AWP15-ENR-01/JSI-02

EUROfusion

Fast Model Predictive Control for Magnetic Plasma Control

Project Meeting Ljubljana Feb. 2016

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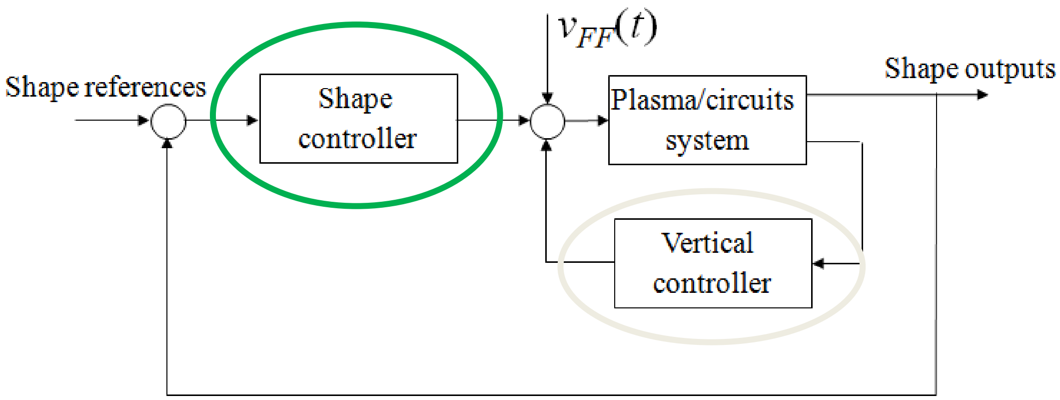
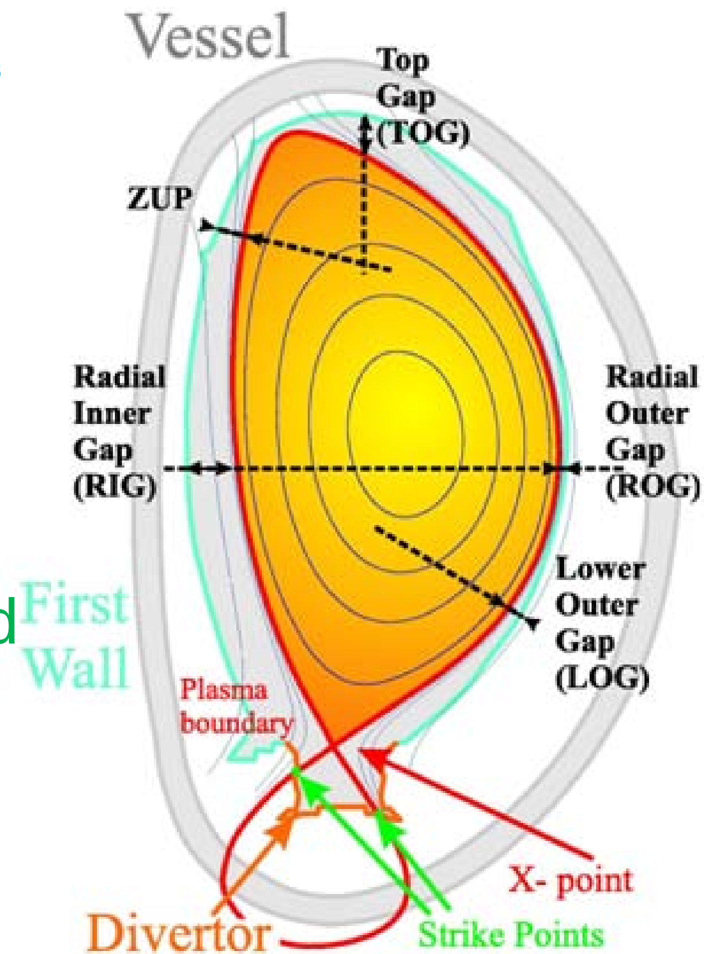
SLOVENIAN RESEARCH AGENCY

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Plasma magnetic control cascade





- Inner loop VS: fast stabilization of vertical position
- Outer loop CSC: plasma current and shape control
- Specific disturbances:
  Vertical Displacement Events
  H-L transitions
  Edge Localised Modes...

