

The logo for MAX IV, featuring the letters 'MAX IV' in a white, stylized, sans-serif font. A white, curved line representing a particle path or orbit loops through the letters, starting above the 'M', passing through the 'A' and 'X', and ending above the 'V'.

MAX IV

**Implementation of Model Predictive Control for Slow Orbit Feedback Control
in MAX IV Accelerators Using PyTango Framework**



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Carla Takahashi

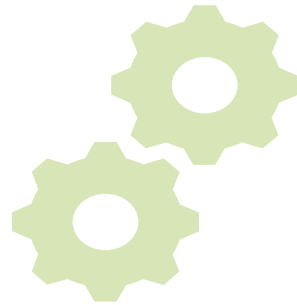
Outline

Introduction



- Orbit Control
- Model Predictive Control

Implementation



- MPC Design
- Tango Device

Results



- Tests on Storage Rings
- Challenges

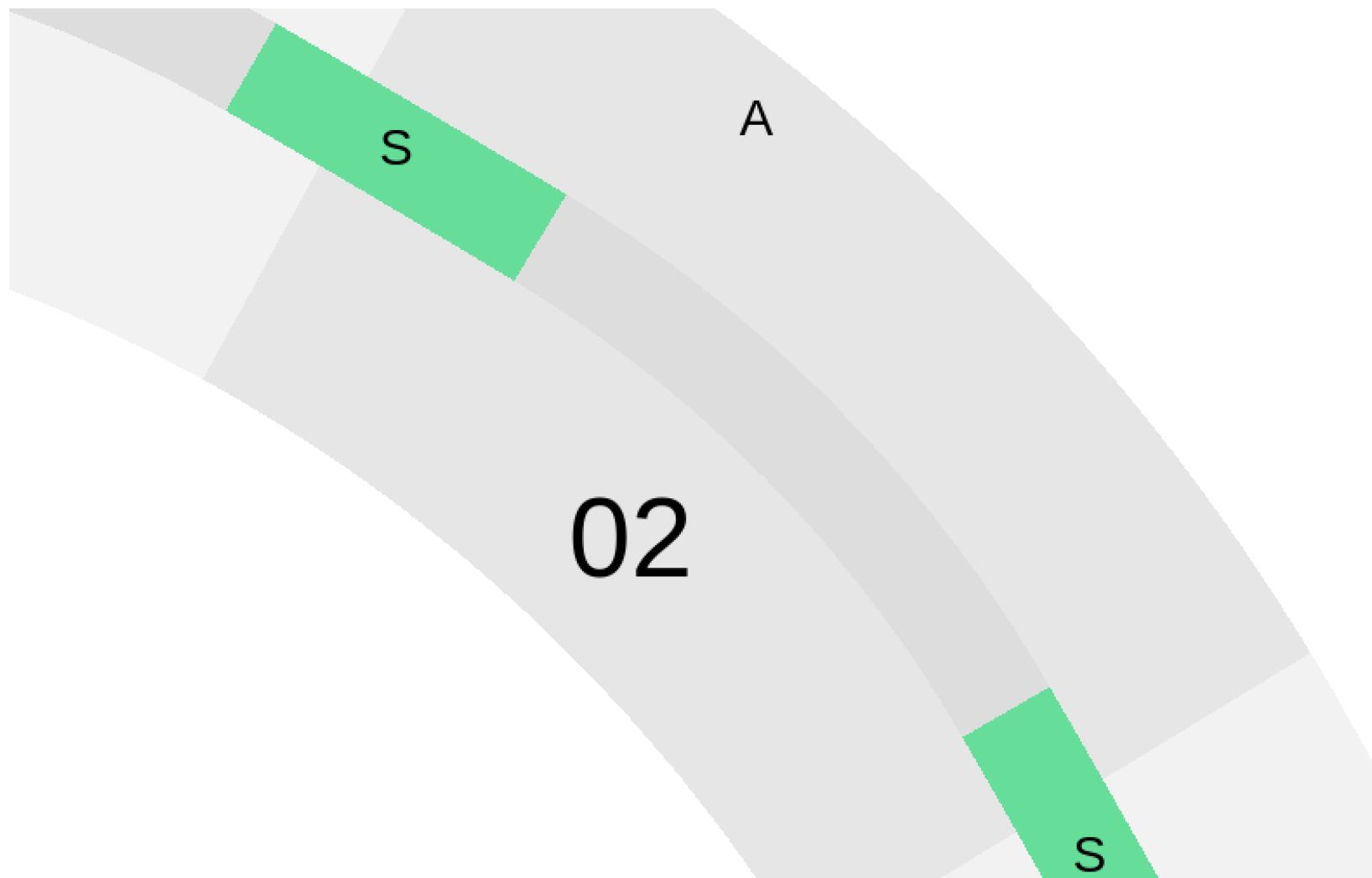
INTRODUCTION

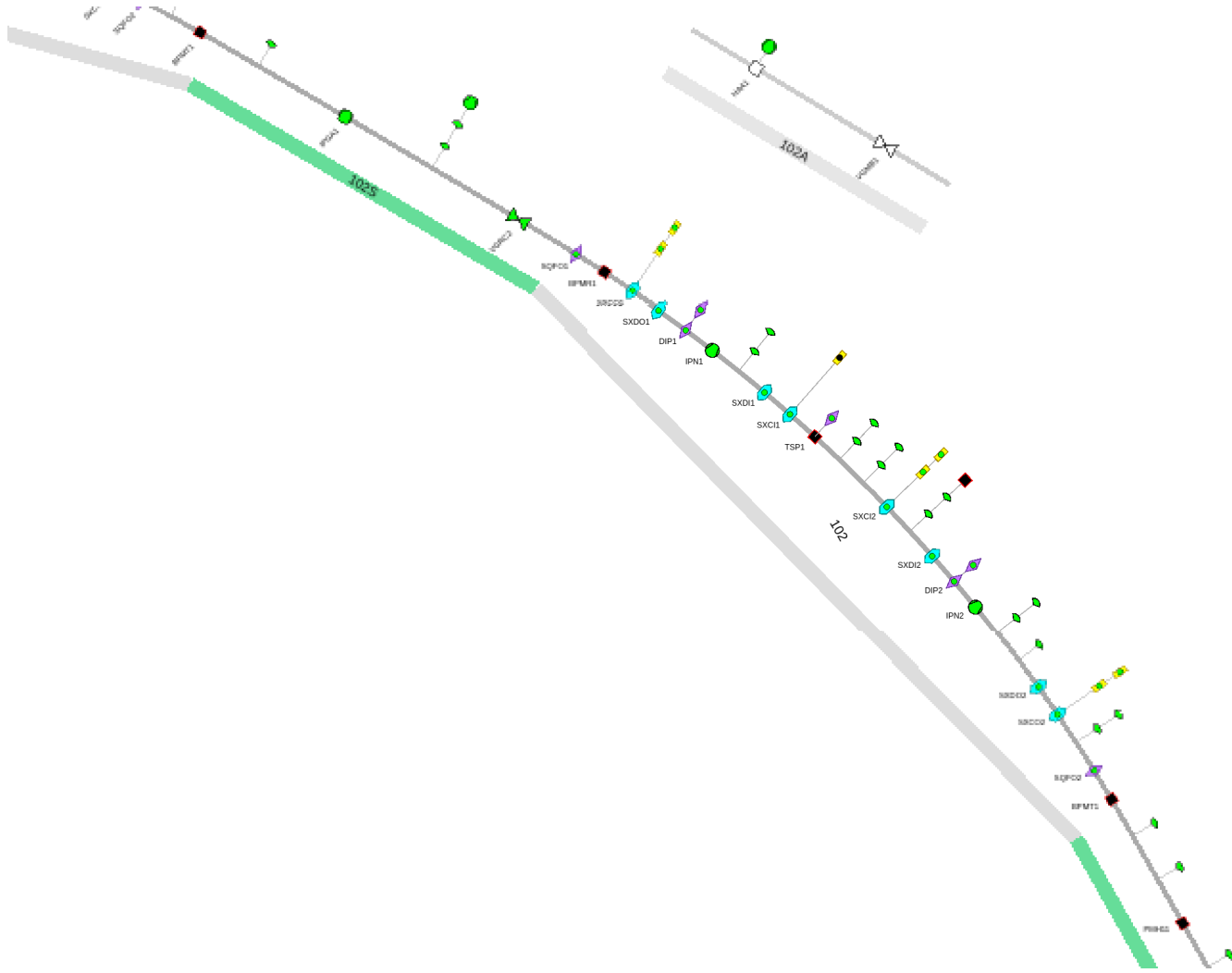
Orbit Control

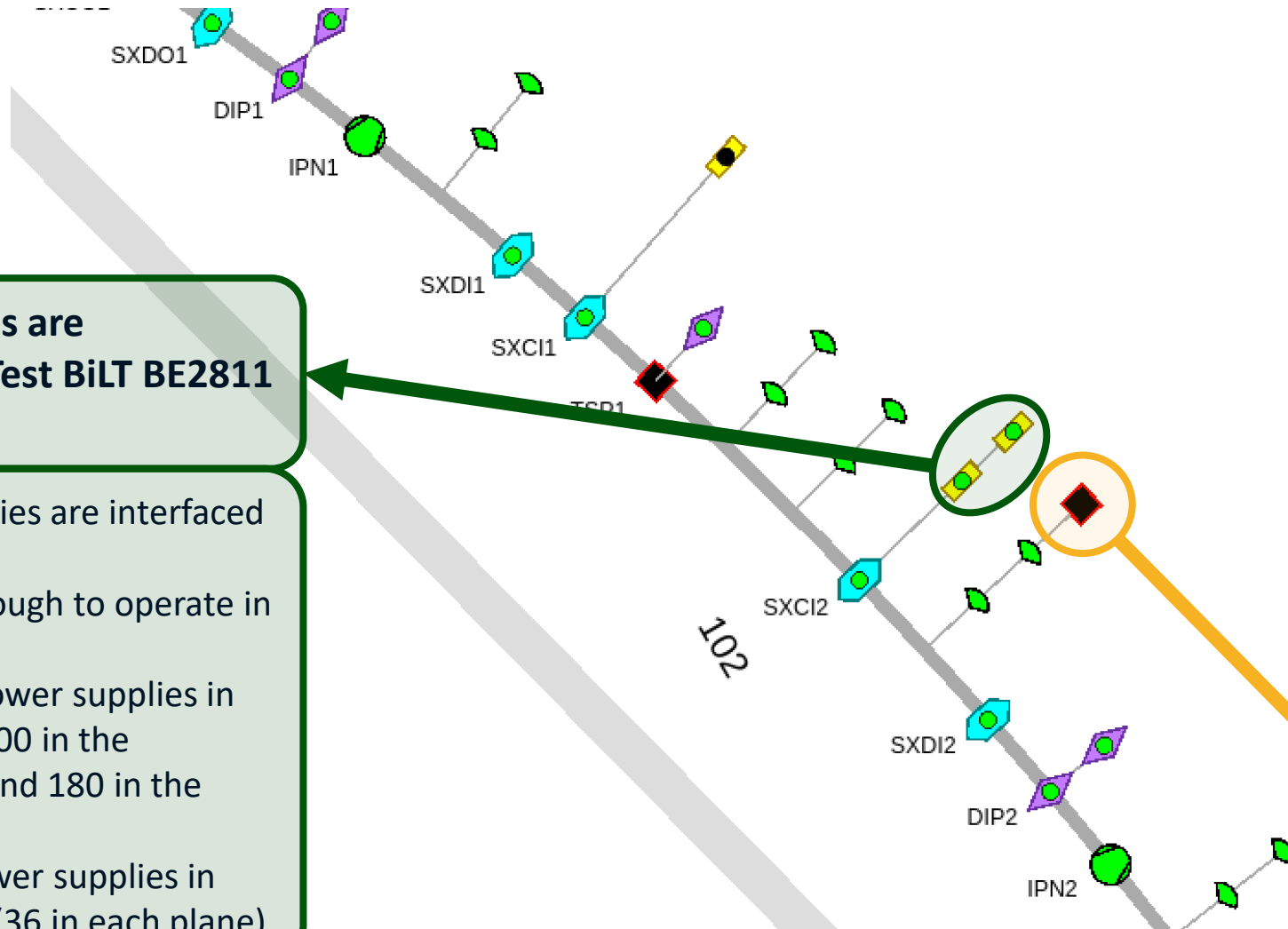
Storage Rings Orbit at MAX IV

Storage Rings at MAX IV

- The accelerator complex at the MAX IV laboratory consists of a 3 GeV, 250 m long full energy linac, two storage rings of 1.5 GeV and 3 GeV and a Short Pulse Facility.
- Transverse stability of the beam is commonly achieved via feedback solutions with various different implementations.
- At the MAX IV light source, there are two separate feedbacks working together in two different, but overlapping frequency regions and sets of sensors.
- The Fast Orbit Feedback has 10 kHz repetition rate and attenuates noise up to 50 – 150 Hz in the most critical regions.
- The Slow Orbit Feedback is implemented in software over a distributed control system and should work with a rate up to 10Hz







Corrector Magnets are Controlled with ITest BiLT BE2811 Power Supplies

- The power supplies are interfaced in TANGO.
- They are fast enough to operate in 10Hz.
- There are 380 power supplies in the 3GeV ring (200 in the horizontal plan and 180 in the vertical plane)
- There are 72 power supplies in the 1.5GeV ring (36 in each plane)

- The BPMs are interfaced in TANGO so the beam positions in both planes are available as attributes.
- The attributes push events at the 10 Hz rate of the “slow” Libera data acquisition stream.
- There are 2×200 BPMs in the 3GeV ring.
- There are 2×36 BPMs in the 1.5GeV ring.

