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MULTI-DIMENSIONAL FEEDFORWARD CONTROLLER AT MAX IV

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Abstract

Feedforward control loops are used in numerous applications to correct process variables. While feedforward control loops correct process variables according to the expected behavior of a system at any given setpoint, feedback loops require measurements of the output to correct deviations from the setpoint. At MAX IV, a generic multi-dimensional input and output feedforward controller was implemented using TANGO Control System. This paper describes the development and use cases of this controller for beam orbit and optics corrections at MAX IV.

INTRODUCTION

MAX IV Laboratory is a fourth-generation light-source facility comprised of a 3 GeV storage ring, a 1.5 GeV storage ring, and a linear accelerator that serves as a full-energy injector to the rings and as a driver for the Short Pulse Facility. Yearly, the laboratory receives around 1000 users from academia, research institutes, industry, and government agencies through user access programs. With this, MAX IV has consistently delivered to users at 300 mA and 400 mA, on the 3 GeV and 1.5 GeV storage rings respectively.

The MAX IV distributed control system is composed of a three-layer architecture, in which TANGO [1] is the distributed control framework used on the middle layer to interface the equipment available in the facility and supervise their operation. The critical tasks are handled by dedicated hardware, and, from the client layer, Python and Matlab scripts can be used to interact with TANGO.

TANGO allows the implementations of devices to interface with real-world equipment and also to act on them according to a desired logic. In this context, TANGO devices can be used to implement controllers that read signals and actuate on other devices. Controllers act on system output in order to guarantee its stability and robustness by compensating for disturbances in the system. In this context, the controller can either react to errors on the output signal/setpoint or react to the input disturbance against an expected value. The first category is named feedback control, and the last one is feedforward control. While feedback control is more common in the literature and has obvious importance in stabilizing the system and satisfying its robustness requirements, feedforward control is required when large disturbances occur on a well-tracked system [2]. At MAX IV, the beam orbit and optics fall under the second category. These systems are controlled and have excellent tracking performance; however, they are subject to disturbances determined by insertion devices (ID) undulators positions. Thus, it became necessary to implement a Multi-Dimensional Feedforward device to compensate that.

The first section of this paper will describe the general multi-dimensional feedforward device implemented at MAX IV, and the second section will detail some of its applications on the accelerator.

FEEDFORWARD CONTROL

Generally, feedforward control measures the disturbances on the input beforehand and adjusts the manipulated variable in order to minimize the deviation on the controlled variable [3]. Furthermore, when the effects of the disturbances can not be eliminated by the feedback loop alone, the feedforward controller can improve the overall performance of the system [2]. In this context, an ideal feedforward compensator could be derived by multiplying the transfer function of the disturbance by the inverse of the process variable; however, this realization is frequently unfeasible, unstable, or non-causal [4]. Therefore, different feedforward devices implementations have been proposed in the literature. The TANGO feedforward device implemented at MAX IV has a minimalist approach to a multi-dimensional controller.

Overall, it is necessary that the systems are already stable and tracked before using a feedforward strategy. In this context, feedforward controllers are often used jointly with a closed loop feedback control [2, 4]. Figure 1 presents a generic diagram of a feedforward-feedback control loop in which the feedforward controller compensates the disturbances. Hence, disturbances do not travel through the whole control path, minimizing the risks of oscillations and over-corrections.

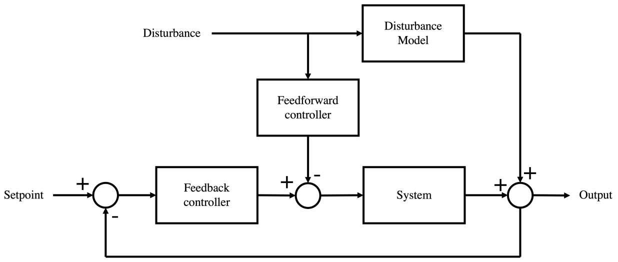

Figure 1: Block diagram of feedforward-feedback control system.

