial Refrigeration

We consider the control of a commercial multi-zone refrigeration system, consisting of several cooling units that share a common compressor. The goal is to minimize the total energy cost, using real-time electricity prices, while obeying temperature constraints on the zones. We propose a variation on model predictive control to achieve this goal. When the right variables are used, the dynamics of the system are linear, and the constraints are convex. The cost function, however, is nonconvex. To handle this nonconvexity we propose a sequential convex optimization method, which typically converges in fewer than 5 or so iterations. We employ a fast convex quadratic programming solver to carry out the iterations, which is more than fast enough to run in real-time. We demonstrate our method on a realistic model, with a full year simulation, using real historical data. These simulations show substantial cost savings, and reveal how the method exhibits sophisticated response to real-time variations in electricity prices. This demand response is critical to help balance real-time uncertainties associated with large penetration of intermittent renewable energy sources in a future smart grid.
High Order Adjoint Derivatives using ESDIRK Methods for Oil Reservoir Production Optimization

In production optimization, computation of the gradients is the computationally expensive step. We improve the computational efficiency of such algorithms by improving the gradient computation using high-order ESDIRK (Explicit Singly Diagonally Implicit Runge-Kutta) temporal integration methods and continuous adjoints. The high order integration scheme allows larger time steps and therefore faster solution times. We compare gradient computation by the continuous adjoint method to the discrete adjoint method and the finite-difference method. The methods are implemented for a two phase flow reservoir simulator. Computational experiments demonstrate that the accuracy of the sensitivities obtained by the adjoint methods are comparable to the accuracy obtained by the finite difference method. The continuous adjoint method is able to use a different time grid than the forward integration. Therefore, it can compute these sensitivities much faster than the discrete adjoint method and the finite-difference method. On the other hand, the discrete adjoint method produces the gradients of the numerical schemes, which is beneficial for the numerical optimization algorithm. Computational experiments show that when the time steps are controlled in a certain range, the continuous adjoint method produces gradients sufficiently accurate for the optimization algorithm and somewhat faster than the discrete adjoint method.

General information
State: Published
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Iterative Methods for MPC on Graphical Processing Units

The high floating point performance and memory bandwidth of Graphical Processing Units (GPUs) makes them ideal for a large number of computations which often arises in scientific computing, such as matrix operations. GPUs achieve this performance by utilizing massive parallelism, which requires reevaluating existing algorithms with respect to this new architecture. This is of particular interest to large-scale constrained optimization problems with real-time requirements. The aim of this study is to investigate different methods for solving large-scale optimization problems with focus on their applicability for GPUs. We examine published techniques for iterative methods in interior points methods (IPMs) by applying them to simple test cases, such as a system of masses connected by springs. Iterative methods allow us deal with the ill-conditioning occurring in the later iterations of the IPM as well as to avoid the use of dense matrices, which may be too large for the limited memory capacity of current graphics cards.

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Organisations: Center for Energy Resources Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Modeling Smart Energy Systems for Model Predictive Control

Integrating large amounts of renewable energy sources like wind and solar power introduces large fluctuations in the power production. Either this energy must be stored or consumed right away. Storage solutions are very expensive and not applicable everywhere. So utilizing all of this green energy as it is produced requires a very flexible and controllable power consumption. Examples of controllable electric loads are heat pumps in buildings and Electric Vehicles (EVs) that are expected to play a large role in the future Danish energy system. These units in a smart energy system can potentially offer flexibility on a time scale ranging from seconds to several days by moving power consumption, exploiting thermal inertia or battery storage capacity, respectively. Using advanced control algorithms these systems are able to reduce their own electricity costs by planning ahead and moving consumption to periods with green and cheap electricity. This situation occurs when there is a lot of excess wind power in the system which is reflected in the electricity price and in turn creates an incentive to absorb the energy. In this paper a decentralized control strategy is investigated where prices indirectly influence the total power consumption of the smart energy systems connected to the power grid. Compared to a direct control strategy the complexity of the problem is reduced and decreases both the computation efforts and the need for communication. However, not only the current price, but a forecast of the expected future price should also be available in order for the individual units to plan ahead in the most feasible way. This is necessary since Economic MPCs do not respond to the absolute cost of electricity, but to variations of the price over the prediction horizon. Economic MPC is ideal for price responsive units where the model is known very well. Constraints and disturbance forecasts are straightforward to implement in the controller. MPC relies on the receding horizon principle, where a new optimal control signal is calculated at each time step for the prediction horizon. Only the optimal control signal at the current time step is implemented and consequently closed loop feedback is obtained. A generic model of an energy component is proposed in this paper, so the same Economic MPC framework can be used to design controllers for the different units. However, different signals and forecast, e.g. weather forecasts and usage patterns, are used depending on the unit. The generic state space will be a discrete time state space model with hard input constraints and soft output constraints. For the considered energy systems there is usually a strict limit on the maximum available power, but the output, e.g. a temperature or an EV battery state of charge, can often be relaxed. The output constraints thus define a band of operation, that can be time varying, and the controller must keep the output within these limits in the cheapest possible way. In this paper the price forecast available by all units is assumed to be known and equal to the day-ahead elspot price from the Nordic electricity exchange market NordPool. The resulting electricity cost savings compared to an MPC with no price considerations are around 30-50% for the chosen units. In future work the price could be replaced by an intrahour price that is related to the deviation between the planned and the actual consumption. In this way all units are motivated to stick to the predicted consumption plan.
Model Predictive Control Algorithms for Pen and Pump Insulin Administration

Despite recent developments within diabetes management such as rapidacting insulin, continuous glucose monitors (CGM) and insulin pumps, tight blood glucose control still remains a challenge. A fully automated closedloop controller, also known as an artificial pancreas (AP), has the potential to ease the life and reduce the risk of acute and chronic diabetic complications. However, the noise associated to CGMs, the long insulin action time for continuous subcutaneous infusion of insulin (CSII) pumps, and the high intra- and inter-patient variability significantly limits the performance of current closed-loop controllers.

In this thesis, we present different control strategies based on Model Predictive Control (MPC) for an artificial pancreas. We use Nonlinear Model Predictive Control (NMPC) in order to determine the optimal insulin and blood glucose profiles. The optimal control problem (OCP) is solved using a multiple-shooting based algorithm. We use an explicit Runge-Kutta method (DOPRI45) with an adaptive stepsize for numerical integration and sensitivity computation. The OCP is solved using a Quasi-Newton sequential quadratic programming (SQP) with a linesearch and a BFGS update for the Hessian of the Lagrangian. In addition, we apply a Continuous-Discrete Extended Kalman Filter (CDEKF) in order to simulate cases where the meal size is uncertain, or even unannounced.

We also propose a novel control strategy based on linear MPC for overnight stabilization of blood glucose. The model parameters are personalized using a priori available patient information. We consider an autoregressive integrated moving average with exogenous input (ARIMAX) model. We summarize and the results of the overnight clinical studies conducted at Hvidovre Hospital. Based on these results, we propose improvements for the stochastic part of our controller model. We state and compare three different stochastic model structures. The first one is the ARIMAX structure that has been used for the clinical studies. The second one is an autoregressive moving average with exogenous input (ARMAX) model. The third one is an adaptive ARMAX model in which we estimate the parameters of the stochastic part using a Recursive Least Square (RLS) method. We test the controller in a virtual clinic of 100 patients. This virtual clinic is based on the Hovorka model. We consider the case where only half of the bolus is administrated at mealtime, and the case where the insulin sensitivity increases during the night.

This thesis consists of a summary report, glucose and insulin proles of the clinical studies and research papers submitted, peer-reviewed and/or published in the period September 2009 - September 2012.
Model Predictive Control for an Industrial SAG Mill

We discuss Model Predictive Control (MPC) based on ARX models and a simple lower order disturbance model. The advantage of this MPC formulation is that it has few tuning parameters and is based on an ARX prediction model that can readily be identified using standard technologies from system identification. When applied to MIMO systems we call this controller a MIMO-ARX based MPC. We use an industrial Semi-Autogenous Grinding (SAG) mill to illustrate the performance of this controller. SAG mills are the primary units in a grinding chain and also the most power consuming units. Therefore, improved control of SAG mills has the potential to significantly improve efficiency and reduce the specific energy consumption for mineral processes. Grinding circuits involving SAG mills are multivariate processes. Commissioning of a control system based on a classical single-loop controllers with logic is time consuming, while MPC has the potential to both improve the control performance and the commissioning time and expertise required. The simulation results demonstrate that the MPC based on a MIMO-ARX model is able to provide nice control performance measured by its ability to track an output reference and reject unknown disturbances. Furthermore, the method used to design the controller represents a systematic method that can be automatized for wide-spread deployment in industrial environments.

General information
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Model predictive control for a smart solar tank based on weather and consumption forecasts

In this work the heat dynamics of a storage tank were modelled on the basis of data and maximum likelihood methods. The resulting grey-box model was used for Economic Model Predictive Control (MPC) of the energy in the tank. The control objective was to balance the energy from a solar collector and the heat consumption in a residential house. The storage tank provides heat in periods where there is low solar radiation and stores heat when there is surplus solar heat. The forecasts of consumption patterns were based on data obtained from meters in a group of single-family houses in Denmark. The tank can also be heated by electric heating elements if necessary, but the electricity costs of operating these heating elements should be minimized. Consequently, the heating elements should be used in periods with cheap electricity. It is proposed to integrate a price-sensitive control to enable the storage tank to serve a smart energy system in which flexible consumers are expected to help balance fluctuating renewable energy sources like wind and solar. Through simulations, the impact of applying Economic MPC shows annual electricity cost savings up to 25-30%.

General information
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Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Mathematical Statistics, Department of Civil Engineering, Section for Building Physics and Services
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Model predictive control technologies for efficient and flexible power consumption in refrigeration systems

Considerable amounts of energy are consumed in supermarket refrigeration systems worldwide. Due to the thermal capacity of refrigerated goods and the rather simplistic control most commonly applied, there is a potential for distributing the system load over time in a more cost-optimal way. In this paper we describe a novel economic-optimizing Model Predictive Control (MPC) scheme that reduces operating costs by utilizing the thermal storage capabilities. A nonlinear optimization tool to handle a non-convex cost function is utilized for simulations with validated scenarios. In this way we explicitly address advantages from daily variations in outdoor temperature and electricity prices. Secondly, we formulate a new cost function that enables the refrigeration system to contribute with ancillary services to the balancing power market. This involvement can be economically beneficial for the system itself, while crucial services can be delivered to a future flexible and intelligent power grid (Smart Grid). Furthermore, we discuss a novel incorporation of probabilistic constraints and Second Order Cone Programming (SOCP) with economic MPC. A Finite Impulse Response (FIR) formulation of the system models allows us to describe and handle model as well as prediction uncertainties in this framework. This means we can demonstrate means for robustifying the performance of the controller.

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MPC Toolbox with GPU Accelerated Optimization Algorithms

The introduction of Graphical Processing Units (GPUs) in scientific computing has shown great promise in many different fields. While GPUs are capable of very high floating point performance and memory bandwidth, its massively parallel architecture requires algorithms to be reimplemented to suit the different architecture. Interior point method can be used to...
solve convex optimization problems. These problems often arise in fields such as in Model Predictive Control (MPC), which may have real-time requirements for the solution time. This paper presents a case study in which we utilize GPUs for a Linear Programming Interior Point Method to solve a test case where a series of power plants must be controlled to minimize the cost of power production. We demonstrate that using GPUs for solving MPC problems can provide a speedup in solution time.

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Numerical Methods for Solution of the Extended Linear Quadratic Control Problem
In this paper we present the extended linear quadratic control problem, its efficient solution, and a discussion of how it arises in the numerical solution of nonlinear model predictive control problems. The extended linear quadratic control problem is the optimal control problem corresponding to the Karush-Kuhn-Tucker system that constitute the majority of computational work in constrained nonlinear and linear model predictive control problems solved by efficient MPC-tailored interior-point and active-set algorithms. We state various methods of solving the extended linear quadratic control problem and discuss instances in which it arises. The methods discussed in the paper have been implemented in efficient C code for both CPUs and GPUs for a number of test examples.

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Oil Reservoir Production Optimization using Single Shooting and ESDIRK Methods
Conventional recovery techniques enable recovery of 10-50% of the oil in an oil field. Advances in smart well technology and enhanced oil recovery techniques enable significant larger recovery. To realize this potential, feedback model-based optimal control technologies are needed to manipulate the injections and oil production such that flow is uniform in a given geological structure. Even in the case of conventional water flooding, feedback based optimal control technologies may enable higher oil recovery than with conventional operational strategies. The optimal control problems that must be solved are large-scale problems and require specialized numerical algorithms. In this paper, we combine a single shooting
optimization algorithm based on sequential quadratic programming (SQP) with explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods and the a continuous adjoint method for sensitivity computation. We demonstrate the procedure on a water flooding example with conventional injectors and producers.

**General information**

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**Optimal Energy Consumption in Refrigeration Systems - Modelling and Non-Convex Optimisation**

Supermarket refrigeration consumes substantial amounts of energy. However, due to the thermal capacity of the refrigerated goods, parts of the cooling capacity delivered can be shifted in time without deteriorating the food quality. In this study, we develop a realistic model for the energy consumption in super market refrigeration systems. This model is used in a Nonlinear Model Predictive Controller (NMPC) to minimise the energy used by operation of a supermarket refrigeration system. The model is non-convex and we develop a computational efficient algorithm tailored to this problem that is somewhat more efficient than general purpose optimisation algorithms for NMPC and still near to optimal. Since the non-convex cost function has multiple extrema, standard methods for optimisation cannot be directly applied. A qualitative analysis of the system's constraints is presented and a unique minimum within the feasible region is identified. Following that finding we propose a tailored minimisation procedure that utilises the nature of the feasible region such that the minimisation can be separated into two linear programs; one for each of the control variables. These subproblems are simple to solve but some iterations might have to be performed in order to comply with the maximum capacity constraint. Finally, a nonlinear solver is used for a small example without separating the optimisation problem, and the results are compared to the outcome of our proposed minimisation procedure for the same conceptual example. The tailored approach is somewhat faster than the general optimisation method and the solutions obtained are almost identical.

