Development and Implementation of the ClearPEM-Sonic Detector Control System

(Master Thesis Extended Abstract)

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Abstract – **In order to improve early breast cancer detection, the ClearPEM and the ClearPEM-Sonic scanners were developed, within the PET Consortium. Both are composed of two planar detector heads supported by a robotic arm and a trigger and data acquisition system.**

Each head is composed of 96 arrays with 32 crystal scintillators. The radiation emitted by the human body, due to the injection of a radioactive substance in the patients, is detected by crystal scintillators, which transform the radiation into visible light. This light is converted into electric signals by avalanche photodiodes (APDs). Amplification and processing of the signals is done by Application Specific Integrated Circuits (ASICs), developed specifically for this project. Each ASIC can process signals from 192 avalanche photodiodes. The system is composed of 64 ASICs, which allows processing 12288 APDs. The necessary voltages for the APDs and ASICs are generated by an electronic board (Service Board - SB). There is also a system to monitor and control these voltages and the data acquisition electronics, the Detector Control System (DCS).

The initial version of the ClearPEM Detector Control System, presented some stability problems. During its utilization, the software stopped responding, being its clinical use impossible for a hospital technician. The first part of the thesis work consisted on the analysis and revision of this system. The alarm policy, the communication protocols, the output voltages monitoring and the detector heads temperature monitoring were revised. The system became stable and usable in a clinical environment. Later on, the ClearPEM Detector Control System was adapted for the ClearPEM-Sonic. Besides previous functionalities, new control and monitoring of the modules were introduced, the control of the cooling system and the revised ClearPEM-Sonic Service Board.

I. INTRODUCTION

The ClearPEM scanners hardware (HW) is composed of two main electronic subsystems, the Front-End Electronics (FE) and the Data Acquisition Electronics (DAE). The FE is responsible for detecting the radiation and for converting it into digital signals. The scintillators crystals translate radiation into light and the Avalanche photodiodes (APDs) convert this light into electric signals. The ASICs [1] perform the amplification and shaping of the electric signals. The output analog electric signals are then digitized by on-board Analog to Digital Converters (ADCs). The FE also includes temperature sensors, which the resistance changes according to the temperature. The DAE selects the relevant information generated by the FE. The power supply voltages for the FE sub-system are provided by another electronic board, the Service Board. The SB provides the high voltages (HV) for biasing the APDs and low voltages (LV) for ASICs and other integrated circuits (ICs). The SB is powered by external LV and HV power supplies. The voltages at the FE temperature sensors terminals are acquired by ADCs, also in the SB.

The Service Board is monitored and controlled by the Detector Control System [2], which is also responsible for monitoring and control the ClearPEM power supply system, the FE and the DAE. The DCS is a software that runs in a computer (Service Manager), which is connected to the controlled HW. The DCS main functions are to switch ON/OFF the ClearPEM and to detect problems in the HW of the detector. This software has shown stability problems, which limit its clinical use. In fact, the DCS crashed during its utilization. Therefore, modifications were found to be necessary to allow its clinical use. As the new scanner, the ClearPEM-Sonic, has a different hardware, which required the re-implementation of the DCS. Besides previous functionality, the new Detector Control System also controls the cooling system. This thesis addresses both issues.

The work done in the scope of this thesis concerns the improvement of the ClearPEM DCS and the implementation of the DCS for the new ClearPEM-Sonic. The thesis presents an analysis of the ClearPEM DCS and the implemented modifications to improve its stability and therefore its clinical use. Finally the implementation of the DCS for the ClearPEM Sonic and the first calibration on the Service Board are presented.

II. OVERVIEW OF THE CLEAR-PEM DETECTOR

For a PET scanner to detect a cancer lesion, it is necessary to inject a patient with a radio tracer. This substance is absorbed in higher quantities and faster by the cancerigenous cells in the body, due to their higher metabolism. The positrons released by the radio tracer collide with electrons and both are annihilated, emitting two photons which move on a straight path in two opposite directions. In order to detect the resulting photons the PEM system uses scintillant crystals and avalanche photodiodes, that together work as a radiation detector.

ClearPEM and ClearPEM-Sonic are PET scanners, being the ClearPEM-Sonic basically an overhaul of the ClearPEM design with the incorporation of an Ultrasonography detection system. Moreover, the ClearPEM Sonic presents some upgrades especially regarding the electronics. The ClearPEM detectors include two detector heads, supported by a mechanical system. The heads are constituted by arrays of scintillant crystals optically linked to APDs that convert the optical signal in electric signals. These signals are then processed by the Front-End electronics (FE). The detectors heads are also equipped with three cooling plates and a Service Board, which is responsible for providing the voltages to the FE and to measure the temperature.