Proposal overview: Background

Model Predictive Control

- A control methodology in which future control actions are determined by optimisation of a performance criterion defined over a future horizon in which control signals are predicted using dynamic process models

- Related to Linear Quadratic optimal control (LQG), they blend in Constrained LQ optimal control

- may handle constraints on process signals, over a finite horizon

- System $$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k), \quad \mathbf{y}(k) = \mathbf{C}\mathbf{x}(k)$$

- Cost function $$J = \sum_{j=0}^{N-1} \left(\mathbf{x}_{k+j|k}^T \mathbf{Q}_x \mathbf{x}_{k+j|k} + \mathbf{u}_{k+j|k}^T \mathbf{R}_u \mathbf{u}_{k+j|k} \right)$$

- subject to constraints $$\mathbf{u}_{\min} \le \mathbf{u} \le \mathbf{u}_{\max}, \quad \mathbf{x}_{\min} \le \mathbf{x} \le \mathbf{x}_{\max}$$

Model Predictive Control

Successful in many industries (oil&gas, refining, chemical, electric power, pulp&paper, mining&metals, pharma...)

- Enables straightforward design of multivariable control systems,
- Facilitates advanced handling of constraints, allowing better performance near constraints and sustaining larger disturbances,
- Allows optimisation of the operating point considering the state of the system, the available degrees of freedom, and constraints.
- Allows straightforward handling of measured disturbances (interactions with other subsystems in large-scale processes) for feed-forward control,

Model Predictive Control

Online optimisation, typically Quadratic Programming
not applicable to systems with fast dynamics!

However, recent advances:

- **Explicit MPC:** optimisation problem solved parametrically in advance... suitable only to small-scale problems!
- **Partly explicit partly online computation...** complicated
- **Fast on-line solvers:**
  new methods (active set, interior point, **first-order**)
  parallelisation, FPGA or GPU, fixed-point computation
  approximate solutions with guaranteed error bounds
- **Problem simplification:**
  input move blocking
  sparse placement of output constraints (coincidence points)
  Target Calculator (steady-state)

Proposal overview: Description

Two control problems:

- *Plasma shape & current (PSC) control for ITER*
  Control of gaps to maintain an elongated cross-section using radial coils (SuperConductiong + In-Vessel)
  "Regular" Vertical Stabilisation required
  Axisymmetric cross-section
- *Control of Resistive Wall Modes (RWM)*
  Instabilities related to the resistive wall that surrounds the plasma
  Non-axisymmetric, stabilized by using non-axisymmetric coils
  Dynamics are faster (than in PCS),
  model order is higher (compared to "regular" VS)
  ... Fast MPC implementation more difficult

[11] M. Ariola, G. De Tommasi, A. Pironti, F. Villone: 'Control of Resistive Wall Modes in Tokamak Plasmas', Contr. Eng. Pract., 24 (2014), 15-24

