

Design details of Intelligent Instruments for PLC-free Cryogenic measurements, control and data acquisition

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Abstract: Cryogenic network for linear accelerator operations demand a large number of Cryogenic sensors, associated instruments and other control-instrumentation to measure, monitor and control different cryogenic parameters remotely. Here we describe an alternate approach of six types of newly designed integrated intelligent cryogenic instruments called device-servers which has the complete circuitry for various sensor-front-end analog instrumentation and the common digital back-end http-server built together, to make crate-less PLC-free model of controls and data acquisition. These identified instruments each sensor-specific viz. LHe server, LN2 Server, Control output server, Pressure server, Vacuum server and Temperature server are completely deployed over LAN for the cryogenic operations of IUAC linac (Inter University Accelerator Centre linear Accelerator), New Delhi. This indigenous design gives certain salient features like global connectivity, low cost due to crate-less model, easy signal processing due to integrated design, less cabling and device-interconnectivity etc.

1. Introduction

Cryogenics plays an important role in the area of accelerator technology where the temperatures in the range of 4.2 K is maintained for accelerating ion beams using super conducting resonators.¹ Many of the cryogenic systems for accelerators demand remote control from a distant control room due to radiation issues during any ongoing experiment where cryostats are part of the beam line and cryogenic sensors² are mostly attached to cryostats.

A new crate-less model of large number of distributed³ hardware device-servers, each with an analog sensor front-end and a digital back-end is installed specific to a particular sensor-actuator combination, has been designed, which eliminates the use of additional Programmable logic controllers in the control networks.^{4,5} Each device can work as standalone meters for any specific sensor & actuator which runs embedded loops locally or can be taken to remote computer mode of operation over LAN or even one can use their front-panel emergency switches by which each device can be taken to emergency mode temporarily without disturbing the connectivity to control room. In case if there is a communication failure with any one device due to unknown reasons, the device can be selectively rebooted remotely without going down to the physical device location. Closed loop and open loop control and monitoring functions are embedded inside each device for any one particular type of sensor-actuator combination.

The following six categories of such instruments have been developed and deployed over Cryogenic LAN which is meant for a specific sensor and actuators like valves or heaters.



- 1) Liquid helium level meters with built-in servers for resistive superconducting level sensors and proportional valve controllers and others, controlled over web.
- 2) Liquid nitrogen level ⁶ servers for capacitive level sensors and proportional valve controllers and others controlled over web.
- 3) Web-switch /control output server for AC power ON /OFF controls of vacuum pumps, heaters, motors etc.
- 4) Device servers for cryogenic temperature measurements (4.2 K .300 K) and control using silicon diode temperature sensors.⁷
- 5) Cryogenic pressure server.
- 6) Cryogenic vacuum server.

1.1. LHe level servers for Superconducting level sensors & actuator controls over WEB

This device uses Superconducting level gauge as the sensor and proportional valve as actuator.

The liquid helium level sensor is operated by measuring the resistance of a superconductive filament contained within a protective tube. The critical current through the sensor maintains the portion of the filament in helium gas in the normal (resistive) state, while the portion in liquid remains in the superconducting state (zero resistance). The voltage measured across sensor is proportional to the length of filament above the liquid helium and provides a continuous measure of the helium depth. Voltage measurements are made using a four wire technique to eliminate errors resulting from variations in the length of the leads. The small amount of heat generated in the probe is dissipated primarily in the helium gas rather than in the liquid helium. Therefore this device has the measurement current quantity and duration programmable in three different modes to measure the liquid-gas interface. Pulse mode operations reduce heat load to the system compared to the continuous current mode. Whereas the Boost mode heats up the probe faster and measures at a lower current in order to differentiate the liquid-gas interface exactly, independent of the gas pressure.

This instrument, called LHe Server, is an embedded device which is designed with dedicated analog front-end electronics for Liquid helium level sensing, using super conducting level gauges, and digital circuitry to work as a globally accessible distributed network server for remote monitoring and closed loop controls as shown in Fig. 1.