**General information**

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Optimisation of Oil Production in Two – Phase Flow Reservoir Using Simultaneous Method and Interior Point Optimiser

Natural petroleum reservoirs are characterised by 2-phase flow of oil and water in the porous media (e.g. rocks) which they are built of. Conventional methods of extracting oil from those fields, which utilise high initial pressure obtained from natural drive, leave more than 70 % of oil in the reservoir. A promising decrease of these remained resources can be provided by smart wells applying water injections to sustain satisfactory pressure level in the reservoir throughout the whole process of oil production. Basically to enhance secondary recovery of the remaining oil after drilling, water is injected at the injection wells of the down-hole pipes. This sustains the pressure in the reservoir and drives oil towards production wells. There are however, many factors contributing to the poor conventional secondary recovery methods e.g. strong surface tension, heterogeneity of the porous rock structure leading to change of permeability with position in the reservoir, or high oil viscosity. Therefore it is desired to take into account all these phenomena by implementing a realistic simulator of the 2-phase flow reservoir, which imposes the set of constraints on the state variables of optimisation problem. Then, thanks to optimal control, it is possible to adjust effectively injection valves to control 2 phase immiscible flow in every grid block of the reservoir and navigate oil to the production wells so it does not remain in the porous media. The use of such a smart technology known also as smart fields, or closed loop optimisation, can be used for optimising the reservoir performance in terms of net present value of oil recovery or another economic objective. In order to solve an optimal control problem we use a direct collocation method where we translate a continuous problem into a discrete one by applying explicit and implicit Euler methods. A substantial challenge of finding optimal solution in a robust way comes along with handling the scale of the optimal control problem due to discretisation in time and space. Consequently, an Ipopt(Interior Point Optimiser) open source software for large scale nonlinear optimisation was applied. Because of its versatile compatibility with programming technologies, a C++ programming language in Microsoft Visual Studio integrated...
development environment was used for modelling the optimal control problem. Thanks to object oriented features of the language, it was possible to approach the problem in a very modular way by automating the discretisation process and develop interfaces for retrieving information from a continuous problem. When tackling this problem, we reduce approximation error made by discretising of the original problem, by increasing the number of simulation steps and therefore it is necessary to solve large instances of the reformulation. As a result, it is very suitable to use Ipopt algorithm which implements an interior-point linesearch filter method making it very powerful for solving large problems with up to hundreds of millions of constraints and variables.

Optimization based tuning approach for offset free MPC
We present an optimization based tuning procedure with certain robustness properties for an offset free Model Predictive Controller (MPC). The MPC is designed for multivariate processes that can be represented by an ARX model. The advantage of ARX model representations is that standard system identification techniques using convex optimization can be used for identification of such models from input-output data. The stochastic model of the ARX model identified from input-output data is modified with an ARMA model designed as part of the MPC-design procedure to ensure offset-free control. The ARMAX model description resulting from the extension can be realized as a state space model in innovation form. The MPC is designed and implemented based on this state space model in innovation form. Expressions for the closed-loop dynamics of the unconstrained system is used to derive the sensitivity function of this system. The closed-loop expressions are also used to numerically evaluate absolute integral performance measures. Due to the closed-loop expressions these evaluations can be done relatively quickly. Consequently, the tuning may be performed by numerical minimization of the integrated absolute error subject to a constraint on the maximum of the sensitivity function. The latter constraint provides a robustness measure that is essential for the procedure. The method is demonstrated on two simulated examples: A Wood-Berry distillation column example and a cement mill example.
Overnight Control of Blood Glucose in People with Type 1 Diabetes

In this paper, we develop and test a Model Predictive Controller (MPC) for overnight stabilization of blood glucose in people with type 1 diabetes. The controller uses glucose measurements from a continuous glucose monitor (CGM) and its decisions are implemented by a continuous subcutaneous insulin infusion (CSII) pump. Based on a priori patient information, we propose a systematic method for computation of the model parameters in the MPC. Safety layers improve the controller robustness and reduce the risk of hypoglycemia. The controller is evaluated in silico on a cohort of 100 randomly generated patients with a representative intersubject variability. This cohort is simulated overnight with realistic variations in the insulin sensitivities and needs. Finally, we provide results for the first tests of this controller in a real clinic.
Production Optimization for Two-Phase Flow in an Oil Reservoir

Petroleum reservoirs are subsurface formations of porous rocks with hydrocarbons trapped in the pores. Initially, the reservoir pressure may be sufficiently large to push the fluids to the production facilities. However, as the fluids are produced the pressure declines and production reduces over time. When the natural pressure becomes insufficient, the pressure must be maintained artificially by injection of water. Conventional technologies for recovery leaves more than 50% of the oil in the reservoir. Wells with adjustable downhole flow control devices coupled with modern control technology offer the potential to increase the oil recovery significantly. In optimal control of smart wells, downhole sensor equipment and remotely controlled valves are used in combination with large-scale subsurface flow models and gradient based optimization methods in a Nonlinear Model Predictive Control framework to increase the production and economic value of an oil reservoir. Wether the objective is to maximize recovery or some financial measure like Net Present Value, the increased production is achieved by manipulation of the well rates and bottom-hole pressures of the injection and production wells. The optimal water injection rates and production well bottom-hole pressures are computed by solution of a large-scale constrained optimal control problem. The objective is to maximize production by manipulating the well rates and bottom hole pressures of injection and production wells. Optimal control settings of injection and production wells are computed by solution of a large scale constrained optimal control problem. We describe a gradient based method to compute the optimal control strategy of the water flooding process. An explicit singly diagonally implicit Runge-Kutta (ESDIRK) method with adaptive stepsize control is used for computationally efficient solution of the model. The gradients are computed by the adjoint method. The adjoint equations associated with the ESDIRK method are solved by integrating backwards in time. The necessary information for the adjoint computation is calculated and stored during the forward solution of the model. The backward adjoint computation then only requires the assembly of this information to compute the gradients.

Real-Time Optimization for Economic Model Predictive Control

In this paper, we develop an efficient homogeneous and self-dual interior-point method for the linear programs arising in economic model predictive control. To exploit structure in the optimization problems, the algorithm employs a highly specialized Riccati iteration procedure. Simulations show that in comparison to conventional interior-point methods, our solver is a) significantly faster per iteration and b) converges in a smaller and less fluctuating number of iterations.
Sequential Convex Programming for Power Set-point Optimization in a Wind Farm using Black-box Models, Simple Turbine Interactions, and Integer Variables

We consider the optimization of power set-points to a large number of wind turbines arranged within close vicinity of each other in a wind farm. The goal is to maximize the total electric power extracted from the wind, taking the wake effects that couple the individual turbines in the farm into account. For any mean wind speed, turbulence intensity, and direction we find the optimal static operating points for the wind farm. We propose an iterative optimization scheme to achieve this goal. When the complicated, nonlinear, dynamics of the aerodynamics in the turbines and of the fluid dynamics describing the turbulent wind fields’ propagation through the farm are included in a highly detailed black-box model, numerical results for any given values of the parameter sets can easily be evaluated. However, analytic expressions for model representation in the optimization algorithms might be hard to derive and their properties are often not suitable for computationally efficient optimization either. To handle this, we propose a sequential convex optimization method, perturbing the model in each iteration, and demonstrate a typical convergence in fewer than 10 iterations. We derive a coupling matrix from the wind farm model, enabling us to use a very simple linear relationship for describing the turbine interactions. In addition, we allow individual turbines to be turned on or off introducing integer variables into the optimization problem. We solve this within the same framework of iterative convex approximation and compare with mixed-integer optimization tools. We demonstrate the method on a verified model and for various sizes and configurations of the wind farm. For all tested scenarios we observe a distribution of the power set-points which is at least as good as, and in many cases is far superior to, a more naive distribution scheme. We employ a fast convex quadratic programming solver to carry out the iterations in the range of microseconds for even large wind farms.
Single Shooting and ESDIRK Methods for adjoint-based optimization of an oil reservoir

Conventional recovery techniques enable recovery of 10-50% of the oil in an oil field. Advances in smart well technology and enhanced oil recovery techniques enable significant larger recovery. To realize this potential, feedback model-based optimal control technologies are needed to manipulate the injections and oil production such that flow is uniform in a given geological structure. Even in the case of conventional water flooding, feedback based optimal control technologies may enable higher oil recovery than with conventional operational strategies. The optimal control problems that must be solved are large-scale problems and require specialized numerical algorithms. In this paper, we combine a single shooting optimization algorithm based on sequential quadratic programming (SQP) with explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods and a continuous adjoint method for sensitivity computation. We demonstrate the procedure on a water flooding example with conventional injectors and producers.

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Single Shooting and ESDIRK Methods for adjoint-based optimization of an oil reservoir

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Single Cell Protein, MPC, PID, Simulation, Real-Time Optimization, Optimization, Control
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Solution of Constrained Optimal Control Problems Using Multiple Shooting and ESDIRK Methods

In this paper, we describe a novel numerical algorithm for solution of constrained optimal control problems of the Bolza type for stiff and/or unstable systems. The numerical algorithm combines explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods with a multiple shooting algorithm. As we consider stiff systems, implicit solvers with sensitivity computation capabilities for initial value problems must be used in the multiple shooting algorithm. Traditionally, multi-step methods based on the BDF algorithm have been used for such problems. The main novel contribution of this paper is the use of ESDIRK integration methods for solution of the initial value problems and the corresponding sensitivity equations arising in the multiple shooting algorithm. Compared to BDF-methods, ESDIRK-methods are advantageous in multiple shooting algorithms in which restarts and frequent discontinuities on each shooting interval are present. The ESDIRK methods are implemented using an inexact Newton method that reuses the factorization of the iteration matrix for the integration as well as the sensitivity computation. Numerical experiments are provided to demonstrate the algorithm.

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State Estimation for the Automotive SCR Process
Selective catalytic reduction (SCR) of NOx is a widely applied diesel engine exhaust gas aftertreatment technology. For advanced SCR process control, like model predictive control, full state information of the process is required. The ammonia coverage ratio inside the catalyst is difficult to measure. Therefore we design an ordinary Kalman filter as well as an extended Kalman filter to estimate the ammonia coverage. The filters are built over a first principle model with four states. Among the four states, NO, NO2 and NH3 concentration are measured by the sensors, while the ammonia coverage ratio is left to be unknown. The performance of the filters is shown by simulation with the World Harmonized transient cycle. In particular, during transient operations the extended Kalman filter performs significantly better than the ordinary Kalman filter. Since such operation regimes are always present for SCR in engine applications, we recommend to estimating the ammonia coverage using the extended Kalman filter.

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State Estimation in the Automotive SCR DeNOx Process

Selective catalytic reduction (SCR) of nitrogen oxides (NOx) is a widely applied diesel engine exhaust gas after-treatment technology. For effective NOx removal in a transient operating automotive application, controlled dosing of urea can be used to meet the increasingly restrictive legislations on exhaust gas emissions. For advanced control, e.g. Model Predictive Control (MPC), of the SCR process, accurate state estimates are needed. We investigate the performance of the ordinary and the extended Kalman filters based on a simple first principle system model. The performance is tested through a series of simulation studies reflecting realistic challenges such as under-modelling and few gas composition sensors.

State Estimation in the Automotive SCR DeNOx Process

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**Stochastic Model Predictive Control with Applications in Smart Energy Systems**

In response to growing concerns related to environmental issues, limited resources and security of supply, the energy industry is changing. One of the most significant developments has been the penetration of renewable energy sources. In Denmark, the share of wind power generation is expected to cover more than 50% of the total consumption by 2050. Energy systems based on significant amounts of renewable energy sources are subject to uncertainties. To accommodate the need for model predictive control (MPC) of such systems, the effect of the stochastic effects on the constraints must be accounted for. In conventional MPC, the stochastic effects on the constraints is handled by constraint back-off and the MPC problem can still be solved by solution of either a linear program or a quadratic program. Treating the constraints as probabilistic constraints provides a more systematic approach to handle the stochastic effects on constraints. In this formulation, the MPC may be represented by a chance constrained mathematical program. The chance constraints allow a direct tradeoff between a certain (low) frequency of violating the constraints and a performance function (e.g. an economic loss function). This is convenient for energy systems, since some constraints are very important to satisfy with a high probability, whereas violation of others are less prone to have a large economic penalty. In MPC applications the control action is obtained by solving an optimization problem at each sampling instant. To make the controller applicable in real-time efficient and reliable algorithms are required. If the uncertainty is assumed to be Gaussian, the optimization problems associated with chance constrained (linear) MPC can be expressed as second order cone programming (SOCP) problems. In this paper, we show that tailored interior point algorithms are well suited to handle this type of problems. Namely, by utilizing structure-exploiting methods, we implement a special-purpose solver for control of smart energy systems. The solver is compared against general-purpose implementations. As a case study, we consider a system consisting of fuel-fired thermal power plants, wind farms and electric vehicles.

