Applying Model Predictive Control to Regulate Thermal Stability of a Hard X-ray Monochromator Using the Karabo SCADA Framework

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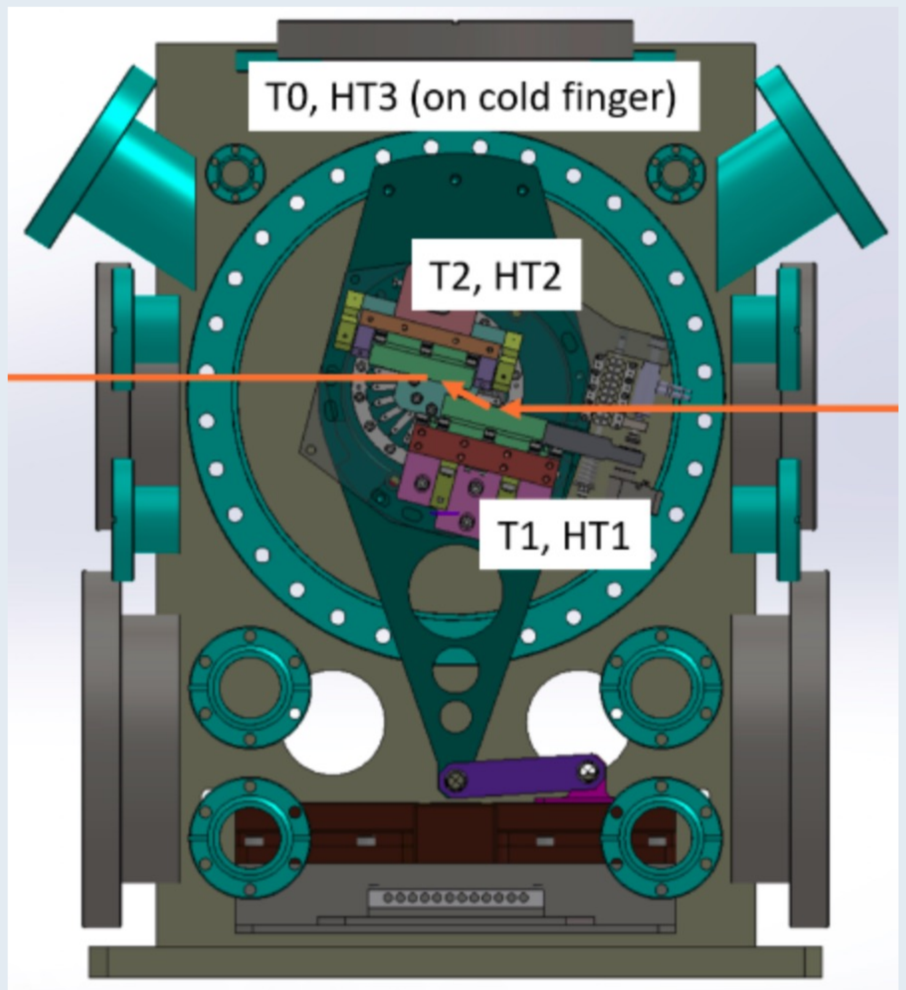
Abstract / Introduction

Model Predictive Control (MPC) is an advanced method of process control whereby a model is developed for a real-life system and an optimal control solution is then calculated and applied to control the system. At each time step, the MPC controller uses the system model and system state to minimize a cost function for optimal control. The Karabo SCADA Framework is a distributed control system developed specifically for European XFEL facility, consisting of tens of thousands of hardware and software devices and over two million attributes to track system state.

This contribution describes the application of the Python MPC Toolbox within the Karabo SCADA Framework to solve a monochromator temperature control problem. Additionally, the experiences gained in this solution have led to a generic method to apply MPC to any group of Karabo SCADA devices.