Beam Position Measurements from Libera Brilliance+

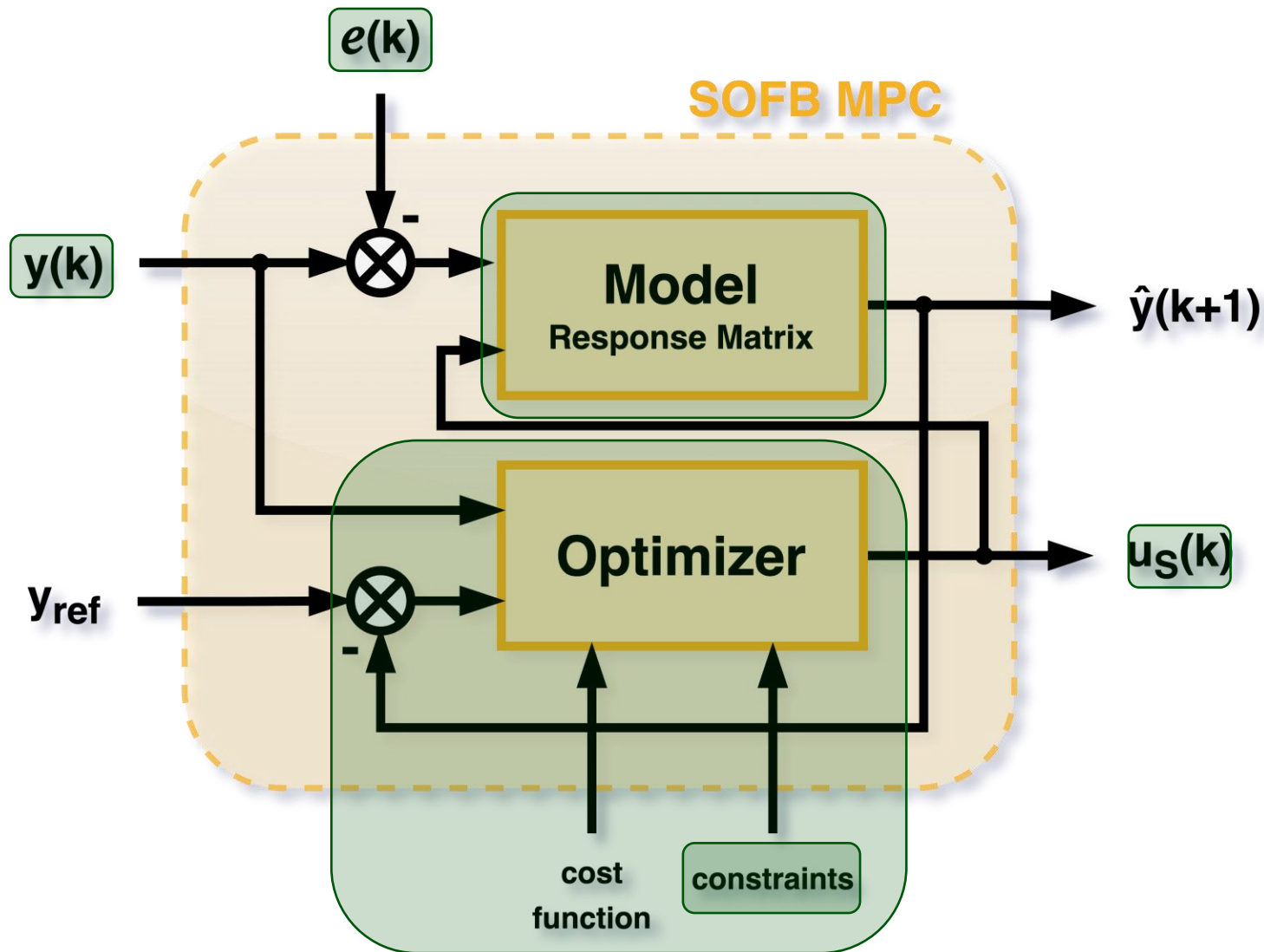
Issues and Requirements

- Corrector magnets are easily saturated, for both the Slow and Fast Orbit FeedBack control systems.
- When some of the the corrector magnets of the SOFB system are saturated it can be hard to bring the feedback control system into operation again.
- The BPM sensor readout have particular transient dynamics, in which it takes around 4 or 5 steps, around 0.5s for the sensor to reach the expected value.
- The Fast corrector magnets, have a shorter operational range, thus the SOFB should help the with the offloading of the FOFB system.
- Compensation of energy shifts can be achieved by adjusting the RF, which should also be managed by the SOFB system for an optimal solution.

INTRODUCTION

Model Predictive Control

Optimal Control for Constrained Dynamic Systems



Theoretical Background

- Model Predictive Control (MPC) is a control system that uses a model of the system's dynamics to predict its future behaviour over a finite receding horizon.
- The prediction is based on the current states, disturbances, and current and future control signals.
- In each step, the optimization problem to minimize the cost function for the control signal is solved so that constraints on states and control actions are satisfied.
- One of the big advantages of MPC is that the controller handles constraints which can be physical limits or safety limits on states and control signals.

Mathematical Definition

- This problem minimizes the cost function J .
- e is the states error.
- u is the control signal.
- $H_{p/u}$ is the prediction horizon.
- The states cost function is given by Q_1 .
- The control signal cost function is given by Q_2 .
- The first term penalizes tracking errors.
- The second penalizes control signals
- The third penalizes state error at the end of the prediction horizon.
- The sytem model is the first constraint of the optimization function.
- The initial state is an estimation of the current state.
- The states and control signal constraint can be defined.

$$\min_{x,u} J = \sum_{i=k+1}^{k+H_p-1} e_i^T Q_1 e_i + \sum_{i=k}^{k+H_u-1} \Delta u_i^T Q_2 \Delta u_i + e_{k+H_p}^T Q_f e_{k+H_p}$$

$$\text{s. t. } \begin{aligned} x_{k+1} &= \Phi x_k + \Gamma u_k \\ y_k &= C x_k \end{aligned}$$

$$\bar{x} = x_0$$

$$\begin{aligned} |x| &\leq x_{max} \\ |u| &\leq u_{max} \end{aligned}$$

IMPLEMENTATION

MPC Design

Model and Controller Outline

Model

- The MPC model uses the Response Matrix as part of the system model.
- The sensors are the BPM.
- The actuators which receive the are the power supplies of the magnets.
- The frequency delta can also be incorporated into the MPC model to account for energy shifts.
- The model is part of the optimization restriction

Model

$$\begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_{k+1} = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_k + \begin{bmatrix} \mathbf{R} \\ -\frac{E_0}{L_0 \alpha} \eta_{actuator}^T \end{bmatrix} \begin{bmatrix} \frac{1}{L_0 \alpha} \eta_{sensor} \\ -\frac{E_0}{\alpha f_0} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta f \end{bmatrix}$$

$$\mathbf{y}_k = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ \Delta E \\ E \end{bmatrix}_k$$

Optimization

$$\min_{\mathbf{x}, \mathbf{u}} J = \sum_{i=k+1}^{k+H_p-1} \mathbf{e}_i^T Q_1 \mathbf{e}_i + \sum_{i=k}^{k+H_u-1} \Delta \mathbf{u}_i^T Q_2 \Delta \mathbf{u}_i + \mathbf{e}_{k+H_p}^T Q_f \mathbf{e}_{k+H_p}$$

$$\text{s. t. } \begin{cases} \mathbf{x}_{k+1} = \Phi \mathbf{x}_k + \Gamma \mathbf{u}_k \\ \mathbf{y}_k = \mathbf{C} \mathbf{x}_k \end{cases}$$

$$\bar{\mathbf{x}} = \mathbf{x}_0$$

$$|\mathbf{x}| \leq \mathbf{x}_{max}$$

$$|\mathbf{u}| \leq \mathbf{u}_{max}$$

$$|\Delta \mathbf{u}| \leq \Delta \mathbf{u}_{max}$$

Optimization

- The BPM sensor importances can be addressed by using the control signal cost matrices Q_1 and Q_f .
- The corrector magnets importance can be addressed by using the control signal cost matrix Q_2 .
- The actuators saturation and sensor end scales are used to define the optimization function constraints.
- The maximum actuator change is also limited.

