DSP-BASED LOW LEVEL RF CONTROL AS AN INTEGRATED PART OF DOOCS CONTROL SYSTEM

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Abstract

The Distributed Object Oriented Control System (DOOCS)[1] has been developed at DESY as a control system for FLASH (Freie-Elektronen-LASer in Hamburg)[2]. The DSP based low level RF control system is one of the main subsystems of the linac. Several DOOCS device servers and client applications have been developed to integrate low level RF control into the FLASH control system. The DOOCS approach defines each hardware device as a separate object and this object is represented in a network by a device server, which handles all device functions. A client application can have access the server data using the DOOCS application programming interface (API). A set of generic and specially devoted programs provide the tools for the operators to control the RF system. The RF operation at the linac is being automated by the DOOCS implementation of finite state machine servers.

INTRODUCTION

FLASH linac is designed to accelerate electrons to an energy up to 1 GeV. The injector consists of a laser-driven photocathode in a 1.5-cell RF cavity operating at 1.3GHz with a peak accelerating field of 40MV/m on the cathode. The electron injector section is followed by a total of five 12.2m long accelerating modules containing eight 9-cell superconducting niobium cavities each. Six undulator sections are installed to operate the machine as vacuum ultra-violet free electron laser for user experiments. In the RF system for the FLASH linac each klystron supplies RF power to up to 32 cavities. The requirements for gradient and phase stability are of the order of 10^{-4} and 0.1 degree respectively. The RF control system employs a completely digital feedback system and it provides field control of the vector sum group of cavities and cavity tuning[3]. It uses the accelerator timing events for the synchronization of the feedback and ADCs for diagnostics. The hardware of the digital feedback for 32 cavities (one RF station) consists of a DSP board with 8 Gigabit Link interfaces, four 8-channel ADC boards (14-bit, clocked at 1MHz) with Gigabit Link interface, and one 8-channel DAC board with Gigabit Link interface. A function generator with VME interface drives a vector-modulator which produces the local oscillator (LO) signal generated from the 1.3GHz.

PRINCIPLE OF RF CONTROL

The digital feedback system for the vector sum control has been developed with the goal of flexibility in different control algorithms (figure 1). This allows to measure and calibrate the accelerating field vector sum with high precision and invokes exception detection and handling.
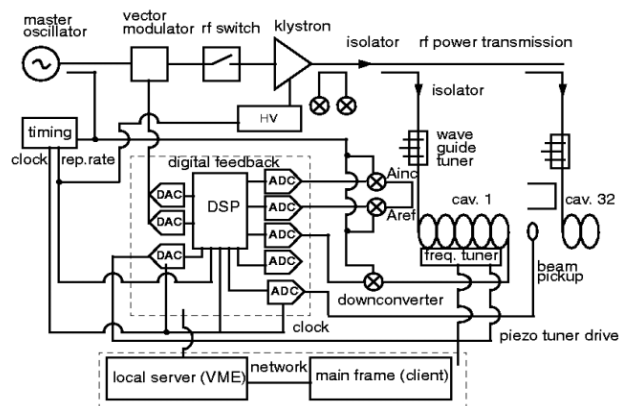

Figure 1: Configuration of the LLRF Control System.

The digital feedback controls in-phase and quadrature component of the cavity field [3]. High frequency probe signals are used to measure the accelerating field in the individual cavities. These 1.3 GHz signals are converted to 250 kHz and sampled by the ADCs with 1 MHz rate, i.e. two subsequent data points describe I and Q component of the cavity field. The samples are scaled and rotated to compensate the phase delay in the cable and calibrate the fields in the individual cavities. Then the sum of individual field vectors is calculated and rotated to adjust the loop phase. The vector sum is filtered by the low pass filter and the feedback algorithm applies the proportional gain to the regulating error values. A feedforward table is added to the value of the calculated control action. The real and imaginary part of the calculated table are converted by the DACs separately and control the RF vector, applying the correction signal to the vector modulator.

IMPEMENTATION OF DOOCS FOR THE RF CONTROL

DOOCS supports multiple communication protocols and the feature to include new protocols. This allows to integrate the various accelerator subsystems with their own features and protocols and design a uniform control system for the whole accelerator based on a client-server model.

