

SOFTWARE ARCHITECTURE FOR THE LHC BEAM-BASED FEEDBACK SYSTEM AT CERN

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Abstract

This paper presents an overview of beam based feedback systems at the LHC at CERN. It will cover the system architecture which is split into two main parts – a feedback controller (OFC) and a service unit (OFSU). The paper presents issues encountered during beam commissioning and lessons learned including proposed follow-up from a recent internal review which took place at CERN.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN employs beam-based feedbacks for the closed-orbit and betatron tune parameters to facilitate setting-up of new operational scenarios to reach a reference situation allowing the feed-forward, simplify daily machine operation due to slow parameter drifts and ensure proper functioning of beam cleaning systems.

The required closed-loop feedback bandwidth at the LHC of ~1 Hz allowed using commercial hardware with large amounts of memory which proved advantageous with respect to the controller’s numerical complexity with 1000’s of input signals.

FEEDBACK ARCHITECTURE

The feedback controller handles input data from about 118 front-end computers (FECs) via CERN’s technical network backbone at a data rate of typically 25 Hz (UDP protocol). Due to stability requirements and the distributed systems involved, global control loops rather than local ones were implemented. This minimised the need for inter-process communication and kept the overall code structure more compact and maintainable [1].

Using CERN’s Ethernet-based technical network infrastructure rather than a dedicated and costly RT-network infrastructure was justified by experiments including initial prototype tests at the SPS [2] verifying worst-case network latencies well below 1 ms (~1% if the required bandwidth). In fact most of the encountered latencies occurred due to non-RT behaviour of FECs or overload of local network switches rather than the technical network infrastructure itself. The overall numerical complexity, medium to firm real-time requirements and availability of high-performance computing hardware, enabled splitting the feedback system into two functional parts as illustrated in Figure 1 below.

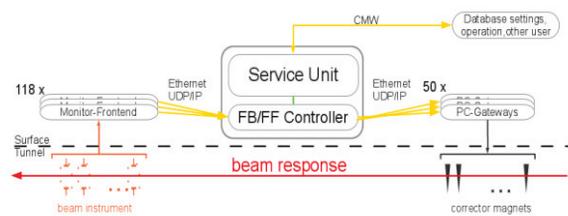


Figure 1: Overall functional diagram of the LHC beam feed-back loops between the feedback (OFC) and the service-unit (OFSU).

OFC SERVER

Aiming for maximum robustness, the OFC server was designed as a simple input-processing-output streaming server, executing a limited number of concurrent threads. The aim was reducing the dynamic load to quantify and guarantee compliance within the given real-time constraints. Consequently, conditional statements, jumps and semi-random/user-driven function execution were avoided whenever possible. The OFC process (as the OFSU) is executed on a multi-CPU/multi-core HP Proliant server (DL380 G5) with a real-time enhanced Linux (SLC5) kernel. Where possible, CPU shielding technique is used and the threads pinned to a given core to avoid undesired process context switching.

The two network interfaces on the Proliant servers are for the OFC server used for 1) communication with beam instrumentation and power converter front-ends over UDP and 2) to exchange data over a private network link with the OFSU server using a mixture of UDP and TCP protocols as described later in this article.

Figure 2 below shows an overview of the OFC server.

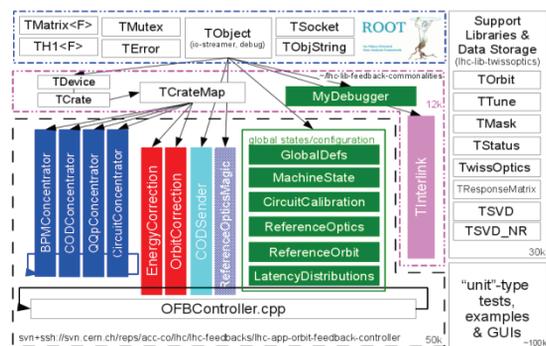


Figure 2: OFC software overview. The pink box to the right shows the ROOT-based “TInterlink” library used for the OFC/OFSU communication.