**Tuning of Controller for Type 1 Diabetes Treatment with Stochastic Differential Equations**

People with type 1 diabetes need several insulin injections every day to keep their blood glucose level in the normal range and thereby avoiding the acute and long term complications of diabetes. One of the recent treatments consists of a pump injecting insulin into the subcutaneous layer combined with a continuous glucose monitor (CGM) frequently observing the glucose level. Automatic control of the insulin pump based on CGM observations would ease the burden of constant diabetes treatment and management. We have developed a controller designed to keep the blood glucose level in the normal range by adjusting the size of insulin infusions from the pump based on model predictive control (MPC). A clinical pilot study to test the performance of the MPC controller overnight was performed. The conclusion was that the controller relied too much on the local trend of the blood glucose level which is a problem due to the noise corrupted observations from the CGM. In this paper we present a method to estimate the optimal Kalman gain in the controller based on stochastic differential equation modeling. With this model type we could estimate the process noise and observation noise separately based on data from the rst clinical pilot study. In doing so we obtained a more robust control algorithm which is less sensitive to fluctuations in the CGM observations and rely more on the global physiological trend of the blood glucose level. Finally, we present the promising results from the second pilot study testing the improved controller.
Tuning SISO offset-free Model Predictive Control based on ARX models

In this paper, we present a tuning methodology for a simple offset-free SISO Model Predictive Controller (MPC) based on autoregressive models with exogenous inputs (ARX models). ARX models simplify system identification as they can be identified from data using convex optimization. Furthermore, the proposed controller is simple to tune as it has only one free tuning parameter. These two features are advantageous in predictive process control as they simplify industrial commissioning of MPC. Disturbance rejection and offset-free control is important in industrial process control. To achieve offset-free control in face of unknown disturbances or model-plant mismatch, integrators must be introduced in either the estimator or the regulator. Traditionally, offset-free control is achieved using Brownian disturbance models in the estimator. In this paper we achieve offset-free control by extending the noise model with a filter containing an integrator. This filter is a first order ARMA model. By simulation and analysis, we argue that it is independent of the parameterization of the underlying linear plant; while the tuning of traditional disturbance models is system dependent. Using this insight, we present MPC for SISO systems based on ARX models combined with the first order filter. We derive expressions for the closed-loop variance of the unconstrained MPC based on a state space representation in innovation form and use these expressions to develop a tuning procedure for the regulator. We establish formal equivalence between GPC and state space based off-set free MPC. By simulation we demonstrate this procedure for a third order system. The offset-free ARX MPC demonstrates satisfactory set point tracking and rejection of an unmeasured step disturbance for a simulated furnace with a long time delay.
Adaptive Disturbance Estimation for Offset-Free SISO Model Predictive Control
Offset free tracking in Model Predictive Control requires estimation of unmeasured disturbances or the inclusion of an integrator. An algorithm for estimation of an unknown disturbance based on adaptive estimation with time varying forgetting is introduced and benchmarked against the classical disturbance modelling approach, where the system description is augmented by a disturbance state. The time varying forgetting renders the new approach less sensitive to the nature of the disturbance. By simulation we demonstrate that this algorithm is advantageous in case of infrequent step disturbances of any magnitude.

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Closed-Loop and Semi Closed-Loop Strategies for Control of Blood Glucose in People with Type 1 Diabetes

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Economic MPC for Power Management in the Smart Grid
To increase the amount of green energy (e.g. solar and wind) significantly a new intelligent electrical infrastructure is needed. We must not only control the production of electricity but also the consumption in an efficient and proactive manner. This future intelligent grid is in Europe known as the SmartGrid. In this paper we demonstrate the use of Economic Model Predictive Control to operate a portfolio of power generators and consumers such that the cost of producing the required power is minimized. With conventional coal and gas fired power generators representing the controllable power production and a significant share of renewable energy, such as parks of wind turbines, representing the uncontrollable power generators we have demonstrated how the addition of controllable consumers, such as large cold rooms or supermarkets with a thermal capacity, can infuse the desired flexibility of the grid for utilization of more green energy and also lower the total cost. We formulate the supply-demand constraint as a probabilistic constraint, thereby robustifying the solution against uncertainties in power demand. We use small conceptual examples for simulations.

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Energy Efficient Refrigeration and Flexible Power Consumption in a Smart Grid

Refrigeration and heating systems consume substantial amounts of energy worldwide. However, due to the thermal capacity there is a potential for storing “coldness” or heat in the system. This feature allows for implementation of different load shifting and shedding strategies in order to optimize the operation energywise, but without compromising the original cooling and indoor climate quality. In this work we investigate the potential of such a strategy and its ability to significantly lower the cost related to operating systems such as supermarket refrigeration and heat pumps for residential houses. With modern Economic Model Predictive Control (MPC) methods we make use of weather forecasts and predictions of varying electricity prices to apply more load to the system when the thermodynamic cycle is most efficient, and to consume larger shares of the electricity when the demand and thereby the prices are low. The ability to adjust power consumption according to the demands on the power grid is a highly wanted feature in a future Smart Grid. Efficient utilization of greater amounts of renewable energy calls for solutions to control the power consumption such that it increases when an energy surplus is available and decreases when there is a shortage. This should happen almost instantly to accommodate intermittent energy sources as e.g. wind turbines. We expect our power management solution to render systems with thermal storage capabilities suitable for flexible power consumption. The aggregation of several units will contribute significantly to the shedding of total electricity demand. Using small case studies we demonstrate the potential for utilizing daily variations to deliver a power efficient cooling or heating and for the implementation of Virtual Power Plants in Smart Grid scenarios.

Exploiting Microorganisms for Animal Feed Production

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Finite Horizon MPC for Systems in Innovation Form

System identification and model predictive control have largely developed as two separate disciplines. Nevertheless, the major part of industrial MPC commissioning is generation of data and identification of models. In this contribution we attempt to bridge this gap by contributing some of the missing links. Input-output models (FIR, ARX, ARMAX, Box-Jenkins) as well as subspace models can be represented as state space models in innovation form. These models have
correlated process and measurement noise. The correct LQG control law for systems with correlated process and measurement noise is not well known. We provide the correct finite-horizon LQG controller for this system and use this to develop a state space representation of the closed-loop system. This representation is used for closed-loop frequency and covariance analysis. These measures are used in tuning of the unconstrained and constrained MPC. We demonstrate our results on a simulated industrial furnace.

Flexible and Cost Efficient Power Consumption using Economic MPC: A Supermarket Refrigeration Benchmark

Supermarket refrigeration consumes substantial amounts of energy. However due to the thermal capacity in the refrigerated goods parts of the delivered cooling capacity can be shifted in time without deteriorating the food quality. In this paper we introduce a novel economic optimizing MPC scheme that reduces operation costs by utilizing the thermal storage capabilities. In the study we specifically address advantages coming from daily variations in outdoor temperature and electricity prices but other aims such as peak load reduction are also considered. An important contribution of this paper is also the formulation of a new cost function for our proposed power management. Hereby the refrigeration system is enabled to contribute with ancillary services to the balancing power market. Since significant amounts of regulating power is needed for a higher penetration of intermittent renewable energy sources such as wind turbines this feature is in high demand in a future intelligent power grid (Smart Grid). Our perspective is seen from the refrigeration system but as it is demonstrated the involvement in the balancing market can be economically beneficial for the system itself while delivering crucial services to the Smart Grid. We simulate the system using models validated against data from real supermarkets as well as weather data and spot and regulating power prices from the Nordic power market.

Biological system modeling, Cooling, Cost function, Economics, Electricity, Heating, Power demand

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Hierarchical model-based predictive control of a power plant portfolio

One of the main difficulties in large-scale implementation of renewable energy in existing power systems is that the production from renewable sources is difficult to predict and control. For this reason, fast and efficient control of controllable power producing units – so-called “portfolio control” – becomes increasingly important as the ratio of renewable energy in a power system grows. As a consequence, tomorrow’s “smart grids” require highly flexible and scalable control systems compared to conventional power systems. This paper proposes a hierarchical model-based predictive control design for power system portfolio control, which aims specifically at meeting these demands. The design involves a two-layer hierarchical structure with clearly defined interfaces that facilitate an object-oriented implementation approach. The same hierarchical structure is reflected in the underlying optimisation problem, which is solved using Dantzig–Wolfe decomposition. This decomposition yields improved computational efficiency and better scalability compared to centralised methods. The proposed control scheme is compared to an existing, state-of-the-art portfolio control system (operated by DONG Energy in Western Denmark) via simulations on a real-world scenario. Despite limited tuning, the new controller shows improvements in terms of ability to track reference production as well as economic performance.
Insulin Administration for People with Type 1 diabetes

In this paper, we apply model predictive control (MPC) for control of blood glucose in people with type 1 diabetes. The two first control strategies are based on nonlinear model predictive control (NMPC). The first control strategy is based on meal announcement in advance, while the second one considers meal announcement at mealtimes only. They give a quantitative upper bound on the achievable control performance. The third control strategy is a feedforward-feedback control strategy. This strategy uses a time-varying setpoint to reduce the risk of hypoglycemia. The feedback controller computes the optimal basal insulin infusion rate. The feedforward controller consists of a bolus calculator. It computes the optimal bolus, along with the time-varying glucose setpoint. We test these three strategies on a virtual patient with type 1 diabetes. The numerical results demonstrate the robustness of the last control strategy with respect to changes in the model parameters and incorrect meal announcement.

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Model predictive control for plant-wide control of a reactor-separation-recycle system

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NMPC for Oil Reservoir Production Optimization
In this paper, we use nonlinear model predictive control (NMPC) to maximize secondary oil recovery from an oil reservoir by controlling two-phase subsurface porous flow using adjustable down-hole control valves. The resulting optimal control problem is nonlinear and large-scale. We solve this problem numerically using a single shooting sequential quadratic programming (SQP) based optimization method. Explicit singly diagonally implicit Runge-Kutta (ESDIRK) methods are used for integration of the stiff system of differential equations describing the two-phase flow, and the adjoint method is used for sensitivity computations. We report computational experiences and oil recovery improvements for a standard test case.

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Noise Modelling and MPC Tuning for Systems with Infrequent Step Disturbances
In this paper, an offset-free SISO MPC implementation based on an ARX model of the system dynamics is investigated. Special emphasis is directed to achieving good closed loop performance for systems which may be step wised perturbed by a sustained, unmeasured disturbance. Hence a noise model which expresses the behaviour of this non-stationary noise process is sought. Tuning of the ARX-based MPC implementation is discussed and illustrated in a simulation example. Guidelines for tuning of the free parameters are presented.

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Noise Modelling and MPC Tuning for Systems with Infrequent Step Disturbances

In this paper, an offset-free SISO MPC implementation based on an ARX model of the system dynamics is investigated. Special emphasis is directed to achieving good closed loop performance for systems which may be step-wise perturbed by a sustained, unmeasured disturbance. Hence a noise model which expresses the behaviour of this non-stationary noise process is sought. Tuning of the ARX-based MPC implementation is discussed and illustrated in a simulation example. Guidelines for tuning of the free parameters are presented.

Oil Reservoir Production Optimization using Optimal Control

Practical oil reservoir management involves solution of large-scale constrained optimal control problems. In this paper we present a numerical method for solution of large-scale constrained optimal control problems. The method is a single-shooting method that computes the gradients using the adjoint method. We use an Explicit Singly Diagonally Implicit Runge-Kutta (ESDIRK) method for the integration and a quasi-Newton Sequential Quadratic Programming (SQP) algorithm for the constrained optimization. We use this algorithm in a numerical case study to optimize the production of oil from an oil reservoir using water flooding and smart well technology. Compared to the uncontrolled case, the optimal operation increases the Net Present Value of the oil field by 10%.
On Implementing a Homogeneous Interior-Point Algorithm for Nonsymmetric Conic Optimization

Based on earlier work by Nesterov, an implementation of a homogeneous infeasible-start interior-point algorithm for solving nonsymmetric conic optimization problems is presented. Starting each iteration from (the vicinity of) the central path, the method computes (nearly) primal-dual symmetric approximate tangent directions followed by a purely primal centering procedure to locate the next central primal-dual point. Features of the algorithm include that it makes use only of the primal barrier function, that it is able to detect infeasibilities in the problem and that no phase-I method is needed. The method further employs quasi-Newton updating both to generate (pseudo) higher order directions and to reduce the number of factorizations needed in the centering process while still retaining the ability to exploit sparsity. Extensive and promising computational results are presented for the p-cone problem, the facility location problem, entropy problems and geometric programs; all formulated as nonsymmetric conic optimization problems.

