BEAGLEBONE FOR EMBEDDED CONTROL SYSTEM APPLICATIONS*

S. Cleva, L. Pivetta, P. Sigalotti
Elettra - Sincrotrone Trieste S.C.p.A., Trieste, Italy

Abstract

The control system architecture of modern experimental physics facilities needs to meet the requirements of the ever increasing complexity of the econtrolled devices. Whenever feasible, moving from a distributed architecture based on powerful but complex and expensive computers to an even more pervasive approach based on simple and cheap embedded systems, allows shifting the knowledge close to the devices. The BeagleBone computer, being capable of running a full featured operating system such as GNU/Linux, integrates effectively into the existing control systems and allows executing complex control functions with the required flexibility. The paper discusses the choice of the BeagleBone as embedded platform and reports some examples of control applications recently developed for the Elettra and FERMI light sources.

INTRODUCTION

The Elettra Sincrotrone Trieste research centre manages two light sources: Elettra, a 2.4 GeV third generation synchrotron [1], and FERMI, a 1.5 GeV seeded Free Electron Laser (FEL) based on a linear accelerator [2]. The large number of subsystems that make it possible to generate and deliver the photon beams to the users, require an up-to-date distributed control system technology.

The ever growing capabilities of modern micro-controllers, together with the cost reduction induced by the competition between manufacturers, make a number of small, flexible and powerful Systems On Board (SOB) commercially available at low cost. Available with a wide range of clock frequencies and I/O capabilities, SOBs can be effectively used in a particle accelerator control systems as a customizable embedded platform.

With these considerations in mind, a survey has been carried out to find the most suitable SOB to be used as the core for a general purpose embedded platform, or "smart node" [3]; the BeagleBone [4] has been eventually selected.

THE SMART NODE

The "smart node" concept summarizes a number of features and characteristics that indicate the capability of the embedded platform to perform some autonomous actions in terms of control, communication and diagnostics. The concept is similar to the one of the Network Capable Application Processor (NCAP) described in the IEEE 1451 standard [5], but it has been focussed and tailored on the requirements and constrains of the Elettra Sincrotrone Trieste control systems. Valuable capabilities of a smart node are:

- available functionalities;
- interoperability between smart node subsystems;
- interoperability between the smart node and the installation environment;
- real-time support.

THE BEAGLEBONE AS A SMART NODE

Desirable characteristics of an embedded platform are:

- wide set of low level analog and digital I/O subsystem (e.g. GPIO, SPI, ADC, …);
- remote communication interfaces;
- multiple communication protocol support;
- high level operating system support;
- software and documentation availability;
- long term commercial availability and support;
- flexibility and modularity;
- competitive purchasing and maintenance costs;
- deterministic (real-time) capabilities.

The BeagleBone embedded platform fulfils most of these requirements; thanks to the open source approach of the "Beagle" community, it has been adopted in a wide range of different applications.

UNIFIED CONTROLLER

Using a single embedded system platform for many applications is a major added value. The unified controller concept simplifies the work for maintaining the embedded systems and allows focusing on the development of the specific applications. This approach is particularly convenient in research laboratories like Elettra Sincrotrone Trieste where the number of units produced and deployed is generally quite small. In addition, the open-source non-proprietary solution allows to keep in house the know-how required to develop new applications and effectively maintain the existing ones.

In some cases, the advantages of standardization together with the low-cost of the hardware, justifies using these controllers also for very simple applications where they may seem "overkilling".

CONTROL APPLICATIONS

The characteristics of the BeagleBone, the number and quality of existing projects reported by the Beagle community, and the in house experience confirm that the distributed control can be a target for this embedded platform. Control applications, ranging from low to

*Work supported in part by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3

ISBN 978-3-95450-139-7

middle complexity, can be easily implemented. Some examples of in house developments are reported below.

Tip-Tilt Controller (TTC)

Free Electron Lasers, like FERMI, are fundamental tools to investigate the dynamic behaviour of atomic and molecular systems. Thanks to the temporal resolution in the order of few femtoseconds, these coherent light sources are able to perform a wide range of experiments. Among them, pump-probe experiments are used to study the ultra fast regime properties of matter. One short optical pulse of about 100 fs pumps the sample, exciting some fast variations of its physical properties. A second optical pulse, the probe, measures the time evolution of the sample at different delays with respect to the pump excitation. Being FERMI a seeded machine, the arrival time of the FEL pulse on the sample is determined by the Seed Laser timing [6]. To achieve the highest possible time resolution, the set up depicted in Fig. 1 has been implemented, where a portion of the seed laser photon beam (Seed Laser for Users - SLU) is transported to the experimental stations.