Proposal overview: Description

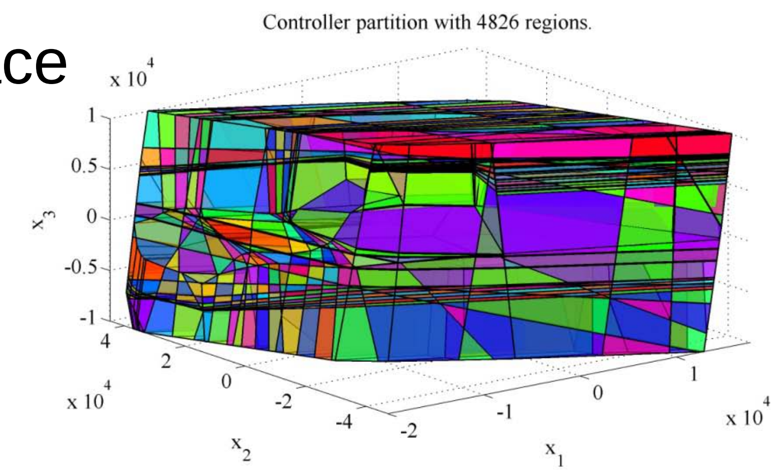
Fast MPC

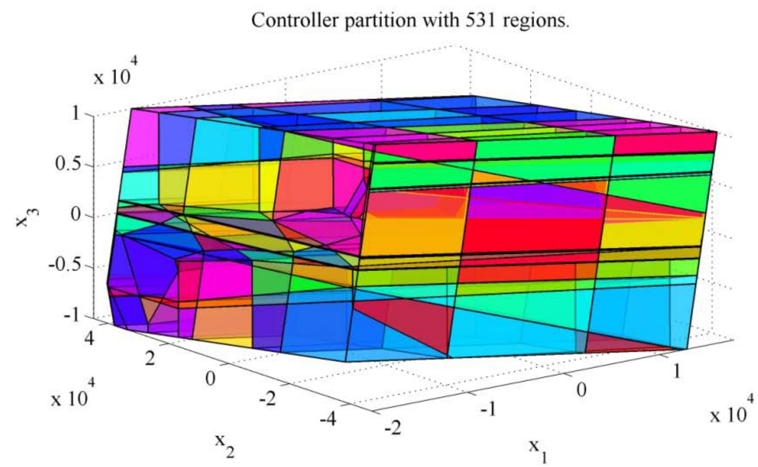
- **Standard MPC using on-line optimisation**:
  typically not for sub-second sampling;
  active-set methods have an upper bound for computation but it is muuuuch higher than a typical computation time
  (computation takes longer where constraints are "dense")

- **Simplified unconstrained MPC**:
  off-line solution via "least squares", or just use LQR
  on-line linear controller, + clipping for actuator constraints
  Suboptimal, but may be useful with the Target Calculator

Fast MPC

- **Explicit MPC**: off-line multi-parametric solution to opt. problem
  ...polyhedral partition of the state-space
  On-line: look-up table
  (affine local controller),
  Binary Search Tree
  Multi-Parametric Toolbox,
  Hybrid Toolbox
  Fine for small-scale problems
  then parametric explosion in the off-line phase!
  (storage of huge partitions and BST on-line an issue too)





[6] A. Bemporad, M: Morari, V. Dua, E. Pistikopoulos: 'The explicit LQ regulator for constrained systems', Automatica 38, 1 (2002)
[7] S. Gerkšič, G. De Tommasi: 'Vertical stabilization of ITER plasma using explicit model predictive control', Fus. Eng. Design 88 (2013), 1082– 1086

Proposal overview: Description

Fast MPC

- **Explicit and on-line MPC combined**:
  a rather complicated approach, both solvers needed
  suboptimal, does not seem to be used much
  [9] M. N. Zeilinger, C. N. Jones, M. Morari: 'Real-time suboptimal Model Predictive Control using a combination of Explicit MPC and Online Optimization', IEEE Trans. Auto. Contr., (2011), 56, pp. 1524–1534

Proposal overview: Description

Fast MPC

- **Fast on-line MPC**: fast online Quadratic Programming solvers
  Specific solvers that can solve specific MPC QPs faster
  Also geared at parallel hardware for even faster sampling:
  multicore CPU, GPU, FPGA
  All QP algorithms are iterative,
  each iteration starts with the result of the previous one
  ... simple parallelisation not possible
  but: parallelisation possible within an iteration!
  Challenge: certify that sufficient accuracy is achievable with
  a limited number of iterations (and restricted precision)
  FiOrdOs, FORCES Pro, QPgen, CVXGEN, qpOASES, MPT3

