EUROfusion

Fast Model Predictive Control for Magnetic Plasma Control Kick-off Meeting

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SLOVENIAN RESEARCH AGENCY

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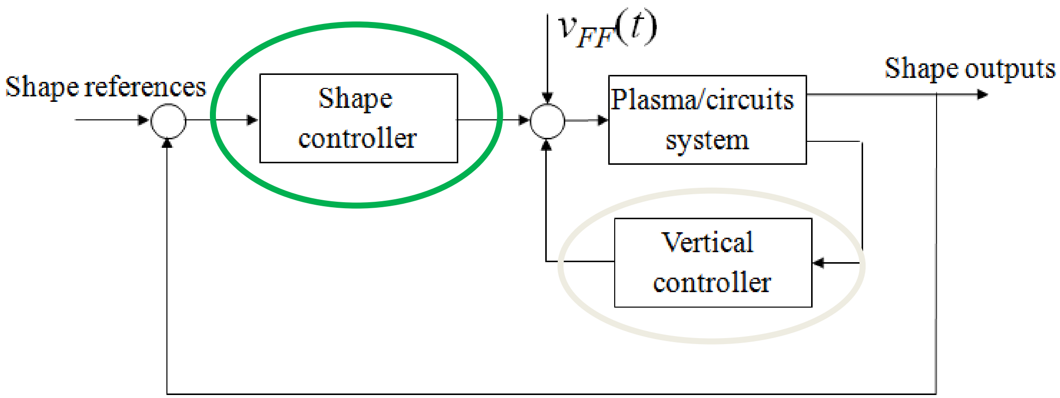
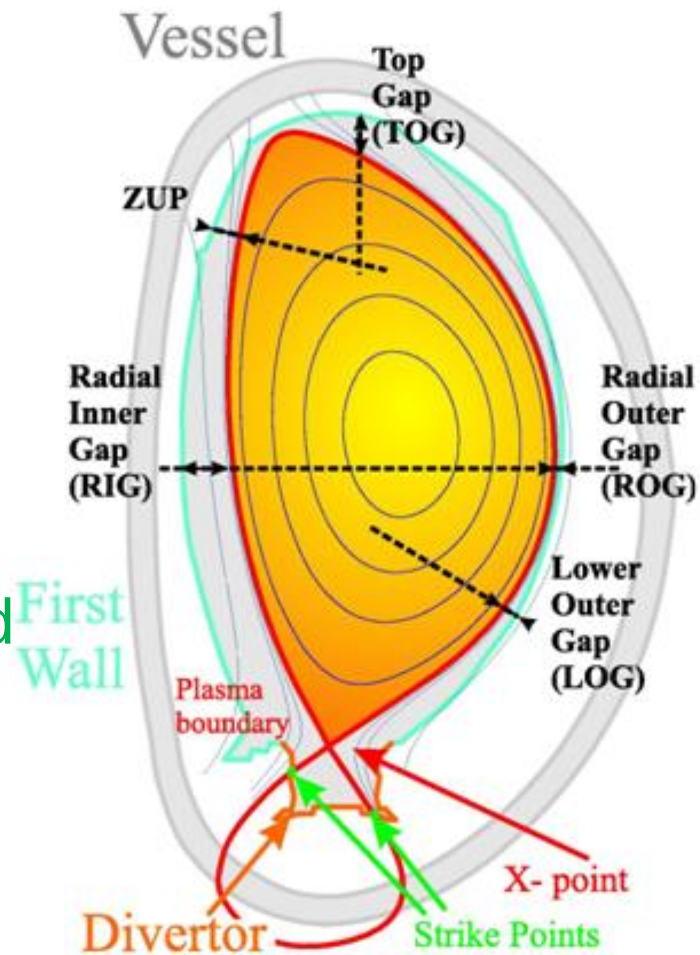
Proposal overview: Background

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...