The Service Board of the ClearPEM scanner has one power supply with 3.3 V, one power supply with 5 V and four power supplies with 500 V. In order to provide the 32 threshold voltages to the ASICs, a 32 channel Digital to Analog Converter (DAC) is used. This DAC has an I^2C communication port and the output voltage is set through I^2C commands. To provide the high voltage to the APDs biasing, the SB has 32 high voltage regulation circuits. The output voltage of these circuits is controlled by a 32 channel DAC, which is equal to the one used to provide the threshold voltages. The HV circuits output has a linear response to the output voltage of the DAC. The SB includes two temperature sensors, to provide information about the temperature in the detector head to the Detector Control System. Four 12 bit ADCs read the voltage on the PT100 temperature probes of the Front-End Electronics.

In the Service Board of the ClearPEM-Sonic the DAC sub-system was modified, in order to give more resiliency to the SB. Instead of one DAC with 32 channels to provide the threshold voltages, four eight channels DACs are used. For the 32 HV values the single DAC was also replaced by four DACs. Eight ADCs with eight channels each have also been added to the SB, in order to monitor the eight DACs output voltages.

To monitor the temperature, the SB has eight built-in temperature sensors. A humidity and temperature sensor to ensure the detection of a water leak was also introduced in the new Service Board. The control of the SB integrated circuits is made through I^2C protocol with a FPGA. To communicate with the FPGA two types of connectors are available, DB-9 and a shielded RJ45.

One cold graphite and two cold aluminum plates are used to reduce the temperature in the detector heads. The plates are crossed by pipes which carry water with a temperature around 18ºC, cooled down by a recirculating chiller.

The electric signals received by the Data Acquisition Electronics are sent by the Front-End electronic boards. The first level of data processing takes place in the DAE. The Data Acquisition Electronics are composed of four Data Acquisition Boards and one Trigger and Data Concentrator Board, which are inside a Compact PCI 6U Crate.

The Acquisition Tool (AT) is the graphical user interface available to the technicians that operate the scanner. It interfaces directly with the other two subsystems, Acquisition Manager and Detector Control System. With the Acquisition Tool is possible to turn on, calibrate, perform an exam and switch off the scanner. The Acquisition Manager is responsible for acquiring the data processed by the Data Acquisition Electronics. The power supplies status and alarms displayed in the Acquisition Tool are provided by the Detector Control System.

III. CLEAR-PEM DCS ANALYSIS AND IMPROVEMENTS

A. Detector Control System

The DCS is a software developed using the National Instruments software, LabVIEW. The main function of the DCS is to control and to monitor the hardware of the Clear-PEM detector:

- To turn ON/OFF the power supplies.
- To measure voltages and currents of LV and HV power supplies.
- To set the output voltages of the SB DACs.
- To monitor the FEBs temperature.
- To monitor the detector heads pressure.
- To monitor DAE and its crate.

The DCS has an alarm system which informs that an error has occurred. There are several types of errors, communication errors, power supplies internal errors, SB errors and DAE internal errors.

DCS communicates with the Kepco controller using GPIB, with the ISEG high voltage power supplies using CANBus, with the SB using I^2C and with the DAE using RS-232. The data concerning the monitoring of the power supplies voltages is sent to the Acquisition Manager through the Distributed Information Management (DIM) protocol [3]. The Acquisition Manager communicates with the Working Station using Ethernet. On Fig. 3.1 the ClearPEM communication architecture is presented.

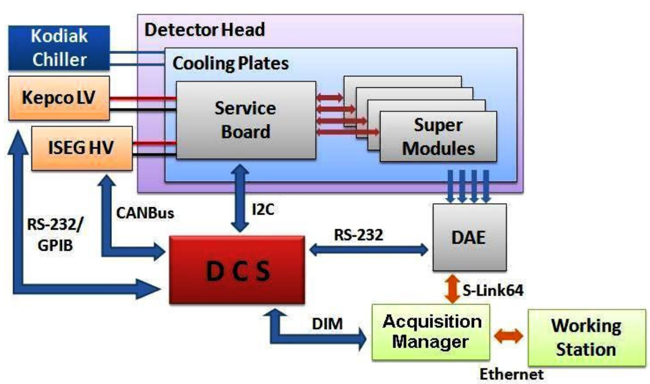

Figure 1 - ClearPEM communication architecture.

The control and monitor software is organized in three main stages:

- Initialization:
  Of the global variables and the creation of semaphores for the communication protocols take place.
- Hardware Control:

Consists on the hardware monitoring and control. All routines for the hardware control, monitoring and communication are designed to work in parallel.

- Finalization:
  Responsible for the communication semaphores termination.

The main feature of the hardware control is the State Machine, composed by five states: Error, Idle, Stop, Ready and Running. This state machine is very important for the scanner correct operation, because some hardware systems can only be turned ON or accessed if other hardware system is already ON. Table I shows the status of the different systems regarding the state machine.