Model

$$\begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_{k+1} = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_k + \begin{bmatrix} \mathbf{R} & -\frac{1}{L_0\alpha}\eta_{sensor} \\ -\frac{E_0}{L_0\alpha}\eta_{actuator}^T & -\frac{E_0}{\alpha f_0} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta f \end{bmatrix}$$

$$\mathbf{y}_k = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ \Delta E \\ E \end{bmatrix}_k$$

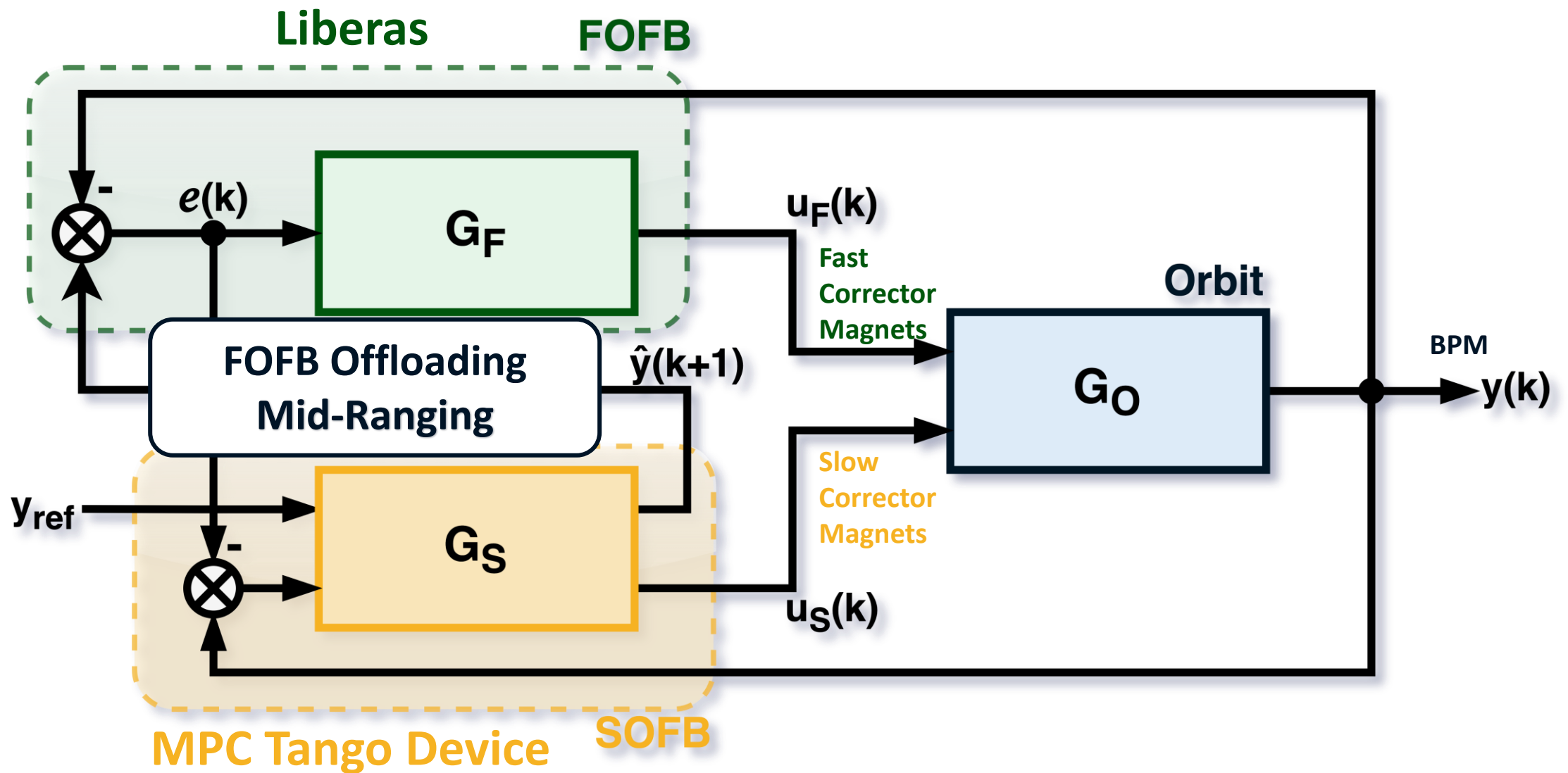
Optimization

$$\min_{\mathbf{x}, \mathbf{u}} J = \sum_{i=k+1}^{k+H_p-1} \mathbf{e}_i^T Q_1 \mathbf{e}_i + \sum_{i=k}^{k+H_u-1} \Delta \mathbf{u}_i^T Q_2 \Delta \mathbf{u}_i + \mathbf{e}_{k+H_p}^T Q_f \mathbf{e}_{k+H_p}$$

$$\text{s. t. } \begin{aligned} \mathbf{x}_{k+1} &= \Phi \mathbf{x}_k + \Gamma \mathbf{u}_k \\ \mathbf{y}_k &= \mathbf{C} \mathbf{x}_k \\ \bar{\mathbf{x}} &= \mathbf{x}_0 \end{aligned}$$

$$\begin{aligned} |\mathbf{x}| &\leq \mathbf{x}_{max} \\ |\mathbf{u}| &\leq \mathbf{u}_{max} \end{aligned}$$