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 $J = \sum_{j=0}^{N-1} (\mathbf{x}_{k+j|k}^T \mathbf{Q}_x \mathbf{x}_{k+j|k} + \mathbf{u}_{k+j|k}^T \mathbf{R}_u \mathbf{u}_{k+j|k})$
- subject to constraints $\mathbf{u}_{\min} \leq \mathbf{u} \leq \mathbf{u}_{\max}, \quad \mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{x}_{\max}$

Proposal overview: Background

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**
- **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:**
  Target Calculator (steady-state)
  input move blocking
  sparse placement of output constraints

Proposal overview: Objectives

- O1: Review possible approaches of complexity reduction for fast MPC suitable for PSC control and possibly to RWM control
- O2: Implement the most appropriate fast MPC method
- 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
- O4: Develop a suitable state-estimation technique
- O5: Apply fast MPC to PSC control
- O6: Evaluate fast MPC performance and robustness to disturbances and variation of local dynamics in comparison to existing approaches
- O7: Evaluate the applicability of fast MPC to RWM control

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

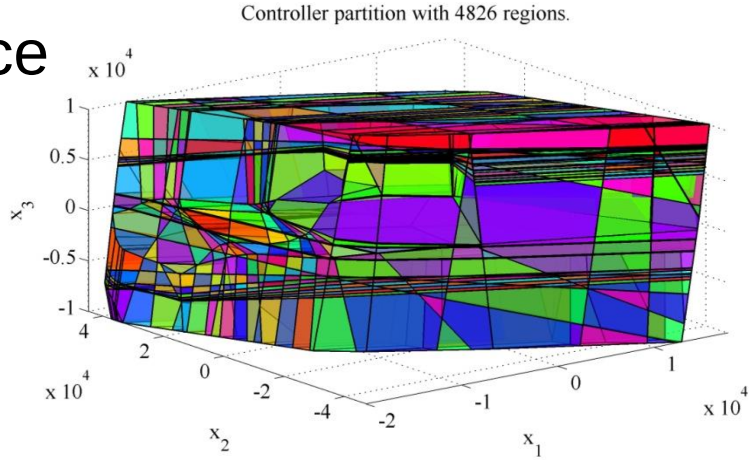
- **Standard MPC using on-line optimisation**:
  not for sub-second sampling;
  active-set methods have an upper bound for computation but it is muuuuch higher than a typical computation time (computation takes longer in the vicinity of constraints)

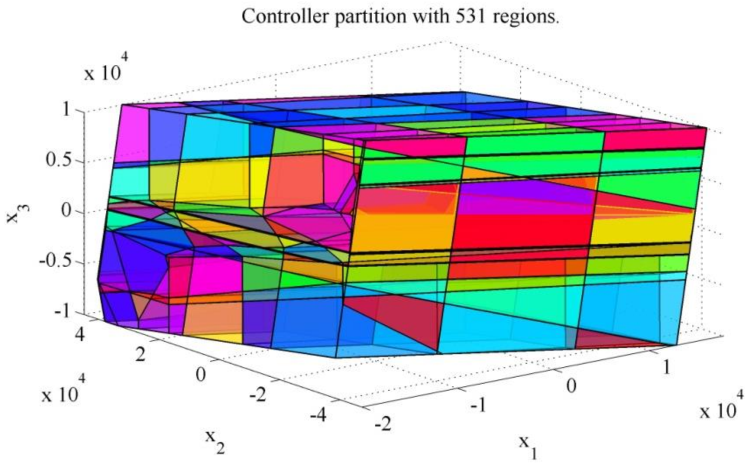
- **Simplified unconstrained MPC**:
  off-line solution via "least squares", or just use LQR
  on-line linear controller, + clipping for actuator constraints
  Suboptimal, but may be useful with the Target Calculator

Proposal overview: Description

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: show 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
- possibly 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:
  - LF asymptotes were not as expected
- ...Patches implemented
- 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???