Table I
Hardware systems status, regarding the state machine.

State	Kepco	ISEG	SB
Error	OFF	OFF	OFF
Idle	OFF	OFF	OFF
Stop	ON	OFF	OFF
Ready	ON	ON	OFF
Running	ON	ON	ON

1) DCS Main Menu

The graphical interface of the DCS Main Menu allows turning ON/OFF the scanner by pressing a button. The status (ON/OFF) of the Kepco low voltage power supplies, the ISEG high voltage power supplies and SB can be monitored. It has a status table, which shows the status of the ClearPEM hardware.

2) Power Supplies Control and Monitoring

Allow the user to control and monitor the low and high voltages power supplies. The functions include:

- Detection of communication failure between the controller and the DCS.
- Power modules voltage configuration.
- Monitoring in terms of voltages, currents and internal status.
- Measured values storage.
- Report of monitoring information to the acquisition Manager.

The communication with the Kepco low voltage power supplies modules is done using Standard Commands for Programmable Instruments (SCPI). With the ISEG high voltages power supplies modules is done using a Dynamic Linked Library (DLL).

3) Service Boards Control and Monitoring

The SBs control and monitoring main functions are:

- Detection of communication failure.
- To configure all the 64 DAC channels.
- To measure the mean and individual temperature of the PT100 temperature probes.
- To measure the scanner head pressure.

The APD high voltage DAC configuration is done by ramping up the voltages, in a controlled rate, due to the high voltage final values. The ASICs threshold DAC configuration is only made in one step because the output voltage is usually around 1.65 V. In the SBs menu, pressure and temperature can be monitored, threshold voltage and APD bias voltage can be seen and advanced menus can be called.

4) DAE Monitoring

The DAE monitoring is divided in two sub-modules. One sub-module is responsible for monitoring the five DAE boards voltages, currents and temperature. The other sub-module is responsible for the DAE crate voltages, current and temperature monitoring and also for the fan control.

5) DCS Limitations

The analysis done on the DCS shown some limitations in its utilization. The main problem is that the software crashes during its utilization. This crash occurs at any period of utilization. Another issue was the fact that the DCS does not perform automatic monitoring of voltages and currents. If any problem occurs with the output of the power supply voltages, the ClearPEM is only switched OFF if the user is monitoring the voltages and currents status. If the DCS crashes and scanner is turned ON, when the DCS is turned ON again, the DCS forces the scanner to be turned off. This procedure is not wanted. The DCS should be able to recover in the state that it was before the crash.

B. Improvements on the Original ClearPEM DCS

In the course of this thesis several improvements were made in the DCS in order to allow its clinical use. The high voltage power supplies control and monitoring was improved. The low voltage power supplies control and monitoring was modified. The SB control and monitoring has also been modified due to some modifications in its hardware. The number of status alarms has been increased and the critical errors handling has been improved.

1) Kepco Control and Monitoring Modifications

The GPIB port of the Kepco controller has a work rate of 1.8 MB/s. The S-232 port has a working rate between 4.8 kb/s and 19.2 kb/s. Since the system does not require a fast control and the RS-232 system is a low cost system, it was decided to change the Kepco controller communication, from GPIB to RS-232.

In order to avoid hardware damage, an automatic voltage and current sub-routine was implemented. When the scanner is ON and the Kepco output voltage or current are different from the defined values, the sub-routines shutdowns the scanner.

In order to send the output voltages values to the AM through the DIM protocol, an additional measure, for each Kepco module, was made. In order to reduce the number of measures, global variables were created, that keep the regular measurements and are sent to the AM.

2) *ISEG Control and Monitoring Modifications*

Communication with the ISEG controller is done through the CANBus protocol, using a DLL developed in C++, to establish the communication between LabVIEW and the CANBus-to-USB converter. The original DCS crashed during its utilization. Every time the software stop responding, a warning about memory allocation appeared. This happened due to lack of memory allocation by LabVIEW, to the correct CANBus communication initialization. To solve this problem, the initialization function, in the DLL, which had three required parameters (two integers and one string), was modified. Since the three parameters have always the same values, they were deleted as parameters and defined as constants, making the memory allocation unneeded.

An automatic voltage and current sub-routine monitoring like the one for the Kepco monitoring was also developed.

3) *Service Board Control and Monitoring Modifications*

It was found that the temperature reading was incorrect due to a voltage loss of 300 mV in the power cables between the SB and the FEBs. Therefore the FEBs temperature reading was deactivated and two temperature sensors were added to each detector head and connected to the respective SB. The temperature measurement, now, plays a roll on the turning ON of the SB. When the SB is turned ON, the first action is to read the temperature measured by the sensors. If the temperature is out of bounds, the DCS waits for the cooling to act on the SB temperature. If after a while the temperature limits are not reached the DCS goes to error. If the temperature is correct, the DACs are configured and the temperatures are constantly measured. If temperatures exceed the limits, the DCS goes to error and the scanner is turned OFF.