The real time low level RF control system is one of the accelerator subsystems. It is integrated with the FLASH control system, by the development of several DOOCS servers. The architecture is based on three main layers. On

the lower layer all services with device connection are located. Application programs with user interface are in the top layer. The middle layer contains high level services. The DSP server controls the DSP board hardware and contains the required functionality for managing the real-time digital feedback subsystem. Other servers relates to local oscillator signal generation, RF system calibration, waveguide tuner control, cavity resonance frequency control, timing control, the ADC server for measurement of probe, forward and reflected power, and hardware and software diagnostics.

DSP Server

The control system for the cavities which are driven by a single klystron is considered as a functionally complete unit of the RF system. The feedback algorithm is implemented in the DSP system. The digital signal processing in turn gets its parameters from the DSP server. The DSP server software handles: generation of set point and feed-forward tables from basic settings, rotation matrices for I and Q of each cavity, loop phase constant, start-up configuration files, feedback parameters and exception handler control parameters. The interrupt service routines are used to start the data reading from the ADCs via Gigabit Link interface. The parameters of the feedback algorithm are modified by the DSP programs in the time slot between beam macro pulses. It allows to safely change the parameters of the control algorithm. Due to time critical requirements all programs were developed in assembly language to minimize computational delay.

The DSP server was designed based on DOOCS approach. It receives requests from the client application programs, does required actions and sends the reply to the client. The functionality of the server gives the user the opportunity to down/upload data into the DSP (feedback algorithm parameters) and download and start the DSP program. The DSP server maintains the cavity field gradient settings, exploring the number of parameters defined in terms of amplitudes and phases of the RF system data. It calculates and adjusts the set of the feedback algorithm parameters in accordance with the required field gradient value.

ADC Server

The ADC board has 8 channels of 14 bit converters with an integrated sample and hold unit. The sample and hold receives a signal from an external 1 MHz clock. All 8 channels are sampled at the same rate and at the same time. The data acquisition is started by an external trigger. This trigger is controlled by the FLASH timing system. The number of samples to take is programmable in the ADC server. The ADC server combines two operation modes: a digital scope mode and a phase and amplitude detection mode. In the digital scope mode the current, e.g. the last samples taken, as well as old samples from the buffer memory of the ADC can be read. With the trigger rate of the ADC, typically 10Hz, a programable point of the last samples is stored in a long time archives. This is the standard archives of the system. It stores the values together with a timestamp in a ring buffer. Storage is controlled by a filter setting. Long time drifts can be measured in this mode, for instance. There is a provision to store the last samples in an archive too. Read-back is done in the same way as the current reading. In an additional argument to the server the time stamp of the archived samples are specified. In the phase and amplitude mode all the mentioned functions are available, too.

Function Generator Server

The FLASH has local reference oscillator for both basic 1.3GHz frequency generation and for driving the system that supplies down conversion of the RF monitor signals and sampling gates that produce the I and Q components of the monitored signals. Generation of LO signal is provided by 8-channel DAC board (DAC8) and is managed by a DOOCS server. The server provides various modes of operation for RF cavities. DAC8 programming includes interface initialization, operational mode settings, data writing and reading and status reading.

Timing Server

Timing events from the FLASH linac are used to synchronize all accelerator subsystems and are managed by the timing server. Programable timers are triggered by these events to generate the start pulses for the klystrons, DSPs or ADCs. A timer unit provides several independent output channels. Some machine parameters that change from macro pulse to macro pulse need to be delivered in time to run all digital feedback loops in parallel. The data words from the telegrams are stored in a dual port memory. This information is readable from the local connected computers.

LLRF OPERATION AUTOMATION SCHEME

Finite state machines (FSMs) model time-discrete systems with quantized input and output data flows. The complex FLASH LLRF system is not time-discrete and quantized, but an appropriate set of procedures can make it look discrete to the outside world. Figure 2 depicts the major elements of the FLASH LLRF automation scheme. The continuous LLRF system is accessible only via procedures that execute defined tasks like 'measure data quality', 'apply loop phase correction' or 'ramp-up the feedback gain'. Every procedure returns a quantized result like 'data quality is good', 'loop phase corrected' or 'feedback gain successfully ramped'.