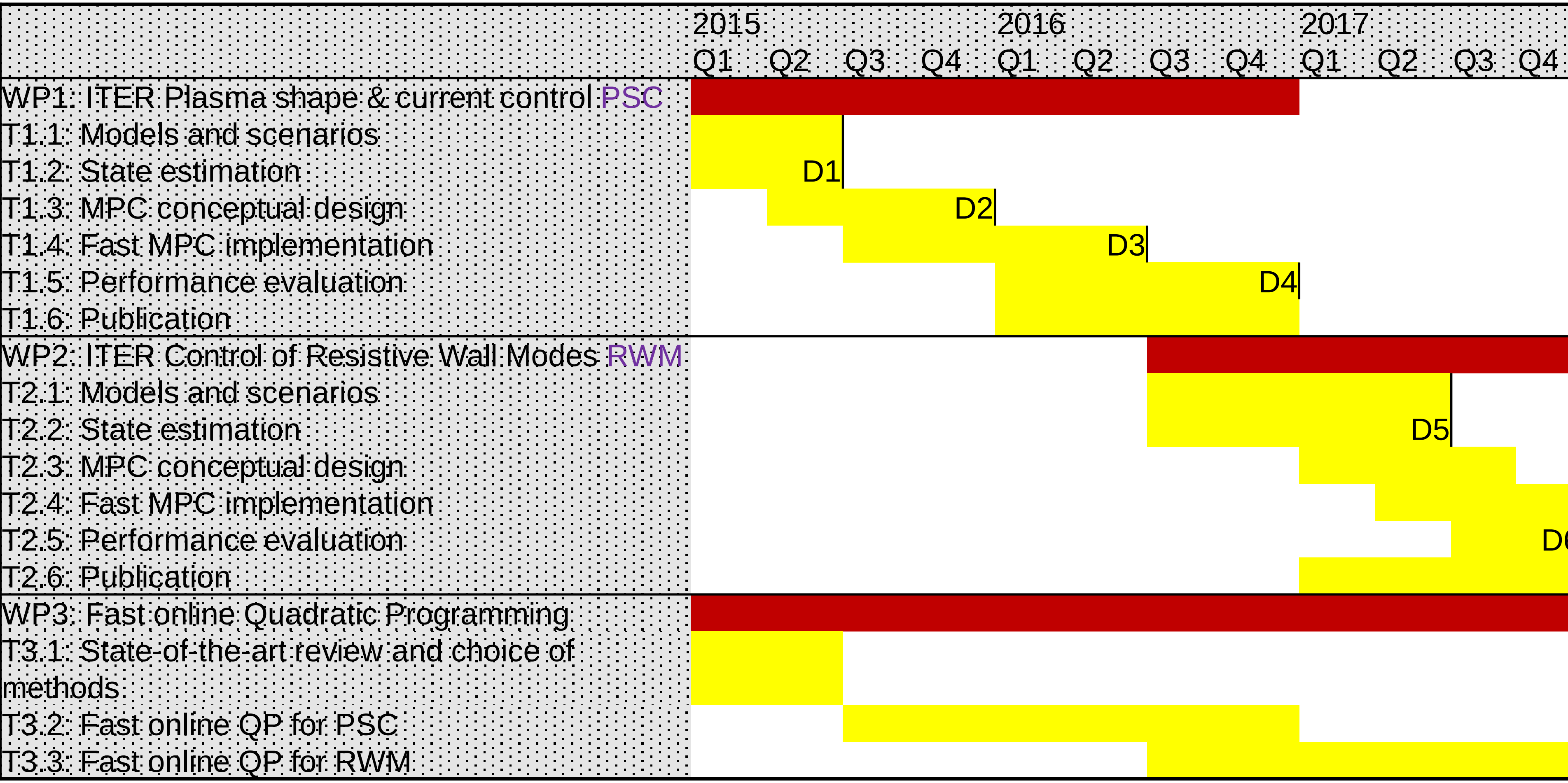
Proposal Overview: Deliverables

- 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: 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

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.