4) *DCS Alarms and Crash Recovery*

The alarm system was modified. Regarding the Kepco control, the alarm that signals the lost of GPIB communication, now refers to the lost of RS-232 communication. The Low Voltage, voltage error and power loss refers to the Kepco output voltage error detected by the DCS. High Voltage, current error and voltage error refers to wrong output current or voltage by the ISEG power supplies. Temperature DH1 and DH2 now refer to the temperature on the SB instead of the FEBs mean temperature.

In order to increase the DCS crash recovery, the state is saved in a text file. If the PC or the software crashes, this file contains the state before the crash. So, when the DCS crashes and is turned ON, it goes to the state saved in the text file, but only if the hardware status corresponds to the state.

5) *ClearPEM DCS Tests and Results*

In order to test the ClearPEM DCS, a software capable of emulating hardware errors into the DCS, was also developed. This software is mainly composed of global variables that simulate the presence of errors in the DCS.

The DCS was modified in order to accept the errors emulation, instead of reading the real hardware status, the DCS read the simulated errors.

The test bench included 3 Kepco LV power supplies, one ISEG HV power supply and one Service Board.

Several tests were carried out, including:

- ISEG Crate internal status errors.
- ISEG voltage and current wrong output.
- Kepco internal status errors.
- Kepco voltage wrong output.
- SB temperature out of bounds.
- Communications failures.

The DCS was able to process this errors, going to the error state and turning OFF the scanner. Tests were taken for several twelve hours runs, and once 48 hours runs. During the entire time the DCS ran without any problem.

The ClearPEM DCS improvements were implemented, and deployed in October 2009 on the scanner at IPO-Porto. Several acquisition runs were done with the scanner and the DCS has not crashed, being able to detect problems in the scanner demonstrating full and stable control of the power supplies and service boards.

IV. Development of the ClearPEM-Sonic Detector Control System

The DCS controls and monitors the detector hardware sub-systems: Kepco low voltage power supplies, ISEG high voltage power supplies, Service Boards, Data Acquisition Electronics and its crate, and the Kodiak cooling system.

ClearPEM-Sonic DCS is, basically, a reimplementation of the ClearPEM DCS, but including new functionalities. The DCS includes two new sub-modules to control and monitor the new SBs, that are different from the previous one, and to control and monitor the cooling system.

A. *Developing Environment*

The initial goal was to develop the ClearPEM-Sonic DCS in C/C++ programming language. This was thought due to the fact that the ClearPEM DCS implemented in LabVIEW was unstable and did not allow a clinical technician to use the detector. However, results from Chapter 3 demonstrated that there was no need to change the development approach, therefore LabVIEW development was maintained.

B. DCS Architecture

The ClearPEM-Sonic DCS architecture is similar to the ClearPEM DCS architecture, being also composed of three stages: Initialization, Hardware Control and Finalization.

The state machine (Figure 2) ensures the correct order of switching ON/OFF the hardware sub-systems. Another state is added to the state machine to control the Kodiak chiller. This state is located between the idle state and the stop state.

The introduction of this state ensures that the Kepco power supplies can only be turned ON if the Kodiak chiller is turned ON. This is necessary because the heat originated by the power dissipated on the detector heads (total of 100W) has to be removed. When the DCS is in this state, the Kodiak chiller is turned ON and the remaining hardware of the detector is kept OFF. If the temperature in the chiller is not right or a chiller internal error occurs, the state machine goes to the Error State.

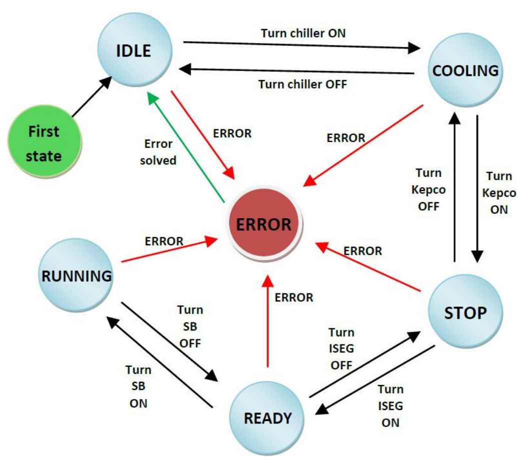

Figure 2 - The new DCS state machine

C. Control and Monitoring Software Modules

Each of the five sub-modules is responsible for controlling and monitoring the respective hardware sub-system. Three of them, Kepco, ISEG and DAE are reused from ClearPEM DCS. The remaining sub-modules, for the Service Board and Kodiak chiller, were implemented from scratch. The alarm policy and the recovery systems were also modified.

