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REAL-TIME EMBEDDED FEEDFORWARD CORRECTION FOR SIRIUS UNDULATORS

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Abstract

SIRIUS, the Brazilian 4th generation synchrotron light source, has been in operation since 2020. Over time, insertion devices (IDs) are expected to populate its straight sections. To supress edge effects from undulators and support overall beam stability, a feedforward correction system is currently available through EPICS layer for the first installed ID. However, performance could be improved by adopting a lower-level solution with higher actuation rates and reduced jitter. To address this, a new approach has been developed using hardware technology already available: control system nodes based on BeagleBone Black platform, which integrates both embedded linux and dedicated real-time processors within the same SoC. This setup is able to update current setpoints up to 1 kHz and aiming to be scalable. This paper presents an overview of the system's architecture and objectives, first results with IVU and VPU undulators as well as future developments and improvements.

INTRODUCTION

SIRIUS has been opened to external users since March 2023 and has 10 beamlines fully operational and 4 under commissioning or construction [1,2]. Several subsystems contribute to beam stability, providing a set of important parameters that must be achieved and maintained to ensure photon beam and experimental viability. Among those subsystems, orbit stability relies on slow orbit feedback (SOFB) and fast orbit feedback (FOFB), this one operating at 48 kHz update rate with 1 kHz cross-over frequency [3].

Commissioning and titular insertion devices (IDs) have been added to SIRIUS storage ring along these years, as listed on Table 1, and some more are expected to be installed in the future. The beam dynamics in an insertion device must be handled in order to minimize the impact on the overall beam stability. The correction system responsible to compensate IDs disturbances are known as feedforward correction, this kind of devices are being employed to improve stability in other synchrotron facilities as well [4,5]. To cancel the first and second undulator field integrals, operation with feedforward correctors mitigates angular and offset disturbances/perturbations.

Both in-vacuum (IVU) and vertical polarizing (VPU) undulators consider vertical and horizontal correctors, therefore requiring four independent current power supplies. Delta undulator operates with two additional skew quadrupoles, which adds two additional channels.

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Table 1: Undulator Beamlines Currently Operating at SIRIUS With Feedforward Correction

Beamlines	Undulator type
SABIA	Delta
EMA	In-vacuum (IVU)
PAINEIRA	In-vacuum (IVU)
CARNAUBA	Vertical Polarizing (VPU)
CATERETE	Vertical Polarizing (VPU)

FEEDFORWARD CORRECTION TOPOLOGY

Different system architectures have been evaluated considering a standalone solution, independent of EPICS and network layers. In addition, a platform already in use in accelerators' subsystem would be preferable, optimizing spare parts and technical know-how sharing. Fast orbit feedback (FOFB) system integration for further studies is also a valuable requirement, yet optional.

Concerning the controller, both control system node controller (Beaglebone Black, with embedded Linux and real-time cores) [6] and microTCA AFC board (FPGA-based) [7], either shared with FOFB or a dedicated one, were considered. For the actuators, fast correctors FOFB power supply [8] (LAMP, up to ±1 A, in-house developed) could be a candidate as well as SIRIUS standard low-power power supplies [9] (FBP, up to ±10 A, in-house developed) largely used for other accelerators' magnets such as slow correctors and trims.

The proposed modular topology is defined by the BeagleBone Black single board computer and SIRIUS' low-power power supplies, as shown in Fig. 1, which leads to system decoupling, resource and development efforts optimization.

Each module interfaces with up to four current channels, grouped together by construction in one single crate with a RS-485 channel as control interface, making it possible to adjust all current setpoints independently and synchronously at once.

Motion control loops for recent IVU and VPU undulators run on dedicated Beckhoff PLCs and data streaming for feedforward application has been internally developed. Delta undulator is controlled by a Rockwell PLC and has its feedforward loop currently running on high level applications. Incorporate Delta correction in this topology will be addressed in the future to improve its performance.