$$|\Delta \mathbf{u}| \leq \Delta \mathbf{u}_{max}$$



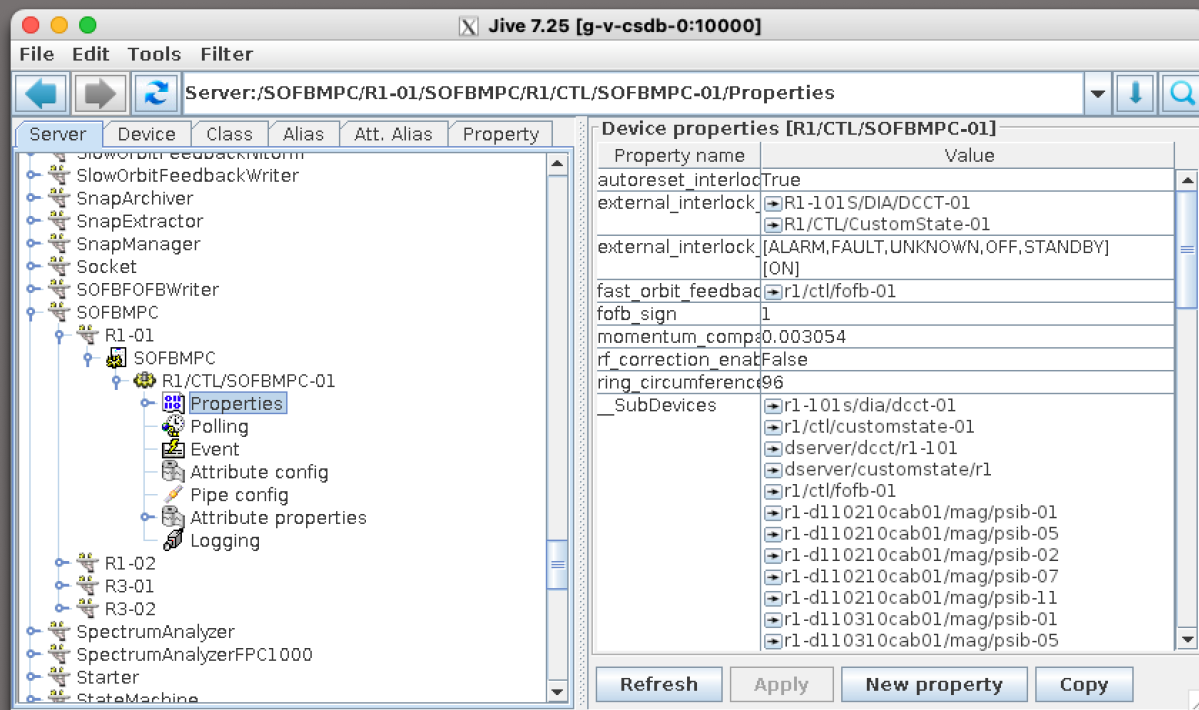
Mid-ranging Interaction with FOFB

- Saturation is an issue for both the Fast Orbit FeedBack fast correctors and the Slow Orbit FeedBack slow correctors.
- The Fast Correctors should optimally be working in the middle of its operational range.
- A mid-ranging design was implemented to offload the strain on the FOFB system.
- The reference value of the MPC is adjusted to match the middle of the range which the FOFB is working.
- This offloading occurs every 5s.

IMPLEMENTATION

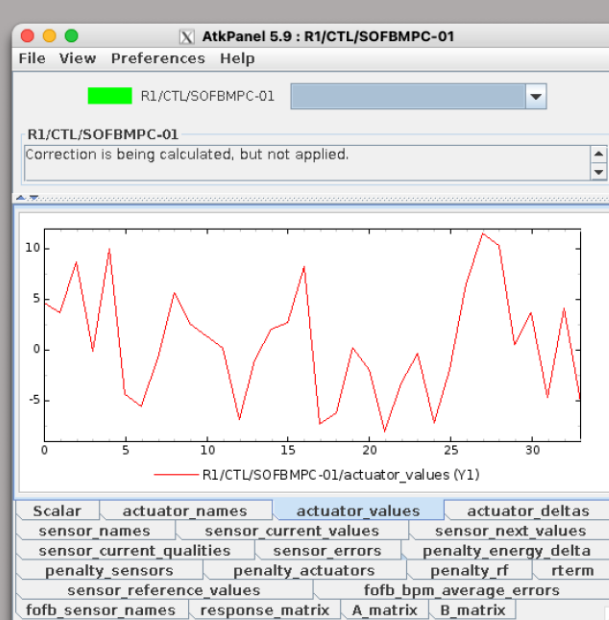
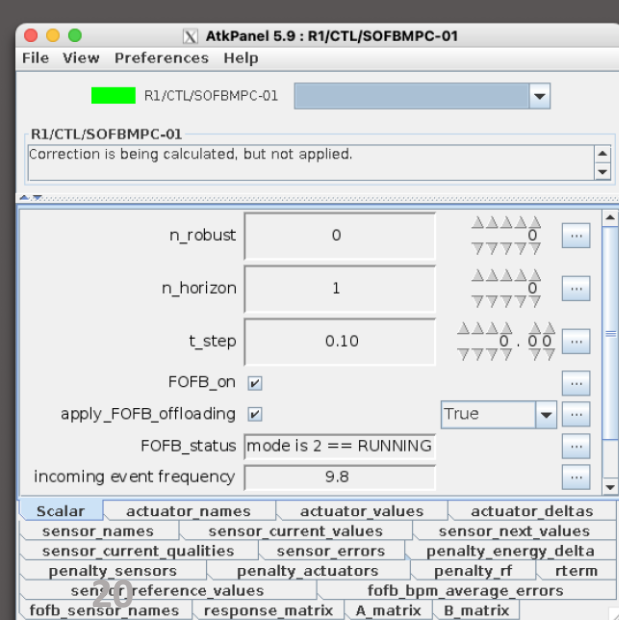
Tango Device