Motivation

- Silicon monochromators are used to select the pass band of X-ray energies that continue through to the instrument. Thermal drift in a monochromator causes a drift of the transmitted photon energy.
- To mitigate the impact of temperature jumps caused by the X-ray pulse trains at European XFEL, the monochromator temperature has to stay just below this temperature.
- There are multiple sources and sinks of energy in the system that affect temperature, making temperature regulation of both crystals challenging:



1. Cryogenic cold head to cool both crystals down
2. Local heater attached to each crystal
3. Parasitic heat from the local heater of the other crystal
4. Heating of the first incident crystal due to the X-ray beam input

CAD drawing of the X-ray monochromator, showing the path of the X-ray beam through the two silicon crystals of the monochromator. Tx and HTx identify the temperature sensors and heater elements respectively.

Methods

- The Python MPC Toolbox is a comprehensive python library that supports creation, simulation, and runtime implementation of Model Predictive Controllers.
- This toolbox provides a framework in Python for describing a system's behaviour by defining the ordinary differential equations (ODEs) that relate the rate of change of its process variables to other measurable states of the system.

$$\frac{dT_{crystal}}{dt} = \frac{1}{mc}\left(P_{cryo} + P_{heater} + P_{beam}\right)$$

m = mass of crystal
c = specific heat capacity of crystal
P = powers added to and removed from crystal

- Once these are defined, a 'model' instance is created and can be used by other parts of the MPC Toolbox to synthesize an optimal MPC controller as well as a model simulator.

Integration

- Karabo has a declarative API which enables the creation of a generic, reusable datatype that can update the MPC model parameters seamlessly.
- Model inputs, both locally fixed and remote time-varying parameters retrieved from the control system, are defined in the Karabo device just like other numeric parameters of the device.

```
""" example declaration of Karabo parameter
"""
connectionTimeout = Float(
   displayedName="Connection Timeout",
   description="Maximum time to wait for remote"
               "device connections.",
   unitSymbol=Unit.SECONDS,
   maxInc=10.0)

""" example declaration of Karabo parameter
    that auto-updates MPC parameter
"""
temperature1Setpoint = MPCFloat(
   displayedName="XTAL1 Temperature Setpoint",
   description="Temperature setpoint for the "
               "first crystal in the X-ray path",
   unitSymbol=Unit.DEGREE_CELSIUS,
   minInc=-200.0,
   # the datatype's 'alias' is used to declare
   # the name of the MPC model variable
   alias='T_setpoint1')
```