Power Consumption in Refrigeration Systems - Modeling for Optimization

Refrigeration systems consume a substantial amount of energy. Taking for instance supermarket refrigeration systems as an example they can account for up to 50–80% of the total energy consumption in the supermarket. Due to the thermal capacity made up by the refrigerated goods in the system there is a possibility for optimizing the power consumption by utilizing load shifting strategies. This paper describes the dynamics and the modeling of a vapor compression refrigeration system needed for sufficiently realistic estimation of the power consumption and its minimization. This leads to a non-convex function with possibly multiple extrema. Such a function can not directly be optimized by standard methods and a qualitative analysis of the system’s constraints is presented. The description of power consumption contains nonlinear terms which are approximated by linear functions in the control variables and the error by doing so is investigated. Finally a minimization procedure for the presented problem is suggested.
Production Optimization of Oil Reservoirs

With an increasing demand for oil and difficulties in finding new major oil fields, research on methods to improve oil recovery from existing fields is more necessary now than ever. The subject of this thesis is to construct efficient numerical methods for simulation and optimization of oil recovery with emphasis on optimal control of water flooding with the use of smartwell technology. We have implemented immiscible flow of water and oil in isothermal reservoirs with isotropic heterogeneous permeability fields. We use the method of lines for solution of the partial differential equation (PDE) system that governs the fluid flow. We discretize the two-phase flow model spatially using the finite volume method (FVM), and we use the two point flux approximation (TPFA) and the single-point upstream (SPU) scheme for computing the fluxes. We propose a new formulation of the differential equation system that arise as a consequence of the spatial discretization of the two-phase flow model. Upon discretization in time, the proposed equation system ensures the mass conserving property of the two-phase flow model. For the solution of the spatially discretized two-phase flow model, we develop mass conserving explicit singly diagonally implicit Runge-Kutta (ESDIRK) methods with embedded error estimators for adaptive step size control. We demonstrate that high order ESDIRK methods are more efficient than the low-order methods most commonly used in reservoir simulators. Most commercial reservoir simulation tools use step size control, which is based on heuristics. These can neither deliver solutions with predetermined accuracy or guarantee the convergence in the modified Newton iterations. We have established predictive step size control based on error estimates, which can be calculated from the embedded ESDIRK methods. We change the step size control in order to minimize the computational cost per simulation. We implement a numerical method for nonlinear model predictive control (NMPC) along with smart-well technology to maximize the net present value (NPV) of an oil reservoir. The optimization is based on quasi-Newton sequential quadratic programming (SQP) with line-search and BFGS approximations of the Hessian, and the adjoint method for efficient computation of the gradients. We demonstrate that the application of NMPC for optimal control of smart-wells has the potential to increase the economic value of an oil reservoir.
Robust Economic MPC for a Power Management Scenario with Uncertainties
This paper presents a novel incorporation of probabilistic constraints and Second Order Cone Programming (SOCP) with Economic Model Predictive Control (MPC). Hereby the performance of the controller is robustified in the presence of both model and forecast uncertainties. Economic MPC is a receding horizon controller that minimizes an economic objective function and we have previously demonstrated its usage to include a refrigeration system as a controllable power consumer with a portfolio of power generators such that total cost is minimized. The main focus for our work is the power management of the refrigeration system. Whereas our previous study was entirely deterministic, models of e.g. supermarket refrigeration systems are uncertain as is the forecasts of outdoor temperatures and electricity demand. The linear program we have formulated does not cope with uncertainties and thus, such are prone to drive an optimal solution to an infeasible or very expensive solution. The main contribution of this paper is the Finite Impulse Response (FIR) formulation of the system models allowing us to describe and handle model uncertainties in the framework of probabilistic constraints. Our new solution using this setup for robustifying the economic MPC is demonstrated by simulation of a small conceptual example. The scenario is primarily chosen for illustrating the effect of our proposed method in that it can be compared to our previous deterministic simulations.

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering, Danfoss A/S
Authors: Hovgaard, T. G. (Intern), Larsen, L. F. (Ekstern), Jørgensen, J. B. (Intern)
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Source: orbit
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

Strategies for glucose control in people with type 1 diabetes
In this paper we apply a robust feedforward-feedback control strategy to people with type 1 diabetes. The feedforward controller consists of a bolus calculator which compensates the disturbance coming from meals. The feedback controller is based on a linearized description of the model describing the patient. We minimize the risk of hypoglycemia by introducing a time-varying glucose setpoint based on the announced meal size and the physiological model of the patient. The simulation results are based on a virtual patient simulated by the Hovorka model. They include the cases where the insulin sensitivity changes, and mismatches in meal estimation. They demonstrate that the designed controller is able to achieve offset-free control when the insulin sensitivity change, and that having a time-varying reference signal enables more robust control of blood glucose in the cases where the meal size is known, but also when the ingested meal does not match the announced one.

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DOIs: 10.3182/20110828-6-IT-1002.03714
Systematic identification and robust control design for uncertain time delay processes

A systematic procedure is proposed to handle the standard process control problem. The considered standard problem involves infrequent step disturbances to processes with large delays and measurement noise. The process is modeled as an ARX model and extended with a suitable noise model in order to reject unmeasured step disturbances and unavoidable model errors. This controller is illustrated to perform well for both set point tracking and a disturbance rejection for a SISO process example of a furnace which has a time delay which is significantly longer than the dominating time constant.

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Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Scientific Computing, Center for Energy Resources Engineering
Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
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Systematic identification and robust control design for uncertain time delay processes

Advanced control strategies such as Model Predictive Control have gained wide spread interest in many areas in the chemical industries, due to fast algorithms, a well established theory and growing number of successful industrial implementations. The main feature is that the optimal control signal is determined as a constrained optimization which utilizes future predictions of the plant behaviour. Hence the controller has a plant model embedded for state estimation. The achieved closed loop performance is therefore dependent on the quality of the future predictions. The performance of the state estimator is on the other hand dependent on the accuracy of the process and the noise model. Systems with long delays in the dynamic response between the actuators and the controlled variables are notoriously difficult to control or tune. A model predictive control implementation based on a model with the correct delay will provide good set-point tracking performance as long as the prediction horizon of the controller is longer than the delay. Hence a predictive controller would perform better in rejecting known disturbances and changes between operation modes than a PI controller with time-delay compensation as e.g. a Smith predictor. A common problem for all controllers, operating on a system with a delay longer than the dominating time constant, is that a stable system may reject small disturbances before the controller have an opportunity to act. If the controller is tuned to react on these minor disturbances the change in the actuator would lead to an increase in the variance of the system output. It is therefore desired if the controller does not react on minor disturbances or measurement noise. It is on the other hand important that the controller is not detuned such that significant or sustained disturbances cannot be effectively rejected. We proposed a model predictive control implementation with a dead-band on the penalty of the tracking error as a mean to achieve good closed loop performance on time delay system. We have in simulation tested our controller on a SISO system of an industrial furnace and a MIMO system on a cement grinding circuit.

General information
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Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Scientific Computing, Center for Energy Resources Engineering
Towards benchmarking of multivariable controllers in chemical/biochemical industries: Plantwide control for ethylene glycol production

In this paper we discuss a simple yet realistic benchmark plant for evaluation and comparison of advanced multivariable control for chemical and biochemical processes. The benchmark plant is based on recycle-separator-recycle systems for ethylene glycol production and implemented in Matlab-Simulink platform. The benchmark plant is used to illustrate a procedure for plantwide control design in which Model Predictive Control (MPC) is evaluated and compared to a control structure based on single-input/single-output PID-controllers. We believe such a benchmark plant has a promising potential for education purposes (operator training, student education, etc) as well as scientific research into chemical process control where it enables rapid evaluation and comparison of advanced multivariable controllers as demonstrated in this study.

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Huusom, J. K. (Intern), Bialas, D. J. (Intern), Jørgensen, J. B. (Intern), Sin, G. (Intern)
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A Dantzig-Wolfe MPC Algorithm for Power Plant Portfolio Control

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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Edlund, K. (Ekstern), Jørgensen, J. B. (Intern)
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Adaptive Step Size Control in Implicit Runge-Kutta Methods for Reservoir Simulation

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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Center for Energy Resources Engineering
Authors: Völcker, C. (Intern), Jørgensen, J. B. (Intern), Thomsen, P. G. (Intern), Stenby, E. H. (Intern)
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Application of Soft Constrained MPC to a Cement Mill Circuit

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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Prasath, G. (Ekstern), Recke, B. (Ekstern), Chidambaram, M. (Ekstern), Jørgensen, J. B. (Intern)
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ARX-based Model Predictive Control of Systems with Time Delays

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Organisations: Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Center for Energy Resources Engineering
Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
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Main Research Area: Technical/natural sciences
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ARX-Model based Model Predictive Control with Offset-Free Tracking

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Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
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ARX MPC for people with type 1 diabetes

Type 1 diabetes is a chronic disease characterized by a lack of production of pancreatic insulin, consequently leading to high blood glucose concentrations (hyperglycemia). Hyperglycemia has negative health effects in the long term such as eye, nerve, and kidney disease. Exogenous insulin must be injected to keep the blood glucose in the normoglycemic range (approximately 60 – 140 mg/dL, or 3.3 – 8 mmol/L). However, the dosing of exogenous insulin must be done carefully, because low blood glucose concentrations (hypoglycemia) can have immediate and severe consequences like insulin shock, coma, or even death. Currently, insulin administration is performed by the subject with type 1 diabetes based on infrequent glucose measurements (in the form of finger-sticks), often resulting in an unsatisfactory blood glucose control. An artificial pancreas is a medical device that injects exogenous insulin automatically in order to regulate the glucose concentration. Blood glucose measurements are obtained from a continuous glucose monitor (CGM). Insulin is administrated either continuously through an insulin pump, or at discrete times using an insulin pen. A control algorithm uses previous glucose measurements and insulin injection information to compute the optimal insulin administration for the current conditions. We use model predictive control (MPC) to compute the optimal insulin administration for 20 virtual type 1 diabetes subjects. The system (i.e., subject) has one manipulated input (insulin infusion rate), one disturbance input (carbohydrate meals), and one measured output (blood glucose concentration). The subject is represented by a system of nonlinear differential equations describing the dynamic effects of insulin and meals on blood glucose. Twenty parameter sets are used in the study, each representing a different virtual subject. The model used in the MPC is a low order autoregressive exogenous-input (ARX) model. Due to both the linearity and relative parsimony of the ARX model, there is a significant amount of subject/model mismatch in the model predictions, reflecting real-world conditions. In general, a simple ARX MPC cannot reject a step disturbance without a resulting offset; thus, the state vector is reformulated using an extended ΔARX description (E-ΔARX). The reference signal is time-varying, and is based on the optimal open-loop glucose profile. Insulin-on-board constraints are implemented to avoid overdosing insulin. State estimation is based on a Kalman filter using the noise model to simulate a realistic CGM. We present the MPC results for simulations of the 20 virtual subjects with type 1 diabetes. In particular, we investigate the effects of the prediction horizon length on the control quality of blood glucose and the robustness of the solution.
Explicit Singly Diagonally Implicit Runge-Kutta Methods and Adaptive Stepsize Control for Reservoir Simulation

The implicit Euler method, normally referred to as the fully implicit (FIM) method, and the implicit pressure explicit saturation (IMPES) method are the traditional choices for temporal discretization in reservoir simulation. The FIM method offers unconditionally stability in the sense of discrete approximations, while the IMPES scheme benefits from the explicit treatment of the saturation. However, in terms of controlling the integration error, the low order of the FIM method leads to small integration steps, while the explicit treatment of the saturation may restrict the stepsizes for the IMPES scheme. Current reservoir simulators apply timestepping algorithms that are based on safeguarded heuristics, and can neither guarantee convergence in the underlying equation solver, nor provide estimates of the relations between convergence, integration error and stepsizes. We establish predictive stepsize control applied to high order methods for temporal discretization in reservoir simulation. The family of Runge-Kutta methods is presented and in particular the explicit singly diagonally implicit Runge-Kutta (ESDIRK) method with an embedded error estimate is described. A predictive stepsize adjustment rule based on error estimates and convergence control of the integrated iterative solver is presented. We try to improve the predictive stepsize control through an extended communication between the convergence rate, the error control and the stepsize. Keywords: Reservoir simulation, implicit Runge-Kutta methods, ESDIRK, Newton-Raphson, convergence control, error control, stepsize selection.

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemistry, Center for Energy Resources Engineering
Authors: Völcker, C. (Intern), Jørgensen, J. B. (Intern), Thomsen, P. G. (Intern), Stenby, E. H. (Intern)
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Implications and Limitations of Ideal Insulin Administration for People with Type 1 Diabetes

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Meal Estimation in Nonlinear Model Predictive Control for Type 1 Diabetes

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Modeling and Simulation of Single Cell Protein Production

General information
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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for BioProcess Engineering, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center, Center for Energy Resources Engineering
Authors: Olsen, D. F. (Ekstern), Jørgensen, J. B. (Intern), Villadsen, J. (Intern), Jørgensen, S. B. (Intern)
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Model predictive control for plant-wide control of a reactor-separator-recycle system

General information
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Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Center for Energy Resources Engineering
Authors: Bialas, D. J. (Ekstern), Huusom, J. K. (Intern), Jørgensen, J. B. (Intern), Sin, G. (Intern)
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Optimal Insulin Administration for People with Type 1 Diabetes

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Optimal Operating Points for SCP Production in the U-Loop Reactor

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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for BioProcess Engineering, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center, Center for Energy Resources Engineering
Authors: Olsen, D. F. (Ekstern), Jørgensen, J. B. (Intern), Villadsen, J. (Intern), Jørgensen, S. B. (Intern)
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Optimal Operating Points for SCP Production in the U-Loop Reactor

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Potential of Economic Model Predictive Control for Management of Multiple Power Producers and Consumers

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Production Optimization for Two-Phase Flow in an Oil Reservoir

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Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Chemistry
Authors: Völcker, C. (Intern), Jørgensen, J. B. (Intern), Thomsen, P. G. (Intern), Stenby, E. H. (Intern)
Publication date: 2010
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Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2010

Robust model identification applied to type 1diabetes

In many realistic applications, process noise is known to be neither white nor normally distributed. When identifying models in these cases, it may be more effective to minimize a different penalty function than the standard sum of squared errors (as in a least-squares identification method). This paper investigates model identification based on two different penalty functions: the 1-norm of the prediction errors and a Huber-type penalty function. For data characteristic of some realistic applications, model identification based on these latter two penalty functions is shown to result in more accurate estimates of parameters than the standard least-squares solution, and more accurate model predictions for test data. The identification techniques are demonstrated on a simple toy problem as well as a physiological model of type 1 diabetes.

