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A GENERAL MULTIPLE-INPUT MULTIPLE-OUTPUT FEEDBACK DEVICE IN TANGO FOR THE MAX IV ACCELERATORS

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Abstract

A general multiple-input multiple-output feedback device has been implemented in TANGO for various applications in the MAX IV accelerator system. The device has a configurable, weightable list of sensors and actuators, response matrix inversion (via SVD), gain and frequency regulation, takes account of the validity of the sensor readings and limits of actuator settings, and may respond to external interlocks. In the storage rings, it performs the slow orbit feedback using the 10 Hz data stream from the Libera Brilliance Plus Beam Position Measurement electronics, reading 400 (72) beam positions in the large (small) ring as sensor inputs. The position readings are received as TANGO events and a corrector-to-beam-position response matrix calculation outputs the corrector magnet settings. In the linac, the device is used for the trajectory correction, again with sensor input data sent as TANGO events, in this case from the Single Pass Beam Position Measurement electronics. The device is also used for tune feedback in the storage rings, making use of its own polling thread to read the sensors. Future developments will see a dedicated slow orbit feedback device derived from the general implementation in order to integrate the hardware-based fast orbit feedback, while the general device is also seeing new applications at the beamlines.

INTRODUCTION

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. During 2019 eight beamlines are receiving users and the 3 GeV ring is now well proven for regular delivery to users at 250 mA stored current.

The MAX IV control system has a three-tier architecture, with specific hardware handling the real-time tasks and TANGO [1] representing the middle tier as the primary control system. For the client layer, physicists and operators can interact with TANGO via its Python and MATLAB bindings or through the SARDANA [2] layer which brings a macro server and standardised Graphical User Interfaces based on TAURUS [3]. In the control of the accelerator the MATLAB layer is used extensively, taking advantage of the rich "accelerator toolkit" developed in the wider accelerator physics community [4].

During early operation of the machine several use cases for feedback systems implemented in the TANGO layer were identified. Being able to take advantage of the TANGO event system, such devices are more performant than equivalent applications implemented in the MATLAB client layer. A TANGO device for the slow orbit feedback (SOFB) in the storage rings was first to be developed, but at an early stage this was generalised into the current TANGO Feedback Device such that it can be configured for any multiple input multiple output (MIMO) application. The first section of this report describes the design and main features of the general TANGO Feedback Device and the second section details some of its current applications at MAX IV.

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TANGO FEEDBACK DEVICE DESIGN AND FEATURES

A Generic Device

The TANGO Feedback Device, written in Python, is completely generic and configurable for both MIMO and SISO systems. It currently implements an (adjustable) proportional gain term only, as this was found to be sufficient for the initial SOFB application. Interaction with the device is through the attributes and commands shown in Fig. 1, which also illustrates the state logic of the device. Two writeable spectrum attributes *SensorNames* and *ActuatorNames* provide proxies to TANGO attributes that act in those roles, i.e. provide the input signals to and writeable outputs from the feedback calculation. These may be weighted. The *SensorReferenceValues*, i.e. target values, must also be provided and the *ResponseMatrix*, **R**, which gives the change in the sensor response for unit change in the actuator settings.

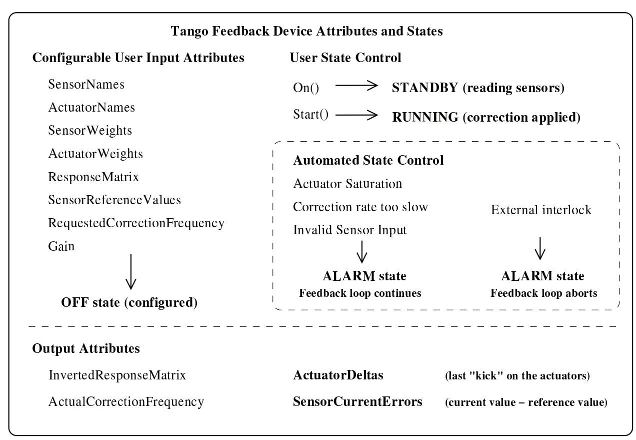

Figure 1: Commands, selected attributes and states of the generic TANGO Feedback Device. The output attributes *ActuatorDeltas* (the change in actuator settings) and *SensorCurrentErrors* (the different between the sensor values and the target) are updated for each iteration of the feedback. They are spectrum attributes but will have length 1 in case of a SISO application (one sensor, one actuator).