Also, a secondary input from FOFB subsystem has been considered in hardware requirements, machine studies are

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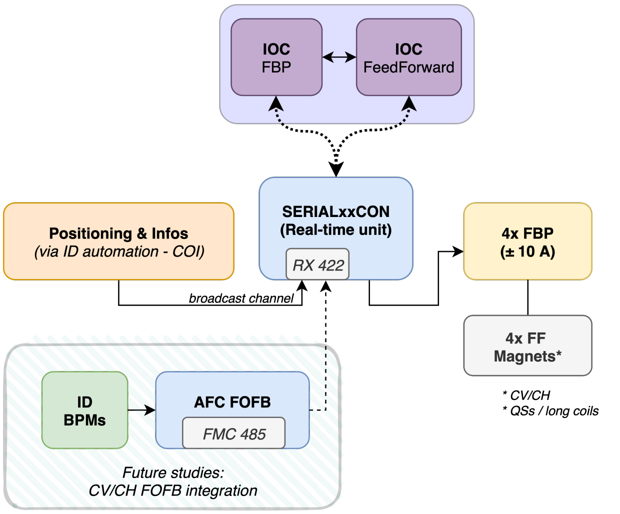

Figure 1: Block diagram for undulators' feedforward correction, based on BeagleBone Black embedded system controller and SIRIUS power supply family.

under consideration for including feedforward magnets into fast orbit correction loop.

SYSTEM DESIGN

Requirements and Limitations

System requirements have been established, also considering integration with undulator motion controller. Motion parameters and variables are internally updated at 1 kHz and streamed to feedforward controller at 1 Mbps and big-endian mode through Beckhoff PLC module EL1262-001. The dataset has 51 bytes, packing a set of chosen variables that shall be considered for feedforward applications:

- Operation/Polarization mode
- Current gap/phase (kparameter)
- Moving speed
- Current position monitor, for each axis
- Current position setpoint, for each axis
- Motion controller timestamp (epoch)
- Motion controller cycle counter

Given that power supply presents a mature and modular high-level application and considering that feedforward controller should be dedicated to act with a latency as lower as possible, all monitoring and minor adjustments should be done through regular power supply EPICS IOCs and interfaces. feedforward controller must be limited to adjusting setpoints only. Firmware and software developments take into account the need for sharing a serial communication line for the power supply interface.

An important feature is to recover the feedforward application automatically after a power cycle, which also implies storing the correction table in local non-volatile memory to reduce high-level and network dependencies.

Firmware and Software Developments

Once the application relies on determinism for applying a current setpoint after receiving data streamed from the undulator motion controller, firmware structure must ensure that critical tasks must not be allocated on BeagleBone Black Linux core. Programmable real-time units (PRUs) [10] could handle this task. Running at 200 MHz, one core has been in use for power supply communication and the second one is dedicated to the feedforward application.

Data and flow control are shared among processors (main ARM core and both PRUs) through shared memory and correction tables are transferred to an external data RAM (600 kbytes reserved at DDR) at application startup. Task distribution and intercommunication are shown in Fig. 2.

The development can be splitted into three layers:

- PRU firmware (PRU level): C-coded, handles incoming data from undulator PLC, chooses corresponding table point and requests to send it to power supplies
- Feedforward Module (ARM/Linux level): C-coded and Python-integrated, shared memories management, pack/unpack commands and data between processors (ARM/PRU)
- Feedforward bridge (ARM/Linux level): Python-coded, bridge for feedforward application to EPICS IOC.

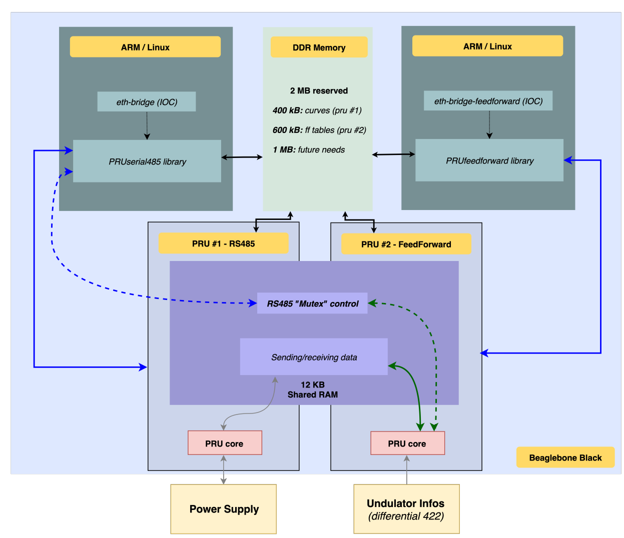

Figure 2: System architecture considering both regular power supply application and feedforward application, hosted and sharing resources on the same BeagleBone Black.