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Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Center for Energy Resources Engineering
Authors: Finan, D. A. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Madsen, H. (Intern)
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Single-Cell Protein Production in a U-Loop Reactor

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Single-Cell Protein Production in a U-Loop Reactor

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Authors: Olsen, D. F. (Ekstern), Jørgensen, J. B. (Intern), Villadsen, J. (Intern), Jørgensen, S. B. (Intern)
Number of pages: 88
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Systematic Model Analysis for Single Cell Protein (SCP) Production in a U-Loop Reactor

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Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Prado Rubio, O. A. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
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Systematic Model Analysis for Single Cell Protein (SCP) Production in a U-Loop Reactor

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State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Prado Rubio, O. A. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2010

The Potential of Economic MPC for Power Management
Economic Model Predictive Control is a receding horizon controller that minimizes an economic objective function rather than a weighted least squares objective function as in Model Predictive Control (MPC). We use Economic MPC to operate
a portfolio of power generators and consumers such that the cost of producing the required power is minimized. The power generators are controllable power generators such as combined heat and power generators (CHP), coal and gas fired power generators, as well as a significant share of uncontrollable power generators such as parks of wind turbines. In addition, some of the power consumers are controllable. In this paper, the controllable power consumers are exemplified by large cold rooms or aggregations of super markets with refrigeration systems. We formulate the Economic MPC as a linear program. By simulation, we demonstrate the performance of Economic MPC for a small conceptual example.
Tuning of ARX-based Model Predictive Control for Offset-free Tracking

**General information**
- State: Published
- Organisations: Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Scientific Computing, Center for Energy Resources Engineering
- Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
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Tuning of methods for offset free MPC based on ARX model representations

In this paper we investigate model predictive control (MPC) based on ARX models. ARX models can be identified from data using convex optimization technologies and is linear in the system parameters. Compared to other model parameterizations this feature is an advantage in embedded applications for robust and automatic system identification. Standard MPC is not able to reject a sustained, unmeasured, non zero mean disturbance and will therefore not provide offset free tracking. Offset free tracking can be guaranteed for this type of disturbances if Δ variables are used or if the state space is extended with a disturbance model state. The relation between the base case and the two extended methods are illustrated which provides good understanding and a platform for discussing tuning for good closed loop performance.

**General information**
- State: Published
- Organisations: Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Scientific Computing, Center for Energy Resources Engineering
- Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
- Pages: 2255-2360
- Publication date: 2010

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- Title of host publication: Proceedings of the American Control Conference
- Publisher: IEEE
- ISBN (Print): 978-1-4244-7426-4
- Main Research Area: Technical/natural sciences
- Conference: American Control Conference (ACC 2010), Baltimore, MD, United States, 03/06/2010 - 03/06/2010
- Electronic versions: Jakob.pdf

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Tuning of Offset-Free ARX-based SISO Model Predictive Control

General information
State: Submitted
Organisations: Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Scientific Computing, Center for Energy Resources Engineering
Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
Publication date: 2010

Host publication information
Title of host publication: CDC49
Main Research Area: Technical/natural sciences
Conference: IEEE Conference on Decision and Control, Atlanta, Georgia, USA, 01/01/2010
Source: orbit
Source-ID: 264877
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Adaptive Disturbance Estimation for Offset-Free Model Predictive Control

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Scientific Computing
Authors: Huusom, J. K. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern)
Publication date: 2009

Publication information
Publisher: Technical University of Denmark (DTU)
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 265094
Publication: Research - peer-review › Report – Annual report year: 2009

A Primal-Dual Interior Point-Linear Programming Algorithm for MPC

Constrained optimal control problems for linear systems with linear constraints and an objective function consisting of linear and 1-norm terms can be expressed as linear programs. We develop an efficient primal-dual interior point algorithm for solution of such linear programs. The algorithm is implemented in Matlab and its performance is compared to an active set based LP solver and linprog in Matlab's optimization toolbox. Simulations demonstrate that the new algorithm is more than one magnitude faster than the other LP algorithms applied to this problem.

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, DONG Energy A/S
Authors: Edlund, K. (Ekstern), Sokoler, L. E. (Intern), Jørgensen, J. B. (Intern)
Pages: 351-356
Publication date: 2009

Host publication information
Title of host publication: Proceedings of the 48th IEEE Conference on Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009
Publisher: IEEE
ISBN (Print): 978-1-4244-3871-6
Main Research Area: Technical/natural sciences
Conference: The 48th IEEE Conference on Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009, 01/01/2009
Electronic versions: Edlund.pdf
Convex Optimization for System Identification and Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2009

Host publication information
Title of host publication: 14th Belgian-French-German Conference on Optimization
Main Research Area: Technical/natural sciences
Conference: 14th Belgian-French-German Conference on Optimization : BFG'09, Leuven, Belgium, 01/01/2009
Source: orbit
Source-ID: 260194
Publication: Research - peer-review › Conference abstract in proceedings – Annual report year: 2009

DiaCon: an interdisciplinary approach to diabetes control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Center for Systems Microbiology, Department of Systems Biology
Publication date: 2009
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 257648
Publication: Research - peer-review › Poster – Annual report year: 2009

Efficient Computational Methods for Model Predictive Control

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Jørgensen, J. B. (Intern)
Publication date: 2009

Publication information
Original language: English
Main Research Area: Technical/natural sciences

Bibliographical note
Invited plenary talk.
Source: orbit
Source-ID: 260192
Publication: Research › Sound/Visual production (digital) – Annual report year: 2009

Glucose modeling and prediction using physical activity variables

General information
Improvements to least-squares model identification: an application to diabetes modeling

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics
Authors: Finan, D. A. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Madsen, H. (Intern)
Publication date: 2009

Publication Information
Original language: English
Main Research Area: Technical/natural sciences
Links:
http://www.aiche.org/Conferences/AnnualMeeting/index.aspx
Source: orbit
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Publication: Research › Sound/Visual production (digital) – Annual report year: 2009

Modelling, Simulation and Optimization of Single-Cell Protein Production in a U-Loop Reactor

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for BioProcess Engineering, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center
Authors: Olsen, D. F. (Ekstern), Jørgensen, J. B. (Intern), Villadsen, J. (Intern), Sin, G. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2009

Publication Information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 252816
Publication: Research › Sound/Visual production (digital) – Annual report year: 2009

Moving Horizon Estimation based on Finite Impulse Response Models

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Prasath, G. (Ekstern), Jørgensen, J. B. (Intern)
Pages: 2839-2844
Publication date: 2009

Host publication Information
Title of host publication: Proceedings of the European Control Conference 2009
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 260191
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Simulation of Subsurface Two-Phase Flow in an Oil Reservoir
Simulation of Two-Phase Flow in an Oil Reservoir using Adaptive High-Order Runge-Kutta based Time-Integration

Soft Constraints for Robust MPC of Uncertain Systems

A Dynamic Model for a Cupola Furnace
A Generalized Autocovariance Least-Squares Method for Kalman Filter Tuning
This paper discusses a method for estimating noise covariances from process data. In linear stochastic state-space representations the true noise covariances are generally unknown in practical applications. Using estimated covariances a Kalman filter can be tuned in order to increase the accuracy of the state estimates. There is a linear relationship between covariances and autocovariance. Therefore, the covariance estimation problem can be stated as a least-squares problem, which can be solved as a symmetric semidefinite least-squares problem. This problem is convex and can be solved efficiently by interior-point methods. A numerical algorithm for solving the symmetric is able to handle systems with mutually correlated process noise and measurement noise. (c) 2007 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Computer Aided Process Engineering Center
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern)
Pages: 769-779
Publication date: 2008
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Process Control
Volume: 18
Issue number: 7
ISSN (Print): 0959-1524
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 3.41 SJR 1.21 SNIP 2.241
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.338 SNIP 2.028 CiteScore 3.35
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.521 SNIP 2.735 CiteScore 3.92
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.507 SNIP 2.607 CiteScore 3.47
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.563 SNIP 2.954 CiteScore 3.39
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.316 SNIP 2.59 CiteScore 2.9
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.305 SNIP 2.203
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.282 SNIP 2.772
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.458 SNIP 2.698
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.425 SNIP 2.086
Scopus rating (2006): SJR 1.739 SNIP 2.369
Model Predictive Control based on Finite Impulse Response Models

We develop a regularized l2 finite impulse response (FIR) predictive controller with input and input-rate constraints. Feedback is based on a simple constant output disturbance filter. The performance of the predictive controller in the face of plant-model mismatch is investigated by simulations and related to the uncertainty of the impulse response coefficients. The simulations can be used to benchmark l2 MPC against FIR based robust MPC as well as to estimate the maximum performance improvements by robust MPC.

DIACON. Control Algorithms for Semi- and Fully-Automated Pen and Pump Insulin Administration

DIACON. Control Algorithms for Semi- and Fully-Automated Pen and Pump Insulin Administration

A Runge-Kutta Based Software Package for Nonlinear Model Predictive Control

A Runge-Kutta Based Software Package for Nonlinear Model Predictive Control
Prevent Refrigerated Foodstuff in the Supermarket from Discard

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Cai, J. (Ekstern), Stoustrup, J. (Ekstern), Jørgensen, J. B. (Intern)
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the 17th IFAC World Congress
Publisher: International Federation of Automatic Control
ISBN (Print): 978-3-902661-00-5
Main Research Area: Technical/natural sciences
Conference: 17th IFAC World Congress, Seoul, Korea, Republic of, 06/07/2008 - 06/07/2008
Source: orbit
Source-ID: 224350
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Software for Large-Scale Nonlinear Model Predictive Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2008
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224379
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2008

Unreachable Setpoints in Model Predictive Control
In this work, a new model predictive controller is developed that handles unreachable setpoints better than traditional model predictive control methods. The new controller induces an interesting fast/slow asymmetry in the tracking response of the system. Nominal asymptotic stability of the optimal steady state is established for terminal constraint model predictive control (MPC). The region of attraction is the steerable set. Existing analysis methods for closed-loop properties of MPC are not applicable to this new formulation, and a new analysis method is developed. It is shown how to extend this analysis to terminal penalty MPC. Two examples are presented that demonstrate the advantages of the proposed setpoint-tracking MPC over the current target-tracking MPC.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center
Authors: Rawlings, J. B. (Ekstern), Bonné, D. (Intern), Jørgensen, J. B. (Intern), Venkat, A. N. (Ekstern), Jørgensen, S. B. (Intern)
Pages: 2209-2215
Publication date: 2008
Main Research Area: Technical/natural sciences

Publication information
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ISSN (Print): 0018-9286
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BFI (2017): BFI-level 2
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 2
Scopus rating (2016): SJR 4.174 SNIP 3.159 CiteScore 6.06
BFI (2015): BFI-level 2
A Computationally Efficient and Robust Implementation of the Continuous-Discrete Extended Kalman Filter

We present a novel numerically robust and computationally efficient extended Kalman filter for state estimation in nonlinear continuous-discrete stochastic systems. The resulting differential equations for the mean-covariance evolution of the nonlinear stochastic continuous-discrete time systems are solved efficiently using an ESDIRK integrator with sensitivity analysis capabilities. This ESDIRK integrator for the mean-covariance evolution is implemented as part of an extended Kalman filter and tested on a PDE system. For moderate to large sized systems, the ESDIRK based extended Kalman filter for nonlinear stochastic continuous-discrete time systems is more than two orders of magnitude faster than a conventional implementation. This is of significance in nonlinear model predictive control applications, statistical process monitoring as well as grey-box modelling of systems described by stochastic differential equations.

A Critical Discussion of the Continuous-Discrete Extended Kalman Filter

Adjoint Sensitivity Results for Predictive Control, State- and Parameter-Estimation with Nonlinear Models
A Dynamic Model for in vivo Glucose-Insulin Metabolism

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Hrafnkelsson, V. (Ekstern), Jørgensen, J. B. (Intern)
Publication date: 2007
Event: Abstract from European Congress of Chemical Engineering - 6, Copenhagen, Denmark.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224381
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2007

A Generalized Autocovariance Least-Squares Method for Covariance Estimation
A generalization of the autocovariance least-squares method for estimating noise covariances is presented. The method can estimate mutually correlated system and sensor noise and can be used with both the predicting and the filtering form of the Kalman filter.

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Computer Aided Process Engineering Center
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007
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Publisher: IEEE
ISBN (Print): 1-4244-0988-8
Main Research Area: Technical/natural sciences
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DOIs:
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Source: orbit
Source-ID: 224360
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

An ESDIRK Software Package for DAE Systems

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern)
Publication date: 2007
Event: Abstract from European Congress of Chemical Engineering - 6, Copenhagen, Denmark.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224384
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2007

A Numerically Robust ESDIRK-Based Implementation of the Continuous-Discrete Extended Kalman Filter

General information
State: Published
A Tool for Kalman Filter Tuning

The Kalman filter requires knowledge about the noise statistics. In practical applications, however, the noise covariances are generally not known. A method for estimating noise covariances from process data has been investigated. The method gives a least-squares estimate of the noise covariances, which can be used to compute the Kalman filter gain.

Covariance Estimation, State estimation, Kalman filter

Electronic versions: imm5078.pdf

DOIs: 10.1016/S1570-7946(07)80166-0

Links: http://www.elsevierdirect.com/product.jsp?isbn=9780444531575&dmnum=CWS1

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Source-ID: 199930

Publication: Research › Article in proceedings – Annual report year: 2007
Comparison of Prediction-Error Modeling Criteria

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007

Host publication information
Title of host publication: American Control Conference 2007
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224359
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

Comparison of Prediction-Error-Modelling Criteria
Single and multi-step prediction-error-methods based on the maximum likelihood and least squares criteria are compared. The prediction-error methods studied are based on predictions using the Kalman filter and Kalman predictors for a linear discrete-time stochastic state space model, which is a realization of a continuous-discrete multivariate stochastic transfer function model. The proposed prediction error-methods are demonstrated for a SISO system parameterized by the transfer functions with time delays of a continuous-discrete-time linear stochastic system. The simulations for this case suggest to use the one-step-ahead prediction-error maximum-likelihood (or maximum a posteriori) estimator. It gives consistent estimates of all parameters and the parameter estimates are almost identical to the estimates obtained for long prediction horizons but with consumption of significantly less computational resources. The identification method is suitable for predictive control.