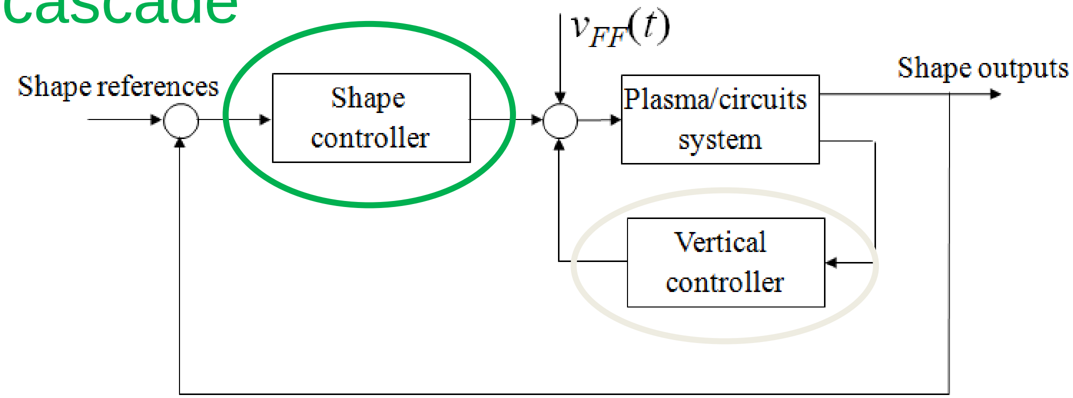
Project Schedule

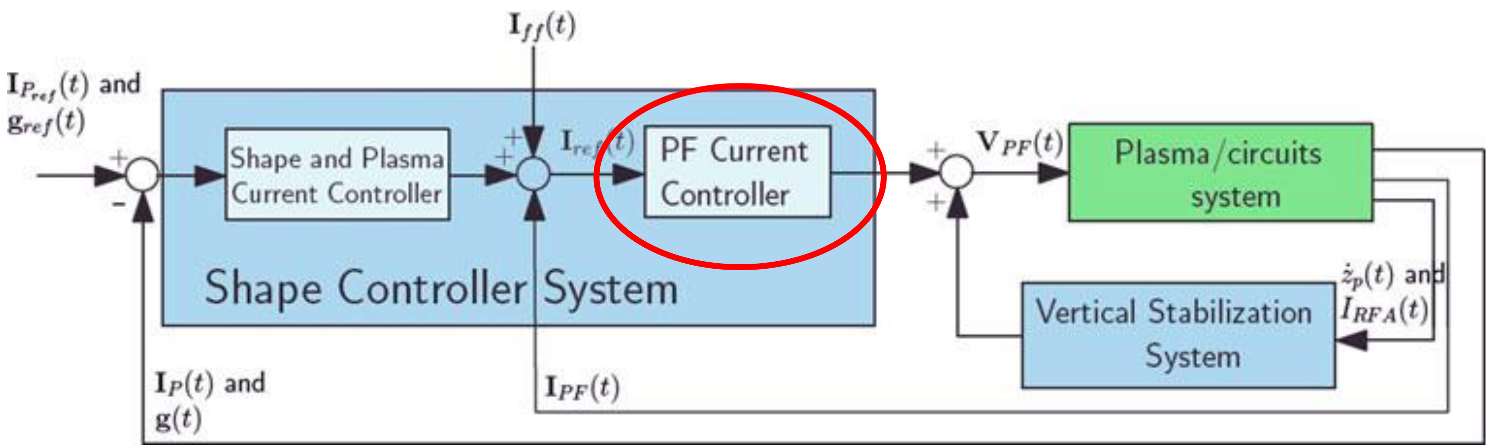
- The official project schedule is rather relaxed;
  the idea is to work faster and have time for iterations and extras (competition...)
- "Extras" not promised in the proposal, for the sake of reachability of the objectives, but important for publications etc:
  DEMO (model availability)
  Experimental implementation (suitable accessible long-pulse device? Control experience, models...)
  Robust MPC design? (uncertain model)
  Zeilinger Raimondo Domahidi Morari Jones 2014 On real-time robust model predictive control, Automatica 50(3) 683-694
  ...not planned in 2015

What we've got so far

"Plasma magnetic control for ITER using Model Predictive Control"

- A working prototype MPC controller for ITER PMC
  Current constraints without an intermediate current controller in the cascade