[16] E. N. Hartley, J. L. Jerez, A. Suardi, J. M. Maciejowski, E. C. Kerrigan, G. A. Constantinides: 'Predictive control using an FPGA with application to aircraft control', IEEE Transactions on Control Systems Technology, 22(3) (2014)

Proposal overview: Description

Model reduction

Models of high orders are not convenient for control
- "over-fitting": only matches local dynamics well

Model reduction: Schur etc
- reduce order as possible while retaining relevant dynamics

A set of models for different operating points
- incl. linearisations of a NL model along a pulse trajectory

... assess robustness of control to model inaccuracy

Low-frequency region important
- Issues detected when preparing models for control:
  - Carefully with LF asymptoted...
- important for model reduction and for Target Calculator

Proposal overview: Description

State estimation

Standard choice: Kalman filter
(MHSE computationally more challenging than MPC)

Integrators for disturbance estimation must be appended to the model to avoid steady-state offsets due to persistent disturbances

Caveat: integrating dynamics due to SC coils
The simple "output step disturbance" MPC approach leads to internal instability, but a stabilising KF is okay
(with non-zero covariance at corresponding I states)

Proposal overview: Description

Performance Evaluation

Comparison to earlier approaches

[8] M. Mattei, C. V. Labate, D. Famularo: 'A constrained control strategy for the shape control in thermonuclear fusion tokamaks', Automatica, 49, 1, (2013), 169-177

[10] G. Ambrosino, M. Ariola, G. De Tommasi, A. Pironti, A. Portone: 'Design of the plasma position and shape control in the ITER tokamak using in-vessel coils', IEEE Trans. Plasma Sci., 37, 7, (2009), 1324-1331

[11] M. Ariola, G. De Tommasi, A. Pironti, F. Villone: 'Control of Resistive Wall Modes in Tokamak Plasmas', Contr. Eng. Pract., 24 (2014), 15-24