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007

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Title of host publication: American Control Conference 2007
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 252591
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

Continuous-Discrete Time Prediction-Error Identification Relevant for Linear Model Predictive Control
A Prediction-error-method tailored for model based predictive control is presented. The prediction-error method studied are based on predictions using the Kalman filter and Kalman predictors for a linear discrete-time stochastic state space model. The linear discrete-time stochastic state space model is realized from a continuous-discrete-time linear stochastic system specified using transfer functions with time-delays. It is argued that the prediction-error criterion should be selected such that it is compatible with the objective function of the predictive controller in which the model is to be applied. The suitability of the proposed prediction error-method for predictive control is demonstrated for dual composition control of a simulated binary distillation column.
Continuous-Discrete Time Prediction-Error Modelling Relevant for Linear Model Predictive Control

Estimation of noise covariances and identification of disturbance structure using the autocovariance least-squares method

Estimation of noise covariances and identification of disturbance structure using the autocovariance least-squares method
Experimental Design for Input/Output Constrained Closed-Loop Systems

General information
State: Submitted
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Bonné, D. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007
Main Research Area: Technical/natural sciences

Improving Model Predictive Control Performance Using Disturbance Estimation

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Computer Aided Process Engineering Center
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007

Improving Model Predictive Control Performance using Disturbance Estimation and Systematic Kalman Filter Tuning

General information
State: Published
Main Research Area: Technical/natural sciences
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Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2007

Improving Model Predictive Control Performance Using Systematic Kalman Filter Tuning

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Mathematical Statistics, Computer Aided Process Engineering Center
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Poulsen, N. K. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007
Keeping Experiments in Control with Interval Methods

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Department of Informatics and Mathematical Modeling
Authors: Bonné, D. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007
Main Research Area: Technical/natural sciences

Publication information
Journal: Reliable Computing
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BFI (2017): BFI-level 1
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.175 SNIP 0.756 CiteScore 0.5
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.137 SNIP 0.464 CiteScore 0.35
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.204 SNIP 0.42 CiteScore 0.33
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.165 SNIP 0.474 CiteScore 0.38
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.141 SNIP 0.725 CiteScore 0.3
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.16 SNIP 0.113 CiteScore 0.2
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.295 SNIP 2.508
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.217 SNIP 1.426
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.214 SNIP 1.272
Scopus rating (2007): SJR 0.563 SNIP 1.713
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.607 SNIP 1.297
Scopus rating (2005): SJR 0.431 SNIP 0.816
Scopus rating (2004): SJR 0.461 SNIP 1.2
Scopus rating (2003): SJR 0.447 SNIP 0.788
Scopus rating (2002): SJR 0.506 SNIP 0.934
Scopus rating (2001): SJR 0.307 SNIP 1.148
Scopus rating (2000): SJR 0.332 SNIP 0.755
Scopus rating (1999): SJR 0.259 SNIP 0.707

Original language: English
Source: orbit
Source-ID: 184619
Publication: Research - peer-review › Journal article – Annual report year: 2007
MPC-Relevant Prediction-Error Identification
A prediction-error-method tailored for model based predictive control is presented. The prediction-error method studied are based on predictions using the Kalman filter and Kalman predictors for a linear discrete-time stochastic state space model. The linear discrete-time stochastic state space model is realized from a continuous-discrete-time linear stochastic system specified using transfer functions with time-delays. It is argued that the prediction-error criterion should be selected such that it is compatible with the objective function of the predictive controller in which the model is to be applied. The suitability of the proposed prediction error-method for predictive control is demonstrated for dual composition control of a simulated binary distillation column.

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2007

Host publication information
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Publisher: IEEE
ISBN (Print): 1-4244-0988-8
Main Research Area: Technical/natural sciences
Electronic versions:
Jørgensen2.pdf
DOIs:
10.1109/ACC.2007.4282550

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Source: orbit
Source-ID: 224358
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

New Extended Kalman Filter Algorithms for Stochastic Differential Algebraic Equations

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Mathematical Statistics
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Madsen, H. (Intern)
Pages: 359-366
Publication date: 2007

Host publication information
Title of host publication: Assessment and Future Direction of Nonlinear Model Predictive Control : NMPC'05
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224377
Publication: Research - peer-review › Book chapter – Annual report year: 2007

Nonlinear Model Predictive Control Start-Up of a Plate Reactor

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Haugwitz, S. (Ekstern), Jørgensen, J. B. (Intern), Hagander, P. (Ekstern)
Publication date: 2007
Main Research Area: Technical/natural sciences
Source: orbit
Numerical Methods for Model Predictive Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2007

Sensitivity Computation for Dynamic Optimization

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Johansen, K. (Intern)
Publication date: 2007
Event: Abstract from European Congress of Chemical Engineering - 6, Copenhagen, Denmark.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224382
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2007

A Continuous-Discrete Extended Kalman Filter Algorithm for Prediction-Error-Modelling

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Mathematical Statistics
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Madsen, H. (Intern)
Publication date: 2006
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224387
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2006

A Family of ESDIRK Solvers for DAE Systems

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Kristensen, M. R. (Intern), Jørgensen, J. B. (Intern), Thomsen, P. G. (Intern)
Publication date: 2006
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224389
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2006

A Generalized Autocovariance Least-Squares Method for Kalman Filter Tuning
Continuous-Time Prediction-Error Identification for MPC

Development of Systematic Tuning Procedures for Extended Kalman Filtering

Dynamic Optimization and Predictive Control

Dynamic Optimization Based on Adjoint Sensitivity Computation
Implementation Issues for High-Level Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern), Recke, B. (Ekstern)
Publication date: 2006

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224422
Publication: Research › Conference abstract for conference – Annual report year: 2006

Model Predictive Control - Why, Where, and How?

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2006

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224426
Publication: Research › Sound/Visual production (digital) – Annual report year: 2006

Numerical Methods for Model Predictive Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2006

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224424
Publication: Research › Sound/Visual production (digital) – Annual report year: 2006

Planned Work in CMBC on Extended Kalman Filtering

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2006

Host publication information
Title of host publication: Proceedings of the 5th CMBC Workshop
Planned Work in CMBC on Extended Kalman Filtering

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center
Authors: Åkesson, B. M. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2006

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 191585
Publication: Research › Article in proceedings – Annual report year: 2006

Start-Up Predictive Control and Estimation. A Numerical Approach

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2006

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224423
Publication: Research › Sound/Visual production (digital) – Annual report year: 2006

A procedure for guaranteed in Control experimental design

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center
Authors: Bonné, D. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2005

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 184824
Publication: Research - peer-review › Report – Annual report year: 2005

Efficient Filtering and Prediction in Stochastic Differential Equations

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Mathematical Statistics
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Madsen, H. (Intern)
Publication date: 2005
Modeling for Predictive Control of Cement Grinding Circuits

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Department of Informatics and Mathematical Modeling
Authors: Huusom, J. K. (Intern), Jensen, A. D. (Ekstern), Jørgensen, S. B. (Intern), Michelsen, M. L. (Intern), Recke, B. (Intern), Knudsen, J. (Ekstern), Jørgensen, J. B. (Intern)
Publication date: 2005

Modelling of Cement Grinding Circuits for Predictive Control

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, CHEC Research Centre, Computer Aided Process Engineering Center, Center for Phase Equilibria and Separation Processes, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Huusom, J. K. (Intern), Jensen, A. D. (Intern), Jørgensen, S. B. (Intern), Michelsen, M. L. (Intern), Knudsen, J. (Ekstern), Recke, B. (Intern), Jørgensen, J. B. (Intern)
Publication date: 2005

Numerically Efficient Filtering and Prediction in Stochastic Differential Algebraic Equations

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Environmental Science and Engineering
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Madsen, H. (Intern)
Pages: 459-466
Publication date: 2005
Sensitivity Analysis in Index-1 Differential Algebraic Equations by ESDIRK Methods

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Department of Chemical and Biochemical Engineering, Scientific Computing
Authors: Jørgensen, J. B. (Intern), Kristensen, M. R. (Intern), Thomsen, P. G. (Intern), Michelsen, M. L. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2005

Host publication information
Title of host publication: 16th IFAC World Congress, Praha May 2005
Main Research Area: Technical/natural sciences
Links:
http://www2.imm.dtu.dk/pubdb/p.php?3409
Source: orbit
Source-ID: 185703
Publication: Research - peer-review › Article in proceedings – Annual report year: 2005

Structured Quadratic Programming Algorithms for Optimization of Dynamic Systems

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2005
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224431
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2005

An ESDIRK Method with Sensitivity Analysis Capabilities

A new algorithm for numerical sensitivity analysis of ordinary differential equations (ODEs) is presented. The underlying ODE solver belongs to the Runge-Kutta family. The algorithm calculates sensitivities with respect to problem parameters and initial conditions, exploiting the special structure of the sensitivity equations. A key feature is the reuse of information already computed for the state integration, hereby minimizing the extra effort required for sensitivity integration. Through case studies the new algorithm is compared to an extrapolation method and to the more established BDF based approaches. Several advantages of the new approach are demonstrated, especially when frequent discontinuities are present, which renders the new algorithm particularly suitable for dynamic optimization purposes.

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Kristensen, M. R. (Intern), Jørgensen, J. B. (Intern), Thomsen, P. G. (Intern), Jørgensen, S. B. (Intern)
Pages: 2695-2707
Publication date: 2004
Main Research Area: Technical/natural sciences

Publication information
Journal: Computers & Chemical Engineering
Volume: 28
Issue number: 12
ISSN (Print): 0098-1354
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed Yes
Efficient Sensitivity Computation for Nonlinear Model Predictive Control
Model Predictive Control - From Real-Time Optimization of Cement Plants to Construction of an Artificial Pancreas

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Jørgensen, J. B. (Intern)
Publication date: 2004
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224392
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 2004

Moving Horizon Estimation and Control
This dissertation concerns numerical procedures for the problems arising in moving horizon estimation and control. Moving horizon estimation and control is also referred to as model predictive control as well as receding horizon estimation and control. Model predictive control is the most successful and applied methodology beyond PID-control for control of industrial processes. The main contribution of this thesis is introduction and definition of the extended linear quadratic optimal control problem for solution of numerical problems arising in moving horizon estimation and control. An efficient structure-employing methodology for solution of the extended linear quadratic optimal control problem is provided and it is discussed how this solution is employed in solution of constrained model predictive control problems as well as in the solution of nonlinear optimal control and estimation problems.

Chapter 1 motivates moving horizon estimation and control as a paradigm for control of industrial processes. It introduces the extended linear quadratic control problem and discusses its central role in moving horizon estimation and control. Introduction, application and efficient solution of the extended linear quadratic control problem is the key contribution of this thesis. In addition chapter 1 provides a comprehensive survey of existing methods for model predictive control.

Chapter 2 discusses computational methods and inherent approximations in model predictive control. By considering the stochastic optimal control problem, the approximations and assumptions of model predictive control are pin-pointed. In an ad hoc fashion the separation principle and certainty-equivalence are assumed to prevail, such that the stochastic optimal control problem may be separated into an estimation problem and a deterministic optimal control problem. Both the estimation problem and the obtained deterministic optimal control problem are demonstrated to be instances of a constrained non-linear optimal control problem. In the sequential quadratic programming algorithm for solution of constrained nonlinear optimal control problems, the quadratic subproblem generated at each iteration is shown to be a constrained linear-quadratic optimal control problem. Procedures for generation of the constrained linear-quadratic optimal control problem and its data from the nonlinear estimation problem, the nonlinear control problem, the linear moving horizon estimator, and the linear moving horizon controller are provided. The significance of these conversions to constrained linear-quadratic optimal control problems is that the entire model predictive control problem can be solved efficiently by having efficient algorithms tailored for solution of the con-strained linear-quadratic optimal control problem. The major intention in this chapter is to emphasize the central role of the constrained linear-quadratic optimal control problem in model predictive control such that tailored algorithms for the constrained linear-quadratic optimal control problem is motivated and justified.

Chapter 3. A primal active set, a dual active set, and an interior point algorithm for solution of the constrained linear quadratic optimal control problem are outlined. The major computational effort in all these algorithms reduces to solution of certain unconstrained linear quadratic optimal control problems, i.e. the extended linear quadratic control problem. A Riccati recursion procedure for effective solution of such unconstrained problems is stated.

Chapter 4. Based on dynamic programming, Riccati recursion procedures for the linear-quadratic optimal control problem...
as well as the extended linear-quadratic optimal control problem are developed. Compared to alternative solution
procedures such as control vector parameterization by elimination of the states, the Riccati based procedure is highly
efficient for long prediction horizons. The extended linear-quadratic optimal control problem may also be regarded as an
equality constrained quadratic program with special structure. The computation of the optimal solution-Lagrange multiplier
pair for a convex equality constrained quadratic program is specialized to the extended linear-quadratic optimal control
problem treated as a quadratic program. Efficient solution of the highly structured KKT-system corresponding to the
extended linear-quadratic optimal control problem is facilitated by the Riccati recursion developed by dynamic
programming.

Chapter 5 presents the principles for efficient solution of unconstrained non-linear optimal control problems described by
ordinary differential equations. These principles are presented through numerical solution of a continuous-time nonlinear
optimal control problem of the Bolza form. To focus on the basic principles involved and for illustrative purposes, the
continuous-time Bolza problem is discretized by the explicit Euler method. The discrete-time nonlinear optimal control
problem of the Bolza form is solved by different SQP methods and an algorithm based on the discrete maximum principle.
The SQP algorithms presented are implementations based on open- and closed-loop feasible path control vector
parameterizations as well as an infeasible path simultaneous procedure. Two procedures for solution of the quadratic
programs are presented. In the first procedure, the structure of the quadratic programs arising in the solution of the
nonlinear optimal control problem is utilized by a Riccati iteration based factorization of the resulting KKT-system. In the
second procedure, an efficient procedure for elimination of the states and solution of a dense reduced space quadratic
program is presented. These methods are compared for a simple process example operated around an unstable
equilibrium. The infeasible path and the closed-loop feasible path algorithms converge for this example. The implemented
open-loop feasible path algorithms are not able to converge to an unstable equilibrium. The Riccati based solution
procedure enables implementation of the stabilized infeasible path SQP algorithm as well as the closed-loop feasible path
SQP algorithm. The methods are presented in a framework that is easily extended to constrained nonlinear optimal control
problems. Such extensions and methodologies for efficient integration of the ordinary differential equations as well as the
 corresponding sensitivity equations are discussed.