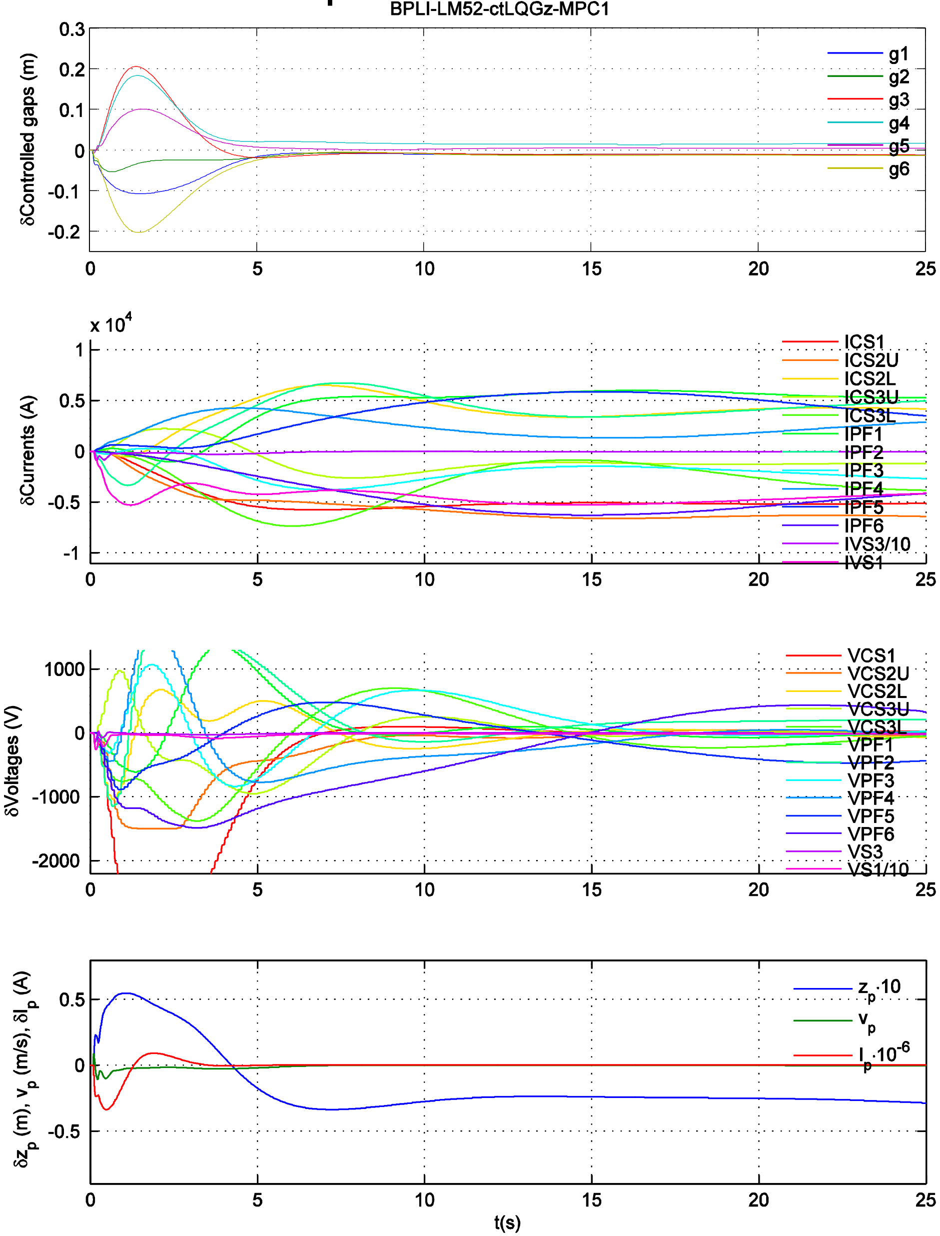




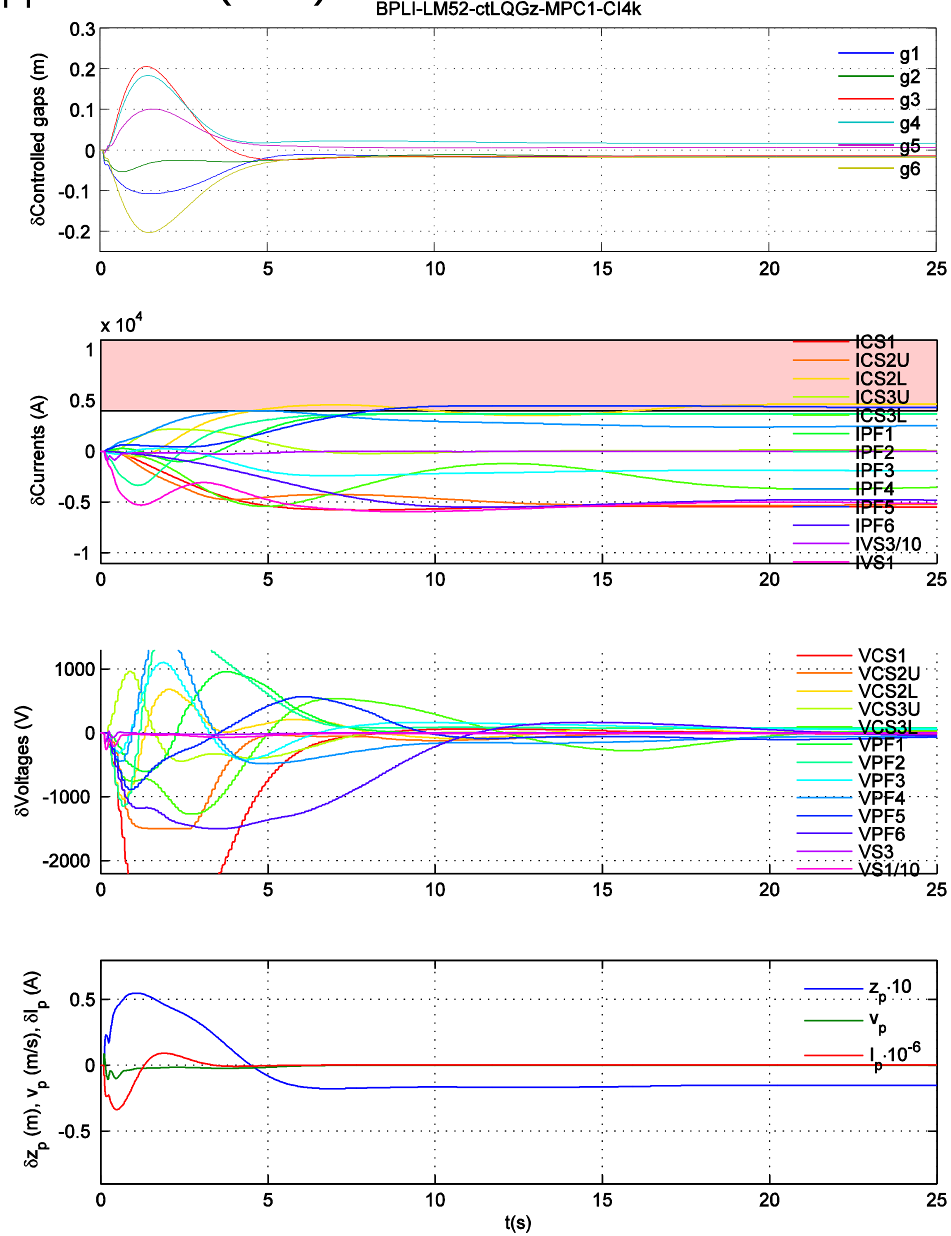
What we've got so far

Simulation: model LM52, BPLI, MPC

No output constraints



I_{PF} < 4 kA (soft)



Plan of activities in 2015 – ITER PSC

- Models and scenarios (CREATE): Configuration & scenarios?
  A revised set of linear models
  Linearised models along a pulse trajectory (ITER Scenarios)
  ... model evolution along the trajectory, do we need LTV?
- Model reduction and state estimation (IJS+CREATE)
  Modelling integrating disturbances for offset-free control
- MPC conceptual design (IJS+CREATE)
  Singular Value Decomposition
  Target Calculator, operating point included
  Signal normalisation?
  Vertical Stabilisation choice
  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 Current Limit Avoidance

Plan of activities in 2015 – Fast MPC

- Review the available methods and toolboxes:
  Standard QP solvers for numerical accuracy: CPLEX
  Fast online QP solvers for real-time control: FiOrdOs, QPgen...
- Real-Time Control:
  solution needed in restricted time (constraints congestions!),
  moderate accuracy is enough (limited actuator resolution...)
  prove that it works with limited iterations, with limited precision,
  without overflows (fixed-point arithmetics)
- Sampling: PSC 0.1 s, should be manageable; RWM faster!
- HW choice: multicore (with FPU, SIMD) / GPU / FPGA
  FPGA fastest but inconvenient for development... perhaps later
- MPC objective formulation and conversion to QP:
  currently MPT2/YALMIP (supports soft constraints, !sparse
  constraints... does not support measured disturbances...)
  MPT3, MPC Toolbox, FORCES?