A large part of the OFC’s resources is spent on data consistency checks. A specific issue for the OFC is implementing strict rules on the maximum latency for UDP packets from the many distributed FECs to the same

UDP port on the Proliant machine (66 are used for beam position only). Presently the time-stamp for the first packet to arrive is used to start a 10 ms acceptance window and packets outside are discarded. Moving a vast majority of the front-end software systems to real-time enhanced Linux during LS1 is expected to get rid of priority-inversion issues and allow additional diagnostics to be put in place.

When the OFC was first put into operation, a stable Linux device-driver for the CERN-standard timing-receiver was not available and solutions had to be found for the reception of beam energy which is required for scaling trims. In the end a majority voting was used on the values received from several tune front-ends. During LS1, a solution based on a standard CERN timing receiver will be sought.

A separate issue is related to operation during periods where data values decoded from individual system packets were seen to be invalid (Nan's etc). Although happening extremely rarely these errors must be caught in order to avoid transmitting non-physical trims to power-converters likely leading to beam dumps. It is believed however that some of the error checking with pre-defined limits can be moved to the individual BPM and Tune FECs leaving the OFC to handle the global feedback calculations and transmit trims to power-converter systems.

OFSU SERVER

The Orbit Feedback Service Unit (OFSU) is a FESA-based [3] control server acting as the visible part of the feedback on the LHC control system. As part of the FESA framework, the class-design is stored as a large XML document and transformed through XSLT design template to produce C++ source-code. The framework offers access to device fields and timing libraries as well as handling persistent data fields through XML files. A schematic overview of the OFSU server can be seen in Figure 3 below.

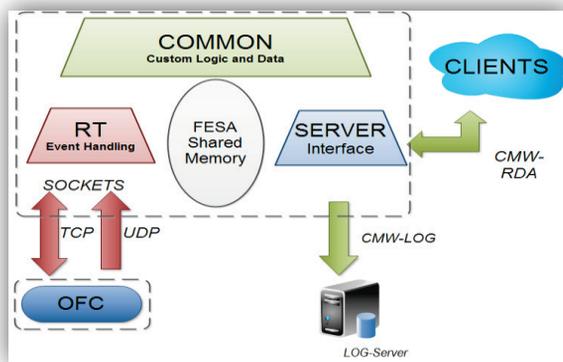


Figure 3: OFSU schematic overview showing the TCP/IP-based CMW interface to operational clients.

The OFSU is responsible for the following tasks for the LHC Orbit & Tune feedback system:

- Triggering of the specific feedback control related actions based on synchronised LHC Timing events or client requests.
- Orbit & Tune Feedback Settings management (ex. Beam Optics computation used for the beam correctors)
- Data monitoring access for Operators to the current orbit, tune and supplementary diagnostics data.
- High-level DB interface (periodic storage of status and orbit positions)
- Matrix inversion for beam response to dipole corrector magnets

The OFSU server is by far the largest and most complex FESA class known at CERN due to the number of involved source-code files (>200), source-code lines (>30000) along with the long list of variables it needs to operate the OFC and provide measurement results to operational clients. Purely due to the OFSU's size (number of variables and real-time actions involved) it is considered mandatory to re-factor its design and move certain points to higher-level layers in the control-system. As an example, it is believed possible to move certain aspects of the response matrix calculation to a dedicated Java-based application server. Allowing for a constant communication-load irrespective on the number of clients, a CMW proxy [4] solution is also being investigated and this can for the OFSU be implemented at a later stage closer to the LHC start-up.

OFC/OFSU COMMUNICATION

The open-source ROOT object-oriented framework developed and maintained at CERN is used as base for serialising objects between the OFC and OFSU servers (see Figure 4 below) for reasons including portability handling for various hardware architecture options (notably the endian-ness based on 32- vs. 64-bit) as well as a streamer implementation which handles the complex data structures and communication protocol while maintaining backward compatibility.