SOFB MPC implementation using PyTango Framework



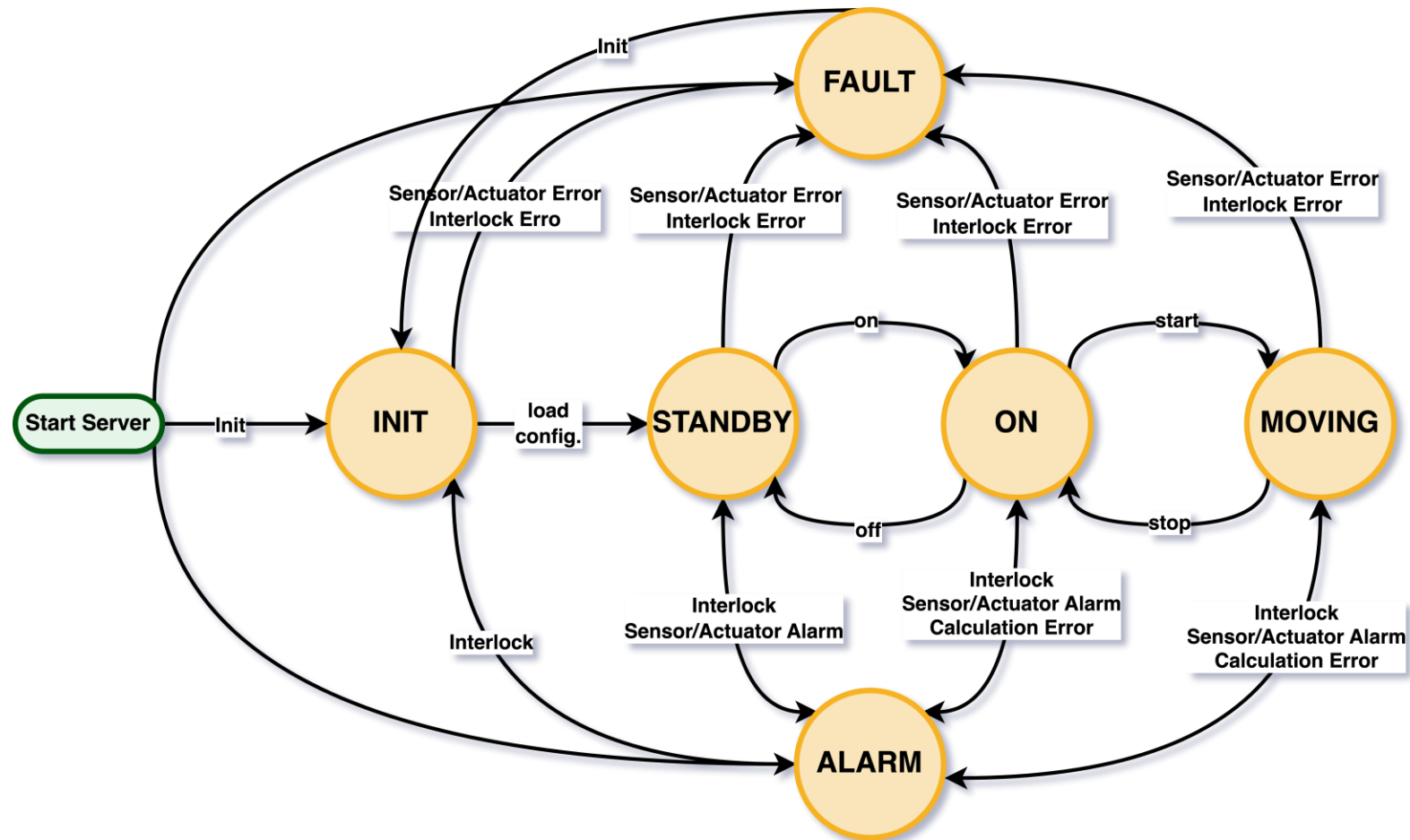
Device Server

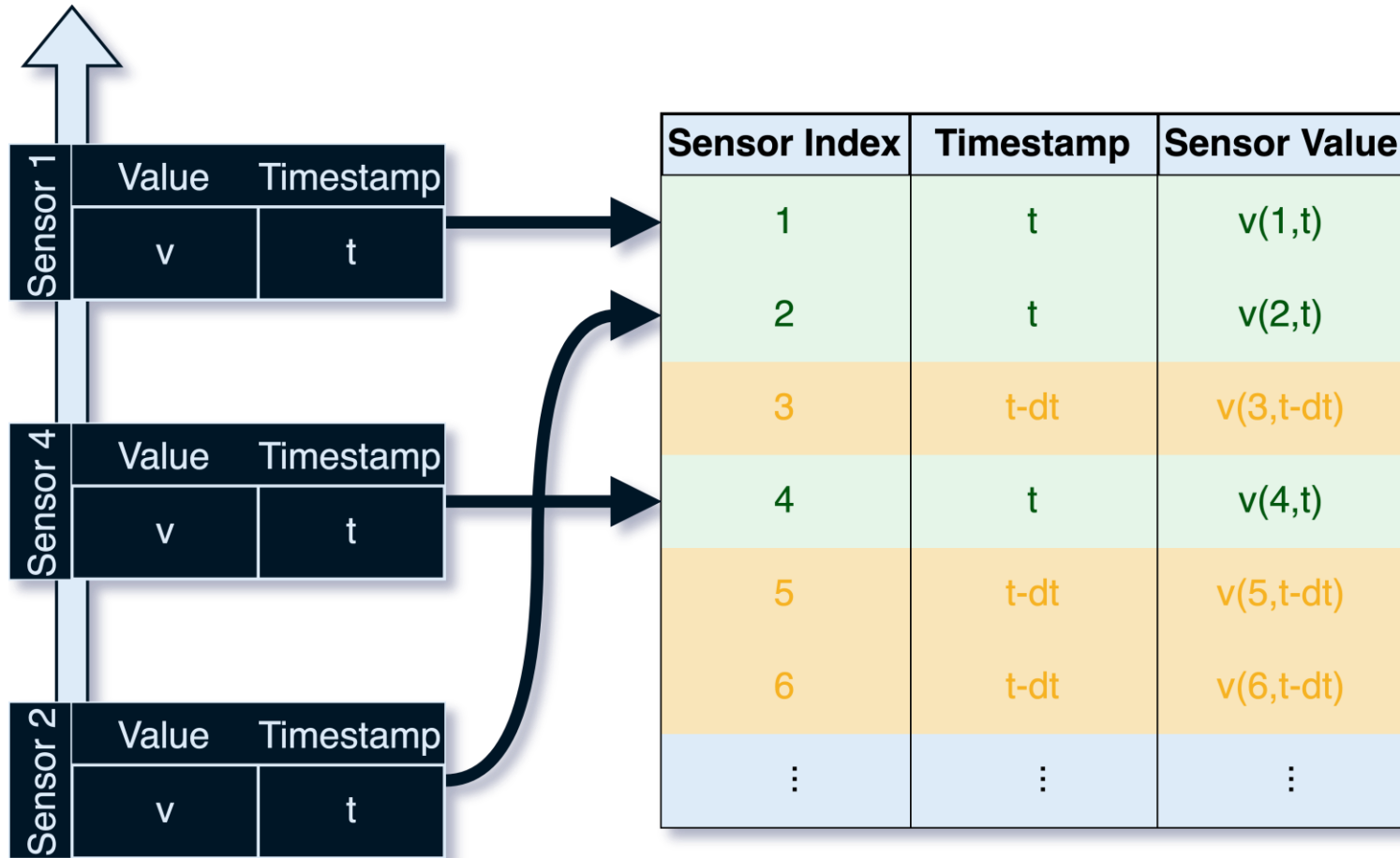
- The device server was implemented using in Python using PyTango framework for distributed control systems.
- The Do-MPC library was used for the MPC implementation.
- The interaction with the device can be done through Tango's standard GUIs, Jive and Atk Panel.
- Additionally it is possible to interact with the device using PyTango Client API in Python or its Matlab binding.



State Handling

- The device transitions to STANDBY when all required configurations are finished. The status states which configurations are missing.
- When on ON state, the controller calculates the control signal but does not update the MPC state neither apply the control signal to the actuators.
- On MOVING, MPC states are updated and the control signal is applied.
- Issues with read out rates, invalid sensor readings will cause controller to go to a reversible ALARM state.
- Issues with external interlock and sensors or actuators faults will cause device to go to FAULT state, which require human intervention.





Sensor Events

- The sensors event handling was inherited from the previously implemented orbit controller and it runs on a separated thread from the main control loop.
- For each event that arrives from a sensor, the timestamp and value for that sensor is updated and the spread in the timestamps is calculated.
- Once all events are within a tolerance time range, the sensor signal input can be considered for the next MPC step.