1) New Service Board Control and Monitoring

The control and monitoring sub-module functions are:

- To set and measure the 64 threshold voltages.
- To set and measure the 64 voltages of the HV regulation circuits DACs.
- To monitor the eight temperature sensors.
- To monitor the humidity temperature sensor.
- To monitor the 64 temperatures of the Super Modules (SMs).

As it can be seen on Figure 3, the control and monitoring module only communicates with the Service Board if the Kepco power supply is turned ON. Otherwise it waits for the power supplies to be switched ON. After the power supply is turned ON, the software checks if the temperature in the SBs is between the allowed limits. If the temperature in the SBs is not inside the limits, the software waits for the temperature to reach the limits (the cooling system is working). If the temperature is not reached, the system is turned OFF. If the temperature is inside this working regime, the software continues to work normally.

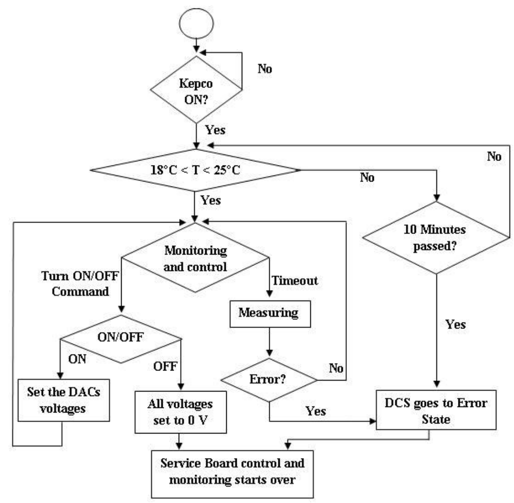

Figure 3 - Service Boards control and monitoring flowchart.

From the temperature and humidity measured by the humidity sensor the dew point temperature is calculated. This calculation indicates for a given humidity, the temperature that the SBs have to be, in order to the water vapor to condensate.

After assuring that the SBs are inside the temperature limits, the software enters in a cycle, where it waits for a Turn ON/OFF signal or monitors the SBs. The SBs monitoring consists on measuring the temperature and humidity sensors and the ADCs. Turning ON the SBs consists on setting the DACs output voltages with the desired working voltages. Turning OFF consists on setting the DACs output voltages to 0V. If the temperature or humidity go out of the allowed limits the SBs control and monitor sub-module makes the DCS to go to the Error State. Also if the communication between the DCS and the SBs fails, the DCS goes to the Error State.

For a visual monitoring of the temperature in the SBs, six pixelized maps were created, three for each SB. One of the maps represents the temperatures read in the eight sensors of the SB. It is a pixelized map composed of 5 x 7 pixels with information about only 8 pixels. So the remaining pixels present a temperature that is the mean temperature of the closest sensors. The other two maps present the temperature in the Super Modules. The SM maps have 4 x 4 pixels and each pixel matches a PT100 temperature probe.

Four advanced control and monitoring menus were also created. The HV SETUP MENU allows an individual control of each HV regulation circuit. The Vth SETUP MENU was implemented to allow an advanced control of the ASICs threshold voltages. To monitor the SMs temperature an advanced menu was also created. This menu presents detailed information about the temperature on the Top and Bottom FEBs of both SB Super Modules. In order to detect malfunctions in integrated circuits, an advanced menu was developed. The created menu points in a SB photograph, the damaged ICs.

2) *Cooling Control and Monitoring*

To control the chiller, commands are sent, and the respective responses are processed by the DCS. Control and monitor the cooling system include:

- To turn ON/OFF the chiller.
- To monitor the water temperature at the output of the chiller.
- To monitor the internal status of the chiller.
- To emulate the chiller presence.
- To setup the upper and downer limits of the water temperature.
- To detect communication failure between the DCS and the chiller.

The flowchart of the chiller control and monitor sub-module software is presented on Figure 4.

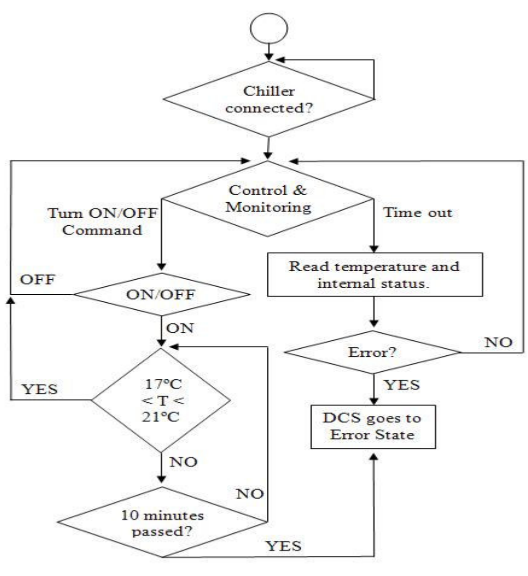

Figure 4 - Cooling control and monitoring flowchart.