After configuring the above attributes the feedback device will be in OFF state. Moving to STANDBY state starts

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the updating of the sensor current value (or values) at the requested frequency, and the calculation of the difference between this (these) and the reference, known as the sensor error, all of which are accessible via attributes. The calculated change of setpoint(s), the *ActuatorDeltas*, are already available for inspection in STANDBY mode before any correction is actually applied. Moving to RUNNING state starts the feedback, i.e. the writing of the *ActuatorDeltas* to the actuator attributes, and this attribute now shows the adjustment being applied to the actuators in the current iteration.

Interlocks and Alarms

The TANGO Feedback Device may be configured to automatically stop the feedback (move from RUNNING back to STANDBY) if any user-definable interlock conditions are met. These are set through device properties and correspond to states of other TANGO devices. It is also configurable whether the feedback should restart once the interlock condition is removed or whether the operator must do this manually.

The device can enter ALARM state for other reasons, which usually mean that a correction was unable to be calculated or applied in the current iteration. The validity of the sensor values, as determined by the sensor TANGO devices, are continuously checked, confirming for example that they are not outside any alarm limits set in TANGO. If the sensor data is invalid the iteration is skipped and an ALARM shown. Similarly for the actuators, if the feedback attempts to set a value which is out of range (actuator saturation) an ALARM is thrown. An ALARM message is also shown if the feedback device cannot keep up with the requested feedback rate, which may happen, for example, if the actuators are too slow to respond.

Synchronised Event Based Sensor Input

From the outset the TANGO Feedback Device was designed to make use of the TANGO event system and so it may be driven by change events on the sensor attributes. Moreover, the feedback loop is synchronised to the sensor event rate if the sensors are synchronised with each other. This is illustrated in Fig. 2. It is assumed the n sensors send events with the same timestamps, with a time between each event of dt. So shortly after time t, and before $t+dt$, n events should arrive to the feedback device, all with the same timestamp (t). Because of the communication to the distributed sensors over the networks, the order in which these events arrive is unknown, but all should arrive before any events with the next timestamp ($t+dt$). Internally the feedback device keeps a dictionary of sensor indices, timestamps and values like the table in the figure. At the moment in time represented in the figure, some of the time t events are still pending, but once they arrive the difference in timestamps will be zero, if the sensor devices are perfectly synchronised. Thus for every event that arrives, the feedback device recalculates the maximum spread in the timestamps and when this becomes zero, within some tolerance, it is known that a complete set of sensor readings are available for that iteration. Only then should the feedback be computed, based on the corresponding sensor values; the device does not compute the feedback each time any event arrives. In practice there can be a small spread in the event timestamps but this should be small compared to the time between events; the feedback device checks that the spread is within some configurable tolerance that should be $\ll dt$. This approach works so long as the sensor event rate does not exceed some tens of Hz, or else events may arrive out of step, i.e. the $t + dt$ event for one sensor may arrive before the t event of another, so the difference in all stored timestamps would always be dt (or even some multiple of dt). The sensor devices sending the events must also be synchronised to much better than dt. If the latency of the actuator response is greater than dt the gain must be tuned accordingly, i.e. kept low.

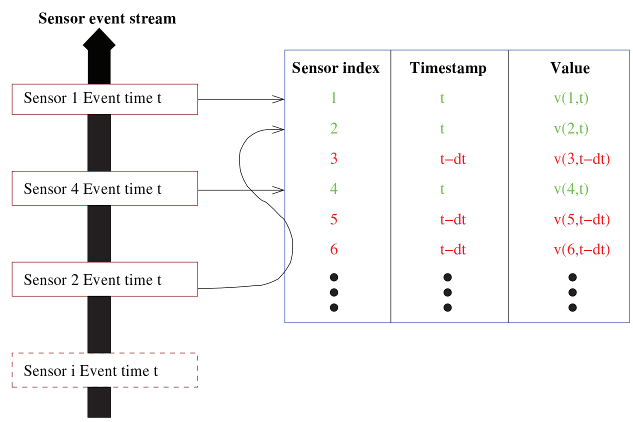

Figure 2: Synchronised operation of the TANGO Feedback Device. For each event that arrives from a sensor, the timestamp and value for that sensor is updated and the spread in the timestamps is recalculated. Once this is zero (within some tolerance) all events for that timestamp must have arrived, so one iteration of the feedback can be calculated and applied based on the current set of sensor values.