Chapter 6 summarizes the main contribution of this thesis. It briefly discusses the pros and cons of using the extended
linear quadratic control framework for solution of deterministic optimal control problems.

Appendices. Appendix A demonstrates how quadratic programs arise in sequential quadratic programming algorithms.
Appendix B uses a control vector parameterization approach to express various extended constrained linear quadratic
optimal control problems as standard quadratic programs. Appendix C discuss construction of maximal output admissible
sets. It provides an algorithm for computation of the maximal output admissible set for linear model predictive control.
Appendix D provides results concerning linear regression. Appendix E discuss prediction error methods for identification of
linear models tailored for model predictive control.
Numerical Methods for Model Predictive Control

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2004
Main Research Area: Technical/natural sciences

Application of Knowledge for Monitoring and Control

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center, Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Jørgensen, S. B. (Intern), Jørgensen, J. B. (Intern), Bonné, D. (Intern), Gregersen, L. (Intern)
Publication date: 2001
Main Research Area: Technical/natural sciences

Model Predictive Control of a Flow Swing Reactor

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center
Authors: Jørgensen, J. B. (Intern), Hansen, J. E. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2001
Event: Abstract from Nordic Reaction Systems Seminar.
Main Research Area: Technical/natural sciences

Plantwide Control Structure Selection

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2001

Publication information
Original language: English
Volume: 0
Main Research Area: Technical/natural sciences
Source: orbit
Towards Automated Selection of Decentralized Control Structures

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2001

Towards Automatic Decentralized Control Structure Selection

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2001

Host publication information
Title of host publication: Computer Aided Chemical Engineering, Elsevier 8
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 153999
Publication: Research › Article in proceedings – Annual report year: 2001

Towards Automatic Decentralized Control Structure Selection

General information
State: Published
Organisations: Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 2001

Automatic Selection of Decentralized Control Structures

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Towards Automatic Decentralized Control Structure Selection

A subtask in integration of design and control of chemical processes is the selection of a control structure. Automating the selection of the control structure enables sequential integration of process and control design. As soon as the process is specified or computed, a structure for decentralized control is determined automatically, and the resulting decentralized control structure is automatically tuned using standard techniques. Dynamic simulation of the resulting process system gives immediate feedback to the process design engineer regarding practical operability of the process. The control structure selection problem is formulated as a special MILP employing cost coefficients which are computed using Parseval's theorem combined with RGA and IMC concepts. This approach enables selection and tuning of large-scale plant-wide decentralized controllers through efficient combination of model formulation and mathematical programming.

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Model Predictive Control Design for an Alternating Nutrient Removal Process

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Computer Aided Process Engineering Center
Authors: Jensen, J. L. (Ekstern), Meinhold, J. (Intern), Krühne, U. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 1998
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224398
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 1998

Model Predictive Control of a Flow Swing Reactor

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Chemical and Biochemical Engineering, Computer Aided Process Engineering Center
Authors: Jørgensen, J. B. (Intern), Hansen, J. E. (Intern), Jørgensen, S. B. (Intern)
Publication date: 1998
Event: Abstract from 1998 AIChE Annual Meeting, Miami Beach, FL, United States.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224397
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 1998
Operational Implications of Optimality

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Computer Aided Process Engineering Center, Department of Chemical and Biochemical Engineering
Authors: Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Publication date: 1998
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 224399
Publication: Research - peer-review › Conference abstract for conference – Annual report year: 1998

An Output Multiplicity in Binary Distillation: Experimental Verification

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering
Authors: Koggersbol, A. (Ekstern), Andersen, T. R. (Intern), Jørgensen, J. B. (Intern), Jørgensen, S. B. (Intern)
Pages: S835-S840
Publication date: 1996
Main Research Area: Technical/natural sciences

Publication information
Journal: Computers & Chemical Engineering
Volume: 20 Suppl.
ISSN (Print): 0098-1354
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.39 SJR 1.008 SNIP 1.607
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.122 SNIP 1.724 CiteScore 3.04
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.184 SNIP 1.738 CiteScore 3.22
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.223 SNIP 1.776 CiteScore 3.06
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.161 SNIP 1.92 CiteScore 3.05
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.185 SNIP 1.736 CiteScore 2.8
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.176 SNIP 1.796
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.154 SNIP 2.166
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.293 SNIP 2.127
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.625 SNIP 1.959
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.304 SNIP 1.936
Scopus rating (2005): SJR 1.314 SNIP 1.953
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 1.125 SNIP 1.908
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 1.348 SNIP 1.936
Scopus rating (2002): SJR 1.042 SNIP 0.92
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.955 SNIP 0.728
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 1.366 SNIP 1.025
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 1.073 SNIP 1.113
Original language: English
Source: orbit
Source-ID: 167836
Publication: Research - peer-review › Journal article – Annual report year: 1996

Projects:

**Stochastic Dynamic Optimization and Control Theory**

Department of Applied Mathematics and Computer Science
Period: 01/09/2017 → 31/08/2020
Number of participants: 4
Phd Student:
Brok, Niclas Laursen (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Madsen, Henrik (Intern)
Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Learning-based Model Predictive Control of Spray Dryers
Department of Electrical Engineering
Period: 01/01/2017 → 31/12/2019
Number of participants: 6
Phd Student:
Miklos, Robert (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Petersen, Lars Norbert (Intern)
Poulsen, Niels Kjølstad (Intern)
Utzen, Christer (Ekstern)
Main Supervisor:
Niemann, Hans Henrik (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Industrial PhD
Project: PhD

SDE-modelling in CITIES
Department of Applied Mathematics and Computer Science
Centre for IT-Intelligent Energy Systems in Cities
Period: 15/07/2016 → 13/11/2019
Number of participants: 4
Phd Student:
Junker, Rune Grønborg (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Thygesen, Uffe Høgsbro (Intern)
Main Supervisor:
Madsen, Henrik (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

SDE-modelling in CITIES
Department of Applied Mathematics and Computer Science
Period: 15/07/2016 → 13/11/2019
Number of participants: 4
Phd Student:
Junker, Rune Grønborg (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Thygesen, Uffe Høgsbro (Intern)
Main Supervisor:
Madsen, Henrik (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD
Simulation and Optimization of Oil Reservoirs in the Danish North Sea

Department of Applied Mathematics and Computer Science
Period: 01/12/2015 → 30/11/2018
Number of participants: 4
Phd Student: Harsholt, Steen (Intern)
Supervisor: Capolei, Andrea (Intern)
Nick, Hamid (Intern)
Main Supervisor: Jørgensen, John Bagterp (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Eksternt finansieret virksomhed
Project: PhD

Optimal Control of PDE-Constrained Systems

Department of Applied Mathematics and Computer Science
Period: 15/09/2015 → 25/01/2019
Number of participants: 4
Phd Student: Christiansen, Lasse Hjuler (Intern)
Supervisor: Engsig-Karup, Allan Peter (Intern)
Pedersen, Michael (Intern)
Main Supervisor: Jørgensen, John Bagterp (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Nonlinear Model Predictive Control for Oil Reservoirs

Department of Applied Mathematics and Computer Science
Period: 15/08/2015 → 14/08/2018
Number of participants: 4
Phd Student: Ritschel, Tobias Kasper Skovborg (Intern)
Supervisor: Capolei, Andrea (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor: Jørgensen, John Bagterp (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

Model Predictive Control based on Stochastic Differential Equations - An Artificial Pancreas with Fast Insulin, Glucagon and Multiple Sensors

Department of Applied Mathematics and Computer Science
Period: 01/09/2014 → 01/12/2017
Number of participants: 5
Phd Student:
Hagdrup, Morten (Intern)

Supervisor:
Madsen, Henrik (Intern)
Poulsen, Bjarne (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Modeling of Pharmacokinetics and Pharmacodynamics of Novel Glucagon Analogues for Closed-Loop Dual Hormone Blood Glucose Control

Department of Applied Mathematics and Computer Science
Period: 15/03/2014 → 16/08/2017
Number of participants: 7
Phd Student:
Wendt, Sabrina Lyngbye (Intern)
Supervisor:
Knudsen, Carsten Boye (Ekstern)
Madsen, Henrik (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Thygesen, Uffe Høgsbro (Intern)
Dalla-Man, Chiara (Ekstern)
Hovorka, Roman (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Industrial PhD

Relations
Publications:
Modeling Pharmacokinetics and Pharmacodynamics of Glucagon for Simulation of the Gluoregulatory System in Patients with Type 1 Diabetes.
Project: PhD

Center for IT-Intelligent Energy Systems for Cities
A wide range of research activities have arisen to support the Danish target of a 100% renewable energy system by 2050. Projects focused on individual aspects of the energy system, such as zero emissions buildings or intelligent power systems provide valuable insight, that facilitates flexibility throughout the energy system. CITIES will address this deficiency by establishing an integrated research centre covering all aspects of the energy system, including gas, power, district heating/cooling and biomass, and most importantly methods to forecast, control and optimize their interactions through the use of advanced ICT solutions.
The high densities of population, energy consumption, and energy and communications networks in cities offer the greatest potential for flexibility at the last cost, and the fact that cities account for 80% of global energy consumption and emissions [1] make the urban environment an ideal setting for energy systems integration research. CITIES will pioneer research into fully integrated city energy systems, building short-term operational models that feed longer term planning models, considering the spatiotemporal variations, interactions, dynamics and stochastics in the energy system. Low level models of system components will inform higher-level aggregate models employed in market and control framework design. The leading position of European academia and industry and the rapidly growing market for smart energy solutions indicates substantial scope for increased competitiveness and job creation within this field. CITIES will, in collaboration with its industrial and academic partners, conduct research with a view to developing tools for the implementation of integrated energy system solutions.

Center granted by Strategic Research Council.

To be a sustainable organisation.
Department of Applied Mathematics and Computer Science

Department of Civil Engineering

Department of Management Engineering

Department of Energy Conversion and Storage

Department of Informatics and Mathematical Modeling

Centre for IT-Intelligent Energy Systems in Cities

Aalborg University

Period: 01/01/2014 → 31/12/2019

Number of participants: 8

Strategic

Acronym: CITIES

Number of related Ph.D. students: 12

Project participant:

Madsen, Henrik (Intern)

Heller, Alfred (Intern)

Nielsen, Per Sieverts (Intern)

Pedersen, Allan Schroeder (Intern)

Rode, Carsten (Intern)

Pinson, Pierre (Intern)

Jørgensen, John Bagterp (Intern)

Project Manager, organisational:

Herrmann, Ivan Tengbjerg (Intern)

Financing sources

Source: Forskningsrådene - Andre

Name of research programme: Energy Programme

Amount: 44.00 Danish Kroner

Year of approval: 2013

Relations

Activities:

Energy Supply Modelling in Cities: Illustrated Using Data from the Danish Municipality of Sønderborg

Energy Supply Modelling in Cities: Illustrated Using Data from the Case of Sønderborg

Big Data som værktøj til at styre byens energi

Executive Development Programme with Technical University of Denmark

Big Data as a tool for controlling the cities energy: Data aspects and data management

3rd International Workshop on Design in Civil and Environmental Engineering

Status and Results of Energy Supply Modelling in CITIES: Illustrated using Data from the Case of Sønderborg

CITIES Annual Conference

Publications:

Model Identification for Control of Display Units in Supermarket Refrigeration Systems

Model Predictive Control for Commercial Refrigeration in the Smart Grid

Department of Applied Mathematics and Computer Science

Period: 15/11/2013 → 14/05/2017

Number of participants: 3

Phd Student:

Mohd. Azam, Sazuan Nazrah (Intern)

Supervisor:

Izadi-Zamanabadi, Roozbeh (Intern)

Main Supervisor:

Jørgensen, John Bagterp (Intern)

Financing sources
Generic interface development and benchmarking of carbon dioxide reduction processes

Department of Chemical and Biochemical Engineering
Period: 01/12/2012 → 20/09/2016
Number of participants: 8
PhD Student:
Gaspar, Jozsef (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Thomsen, Kaj (Intern)
von Solms, Nicolas (Intern)
Main Supervisor:
Fosbøl, Philip Loldrup (Intern)
Examiner:
Skiadas, Ioannis V (Intern)
Douglas, Peter (Ekstern)
Gabrielsen, Jostein (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 FUU, 1/3 inst 1/3 Andet

Relations
Publications:
CO₂ Capture Dynamic and Steady-State Model Development, Optimization and Control: Applied to Piperazine and Enzyme Promoted MEA/MDEA
Project: PhD

Economic Model Predictive Control for Spray Drying Plants

Department of Applied Mathematics and Computer Science
Period: 01/10/2012 → 22/06/2016
Number of participants: 8
PhD Student:
Petersen, Lars Norbert (Intern)
Supervisor:
Niemann, Hans Henrik (Intern)
Poulsen, Niels Kjølstad (Intern)
Utzen, Christer (Ekstern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Huusom, Jakob Kjøbsted (Intern)
Engell, Seabstian (Ekstern)
Pannocchia, Gabriele (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD

Optimization Algorithms for Experimental Design, Parameter Estimation, and Control of Dynamic Systems

Department of Applied Mathematics and Computer Science
Period: 01/10/2012 → 20/04/2016
Number of participants: 6
Stochastic Model Predictive Control with Applications in Smart Energy Systems

Department of Applied Mathematics and Computer Science
Period: 01/07/2012 → 31/03/2016
Number of participants: 7
Phd Student:
Sokoler, Leo Emil (Intern)
Supervisor:
Madsen, Henrik (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Engsig-Karup, Allan Peter (Intern)
Axehill, Daniel (Ekstern)
Ferreau, Hans Joachim (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Stochastic Differential Equations in PK/PD Modelling

Department of Applied Mathematics and Computer Science
Period: 15/01/2012 → 16/07/2015
Number of participants: 3
Phd Student:
Juhl, Rune (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Main Supervisor:
Madsen, Henrik (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD

Economic MPC for Large and Distributed Energy Systems

Department of Applied Mathematics and Computer Science
Period: 01/11/2011 → 04/03/2015
Number of participants: 6
Phd Student:
Protein structure refinement by optimization

Department of Applied Mathematics and Computer Science
Period: 01/08/2011 → 30/09/2015
Number of participants: 6
Phd Student:
 concluded.