Based on this discretization, the controller FSM (see figure 2) can implement a strategy that meets the operator's

specifications. The FLASH LLRF automation scheme has been developed with the premise that the FLASH is a developing system that requires a flexible automation with easily reconfigurable finite state machines and a flexible procedure server that allows to quickly adapt the system to a changing environment. Subsystem experts shall be able provide their procedures without awareness of the automation scheme.
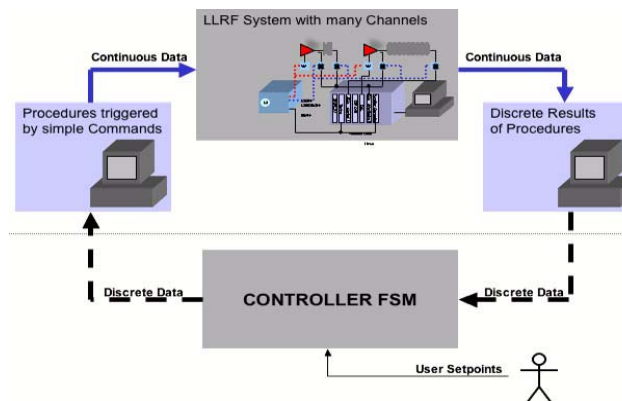

Figure 2: Quantization of the LLRF system by means of procedures.

Therefore we developed a three-layer approach to attach procedures to the automation scheme by introducing procedure servers. The procedure server (middle layer) presents itself towards the controller FSM (top layer) as whatever is the preferred communication medium of the FSM implementation. The procedures (bottom layer) are compiled programs that are executed by the procedure server on request. The subsystem expert is free to choose any toolbox for the implementation of his procedure, he only has to comply to a convention that transports results of the procedure back to the procedure server. This can easily be done via a local file system, if the procedure server resides on the same physical server as its procedures. An implementation of the presented FSM is permanently running at FLASH and is available to the operators. It allows experienced operators to change procedures and conditions for state-transitions on the fly via the user interface of the control system.

APPLICATION TOOLS

A set of generic and specially devoted programs provide the tools for the operators to control the RF system. Some of them are created based on the MATLAB, LabVIEW or ROOT, others are in-house developed DOOCS client applications. However all of them use the DOOCS API to access the data. The application software includes automated operation of the frequency tuners, calibration of the vector-sum, phasing of cavities and adjustment of various control system parameters such as feedback gains, feed forward tables, and setpoint correction during cavity filling. Extensive diagnostics informs the operator about cavity quenches, cavities requiring manual tuning, and an excessive increase in control power.

Adaptive Feedforward

FLASH linear accelerator is operated in pulsed mode with repetition rates of (currently) 2-10Hz and RF-pulse lengths of 1.3ms. As a consequence, field errors are to a high degree repetitive and can be pre-compensated. The pre-compensation of repeating errors is accomplished by the addition of feedforward-tables on top of the drive estimated in the feedback-system. Source of repeating errors are e.g. the Lorentz-force detuning and the beam-induced field. A perfect feedforward table would be the inverse of the transfer-function built from the cavities and the surrounding infrastructure applied on the setpoint table. Therefore feedforward-generation is an inversion problem and exposed to instabilities connected to the inverse of stable, (even non-linear) transfer-functions with many poles and zeros. The most naive approach, namely building the feedforward table by adding the feedback on top of the feedforward table of the next pulse turns out to be instable after a few pulses. Digital, linear filters do not seem to solve this problem entirely. At FLASH, a modification of this approach that is best described in a cookbook-fashion is in use for feedforward generation: 1) time-inverse the feedback signal, 2) apply a digital low-pass-filter on the reversed signal 3) time-inverse the filtered signal and 4) add the result on top of the existing feedforward table. An investigation of this approach shows that this approach is equivalent to applying a (inherently instable) low-pass filter with negative frequency on the feedback signal (non time-inversed) with the boundary condition of zero amplitude at the end of the pulse. The algorithm is very stable for corner-frequencies of the time-inversed low-pass below 10kHz.

CONCLUSION

The new DSP based RF control system is running at FLASH linac more than two years and demonstrates the successful operation. LLRF control has been integrated with FLASH control system with a standard DOOCS interface. First experimental version of automation services are running as well. Based on experience in the operation of the FLASH further automation will be developed in the near future.

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