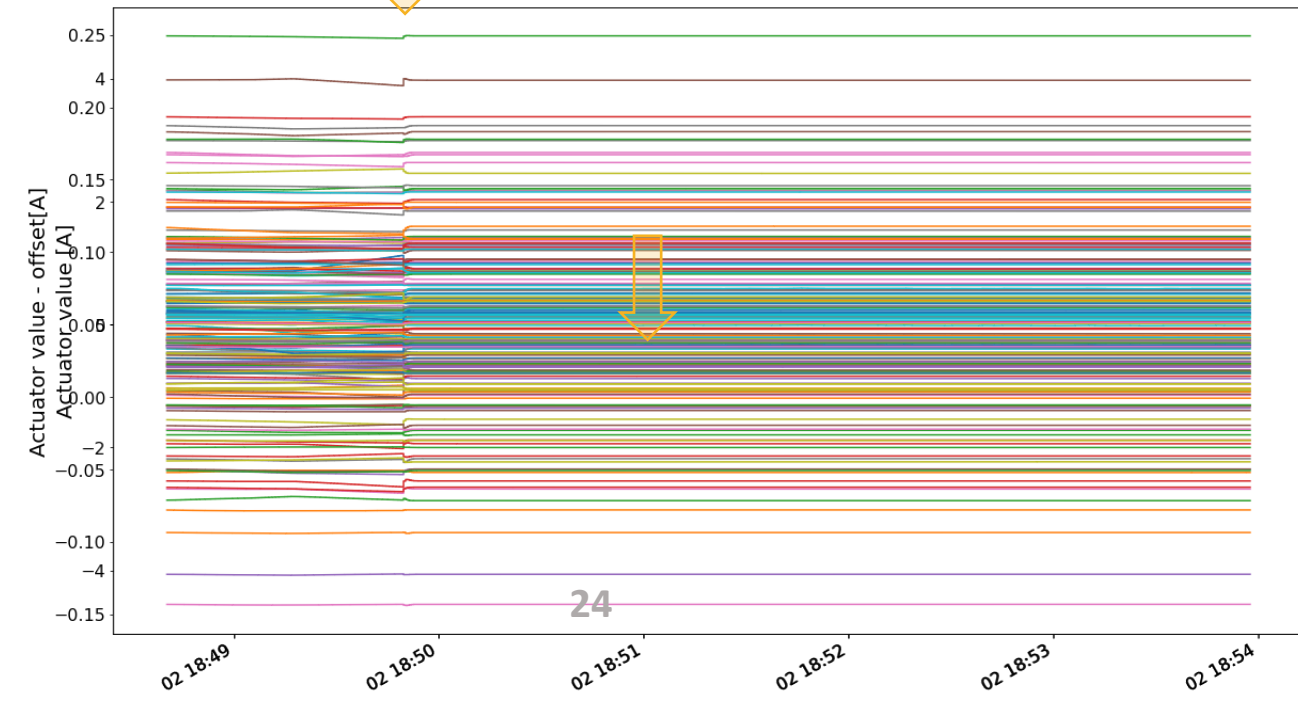
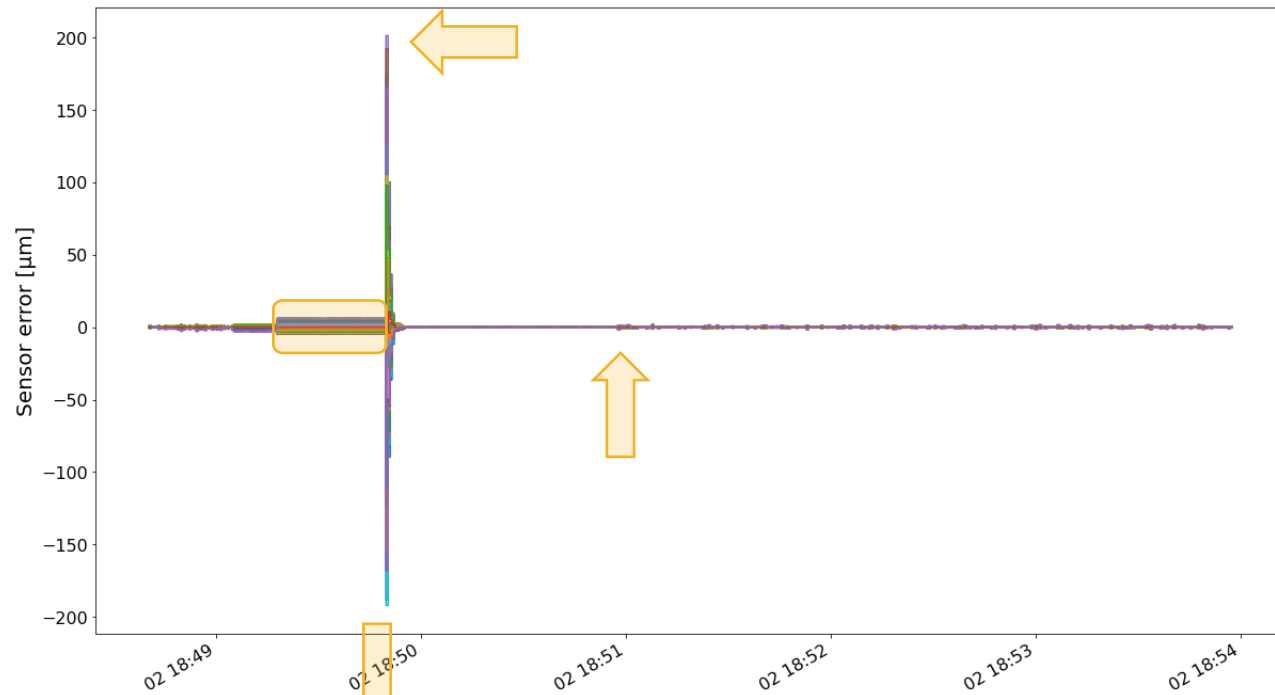
RESULTS