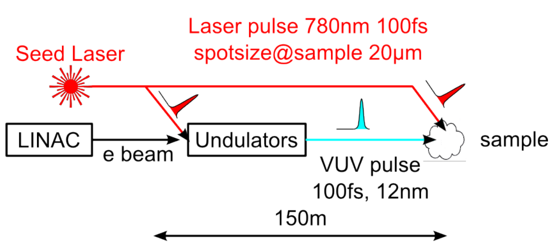

Figure 1: Seed Laser for Users (SLU).

In order to keep stable the optical path of the SLU within a few micrometers, two complementary techniques have been adopted. Three optical lenses have been introduced to reduce the optical lever effect [7]. One active feedback uses a number of CCDs to measure the position of the laser spot in different locations along the SLU path; the trajectory corrections are then applied using piezo actuated mirrors. A central server acquires the images from the SLU CCDs, calculates the errors with respect to the desired optical path and drives the TTCs via Ethernet [8]. The TTC should be able to:

- apply the position corrections at full repetition rate, currently 50 Hz, up to several kHz in the future;
- drive heavy capacitive loads, up to 3 µF;
- prevent the ground loop between the BeagleBone and the actuator connected to ground via the optical breadboard;
- apply a correction of up to 400 µrad with a minimal incremental step of few nrad;
- be fully integrated in the FERMI control system.

The block diagram of the TTC is shown in Fig. 2. The board, developed in house, has the following characteristics:

- two channel 18-bit DAC;
- full galvanic isolation;
- parasitic capacity to ground of the order of tens of pF;
- output amplifier peak current of 200 mA;
- output amplifier analog bandwidth of about 1 kHz (small signal regime);
- output amplifier able to drive up to 10 µF capacitive loads;
- 0-24 V output voltage.

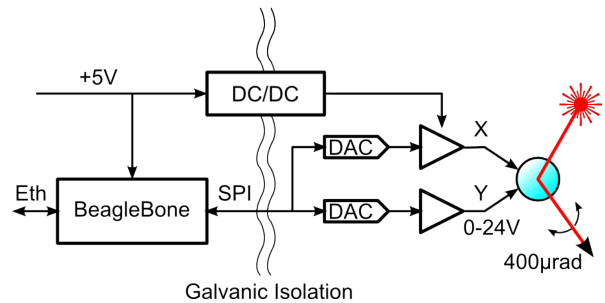

Figure 2: TTC block diagram.

In order to achieve a full range of 400 µrad the driving voltage has been reduced from 0-120 V to 0-24 V. The performance figures, measured during laboratory tests, show that the TTC is a reliable controller up to 3 kHz update rate. The output noise of the 18-bit DAC is around $1LSB_{rms}$ (85 μV_{rms}) on a 3 µF capacitive load, 1-1000 Hz bandwidth. The parasitic capacitance between the floating circuit and the ground is around 60 pF. Fig. 3 shows an exploded view of the TTC assembly, ready for operation.

Figure 3: Tip-tilt Controller assembly.

Power Supply Controller

The quality of the photon beams produced by the Elettra storage ring depends on a number of factors and systems. Some of the most important among them are the magnet power supplies, which can directly affect the overall uptime of the machine and the beam orbit stability. Hence reliability, precision and stability are required for these power supplies.

ISBN 978-3-95450-139-7

The external interface of the existing power supply electronics has the following characteristics:

- one analog input for the voltage reference signal;
- one analog output provided by the Direct-Current Current Transformer (DCCT) used to read back the generated current;
- a number of digital input/output signals used for commands/state.

The Elettra magnet power supplies are conventionally divided into two groups, the first driving the big magnets, bendings, quadrupoles and sextupoles, and the second driving the corrector magnets. Each power supply is currently interfaced to ADC, DAC and digital I/O boards hosted in VME crates inside the power supply cabinets. Ageing considerations, together with the obsolescence of the components and the impossibility to service those boards, have led to an upgrade program which aims at replacing the old VME controllers while maintaining the original power supply power circuits and control interface.