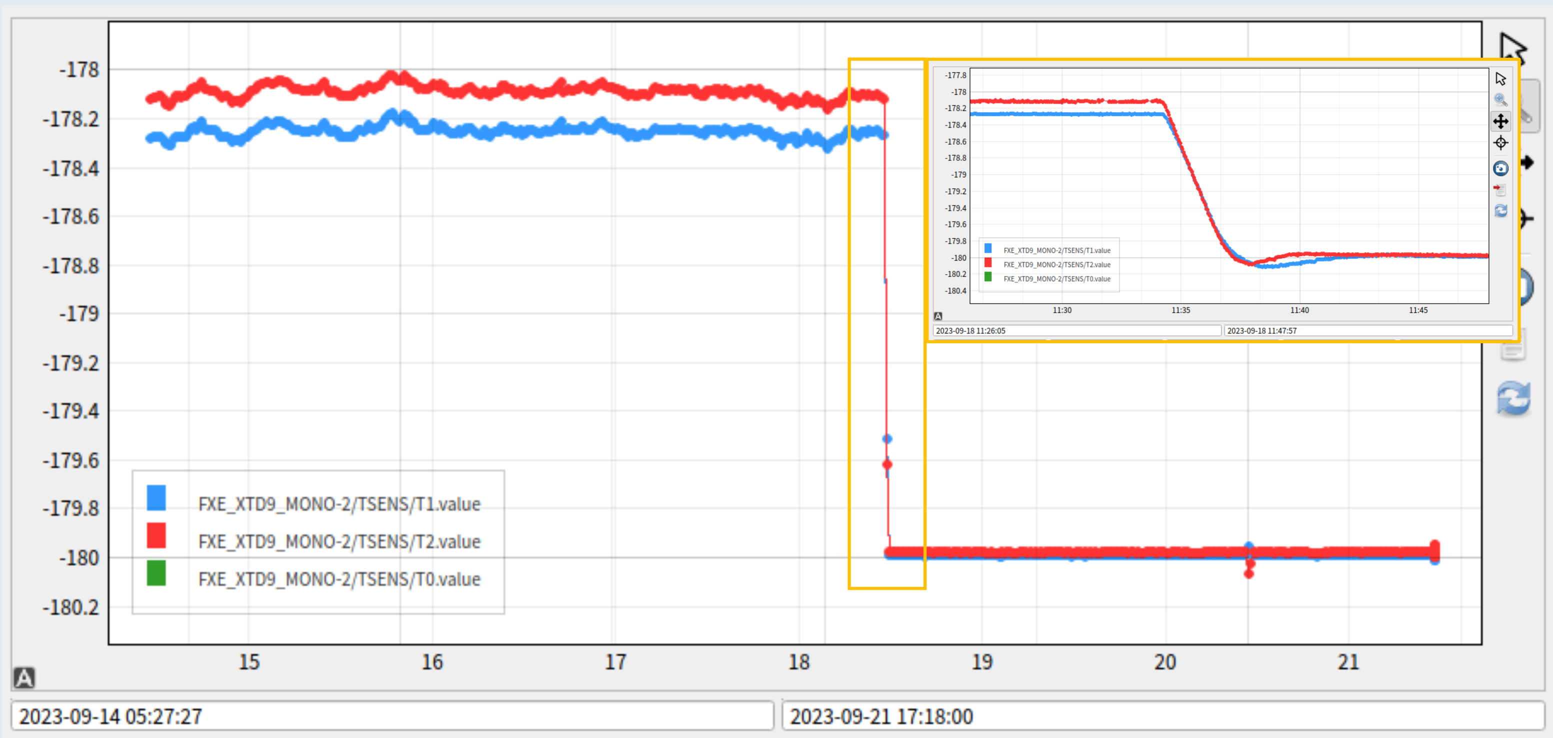
Sample parameter declaration

```
while True:
   self.elapsed_time = time.time()

   # read system state from device proxies
   # (get feedback variables from system)
   y = [proxy.value for proxy
        in self.temperatureProxies]

   # calculate next set of control actions
   u = self.mpc.make_step(y)

   # apply control actions (write
   # new values to device proxies)
   self.heaterProxies[0].targetPower = u[0]
   self.heaterProxies[1].targetPower = u[1]

   # time between control actions is defined
   # in the MPC as self.mpc.t_step
   time_step = self.mpc.t_step - \
       (time.time() - self.elapsed_time)
   await sleep(time_step)
```

Sample control loop

Results

- The Karabo device based on the MPC toolkit was deployed to control two monochromator devices in the Femosecond X-ray Experiments (FXE) instrument in September 2022.
- When the regulator is active, it is able to bring the two crystal temperatures to the setpoint of -180°C within a few minutes and hold the temperature with a standard deviation of 0.006°C.



Temperature plot of both monochromator crystals in °C, showing the temperature regulation before and after the MPC is activated.

This implementation demonstrates that it is possible to capture all the control logic of a high-level process control device into a software model using the MPC Toolbox. Once the model has been synthesized, the effort of writing a control system device is reduced to defining device configuration for the model's constant parameters and writing code to read and write attributes from other remote control system devices. Additionally, the model is fully reusable for unit testing and simulation.

References

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[3] Thermal expansion coefficient of single crystal silicon from 7K to 293K, https://doi.org/10.1103/PhysRevB.92.174113.
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