Table Mapping

As mentioned previously, 600 kbytes have been reserved on DDR memory for correction tables data. Current setpoint values are stored and sent to power supplies as floating variables, what leads to a total of 150000 available current setpoints. These available setpoints are splitted to the number of tables that are initially configured in the application, as shown in Table 2. Each of them can be directly linked to

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an undulator operation mode and current setpoints can be indexed and selected accordingly during feedforward control loop execution.

Table 2: Available Table Configuration for Different Operation or Polarization Modes, Configured Automatically on Application Startup

Number of tables	Floating points per table	Setpoints per power supply
1	150000	37500
2	75000	18750
3	50000	12500
4	37500	9375
5	30000	7500
6	25000	6250

Linear interpolation is currently performed at ARM level before storing data points into DDR memory. This is performed when the configured table size is smaller than the allocated memory map.

SYSTEM AND INTEGRATION RESULTS

The solution was designed, implemented, replicated and currently operating with four undulators at SIRIUS: IVUs and VPUs. System characterization was performed, resulting in 32.95 µs latency and 127 ns jitter, regarding streaming data packet end and start of power supply command transmission.

Total delay is estimated to be ~578 µs, considering the complete data chain and latencies from undulator PLC to power supply control loop cycle for current adjustment.

Embedded feedforward correction is defined individually based on machine studies shifts for correction tables evaluation. Once it was integrated to each of SIRIUS' recent undulators, the results have shown its contribution to beam stability, as shown in Fig. 3, specially to prevent FOFB saturation and orbit spikes [11] during IVU or VPU gap variations.

FUTURE APPROACHES

Even though the feedforward in-hardware application is already running properly and is ready for modular expansion, it is possible to point out system improvements to enhance performance, runtime diagnostics and availability.

- To compensate system and vacuum chamber latencies, current setpoints can be anticipated using predictions based on motion models. Performance can then be improved by achieving better alignment with the FOFB control loop
- Expose more local variables to operating system as well as implement setpoint fast logging, as a runtime acquisition interface
- Design a solution for Delta undulator, which is based on Rockwell PLC controller and has five different polarization modes, thus reducing the setpoints per power supply shown in Table 2

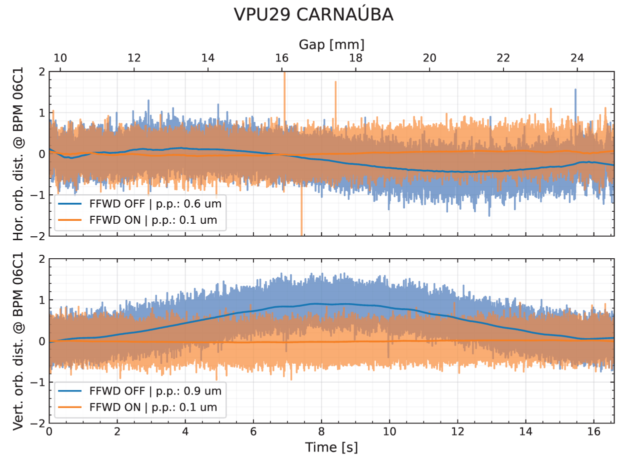

Figure 3: Orbit distortion in a subsection right after CARNAUBA VPU undulator, where IMBUIA beamline is located. BPM 06C1 is not considered for FOFB control loop.

CONCLUSION

SIRIUS facility has been under constant upgrades to reach accelerator's project parameters and expand available beamlines and experiments. Insertion devices have been installed in the machine along these years, which may perturbe beam stability. Adding feedforward correctors with modular local controllers brings important features such as determinism and robustness, that contributes to overall beam stability. Further improvements have been traced and new units are expected to be installed in early 2026 with the SIRIUS' new undulator, UE-44. Considering upcoming SIRIUS beamlines and ORION project [12], more IDs should be installed in the storage ring for the next decade. A robust and scalable system for feedforward correction is essential to ensure beam dynamics stability for the beamlines.

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