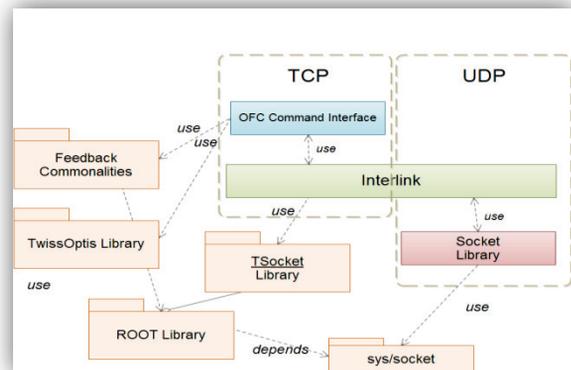


Figure 4: Communication diagram for the OFSU system.

Ideas for replacing the present “TInterlink” libraries with more “standard” C++ libraries supported by BE/CO are under consideration.

OFC/OFSU TESTING

To ensure a minimum of integration testing, a small test suite was set up on the BE/CO Controls Test Bed [5]. The Controls Test Bed is based on a Continuous Integration Server (Atlassian Bamboo [6]), on which Java-based tests can be run.

The current test suite covers mainly small integration tests, which providing simple gets/sets from and to the OFSU FESA class. Those tests were of limited use, since the reaction of the OFC/OFSU system depends on actual beam conditions, when the tests are run. Nevertheless, this approach proved its basic worth and should be extended in the future. To further improve, a better encapsulation of some functionality would have to be foreseen making it possible to provide external input like timing events or BPM readings to the system. All in all this appears feasible with a limited amount of work although some parts of the feedback loop might have to be slowed down.

Another approach for testing, which is highly recommended for the future, is unit testing on the C++ level. The ‘Google test’ framework [7] is under investigation for several CERN products (FESA3, RDA3) and might be a candidate for this project also.

OPTICS AND REFERENCE HANDLING

The reference orbit is not constant along the LHC beam cycle; it changes mainly close to the interaction points where beam separations and crossing angles depend on energy and on the beam optics. There are typically 10 different reference orbits defined for a nominal cycle, and the orbit feedback interpolates linearly between the references.

The references themselves are stored in a central LHC settings database. They can be manipulated with a dedicated GUI. The references are downloaded to the OFSU in preparation of a ramp or of an optics change (squeeze). Dedicated timing events that are distributed synchronously to the ramp and squeeze are used to trigger the OFSU to load the next reference change to the OFC.

The basic optics information is stored in the same settings database. In preparation of beam injection the required optics sets are fetched by the OFSU from the database using a script and the orbit response matrices and their SVD inverse are built from the optics information. The OFSU downloads the appropriate response following a manual trigger from the control room. An automated loading mechanism was implemented but not used operationally. During the present long-shutdown ideas for moving the optics handling to higher-level in control system have started and would possibly allow an extended use of the LHC sequencer. This would likely also alleviate the presently

limited number of optics that can reliably be handled on the OFSU server.

TUNE FEEDBACK ISSUES

The main task for the feedback system is keeping the closed-orbit position as close to the reference-orbits as possible but it also acts on the betatron tunes. Highly sensitive electronics allows measuring with hardly any excitation required. The tune values required for feedback are derived using a fitting of the signal based on a peak-finder. A problem for the tune-feedback arrived when the instabilities required transverse oscillation damping (using the ADT system provided by the RF group). The coherent signal was here polluted by additional frequency lines and Figure 5 below shows the difference on the signal quality which meant that the tune feedback was switched off under certain operational conditions.

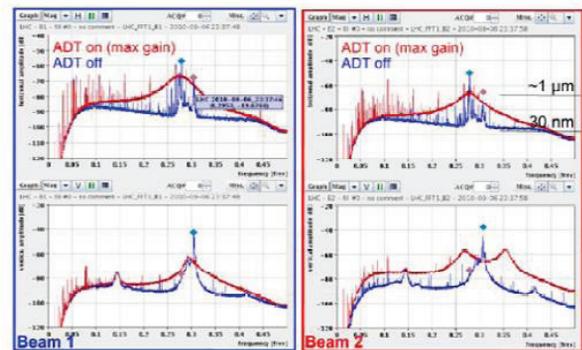


Figure 5: Comparison of tune signals with transverse damper on (red) and off (blue).