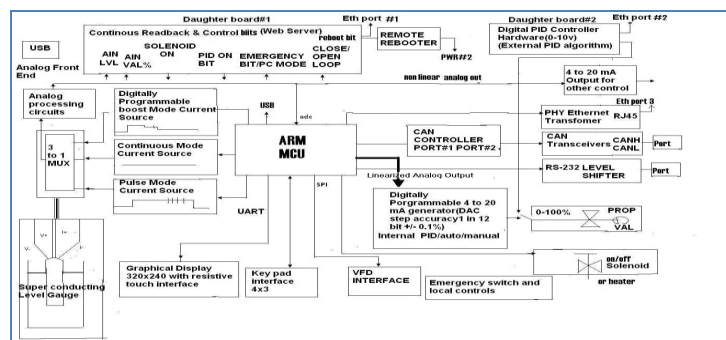


Figure 1 Block diagram for LHe server

The actuators attached to this device are proportional valves and solenoid valves for automatic and manual controls designed to work either in local or remote mode of operation. Each device has its own IP address for unique identification, with a built-in 320x240 graphical display with resistive touch interface to update the information locally and a 4x3 keypad for configuration purposes. The device parameters can be accessed and controlled from any PC in LAN. The physical variables are directly accessed using remote procedure calls (RPC)⁸ implemented in firmware. The user with a remote PC can read from and write into any variable data using a simple internet browser running on any OS (windows/Linux) without any prior programming knowledge. Additionally, API support is extended

on Labview, c, c++ etc. for high level language interface. Each device also has a built-in http server⁹ and IP controlled PID controller card built in-house which are attached as daughter boards with added remote reboot feature. Thus, from an overall perspective, it makes the “Sensor with internet access” a reality at a very low cost with bundled hardware, firmware and software built indigenously to work like “meters with embedded web-PLC” as shown in Fig.2. Each board is a 4 layer design with smd components, using ARM&ATMEL microcontrollers, manufactured using the pick and place re-flow process. Such devices can be distributed at many different geographical locations and accessed by single/multiple clients¹⁰. Since the device is built around Ethernet, WI-Fi mobiles can also be used instead of PCs in a local Wi-Fi network, simply by adding a Wi-Fi router.



Figure 2 The front panel view of all six type of servers

1.2. LN2 level servers for Capacitive level sensor

This device uses capacitance type level sensors as the sensors and proportional valve as the actuator. These are continuous reading capacitance sensors which offer a much better solution for liquid nitrogen level control in cryogenic dewars compared to traditional point sensing based systems. Capacitance sensors are simple design which have no moving parts and are fabricated with two cylindrical metallic tubes to work like the two plates of a capacitor as liquid nitrogen gas and liquid acts as an insulator between the plates. This sensor is extremely sensitive to level variations as the capacitance sensitivity is less than a pf per cm. Therefore stray capacitances due to cable, connectors etc. can possibly give rise to errors of large magnitudes. We have designed and developed the precise sensor instrumentation called stray-capacitance-compensator to get rid of such errors. The block diagram of the LN2 server is shown in a Fig. 3. The oscillator circuit is the heart of the analog design which senses the level and is part of the meter itself.

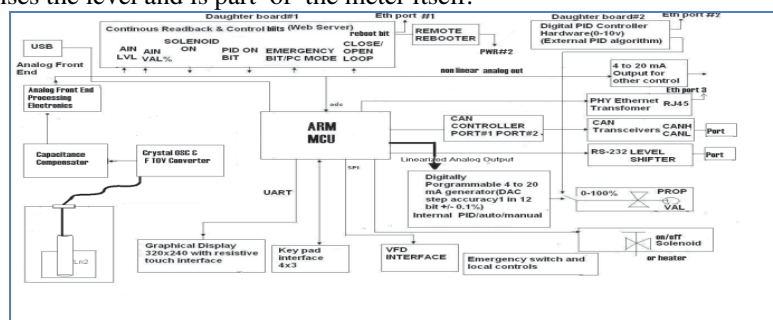


Figure 3 Block diagram for LN2 server

This instrument is also an embedded device which is built with dedicated analog front-end electronics for liquid nitrogen level sensors, using capacitive level gauges, and the digital circuitry to work as globally accessible distributed network servers for remote monitoring & closed loop controls to work either in local or remote mode of operation. This device has an additional circuitry called “cable capacitance compensator” which renders the device to be mountable at far-off distances from