The ideal feedforward controller should compensate the disturbance according to its transfer function. Given that, $D(s)$ and $Y(s)$ are, respectively, the disturbance and the system output, $G_c(s)$ and $G_f(s)$ are the feedback and feedforward controllers and $G_p(s)$ represents the transfer function of the disturbance, then the control loop transfer function is given by Eq. (1). This equation should be zero to reject the

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disturbance [2].

$$\frac{Y(s)}{D(s)} = \frac{G_d(s) - G_f(s)G_p(s)}{1 + G_c(s)G_p(s)} \tag{1}$$

Hence, the feedforward controller transfer function is given by Eq. (2). With this, it is possible to notice that a strict modeling of the disturbance is necessary. However, modeling the disturbances thoroughly enough to reject disturbances altogether is unpractical at best and impossible for most applications. Thus, pragmatically, feedforward control is commonly added only for vital disturbances, and the feedback loop is responsible for compensating minor disturbances.

$$G_f(s) = \frac{G_d(s)}{G_p(s)} \tag{2}$$

Alternatively, feedforward devices can compute preemptive control actions according to mathematical approximations instead of deriving them from an analytical model. In this case, the controller action should compensate for disturbances according to any arbitrary approximation that fits the system. Hence, the feedforward controller response in time can be given by:

$$g_f(t) = f(d(t)) \tag{3}$$

in which $g_f(t)$ is the feedforward controller output, $d(t)$ is the disturbance in time and $f(\cdot)$ is an arbitrary function.

TANGO Device

The feedforward TANGO device at MAX IV has a general implementation in Python, with multiple-input and multiple-output (MIMO) support. It implements an arbitrary compensation based on mathematical interpolation, as modeling the disturbances was unfeasible. The device properties, described in Table 1, define the controller static characteristics, such as the sensors and actuators lists, and also contain the measurements of disturbances and actuator responses necessary to compensate them. Table 2 contains the attribute list and the commands available to interact with the device. The state-machine of the device contains the states described on Table 3 and behaves according to Fig. 2.

Table 1: TANGO Feedforward Device Configurable Properties

Property	**Description**
ActuatorsList	List of TANGO attributes used as actuators.
SensorsList	List of TANGO attributes used as sensors.
SensorsMatrix	Matrix with disturbance values for the controller response interpolation.
ResponseMatrix	Matrix with measured feedforward responses for the controller response interpolation.

Table 2: TANGO Feedforward Device User Available Attributes and Commands

Attributes	**Description**
sensors_last	Current values of sensors signals.
actuators_last	Current values of actuators signals.
actuators_next	Next values of the actuators signals, regardless of the state.
Time	Timestamp of last control loop action.
Commands	**Description**
Start	Start control loop.
Stop	Stop control loop.
UpdateTime	Trigger control action. It is a polled command.

Table 3: TANGO Feedforward Device States

State	**Event**
STANDBY	Control loop is not running.
RUNNING	Control loop is running.
FAULT	Critical error in the loop.
ALARM	Error to read or write to sensors or actuators.

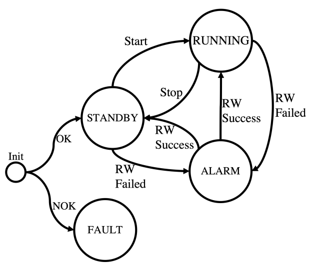


Figure 2: State-machine of the feedforward TANGO device.

The feedforward device was implemented as a Timed-Facade TANGO device [5]; therefore, by default, its main task is triggered periodically according to the polling period of the UpdateTime command, with a maximum frequency of 100 Hz. With this, as presented in the state-machine in Fig. 2, the controller should, ideally, be either RUNNING, so that the control action is performed whenever the UpdateTime is polled, or on STANDBY, when the correction is not applied. In this context, the UpdateTime polling period must be defined according to the system requirements. There are also two exception states: FAULT and ALARM. The first one occurs when the controller faces a critical issue, such as missing interpolation data or the sensors or actuators can not be found, and, thus, it can not be recovered without intervention from the operator. Otherwise, the ALARM state happens mainly when the sensors and actuators can not be read or written to for some reason, this error can be transient, and the controller might recover on its own.