The sub-module waits for the chiller to response to an initialization command. When the chiller is detected, the control and monitoring starts. The software sub-module waits for a turn ON/OFF command, if it does not receive any command, the reading of the temperature and internal status take place. After turning ON the chiller, the temperature is monitored for a while. If the temperature does not reach the limits the DCS is forced into the Error State. After turning ON, if the temperature is inside the limits, the monitoring of the chiller continues normally. If the temperature of the chiller goes out of the limits the DCS is forced into the Error State. Also if the communication between the DCS and chiller fails, the DCS is forced into the Error State.

Among all the hardware modules that communicate with the DCS, the chiller is the only hardware sub-module that can be controlled manually. Therefore this sub-module allows to stop the communication with the chiller, assuming that the chiller is turned ON and the DCS works normally.

3) *Main Menu & Warning System*

The Main Menu allows to control and monitor all the hardware sub-modules of the detector. The status panel has the new warnings that refer to the new DCS monitoring functions. If the monitored status have a problem the correspondent indicator is red, otherwise is green. The critical warnings of the Kodiak chiller monitoring are also shown in the menu, the warnings are:

- Lost of communication.
- Temperature too low.
- Temperature too high.
- Low water level.
- Low water flow.

Concerning both Service Boards, in the status panel, the warnings are:

- Lost of communication.
- Temperature inside/outside the limits.
- Humidity inside/outside the limits.
- Right/wrong high voltage values.
- Right/wrong threshold voltages.

It was also added to the Main Menu, a led that indicates if the Kodiak chiller is turned ON or OFF. Like with the other hardware sub-modules, when the chiller is on, the led is light green, when is of the chiller is dark green.

D. Tests and Results

A test bench was used to analyze robustness of the software. The test bench is composed of: a Service Board, three Kepco low voltage power supplies, one ISEG high voltage power supply, a Kodiak chiller and a PC running the DCS. The ISEG HV power supply is not connected to the Service Board to prevent damaging its circuits.

In order to ensure that the DCS can work for long periods of time, several test runs were done. These tests were conducted:

- Using the DCS for long periods of time.
- Turning ON and OFF the whole system several times.
- Turning ON and OFF each hardware sub-system several times.

DCS was proven to be stable, working without crashing or stop responding for twelve hours test runs. The twelve hours runs were choosen to assure that DCS can be used during an entire day, without being shut downed. Turning ON and OFF the whole detector, to assure that the DCS can work without crashing with constant handling. For the same purpose, several tests, where each hardware sub-module was turned ON and OFF, were taken. The DCS worked without any problems during the tests. All the new functions of the DCS were tested.

To test the capability of DCS to handle errors, the test software used to test the ClearPEM DCS was adapted to test the new DCS. This software purpose is to force errors in the DCS. The simulated status concerns the output voltages, internal status and temperatures. To test the error handling of the DCS, all the control parameters of the test software were activated. In order to assure the robustness of the DCS at all times, all the errors that the test software generates were tested in all the states of the state machine.

To test the response of the DCS to communication failures with hardware sub-modules, tests were carried out. When any communication failure occurs in any State, the behavior of the DCS is the same as the one described for hardware errors handling, except for a communication failure with the ISEG high voltage power supplies. In this case, an indicator in the DCS informs the user to shut down the detector with the emergency button.

V. ClearPEM-Sonic Service Boards Calibration

There are three systems that need to be calibrated: the threshold DACs; the high voltage regulation circuits; and the Super Modules temperature monitoring system.

Due to the intrinsic variability of the gain and offset of the DACs, the voltages defined at the output of the DACs channels differ from the real output voltages. In addition, systematic biases in the gain and offset at the output of the HV regulation circuits can also be observed, due to the behavior variability of the components used in the HV regulation circuits. In order to obtain the desired voltages at the output of the DACs and HV regulation circuits it is necessary to calibrate them. To measure the temperature in the Super Modules is necessary to calibrate the reading of the voltage in the temperature probes.

A. DACs Calibration

The calibration purpose is to guarantee that the desired voltages are obtained at the DACs output. To calibrate the DACs of the SB the best-fit line method was used. This method calculation is based on the full scale of the DACs without favoritism to any point [4].