In collaboration with the power supplies team, a new controller has been developed, called NewPSC. A carrier board (BBC - BeagleBone Carrier) has been developed to host a BeagleBone module and implement all the functionalities to interface the original power supply electronics. The new power supply controller is shown in Fig. 4. The BBC houses:

- the BeagleBone dedicated strip connectors;
- a 24-bit ΣΔ SPI A/D converter, the Texas Instruments ADS1271 capable of 52 kSample/s;
- a ADC voltage reference;
- a 20-bit SPI D/A converter, the AD5791 by Analog Devices;
- two DAC voltage references;
- 22 digital inputs and 6 digital output lines, operating at 3.3 V and connected to the related CMOS voltage level shifter;
- three switching power supplies to generate the required supply voltages;
- a DIN 41612 connector for the interface to the power supply.

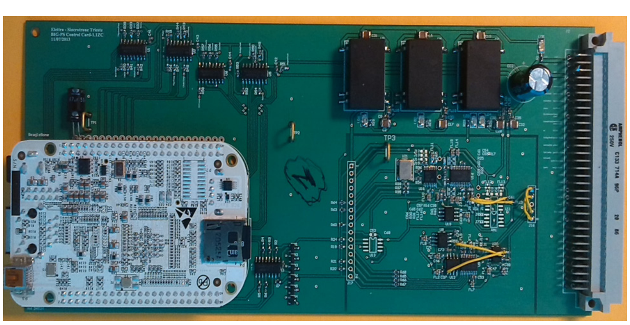

Figure 4: The NewPSC controller assembly with the BeagleBone and a prototype of the BBC.

The control software running on the NewPSC has been developed during the test phase of the BBC prototype. It is based on Linux high level communication routines using UDP packets. To decouple the A/D converter reading operation, triggered by a data-ready signal, from the DAC output settings, the two separate SPI engines of the BeagleBone have been used, and the firmware running in the PRUSS (Programmable Realtime Unit Subsystem [3]) has been accordingly written. Several tests have been carried out on the analog section of the BBC, using a 7½ digit Keithley 2010 digital multimeter. Accuracy, noise, linearity, repeatability and short term stability of both the ADC and DAC subsections have been measured and the results are satisfactory. More in detail, very accurate tests have been carried on the ΣΔ A/D converter to compare the binary codes distribution histogram shown in the ADS1271 data sheet with those acquired during the tests. It is worth mentioning that, with a fixed voltage on the input of the ΣΔ A/D converter, it is mandatory to use a filtering algorithm to obtain a repeatable value and minimize the number of significant bits lost because of the noise. In the current implementation of the read back mechanism, the PRUSS acquires in 39 ms a buffer of 2048 24-bit long binary codes, that are then averaged by the ARM processor.

The measurement of the linearity, carried out connecting the DAC output to the ADC chain input, is depicted in Fig. 5. The DAC setting range, divided into 256 steps, is shown on the horizontal axis. The corresponding voltages, acquired by the multimeter and the NewPSC ADC, are plotted on the vertical axis. Due to the 2.5 V reference used by the ADC, an input rescaling amplifier is required in order to cover the 0-10 V input range. The accuracy of the analog input chain can be evaluated comparing the values measured with the NewPSC to the values acquired with the multimeter, scaled by the gain of the input amplifier. The result, using a gain factor of 0.2306, is depicted in Fig. 6.

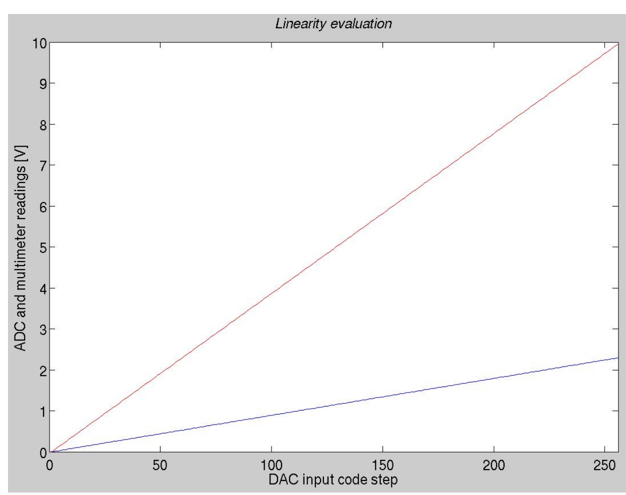

Figure 5: Linearity measurement of ADC and DAC. Red line: multimeter; blue line ADC chain.