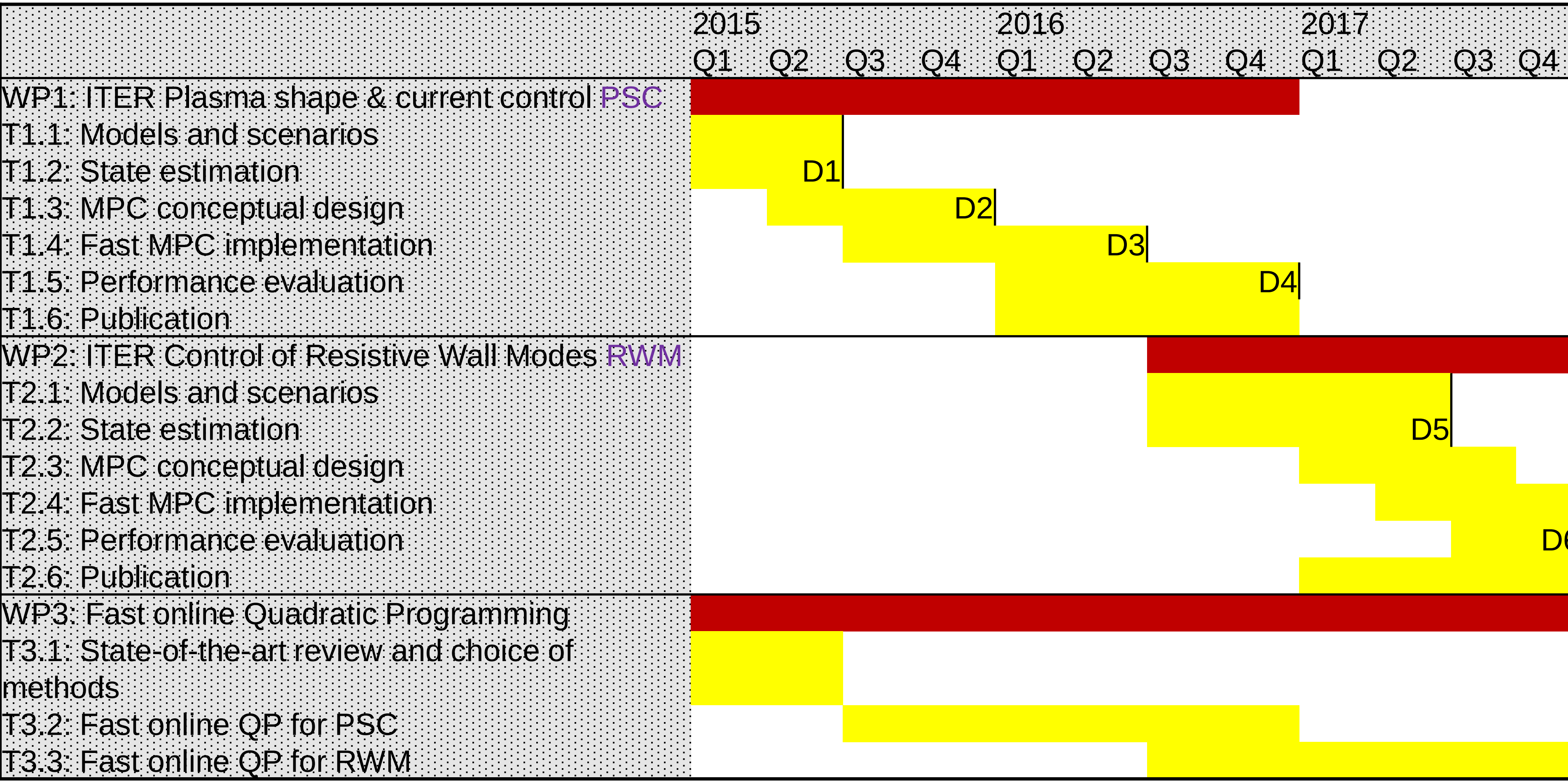
Simulated responses to disturbances typical for tokamak reactors, such as vertical displacement events and H-L transitions, using operational parameters from ITER scenarios

Robustness assessment to the variation of dynamics over different operating points using a set of different local models.
+ simulation with a nonlinear model

Avg and max computation times... real-time control requirements?

ITER constrained PMC Benchmark???

Project Schedule



D1, month 6: A set of reduced-order models and a state-estimation scheme for ITER PSC control

D2, month 12: Conceptual design of fast MPC for ITER PCSC

D3, month 18: Fast MPC implementation

D4, month 24: Performance evaluation of ITER PCSC using fast MPC

D5, month 30: A set of reduced-order models and a state-estimation scheme suitable for ITER RWM control

D6, month 36: Evaluation of fast MPC for ITER RWM control.

Proposal Overview: Deliverables

- D1, month 6:
  A set of reduced-order models and a state-estimation scheme for ITER PSC control ☑

  D1 covers the introductory part of the project, mainly focussed on the work-package WP1: Plasma current and shape (CSC) control for ITER. In this preliminary report we describe the first steps for the design of a CSC using MPC. More specifically we have:
  - Introduced the plasma models which will be used for the design and the validation,
  - Described the overall plasma plus feedback controller scheme, developed in Matlab/Simulink,
  - Described the vertical controller used to stabilise the plasma,
  - Described the state estimator needed for the MPC design. In particular we have tuned a Kalman filter for the estimation of the state of a plasma reduced order model, which produces reasonable state estimates with the model running in open loop.