Tests on Storage Ring

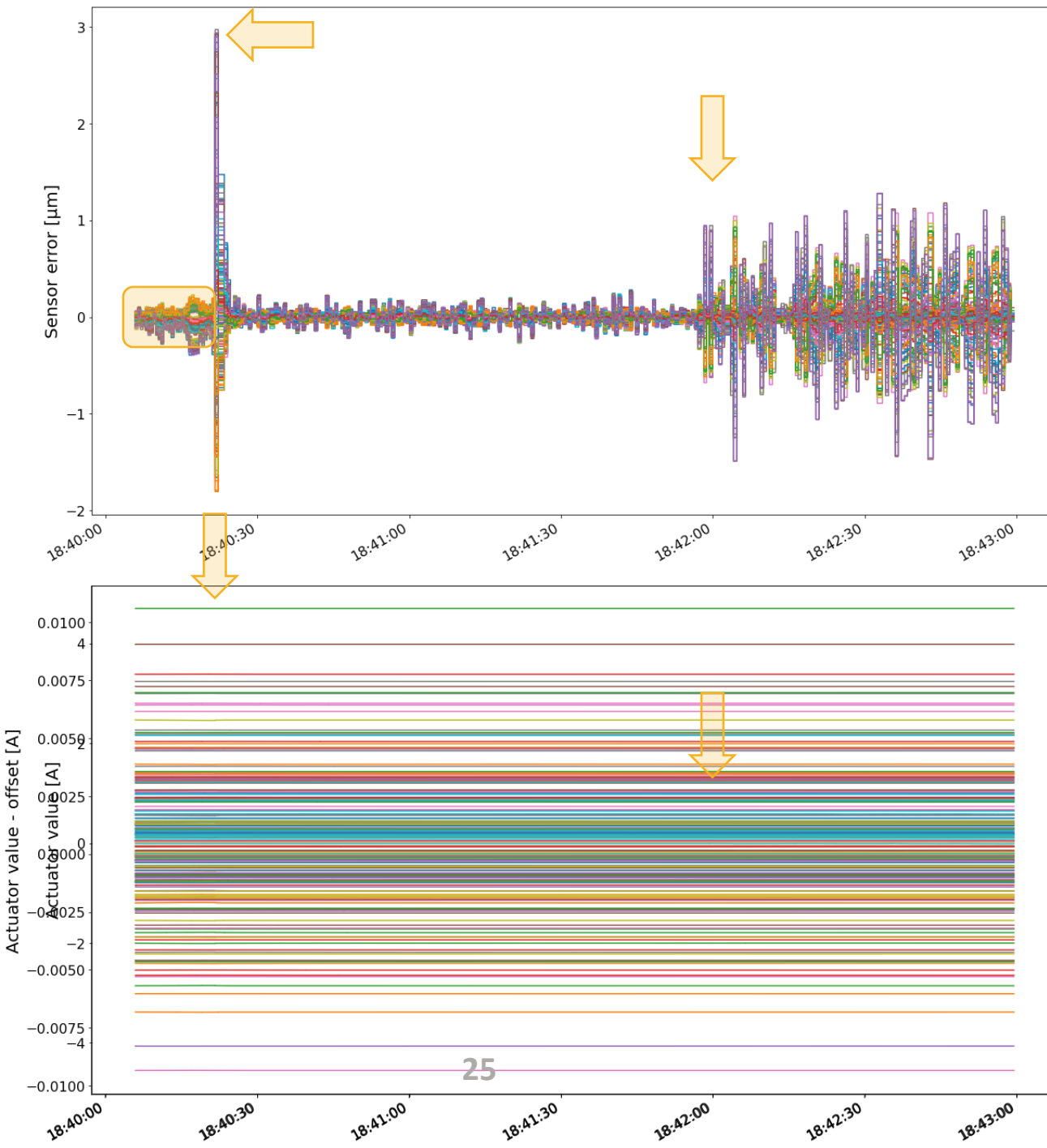
Tests on 3GeV Ring

R3 Tests

- The starting sensor error as around 20 μm .
- When the MPC, started the initial overshoot was around 200 μm .
- Sensor constraints were not defined during this test.
- On start, actuators had a kick but stabilized, this is more evident if we remove the signal mean.
- The FOFB was started, which introduced some noise.
- The actuation level remained stable



R3 Tests



- When the MPC was started with the sensors near the setpoint, the overshoot was significantly smaller.
- The actuators kick is barely noticeable in this case, but it is possible to see the changes around the operational mean values.
- When the FOFB was started the noise was introduced.

RESULTS

Challenges

Findings and Room for Improvement

Challenges

- The RF adjustment does not work as expected
- Calculation time for the 3GeV ring is rather slow and it might fail to meet time constraints under specific conditions, currently we are working on optimizing the implementation.
- It is harder for operators with limited knowledge of the controller or the system to troubleshoot when anything goes wrong.

RF Frequency Adjustment

- Inconsistencies on the dispersion function of the actuators caused the model to be unreliable.

Model

$$\begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_{k+1} = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_k + \begin{bmatrix} \mathbf{R} & -\frac{1}{L_0 \alpha} \eta_{sensor} \\ -\frac{E_0}{L_0 \alpha} \eta_{actuator} & -\frac{E_0}{\alpha f_0} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta f \end{bmatrix}$$

$$\mathbf{y}_k = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ \Delta E \\ E \end{bmatrix}_k$$

Optimization

$$\min_{\mathbf{x}, \mathbf{u}} J = \sum_{i=k+1}^{k+H_p-1} \mathbf{e}_i^T Q_1 \mathbf{e}_i + \sum_{i=k}^{k+H_u-1} \Delta \mathbf{u}_i^T Q_2 \Delta \mathbf{u}_i + \mathbf{e}_{k+H_p}^T Q_f \mathbf{e}_{k+H_p}$$

$$\text{s. t. } \begin{aligned} \mathbf{x}_{k+1} &= \Phi \mathbf{x}_k + \Gamma \mathbf{u}_k \\ \mathbf{y}_k &= \mathbf{C} \mathbf{x}_k \end{aligned}$$

$$\bar{\mathbf{x}} = \mathbf{x}_0$$

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$$|\mathbf{u}| \leq \mathbf{u}_{max}$$

$$|\Delta \mathbf{u}| \leq \Delta \mathbf{u}_{max}$$

RF Frequency Adjustment

- Inconsistencies on the dispersion function of the actuators caused the model to be unreliable.
- It was opted to use a more minimal model to represent the frequency adjustment:

$$\frac{\Delta E}{E_0} = -\frac{\Delta f}{f_0}$$

$$\Delta \mathbf{x} = \mathbf{R} \Delta \mathbf{u} - \frac{\Delta f}{\alpha f_0} \boldsymbol{\eta}_{sensor}$$

Model

$$\begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_{k+1} = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ E \end{bmatrix}_k + \begin{bmatrix} \mathbf{R} & -\frac{1}{\alpha f} \boldsymbol{\eta}_{sensor} \\ 0 & -\frac{1}{\alpha f_0} E_0 \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta f \end{bmatrix}$$

$$\mathbf{y}_k = \mathbf{I} \begin{bmatrix} \mathbf{x} \\ \Delta E \\ E \end{bmatrix}_k$$

Optimization

$$\min_{\mathbf{x}, \mathbf{u}} J = \sum_{i=k+1}^{k+H_p-1} \mathbf{e}_i^T Q_1 \mathbf{e}_i + \sum_{i=k}^{k+H_u-1} \Delta \mathbf{u}_i^T Q_2 \Delta \mathbf{u}_i + \mathbf{e}_{k+H_p}^T Q_f \mathbf{e}_{k+H_p}$$

$$\text{s. t. } \begin{aligned} \mathbf{x}_{k+1} &= \Phi \mathbf{x}_k + \Gamma \mathbf{u}_k \\ \mathbf{y}_k &= \mathbf{C} \mathbf{x}_k \\ \bar{\mathbf{x}} &= \mathbf{x}_0 \end{aligned}$$

$$|\mathbf{x}| \leq \mathbf{x}_{max}$$

$$|\mathbf{u}| \leq \mathbf{u}_{max}$$

$$|\Delta \mathbf{u}| \leq \Delta \mathbf{u}_{max}$$

Future Work

- The model can incorporate sensor readout delays, to allow shorter control cycles and increase prediction horizon. We already have a response matrix with an intermediate that accounts for the power supplies delay and slew rate.
- Known disturbances can be incorporated to the MPC controller to improve states predictions and increase prediction horizon.

Thank you!

Contact info:

carla.takahashi@maxiv.lu.se