ISBN 978-3-95450-139-7

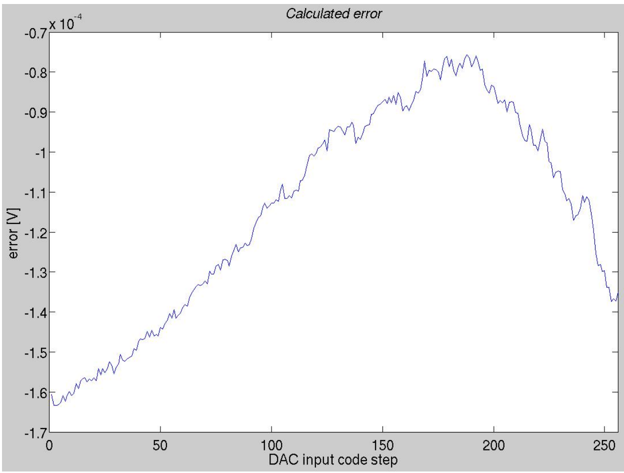

Figure 6: Calculated error between DAC output voltage and ADC chain reading.

A complete test, including DAC and ADC integration and digital I/O management, is currently in progress on a test bench consisting in a NewPSC controller connected to a real power supply electronics (Fig. 7).

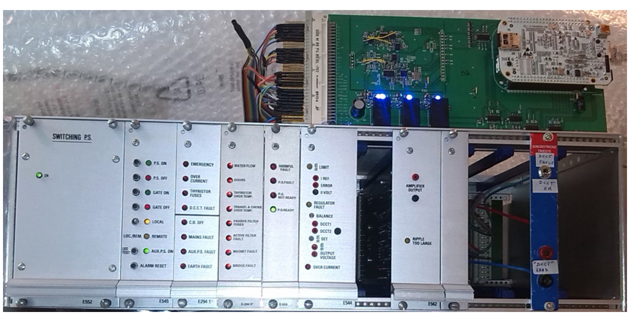
Figure 7: Test bench with the NewPSC controller connected to a power supply.

To fully validate the NewPSC controller, two additional tests are planned. A long term stability test with special regard to the BBC analog subsystem will be performed using a climatic chamber. Then the prototype will be installed into a power supply cabinet in the Elettra service area to perform long-term real-operation tests.

Future Applications

The flexibility of the unified controller approach and the performance of the BeagleBone hardware enables using this embedded platform in a variety of other applications. Among them, two have been identified so far.

In collaboration with the radio frequency team, a high-accuracy large-dynamic power meter for the 500 MHz booster and storage ring radio frequency plants is under design. A prototype, based on a BeagleBone and a demo board with the LTC5587 power meter, has been successfully tested in laboratory. Further tests are planned in a real operation environment to fully characterize its performance.

Moreover, an ongoing study, in collaboration with the diagnostics team, aims at upgrading the existing electron beam current measurement system of the Elettra storage ring currently based on an old digital multimeter interfaced to the control system via GPIB. A BeagleBone carrier board similar to the BBC is foreseen for this specific application.

CONCLUSIONS

The unified controller concept based on the BeagleBone embedded platform, turned out to be an effective solution for a number of control applications at Elettra Sincrotrone Trieste.

The successful operation of the first installed tip-tilt controllers, has triggered its adoption also for other steering and stabilization systems of the lasers and the production of a number of new units.

Moreover, the proven reliability has also been a key feature for the decision to consider using it also for the upgrade of the Elettra power supply controllers, where this characteristic is one of the most important design requirements.

ACKNOWLEDGEMENTS

The authors would like to thank M. Cautero, T.M. Ciesla, R. Visintini (power supply team), M. Bocciai, C. Pasotti (radio frequency team), R. De Monte (diagnostics team), G. Gaio, M. Lonza (controls team), P. Cinquegrana, A. Conte (laser team), for their contribution and support.

REFERENCES

[1] http://www.elettra.eu/lightsources/elettra.html

[2] http://www.elettra.eu/lightsources/fermi.html

[3] S. Cleva, A.I. Bogani, L. Pivetta, “A Low-Cost High-Performance Embedded Platform for Accelerator Controls”, PCaPAC 2012.

[4] http://beagleboard.org

[5] http://www.nist.gov/el/isd/ieee/1451family.cfm

[6] E. Allaria et al., “Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet”, Nature Photonics 6, 699–704 (2012).

[7] M. Danailov et al., “Seed Laser Configurations for Advanced Pump-probe Schemes With FELs”, FEL 2013, New York, August 2013.

[8] G. Gaio, M. Lonza, “Evolution of the FERMI Fast Beam Based Feedbacks”, proc. of ICALEPCS 2013

ISBN 978-3-95450-139-7