After calibrating the DACs, the gain and offset values are obtained. These values are used in

$$x = (y - b) / m \qquad (1),$$

where, x is the voltage set at the DAC output, y is the desired output voltage, b is the offset value and m is the gain value both obtained from the calibration. So using (1), with the values obtained from the calibration, to set the voltage in the DACs, the gain and offset errors are corrected.

1) Calibration Software

A program was developed, to calculate the gain and offset values of the DACs. This software defines a set of voltages in the DAC and measure the DAC output with a multimeter. The set of voltages starts with 0 V and finishes with 3 V, in order to cover the entire working range of the DACs. The set voltages have a 0.2 V interval between them and the set and measurement take 0.6 s. The 0.6 s delay period exist due to delays in the communications between the software and the hardware. This means that a calibration of one channel takes 9 s. After setting and measuring the voltages in the DAC, a linear fit is performed, using the obtained voltages. The offset and gain values are obtained from the linear fit.

2) Calibration Results

To calibrate the DACs, beside the SB, three low voltage power supplies, one multimeter and one PC are used.

After performing the calibration, the obtained gain and offset values are applied to (1). The results of the application of this formula were used to set the desired voltages in the DACs. The desired output voltage is 1.68 V in all DACs channels, which is the threshold voltage for the circuits implemented in the ASIC. The values were set and measured in both Service Boards, in order to evaluate the DACs accuracy. The measured values show a systematic bias less than 0.18%, which represents a maximum difference between the set and measured voltage of 3 mV.

B. HV Regulation Circuits Calibration

The output of the HV regulation circuits has a linear response to the output of the control DAC. Due to variability in the components behavior of the HV regulation circuits, the output voltages have different gain and offset values. So it is necessary to calibrate each of the 32 HV regulation circuit of each SB.

Since the output of the HV regulation circuit has a linear behavior, the best-fit line method is used to obtain the gain and offset error values. After calibrating the HV regulation circuits, the gain and offset values are obtained. These values are used in (1), where x is the value written in the DAC, y is the desired output HV, b is the offset value obtained from the calibration and m is the gain value obtained from the calibration. So using (1) with the values obtained from the calibration, the HV regulation circuit output voltages are the desired ones.

1) Calibration Software

This calibration software is similar to the one used to calibrate the DACs. It sets a set of voltages in the DAC and measures the output voltages of the HV regulation circuits.

Between the setting and the measuring of the voltages, it exists a waiting period of 5 seconds. This is for the output voltage to stabilize. When the DAC voltage reaches 3.8 V, the software ramps it down to 0 V. The DAC voltage steps are of 0.2 V. Finally the software performs a linear fit, in order to obtain the gain and offset values. The calibration of one channel takes about 120 s.

2) *Calibration Results*

To calibrate the HV regulation circuits, besides the SB, three Kepco power supply modules, one ISEG HV power supply module, one multimeter and one PC were used.

In order to verify the precision of the calibration on the HV regulation circuits, the desired voltages for biasing the APDs were set and measured. From these measurements, a systematic bias of 0.045% in the HV regulation circuits of the SB 0 was measured, which indicates a difference of 0.17 V between the desired and the set voltage. In HV regulation circuits of SB 1 the bias is 0.055%, which represents a difference of 0.23 V between the desired and the set voltage. The variation of the APDs gain is 6%/Volt for a gain of 150, which is the gain of the ClearPEM-Sonic APDs [5]. The maximum difference between the output voltage and the set voltage is 0.23 V. So the gain of the APDs has maximum error of 1.38 % (0.23 x 6%) which is despicable.

C. *SMs Temperature Monitoring Calibration*

To convert the read voltages in the probes into the correct temperatures a calibration has also to be performed. To calibrate the temperature reading, three pairs of high precision resistors are used. Each pair of high precision resistors emulates a pair of PT100 resistors in a certain temperature. PT100 probes have a 0.39 Ω / ºC variation between 0ºC and 30ºC [6].

In order to have the correspondence values between the voltage and the temperature, the high precision resistors are connected to the signal conditioner, pair by pair. The 3 different voltages are measured and, due to the probes linearity, a linear fit is performed. From the linear fit, the voltage-to-temperature conversion values are obtained. The calibration has to be performed on all 32 temperature reading channels. This is due to the different resistance values between the signal conditioners and the ADCs. The different resistance values have origin in the different paths between the SMs connectors and the ADCs.

After calibrating the temperature reading channels, the calibration constants, m and b, are obtained. These values are used in (1) where x is the temperature in the probe, y is the read voltage, b is the offset value obtained from the calibration and m is the gain value obtained from the calibration. So using (1) with the values obtained from the calibration, the read voltage is converted into the correct temperature.