The control action of this device is calculated according to Eq. (3) in which the $f(\cdot)$ function is a piece-wise linear interpolation of actuator values according to the sensor input. If sensor values are outside the range, nearest point interpolation is used instead to calculate the actuator value. In this case, the values stored on the SensorMatrix and ResponseMatrix properties are used to create the linear and nearest interpolators using SciPy [6], and, every polling cycle, a new actuator value is calculated by the interpolators given the sensor readings. In this implementation, it is important to notice that the output is the actual actuator value and not a correction added to the actuator's current value.

APPLICATIONS AT MAX IV

Orbit Correction

At MAX IV, the transverse stability of the beam is essential for the requirements of the light source provided by the facility. With this motivation, the orbit is rigorously controlled on feedback loops employing Libera Brillance+ for beam positioning monitors and hardware-based Fast Orbit Feedback (FOFB) control at 10 kHz. Also, an additional MIMO controller implemented in TANGO is used for Slow Orbit Feedback (SOFB) control at 10 Hz [7]. Still, the beam orbit is subject to distortions caused by the insertion devices undulators. In this sense, the IDs cause a disturbance on the beam orbit, which vary according to the configuration of the undulator, such as the gap distance between the magnet blocks and the phase translation [8]. In this context, the feedforward controller is used to minimize the beam orbit displacement caused by the insertion devices for any given configuration of the undulator.

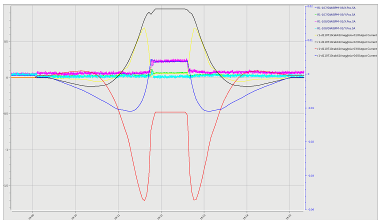


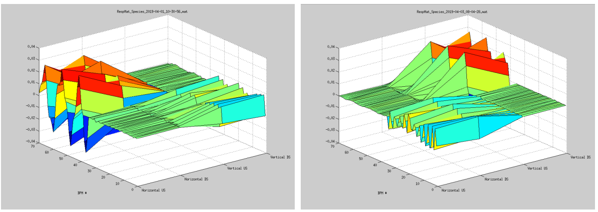
Figure 3: Actuator signals and beam position measurements for Species beamline ID.

For the orbit correction, the feedforward control uses the undulator gap distance as the disturbance and the correction magnets, coils, or strips as actuators. In this case, the TANGO device SensorList receives the position TANGO attribute of the insertion device, and the ActuatorList contains the current attributes of the TANGO device of the PowerSupplies that drive the correction devices. Thus the output current of the corrector magnets power supplies change, reacting the beam position variations, as seen in Fig 3.

The definition of the response matrix is an exhaustive process, presented in Fig. 4 in which the orbit is corrected to match the Golden Orbit, and the response matrix is calculated for each gap and phase combination.

```
Move ID to maximum Gap and initial Phase.
Correct the orbit.
Golden Orbit ← orbit.
for each phase in possible phases do
    while gap ≥ minimum gap do
        Correct orbit to match Golden Orbit
        ResponseMatrix ← Actuator values
        Move to next gap
    end while
end for
```

Figure 4: Process to define the feedforward response matrix.



(a) Distortion (b) Respones Matrix

Figure 5: Vertical distortion showed up in the horizontal plane and vice versa due to the Species beamline ID and the estimated response matrix. The horizontal up-stream(US), horizontal down-stream(DS), vertical US and vertical DS are the corrector magnets power supplies.

During the estimation of the response matrix, the distortion on the beam orbit can be measure on the corrector magnets as shown in Fig. 5(a) from which the response matrix on Fig. 5(b) was derived.

This step is essential and requires meticulous work since the quality of the control action depends on the final matrices. In this context, the number of gap positions used will also greatly affect the quality of the response since the interpolation between any two consecutive points is considered to be linear. If two adjacent gap positions are too distant, any non-linearity between them will be disregarded, which can significantly impact the overall control performance.

Since the displacement on the orbit also depends on the phase configuration of the undulator, the MAX IV Elliptically Polarizing Undulators (EPU's), which allow different phase modes, required modifications on the base feedforward device. The updated device can store and switch between multiple matrices in order to compensate distortions in different phases for any gap position.