Proposal Overview: Deliverables

- D2, month 12:
  Conceptual design of fast MPC for ITER PCSC ☑
  Part I (WP1: Plasma current and shape (CSC) control for ITER).
  Appends D1. The section on the implementation of an MPC controller is added, comprising several controller variants, among them a working variant of the MPC CSC with the output vector reduced via manual selection and averaging.
  The described controller includes set-point tracking, is able to consider a larger number of gaps describing the plasma boundary (like XSC of CREATE), and is based on the new version of plasma models. Tuning is provisional only.
- Part II (WP3: Fast online Quadratic Programming)
  Efficient fast QP methods suitable for the on-line solution of MPC optimization problem.
  A survey of the available QP methods is given, with emphasis on first-order methods, which are considered as prime candidates for fast online MPC control.
  A description of three available open-source fast QP solvers is given.
  A case study on a prototype ITER CSC based on the QP solver QPgen is presented. The dimensions of the ITER CSC control problem (11 manipulated variables, 6 controlled variables, 60 states, soft output constraints) are considerably larger than fast online QP solver benchmarks found in the available literature.
  Several complexity-reduction techniques are tested and successfully combined. Using FGM, applying the complexity reduction techniques and certain modifications of QPgen, on a laptop computer with a 4-core processor, peak sample computation times in the order of 10 ms were reached. This is already considered fast enough for actual controller implementation at the anticipated sampling time of 0.1 s, and is a five-fold speed-up compared to the state-of-the-art commercial solver CPLEX.

Proposal Overview: Deliverables

- D3, month 18:
  Fast MPC implementation
- D4, month 24:
  Performance evaluation of ITER PCSC using fast MPC
- D5, month 30:
  A set of reduced-order models and a state-estimation scheme suitable for ITER RWM control
- D6, month 36:
  Evaluation of fast MPC for ITER RWM control.

Proposal overview: Objectives

- O1: Review possible approaches of complexity reduction for fast MPC suitable for PSC control and possibly to RWM control
  60%:
  A thorough review of fast online QP solvers was made. Several first-order solvers were found to be useful for PSC control, FGM the most promising The efficiency of complexity reduction using techniques of null-space transformations, move blocking, and sparse placement of output constraints, was evaluated on a benchmark ITER CSC scheme. By combining these techniques, the computation is sufficiently fast for the CSC loop using a standard four-core processor of a laptop computer. Approaches suitable for RWM control, which demands faster sampling, require further studies.
- O2: Implement the most appropriate fast MPC method
  60%:
  A working prototype implementation is already made using generalized FGM by appending the QPgen library.
  Other relevant methods (FoOrdOS, HPMPC; ADMM) are still under investigation, further code optimization is planned.
  Convergence rates should be analysed.

Proposal overview: Objectives

- O3: Adapt plasma models for use in MPC, and prepare a set of plasma models in different operation points of ITER scenario to assess robustness
  90%:
  The models have been prepared by CREATE and
  adapted for use in MPC by JSI.
- O4: Develop a suitable state-estimation technique
  70%:
  The state-estimation technique based on the Kalman filter for the MPC CSC is prepared.
  Some further work may be required in finalizing the MPC CSC design and tuning.
- O5: Apply fast MPC to PSC control
  40%:
  A working conceptual design is available, incl. SVD reduction of output space
  Needs to be appended with the Target Calculator, tuned, and applied using the recently tested fast online MPC method.

Proposal overview: Objectives

- O6: Evaluate fast MPC performance and robustness to disturbances and variation of local dynamics in comparison to existing approaches
  10%:
  The models and disturbance test according to the relevant ITER scenarios are prepared.
  Finalized and properly tuned MPC and final reference schemes are not available yet.
- O7: Evaluate the applicability of fast MPC to RWM control
  0%: Not planned in the first project year.