1) *Calibration Software*

To make the calibration process faster, a program was developed. This program main function is to read the voltage that the ADC channel (under calibration) is measuring. The program assumes that the user places the high precision resistors in the correct order (103.9 Ω, 107.79 Ω and 109.73 Ω) and waits for each measure before changing the resistors. After placing the 3 pairs of resistors and measuring the voltages, a linear fit is performed. The calibration values are obtained from the linear fit.

2) *Calibration Results*

The calibration bench is composed of 3 pairs of high precision resistors, one SB, one FEB, three Kepco power supply modules and one PC.

The gain values are between 0.00249 and 0.00259. Being the mean value 0.00255 with a dispersion of 1.16%, this indicates a similar behavior between temperature monitoring channels in terms of gain. The offset values are between 0.664 and 0.67, being the mean value of the offset 0.6674 with a dispersion of 0.22%, which also indicates a similar behavior in terms of offset.

VI. Conclusions

The ClearPEM and ClearPEM-Sonic are PET scanners designed to detect early stage breast cancer. Based on a high granularity APD readout with more than 12000 channels. The scintillator crystals are readout by frontend electronics. The processed data stream is filtered by data acquisition electronics. Power is distributed by state-of-the art power supplies and generated heat removed by a dedicated cooling system. All these systems must have a stable control and monitoring, to assure that the scanners work properly. To control these systems a software application, named Detector Control System was developed. The objectives of this thesis were to improve the ClearPEM DCS and to develop the ClearPEM-Sonic DCS.

A. *ClearPEM DCS analysis and improvements*

During the ClearPEM DCS analysis, that constitutes the initial part of this thesis, one main problem was detected. Due to lack of memory allocation by LabVIEW for the ISEG C++ DLL, used to establish communication between the DCS and the USB-to-CANBus converter, the software stopped responding. The DLL was modified in order to avoid the memory allocation. The Kepco communication interface was changed, from GPIB to RS-232, making the communication interface a low cost system. Several improvements were carried out regarding voltages, currents and hardware status monitoring and control. Specially in the detector heads monitoring, the temperature is now read by two temperature sensors located on the SB. In order to test the modifications performed in the DCS, several software and hardware-based tests were conducted. These tests include lost of communications, wrong output voltages, wrong output currents, wrong temperatures and hardware internal status errors. The system was deployed on the ClearPEM at IPO-Porto. Several runs were done with the detector in a clinical environment, and the DCS has demonstrated a stable behavior.

B. ClearPEM-Sonic DCS

Due to the introduction of the cooling control and monitoring, the State machine of the DCS was modified. Another state was added, where the chiller is the only sub-system turned ON. The state machine only allows the other hardware sub-modules to be turned ON if the chiller is already turned ON. The control and monitoring of the Service Boards is responsible for setting the DAC output voltages, reading the voltages measured by the ADCs, reading the temperature sensors and read the humidity sensor. The software does not allow the scanner to work if the temperature and the humidity are not inside the allowed limits. To monitor the temperature, pixelized maps, with a color grade were created, turning the temperature monitoring easier. To assure a constant temperature inside the Detector Heads, the software that control and monitors the chiller is responsible for setting it to 18ºC. Besides this, the software is also responsible for monitoring the water temperature, level and flow, among other internal status.

The DCS was submitted to robustness and functionality tests. For stability tests, the DCS was used for long periods of time, and were tested its functions during these tests. The DCS showed a long term stability, because it did not crashed and its functionalities worked every time. To test the robustness of the DCS, a software that simulated errors was adapted from the one used for testing the ClearPEM DCS. The tests covered all the errors that could occur during the DCS utilization. The DCS is capable of recognize all the errors of the hardware, and also the communication failures. The DCS is a stable and robust software, capable of controlling and monitoring the detector hardware. At time of writing this thesis, the ClearPEM-Sonic is being assembled. Further tests of the DCS will be made during the final integration phase.

C. Service Boards Calibration

In order to have precise threshold voltages the DACs in the SB were calibrated. The process used to calibrate the DACs is the best fit method, where values are set and measured and a linear fit is performed. The gain and offset values obtained from the linear fit are used to correct the output errors. After calibrating the DACs, the maximum output error is 3 mV, which corresponds to an error of 0.18%.

To assure that the output voltages of the HV regulation circuits are the desired ones, all the circuits were calibrated. To calibrate the HV circuits, a set of voltages were set at the control DACs output and the HV circuits voltages were measured. A linear fit was performed with the measured values and the gain and offset values were obtained. The obtained values were applied to set the HV regulation circuits to the desired values and a maximum difference of 230 mV was observed, which means an error of 0.055%.

The calibration of the temperature measuring system sets a correspondence between the voltage measured in the temperature probes and the temperature. All the channels of the SBs were calibrated because the paths between the reading ADC and the connector to the FEB have different lengths. This leads to different resistance values, which means different voltage reading for the same temperature.

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