Work is on-going to commissioning tune measurement on dedicated bunches for which the transverse damper is inactive allowing the tune feedback to work correctly.

SYSTEM PERFORMANCE

The orbit feedback system is switched on continuously during the ramp and optics squeeze phases of the LHC to ensure appropriate stability of the orbit at all critical places of the LHC ring. To minimize the feedback workload and be more tolerant to possible time-outs or stops of the feedback, the real-time corrections are fed-forward into the power-converter functions since a large fraction of corrections are reproducible and drift rather slowly on the time scale of weeks. This allows operating the feedback with rather moderate bandwidth avoiding instabilities of the control loop due to optics errors, jitters in data collection etc. Figure 5 below indicates the typical bandwidth achieved at injection which can be seen to be much below 1 Hz but adequate for normal beam operation.

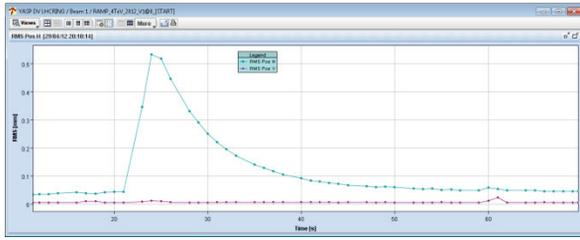


Figure 5: Bandwidth test of the orbit feedback at injection; the vertical axis is the orbit rms in mm, the horizontal axis displays the time in seconds. After deliberate orbit degradation at time 12s, the orbit feedback damps the perturbation within ~30 seconds.

The stability and reproducibility of the orbit that is achieved with the feedback is excellent and well within the system specification. Figure 6 shows the feedback performance during an LHC energy ramp (the duration can be seen to be around 770 seconds). More details concerning the overall system commissioning and feedback performance can be found in [8] and [9].

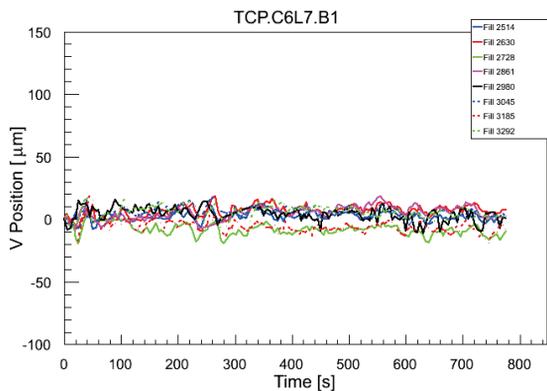


Figure 6: Stability of the vertical orbit at a primary collimator for a number of LHC ramps. The stability is better than 20 μm , corresponding to less than 10% of the RMS beam size.

CONCLUSION AND OUTLOOK

The long shutdown 1 has allowed looking at the OFC/OFSU systems with fresh eyes. A small team between BE/BI and BE/OP has been put in place team to understand the details of the existing system and propose and implement changes to new OFC and OFSU systems. Several areas are identified where improvements can be made allowing for long-term use of these vital systems. As an example, the presently used operating system SLC5 (of which a special version is used for the OFC/OFSU) is considered obsolete and work will therefore start to produce versions of OFC and OFSU servers that works under CERN's standard SLC6 including support for the timing receiver. For the OFSU server this will likely mean porting the system to the new FESA3 framework profiting from additional functionalities in terms of multi-threading and middleware. Extended diagnostics and error handling from both the OFC and OFSU are being looked into, warning LHC operators when issues are starting to

build up. Related to this, large/complex matrix handling will be moved to higher layers in the control system where exceptions can be signalled more clearly through operational GUIs.

Finally, an OFC test-bed simulating the behaviour under controlled conditions including latencies and error recovery would provide a simplified model of the LHC and allow testing several scenarios.

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