Scientific GPU Computing for Dynamical Optimization

Department of Applied Mathematics and Computer Science
Number of participants: 6
Phd Student:
 concluded.

Model Predictive Control for Smart Energy Systems

Department of Applied Mathematics and Computer Science
Period: 01/11/2010 → 25/04/2014
Number of participants: 7
Phd Student:
Halvgaard, Rasmus Fogtmann (Intern)
Supervisor:
Madsen, Henrik (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Bindner, Henrik W. (Intern)
Chmielewski, Donald J. (Ekstern)
Jones, Colin N. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Incremental refinement of process design
Department of Chemical and Biochemical Engineering
Period: 01/06/2010 → 30/09/2013
Number of participants: 7
Phd Student:
Quaglia, Alberto (Intern)
Supervisor:
Gani, Rafiqul (Intern)
Sarup, Bent (Ekstern)
Main Supervisor:
Sin, Gürkan (Intern)
Examiner:
Jørgensen, John Bagterp (Intern)
Bode, Andreas (Ekstern)
Pistikopoulos, Efstratios N. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Marie Curie (EU-stipendium)
Project: PhD

Numerical Methods for Reservoir Simulation and Optimization
Department of Informatics and Mathematical Modeling
Period: 01/05/2010 → 25/04/2014
Number of participants: 5
Phd Student:
Capolei, Andrea (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Poulsen, Niels Kjølstad (Intern)
Jansen, Jan Dirk (Ekstern)
Knudsen, Jørgen K. H. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD
Power Management for Refrigeration Systems

Department of Informatics and Mathematical Modeling
Period: 01/04/2010 → 24/05/2013
Number of participants: 8
Phd Student:
Hovgaard, Tobias Gybel (Intern)
Supervisor:
Blanke, Mogens (Intern)
Larsen, Lars F. S. (Ekstern)
Skovrup, Morten Juel (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Poulsen, Niels Kjølstad (Intern)
Morari, Manfred (Ekstern)
Mølbak, Tommy (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD

Large-Scale Algorithms for Non-Smooth Convex Optimization

Department of Applied Mathematics and Computer Science
Period: 01/02/2010 → 22/11/2013
Number of participants: 6
Phd Student:
Skajaa, Anders (Intern)
Supervisor:
Jørgensen, John Bagterp (Intern)
Main Supervisor:
Hansen, Per Christian (Intern)
Examiner:
Evgrafov, Anton (Intern)
Gondzio, Jacek (Ekstern)
Vandenberghe, Lieven (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Model Predictive Control algorithms for pen and pump insulin administration

Department of Informatics and Mathematical Modeling
Period: 01/09/2009 → 22/11/2012
Number of participants: 7
Phd Student:
Boiroux, Dimitri (Intern)
Supervisor:
Madsen, Henrik (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Sørensen, Mads Peter (Intern)
Knudsen, Jørgen K. H. (Ekstern)
**Concurrent Aero-Servo-Elastic analysis and Design of wind turbines**

Department of Informatics and Mathematical Modeling  
Period: 15/08/2009 → 07/03/2013  
Number of participants: 6  
PhD Student:  
Mirzaei, Mahmood (Intern)  
Supervisor:  
Niemann, Hans Henrik (Intern)  
Main Supervisor:  
Poulsen, Niels Kjølstad (Intern)  
Examiner:  
Jørgensen, John Bagterp (Intern)  
Bottasso, Carlo L. (Ekstern)  
Stoustrup, Jakob (Intern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Forskningsrådsfinansiering  
Project: PhD

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**Control of Process Operations and Monitoring of Product Qualities through Hybrid Multi-Scale Model-Based Analysis**

Department of Chemical and Biochemical Engineering  
Period: 01/01/2009 → 21/11/2012  
Number of participants: 7  
PhD Student:  
Abdul Samad, Noor Asma Fazli Bin (Intern)  
Supervisor:  
Gernaey, Krist V. (Intern)  
Sin, Gürkan (Intern)  
Main Supervisor:  
Gani, Rafiquil (Intern)  
Examiner:  
Jørgensen, John Bagterp (Intern)  
Georgiadis, Michael C. (Ekstern)  
Kalman Nagy, Zoltan (Ekstern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: DTU, Samfinansiering  
Project: PhD

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**Numerical Methods for Simulation and Optimization of Enhanced Oil Recovery Methods**

Department of Informatics and Mathematical Modeling  
Period: 01/01/2008 → 24/08/2012  
Number of participants: 6  
PhD Student:  
Völcker, Carsten (Intern)  
Supervisor:  
Thomsen, Per Grove (Intern)  
Main Supervisor:  
Jørgensen, John Bagterp (Intern)
Examiner:
Engsig-Karup, Allan Peter (Intern)
Foss, Bjarne Anton (Ekstern)
Kristensen, Morten Rode (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

In Silico Models of Blood Coagulation
Department of Mathematics
Period: 01/08/2007 → 20/04/2011
Number of participants: 7
Phd Student:
Andersen, Nina Marianne (Intern)
Supervisor:
Ingwersen, Steen Hvass (Ekstern)
Olsen, Ole Hviisted (Ekstern)
Main Supervisor:
Sørensen, Mads Peter (Intern)
Examiner:
Jørgensen, John Bagterp (Intern)
Monroe, Dougald M. (Ekstern)
Sosnovtseva, Olga (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD

Model-based predictive control of wind turbines
Department of Informatics and Mathematical Modeling
Period: 15/05/2007 → 02/03/2011
Number of participants: 6
Phd Student:
Henriksen, Lars Christian (Intern)
Supervisor:
Hansen, Morten Hartvig (Intern)
Main Supervisor:
Poulsen, Niels Kjølstad (Intern)
Examiner:
Jørgensen, John Bagterp (Intern)
Engelen, T. G. van (Ekstern)
Per, Brath (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut/centerfinansieret
Project: PhD

Ulineær optimal robust styring og vindmølle regulering
Department of Informatics and Mathematical Modeling
Period: 15/10/2006 → 29/09/2010
Number of participants: 5
Phd Student:
Thomsen, Sven Creutz (Intern)
Predictive Tools for Designing new Insulins and Treatment Regimes

Department of Informatics and Mathematical Modeling
Period: 01/07/2006 → 16/12/2009
Number of participants: 7
PhD Student:
Klim, Søren (Intern)
Supervisor:
Ingwersen, Steen Hvass (Ekstern)
Kristensen, Niels Rode (Intern)
Main Supervisor:
Madsen, Henrik (Intern)
Examiner:
Jørgensen, John Bagterp (Intern)
Stoustrup, Jakob (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: DTU-lønnet stipendie
Project: PhD

Topology Optimization Problems with Design-Dependent Sets of Constraints

Department of Mathematics
Period: 01/01/2006 → 30/06/2010
Number of participants: 7
PhD Student:
Schou, Marie-Louise Højlund (Intern)
Supervisor:
Evgrafov, Anton (Intern)
Sigmund, Ole (Intern)
Main Supervisor:
Stolpe, Mathias (Intern)
Examiner:
Jørgensen, John Bagterp (Intern)
Kocvara, Michal (Intern)
Svanberg, Krister (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD

Model Identification for Predictive Control and Optimization

Department of Chemical and Biochemical Engineering
Optimizing control of integrated processes

Department of Chemical and Biochemical Engineering

Optimizing control of integrated processes

Issues in real time optimisation are relevant in many instances of process operation. In this project two instances are investigated. One is in scheduling plant operations in accord with market demands and raw material availability thus providing set points for the control loops. The other deals with operating semi-continuous or fed-batch processes where the feeding profiles are determined to optimise the process productivity under the loads of changing raw material and catalyst properties. A methodology for simultaneous dynamic optimisation of gasoline production and blending in response to market demands of a refinery is being developed. The optimisation decides the set points for the refinery operations as well as the blending recipe such that profit is maximised several time periods into the future. As such the optimisation program has strong similarities to the receding horizon controller employed in model predictive control. The main model requirements are that the gasoline blending model is piecewise linear and that reactors and fractionators in the gasoline production plant are restricted to a finite set of possible operation points. Using these simplifying but realistic assumptions the model can be formulated as a large-scale MILP model. This model is solved using CPLEX. The actual refinery operation profitability of this approach remains to be explored. In control of semi-continuous or fed-batch processes the first engineering principle models are time varying and non-linear thus the resulting control problem becomes a rather complicated non-linear optimisation which however often can be solved within reasonable computational time. In this project optimising control of filamentous fungi cultivations and of Saccharomyces cerevisiae cultivations will be investigated. The applied cultivation models will be structured models for the organisms.
D.3 Operational implications of optimality
The purpose of this research project is to explore the operational and controllability properties of integrated processes and processes designed to operate at optimal profit. The focus is to develop operating strategies for highly integrated processes. It is well known for simple processes in which the optimum is unconstrained, that mathematically the profit is uncontrollable near the optimal profit if only the product quality itself or some related variable is measured. On the other hand if all states are always measured or available, the maximum profit can be controlled. For integrated processes, the process non-linearities imply that these processes are often uncontrollable by simple output feedback.

Department of Chemical and Biochemical Engineering
Period: 01/05/1997 → …
Number of participants: 2
Project participant:
Jørgensen, John Bagterp (Intern)
Project Manager, organisational:
Jørgensen, Sten Bay (Intern)

D.6 Implementation of control into ICAS
The goal of the project is to introduce control aspects into the dynamic simulator included in ICAS. The project includes two parts: 1. Dynamic control: To provide the facilities for specification of simple control loops in dynamic simulation within ICAS. 2. Process analysis: Tools for linearisation will be developed for the purpose of implementing tools for process analysis, such as SVD, RGA, DC-maps etc. The latter aspect will be used in connection with control structuring which is one active research area within process control. Selection of a control structure concerns deciding which variables to manipulate and which variables to control in a multi-loop control structure. Frequency dependent RGA and SVD analysis has been applied. Also a novel method formulating the control structure selection as an assignment problem or MILP problem using a modified steady-state RGA in the objective function has been developed. This research project aims at synthesising a control structure given the design of a plant.

Department of Chemical and Biochemical Engineering
Period: 01/05/1997 → …
Number of participants: 2
Project participant:
Jørgensen, John Bagterp (Intern)
Project Manager, organisational:
Jørgensen, Sten Bay (Intern)

D.7 Development of toolbox for linear and non-linear MPC
The research concerning model predictive control focuses on development of toolboxes for both ICAS and Matlab. The model predictive controllers are based on a receding horizon principle in which the variables that can be manipulated are controlled at each sampling time by solving a quadratic or linear optimisation problem. The linear model predictive controller is in state space form and provides guaranteed nominal stability. A Kalman-filter is used for state estimation from the measurements. The linear models are identified by subspace identification. Stability properties are also investigated. The model predictive control methodologies developed has been applied to a number of periodic operating processes, i.e. to control a simulated industrial flow swing reactor, and is being investigated for control of an activated sludge process. Future work focuses around the non-linear model state estimation and predictive controller. Currently the methodology is based upon a first-principles model and either an extended Kalman-filter or a receding horizon estimator for estimation of the states given the outputs. Approaches for utilising the special structure of the optimisation problem are being investigated.

Department of Chemical and Biochemical Engineering
Period: 01/05/1997 → …
Number of participants: 2
Project participant:
Jørgensen, John Bagterp (Intern)
Project Manager, organisational:
Jørgensen, Sten Bay (Intern)
E.2 System (Tools) Integration

ICAS: Intergrated Computer Aided System Solutions of process integration problems require an integrated set of tools. There is a demand for tools that will enable the engineer to directly transfer information between various phases of process design, process analysis, and process optimisation. Therefore, an integrated computer aided system for process modelling, simulation, design, synthesis and analysis has been developed. This system includes a simulation (steady state and dynamic) engine and tools for physical properties estimation, process/product synthesis and process/product design. The total system, called ICAS, has been evaluated against various test problems. A major part of the tools integration within ICAS has been developed through a PhD-project (PhD thesis of Anne K. Jensen, May 1998), where, emphasis has also been given to the development of a computer aided modelling system. The model generation feature in ICAS consists of a generic modelling language for interactive definition of new building objects and a knowledge-based modelling language that apply rules in order to create new building objects. The methodology for creation of building objects is essentially based on information related to definition of control shells (boundary, physical description of the interior, and interactions between the shell and the surrounding). From the definition of the control shell, the computer aided modelling system generates the model equations describing the control shell. In addition to the creation of new objects, a system for graphical aggregation of the building object into a composite model has also been developed. Finally, integration of the model generator to a process simulator allows direct simulation with the generated model (the appropriate code for the simulator is generated by the model generation feature).

Department of Chemical and Biochemical Engineering
Period: 01/05/1997 → …
Number of participants: 7
Project participant:
Jensen, Anne Krogh (Intern)
Russel, Boris Mariboe (Intern)
Harper, Peter Mathias (Intern)
Hostrup, Martin (Intern)
Jørgensen, John Bagterp (Intern)
Andersen, Torben Ravn (Intern)
Project Manager, organisational:
Gani, Rafiqul (Intern)