Proposal Overview: Budget and Resources

First Name	Surname	Beneficiary	Total Manpower (ppy)	Total Missions (k€)
Samo	Gerksic	JSI	0.90	1.7
			0.80	1.7
			0.70	1.6
Gianmaria	De Tommasi	ENEA	0.30	1.7
			0.30	1.7
			0.30	1.6
Marco	Ariola	ENEA	0.20	1.7
			0.20	1.7
			0.20	1.6
Bostjan	Pregelj	JSI	0.30	0.7
			0.30	0.7
			0.30	0.6
Andrej	Debenjak	JSI	0.50	1
			1.00	1
			0.90	1

Budget and Resources 2015

- **Manpower:**
  within the planned framework
  Changes to personnel:
  Matija Perne has joined the project team and has taken over the assignments of Andrej Debenjak
  (both employed at JSI, Dept. of Systems and Control)
- **Missions:**
  less than planned
  KoM Naples
  (no conferences in 2015)

Publications 2015

No publications planned in 2015

Draft paper prepared:

- "Plasma current and shape control for ITER using fast online MPC"
  Abstract submitted recently to IEEE Real-Time Conference, Padova

Wiki

https://www2.euro-fusion.org/ERwiki/index.php?title=ER15-JSI-02

Plan of activities in 2016 – ITER PSC

- Models and scenarios (CREATE):
  Linear models prepared
  Nonlinear model for validation
- Model reduction and state estimation (IJS+CREATE)
  The state estimation concept is prepared
  Tuning and improvements
- MPC conceptual design (IJS+CREATE)
  Target Calculator, operating point included
  Signal normalisation?
  Infinite-horizon MPC (terminal LQ controller),
  closed-loop parametrisation of control (deviations from LQ)
  Tuning the KF+MPC system (local linear analysis?)
- Performance evaluation (CREATE+IJS): benchmark?
  Simulation with CREATE-NL
  Compare with CREATE scheme; Current Limit Avoidance

Plan of activities in 2016 – Fast MPC

- Fast QP method selection:
  Fast online QP solvers reviewed: FiOrdOs, QPgen, HPMPC
  Currently: modified QPgen + cplx reduction tech,
  PCSC 10 ms peak on a 4-core laptop
  Further:
  - code optimisation via profiling, AVX-512,
  - RT OS
  - Implementation with the final MPC PCSC controller
- Certification: that the solution with specified accuracy is available in restricted time (number of iterations)
- RWM: requires a faster implementation!
  Platform options...
  - faster multicore processors
  - GPU (CUDA)
  - FPGA (fastest but inconvenient for development;
    probably does not have enough storage capacity)

Plan of activities in 2016 – ITER RWM

- Models and scenarios (CREATE):
  A set of linear models
  Linearised models along a pulse trajectory (ITER Scenarios)
  Nonlinear model for validation
- Model reduction and state estimation (IJS+CREATE)
  Model structure choice, disturbance modelling concept
  Kalman filter design
- MPC conceptual design (IJS+CREATE)
  Preliminary activities:
  MPC concept, control signal parametrisation

Plan of activities in 2016 – Publications

Conferences

- IEEE Real-Time Conference, Padova, Jun
  Abstract submitted recently
  "Plasma current and shape control for ITER using fast online MPC"
- ? SOFT 2016, Prague, Sep (abstract deadline 1st March)
- ? Multiconference on Systems and Control, Buenos Aires, September (deadline April 15 full paper) invited session
  ?benchmark, models, 2 controllers, simulations
  Workshop on control in fusion (E. Schuster) before the conference
- ? CDC (deadline March 15 full paper) invited session

Papers

CEP: benchmark – models, evaluation... (before NL perf. evaluation)

Wiki

https://www2.euro-fusion.org/ERwiki/index.php?title=ER15-JSI-02

EUROfusion publication rules!!!
abstracts & papers on Pinboard 2 & 3 weeks in advance; rehearsals...

Plan of activities in 2016 – Missions

Missions planned in 2016:

- Samo visit to Naples (performance assessment)
- Nonlinear simulation, autumn
- IEEE Real-Time Conference, Padova, Jun
- ? SOFT 2016, Prague, Sep

Discussion