The feedback rate may be throttled back so that it is applied at a lower rate than the event stream from the sensors. If the sensors are not well synchronised and/or do not send events, the feedback device may be operated in polling mode. In this case, it simply polls all sensor attributes at the requested frequency and computes the feedback at this rate.

Response Matrix Inversion Using SVD

The response matrix $\mathbf{R}$ used in MIMO applications must be inverted in order to obtain the change in the actuator settings needed to correct for the current sensor error. In under- or over-constrained systems the matrix is not square and a pseudo-inverse must be used. The feedback device performs this inverse using Singular Value Decomposition (SVD). This is a standard technique in which the response matrix is factorised as $\mathbf{R} = \mathbf{USV}^T$, where $\mathbf{U}$ is an $m \times m$ unitary matrix and $\mathbf{V}$ is an $n \times n$ unitary matrix, with m being the number of sensors and n the number of correctors. $\mathbf{S}$ is an $m \times n$ diagonal matrix whole diagonal elements are known as the singular values of $\mathbf{R}$ and are listed in descending order.

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The inverse of the response matrix can then be written as $\mathbf{R}^{-1} = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T$. It can sometimes be necessary to neglect the singular values above some cut off, thereby excluding modes the actuators have little effect on, and this is also an option in the device.

In SISO mode the response matrix is simply -1 and the single sensor and actuator may be configured from properties of the device.

Monitoring and Debugging

Additional expert level attributes and commands are provided in order to facilitate trouble shooting. These include event counters on all sensor attributes to diagnose if one or more channels has stopped sending events, and a method to force an event re-subscription.

APPLICATIONS AT MAX IV

Storage Ring Slow Orbit Feedback

Transverse stability of the beam is an important aspect of achieving the low emittance and high brightness goals of the MAX IV light source and an application to perform the orbit feedback in the two storage rings was the original motivation for a feedback device in TANGO. The SOFB, being implemented in software, is referred to as such to distinguish it from the much higher rate hardware-based fast orbit feedback (FOFB) system which is currently being installed.

Beam Position Monitors (BPMs) numbering 2×200 in the large ring and 2×36 in the small ring, for the horizontal and vertical planes, are read out using commercial Libera Brilliance Plus electronics. These devices are interfaced in TANGO and the beam positions in both planes are available as attributes - the sensors in this feedback system. The attributes push events at the 10 Hz rate of the “slow” Libera data acquisition stream. The events are synchronised in that all Libera TANGO devices follow the same clock, so the position data from all BPMs are read and pushed every 0.1 s stamped with the same hardware time. As described above, the TANGO Feedback Device subscribes to change events on all position attributes and will synchronise itself with the 10 Hz rate.

The actuators in the SOFB are the “slow” corrector magnets controlled by ITest BILT power supplies, numbering 380 in the large ring (200 in the horizontal plane and 180 in the vertical plane) and 72 (36 in each plane) in the small ring. Previous timing studies were performed to confirm that these can handle remote commands to change the current output at 10 Hz. The relation between the change in beam position, $\mathbf{\Delta p}$, and the change of the power supply output to the corrector magnets, $\mathbf{\Delta c}$, is $\mathbf{\Delta p} = \mathbf{R}\mathbf{\Delta c}$, where $\mathbf{\Delta p}$ and $\mathbf{\Delta c}$ are column vectors with length equal to the number of BPM position measurements and number of corrector magnets, respectively. The matrix is inverted as explained in the previous section in order to obtain the necessary corrector strength changes (“kicks”) to counter the current error in the position, $\mathbf{\Delta c} = \mathbf{R}^{-1}(\mathbf{p}_{\text{current}} - \mathbf{p}_{\text{reference}})$.

The response matrix is well known for each ring and regularly calibrated. The full matrix is used, encompassing both the horizontal and vertical planes together; an example is shown in Fig. 3 for the large ring. In inverting the matrix,

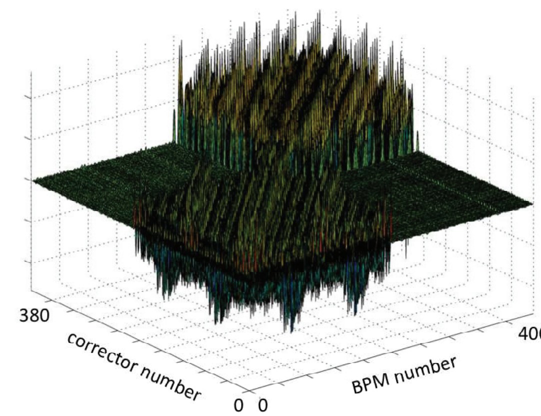

Figure 3: Example response matrix for the 3 GeV storage ring used in the SOFB. There are 400 BPMs (200 for each plane) and 380 (200+180) corrector magnets, so the system is over-constrained.