Plan of activities in 2015 - Publications

- "A model predictive controller for ITER plasma current and shape control" from SOFT 2014 for FED special issue, rejected
  Indeed a bit hurried:
  - unclear performance advantage
  - incomplete validation (no nonlinear simulation)
  - unclear real-time applicability...

  Most likely recycled for NENE conference, Slovenia (May..Sep)
  For a journal paper we'd need at least fast MPC implementation and quite some expansion with omitted details
  but Fast MPC will take some time and is not #1 on the tasklist, the concept will be changed, and this takes time
  ...do we want this, or should we first upgrade the MPC setup?
- Conferences? 2016 IEEE-NPSS RTC Padova IT (Jan..Jun)
- EUROfusion publication rules!!! (abstracts & papers on Pinboard 2/3 weeks in advance; rehearsals...)

Competition...

- **Maljaars Felici de Baar van Dongen Hogeweij Geelen Steinbuch 2015**
  Control of the tokamak safety factor profile with time-varying constraints using MPC, Nuclear Fusion 55(2) http://iopscience.iop.org/0029-5515/55/2/023001
- Not direct competition, one level higher than PCS control
- They started with non-real-time nonlinear MPC, but this paper is simplified to linear MPC, with fast online QP
- CREATE-L and –NL don't model transport etc... we'd use open-loop trajectories if we wanted to simulate whole pulses
- They use a nonlinear model for validation in simulation... we should, too
- They use local linearisations of the nonlinear model along the pulse trajectory (off-line) for LTV-model-based MPC... I'm not sure if this is a good idea in practice for us, but we might need a set of nominal models and controller switching ... Local linearised models in successive points on scenario trajectories from CREATE-NL?
- They use I_p as actuator, and "the 2D magnetic equilibrium is assumed to be fixed in time" (p.8), I gather they are neglecting PMC dynamics (?)... Low-level actuators for EC beams, no mention of simplified dynamics for this (like the FOPTD models used for power supplies in CREATE schemes).
- They impose a rate limit on Ip, though I'd prefer a dynamic lag / tuning via R_Du

Competition...

- 16 CVs and 6 actuators... one unmentioned reason for steady-state offset
- Disturbance estimation with integrating disturbances lacking...
  Heavy on the nominal model, weak on disturbance rejection
- No real-time state estimation here, but they're also working on it (RAPTOR)
- LTV models... Attractive choice instead of nonlinear MPC ;) Caveats...
  Computationally, transferring lots of matrices, even precomputed.
  Disturbances may shift things a lot.
  The same cost matrices may not work best with very different local models, so performance may still be an issue.
  Stability? Not assured generally in MPC, safety-certification? To ensure nominal closed-loop stability, one may impose a terminal constraint that the state is perfectly settled at the end of the horizon (more control effort than necessary), or a terminal LQ controller.
  Following an actual envisioned future trajectory with a restricted freedom of future control moves may not be the best idea; an odd twist that enters the end of the horizon can make the structure of the cost function "unhealthy" ..."artificial" end of the horizon.
- No Target Calculator

Competition...

- Soft output constraints to avoid infeasibility issues
- "Coincidence points" to reduce complexity ("sparse output constraints")...
  Reasonable but not sure about stability theory
- Standard QP solver...
  No comment on worst-case computation time with sufficient precision.
  They reference one early fast-MPC approach, may be working on this...
- The idea of predicting upcoming constraints violations for activating safety measures is attractive, but not realible,
  depends on the prediction model quality
- The disturbances they simulate are not directly applicable for us at the PMC level