Trajectory Correction A special case of the beam displacement appear on the linear accelerator beam trajectory because of the Short Pulse Facility (SPF). This issue arises from reasons similar to the ring orbit displacement, however, the system affected, in this case, is the linear accelerator instead of the rings. Hence, it is said that the injection to SPF causes a disturbance on the beam trajectory and the feedforward controller is used to correct that. As with the orbit correction feedforward devices, the sensor for this controller is the gap distance of the SPF ID and the actuators are the power supplies driving the correction magnets. The tuning process of the SPF feedforward is also the same.

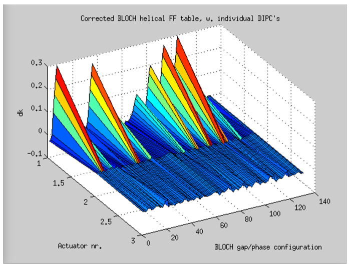
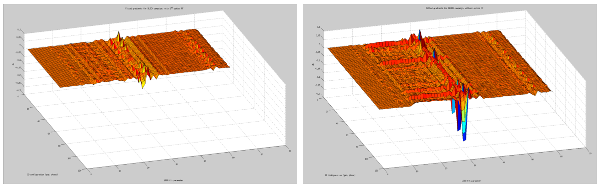


Figure 6: BLOCH ID feedforward response matrix for the helical phase mode.



(a) First FF tuning (b) No FF

Figure 7: Fitted gradients of the SQFO for various BLOCH ID gaps and phase combinations with optics feed-forward control and without optics feed-forward control.

Linear Optics Correction

Another issue with the insertion devices is the ID's intrinsic focusing, which affects the symmetry and periodicity of the ring lattice. Due to the physical characteristics of undulators, they cause a similar effect as the dipole edge focusing; thus, some distortion occurs when the beam traverses the periodic magnetic field in the ID. Furthermore, a small quadrupole focusing is also expected, as imperfections on the ID would cause its residual magnetic field integral to be different from zero [8]. Differently from the ID disturbance on the orbit, which results in a displacement of the orbit, the ID's residual quadrupole field causes a beam shape distortion.

In this case, similarly to the orbit correction, the sensors for the feedforward TANGO device are the undulator gap distances, represented by the ID device TANGO position attributes, and the actuators are the current attributes of the power supplies of the corrector magnets. However, the definition of the response matrix for the optics correction is done by using the Local Optics from Closed Orbit (LOCO) algorithm. The LOCO algorithm generates a linear optics ideal model with the open gaps and a working model with the closed gap. The magnet corrections are chosen so that the closed gap model matches the ideal one; thus, the opposite of the difference between the two models should be applied to the machine in order to compensate for the ID's disturbances. With adjusted feedforward response matrices, represented in Fig. 6, the feed-forward control on the optics subsystem can significantly reduced amplitude of the SQFO strengths as seen in Fig. 7.

FUTURE WORKS

According to continuous software development and support, the feedforward TANGO device is constantly under improvement. New features are delivered based on use cases requirements and stakeholders requests. Thus, some future development is already planned for in order to fulfill issues observed during operation and commissioning. In this context, a slew-rate capability is intended to be added to improve controlability of the corrector magnets. In mid and long term perspectives, the device can be modified to accept external triggers based on TANGO event system instead of periodic polling, which will allow it to be synchronized with the machine timing system; and it is possible to adopt an adaptive approach to build the sensor and response matrices using machine-learning or adaptive and predictive control.

CONCLUSION

The generic Multi-Dimensional Feedforward TANGO Device was implemented at MAX IX in order to improve the performance of the beam orbit and optics control. This device is suitable for both MIMO and single-input single-output (SISO) applications and can be used in any system which has a constrained operational region. The only requirements are that the sensors and actuators are available as TANGO Attributes and that the sensors and actuators' measurements are available to create the response matrices. In this context, the quality of the feedforward control is heavily dependent on the number of points available in the sensor and response matrices, as it directly impacts the quality of the interpolation. Likewise, the quality of the values on the sensor and response matrices also heavily impacts the quality of the control action. In this sense, they should be a careful calibration process to extract the correct matrices.

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