from experience the operators know where to apply the cut-off on the singular values in order to avoid corrector magnet saturation. The highest singular values can be considered to correspond to the modes in which very strong corrector kicks are needed for a small adjustment in the beam position, so it sometimes necessary to exclude these.

The feedback device is typically configured with an external interlock condition that monitors the beam current in the ring, and stops the feedback if the current is too low, or if the beam is lost. It is found that the feedback device can run consistently at the full 10 Hz rate in the small ring. In the large ring there are periodic drops in the correction rate, thought to be caused by the writing to the corrector magnets sometimes taking more than 0.1 s. This is currently under investigation. The performance is a significant improvement over the early MATLAB implementation which was limited to less than 1 Hz due to the need to poll the BPM position attributes. The TANGO Feedback Device is now the standard method of running the SOFB in the storage rings.

As a side effect, since the sensor current values and actuator deltas that are exposed as spectrum attributes are updated at 10 Hz in synchronisation with the BPM data stream, the feedback device makes a convenient backend for a GUI displaying the beam positions and corrector magnet kicks. This is shown in Fig. 4 for the large ring.

Linac Trajectory Feedback

A second place where the TANGO Feedback Device has replaced a slower MATLAB implementation is in the trajectory feedback of the linac. The application here is quite analogous to the SOFB in the storage rings. The beam positions are read from the BPMs located along the linac using Libera Single Pass electronics. Again the position attributes

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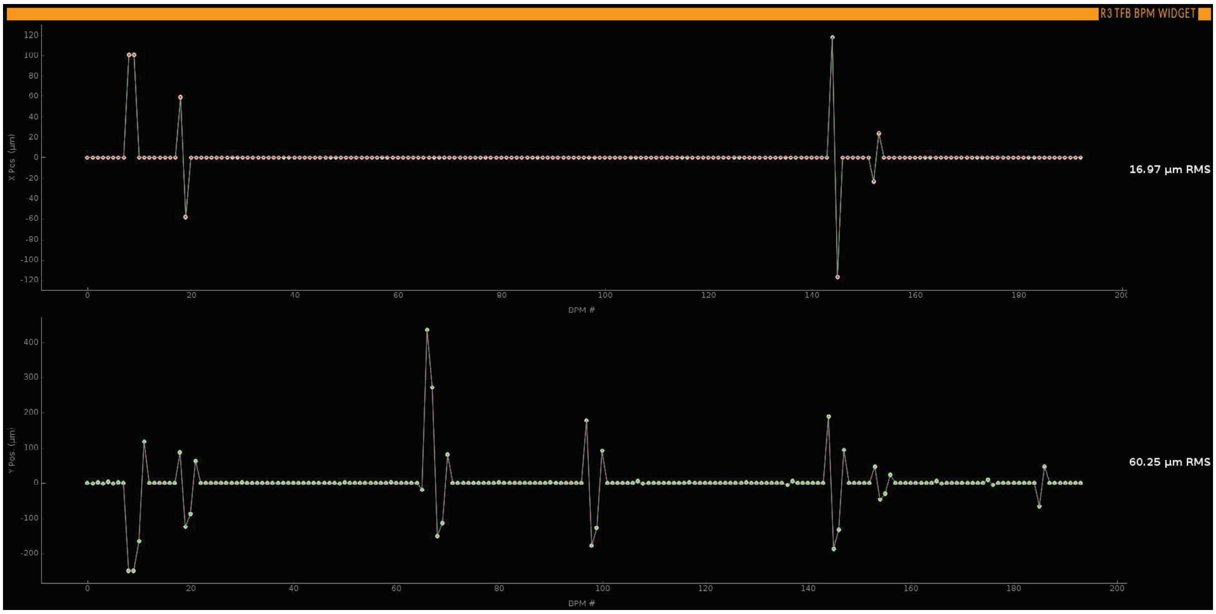

Figure 4: Display of beam positions in the large ring, updated at 10 Hz via the *SensorCurrentValues* attribute of the TANGO Feedback Device. An alternative view in this GUI can show the *ActuatorDeltas*, the kicks being applied to the corrector magnets in each iteration of the feedback.

in both planes are exposed in TANGO. Change events on these attributes are pushed shot by shot at the repetition rate of the linac, currently 2 Hz. The response matrix relates the changes in the beam position at the BPM locations with the changes in the power supply currents governing the magnetic field strength in the corrector magnets. Multiple independent feedback devices are configured, each one handling a different section of the linac with different combinations of them being used depending on the machine operating mode and the length of the beam path.

Tune Feedback

In the 1.5 GeV ring the transverse betatron tunes, i.e. the orbit resonance frequencies, underwent severe drifts during operation of several strong insertion devices. On occasions this has caused beam losses. In order to counteract this a 2×2 MIMO feedback was required. The tune readings from the DimTel bunch-by-bunch system were used as sensors and two power supplies, each powering a global quadrupole magnet circuit, were used as actuators. In this instance a 0.33 Hz iteration frequency was sufficient. Polling instead of event-driven mode had to used, as the TANGO device providing the DimTel read-out does not support events. The tune feedback is now running regularly during delivery.

Beamline Mirror Chamber

This is an example use case of the TANGO Feedback Device outside the accelerator control system, with a SISO configuration. Some beamlines experience problems with horizontal beam shifts due to imperfections that can be caused by misalignment of the optics, or by uneven heat load on the mirrors. The feedback mitigates the problem by tracking the difference of the current signals from the exit slit baffles and moves the affected mirror pitch to keep the currents equal (i.e. stabilize the beam position). The pitch position is corrected at 0.33 Hz. The properties of the TANGO Feedback Device are used to configure the mirror pitch pseudo motor as the actuator and the normalized difference of the current signals as the sensor. The state of the heat absorber acts as the interlock device and the auto-restart mode is used to allow the correction to run whenever the beamline is taking light.

FUTURE DEVELOPMENTS

Several developments are planned for the TANGO Feedback Device in general, such as extending it to be a full PID controller and adding functionality to measure the response matrix by pulling on the actuators while measuring the sensor response. For the SOFB application, a dedicated development may also be needed to include the effect of the RF adjustment in addition to the corrector magnet settings on the beam position.

A hardware based FOFB application inspired by the scheme at SOLEIL [5] is planned for the 3 GeV ring and a reduced scale implementation of this is currently being installed for testing. The FOFB will make use of the fast (10 kHz) data stream from the same BPMs used as sensors in the SOFB. However, dedicated fast corrector magnets will be used as actuators. The Libera Brilliance Plus system is extended with custom SER modules having an RS485 interface to directly output the fast corrector set values. The feedback calculation itself is implemented in an FPGA running in the Libera Brilliance Plus GDX module. A TANGO interface to the GDX module will allow the configuration

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of the FOFB, i.e. the downloading of a response matrix and the position reference values.

The limited strengh of the new fast correctors means that the FOFB and TANGO-based SOFB will need to work together, as the FOFB corrector "kicks" averaged over a time window will have to be periodically off-loaded to the slow correctors, to prevent the saturation of the former. This will require the creation of a dedicated SOFB TANGO device with custom features not implemented in the current generic device, notably a communication channel to the power supplies of the fast correctors which can provide the time-averaged current setting commanded on the RS485 interface. The SOFB device must also know the response matrix of the FOFB system in order to relate these averaged power supply settings to the common BPM sensor data. This software project is currently under development and will proceed with the commissioning of the FOFB system.

CONCLUSION

A generic TANGO Feedback Device has been developed to fulfil numerous roles in the MAX IV control system. The device is fully configurable for SISO or MIMO applications and requires only that the sensor and actuator inputs/outputs are available as TANGO attributes. It can run synchronously with event stream data sent from the sensors or make its own polling of sensor values if required. For MIMO applications the device handles the inversion of the response matrix using SVD. State and alarm handling keep track of sensor and actuator validity, such as actuator saturation, and actions in case of external interlocks.

The TANGO Feedback Device is now the standard way of running the SOFB and tune feedback in the storage rings and the trajectory feedback in the linac. It has also found applications in the beamlines. Future work may be needed to make the device suitable for 100 Hz linac operation, and dedicated developments will be required to integrate the SOFB with the future FOFB in the 3 GeV storage ring.

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