sensors of different cable lengths. The actuators attached to this device are proportional valves and solenoid valves for automatic(linear or Internal/external PID modes) and manual controls. The other digital back-end features are the same as discussed earlier for LHe server except that the control commands are different. The unique design of "Easy in-situ calibration" simply by using a front-panel potentiometer makes this device unique and suitable for linac operations. Stray capacitances associated with any cryostat-mounted capacitance-sensor system are usually unknown and will vary from cryostat to cryostat. Usually stray capacitances will vary due to multiple joint connectors, cabling inside and outside of cryostats etc. Therefore it is difficult to pre-calibrate any LN2 level measurement system off-line, as it has to be done in-situ. A stray-capacitance compensator is incorporated to make it possible. This also gives the extra advantages of not having a pre-amp installed on top of cryostat and also it can drive long lemo cable between device and sensor. A digital look up table can be pre-programmed in memory for non-linear fitting of odd-shaped LN2 vessels.

1.3. Control output server/ Web-switch for AC power controls

These are globally accessible multichannel e-plugs each with 5/15A/230V AC. Power sockets replaced as remote AC plugs operated through WEB. Thus powered devices such as heaters, pumps etc. etc. can be connected to each socket and each port can be controlled over WEB. The read back status of each channel is displayed on a graphical display for remote viewing at local stations and control interface such as labview[®]¹¹. A number of such web-switches can be distributed across a network using Ethernet. The advantage of this device is that the remotely controlled status of each socket and commands are mapped in terms of the device name itself and they are displayed on a TFT display e.g. Rotary pump1 ON, heater1 ON etc. or across LAN. The block diagram of the control output server is shown in Fig. 4. This device uses +24 Volt standard of digital output by adding a level shifter circuit between the microcontroller pin and the real output. Isolation is also provided between the load and the low voltage pins as relays are used on the load side.

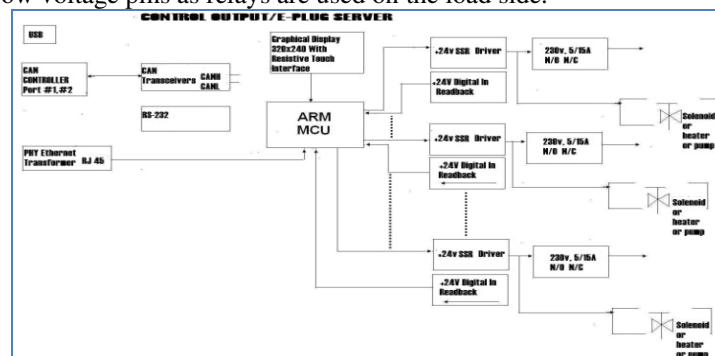


Figure 4 Block diagram of control output server

1.4. Device servers for cryogenic temperature & pressure measurements

This instrument is an embedded device which is built with dedicated analog front-end electronics for cryogenic temperatures [4.2 to 300K] or pressures [-14.7 to +14.7 PSI], and the digital circuitry to work as globally accessible distributed network servers for remote monitoring. This device uses silicon diodes as temperature sensors and piezo resistive sensors as pressure sensors. The precise current sources and programmable instrumentation amplifiers are built inside the front-end analog processing electronics. The other digital back-end features are the same as discussed earlier for LHe server. The block diagram of pressure server is shown in Fig. 5. Usually all pressure gauges come with a connection where you feed in a +24 Vdc into the sensor and it returns a current of 4 to 20mA. This current is converted to voltage by dropping across a resistance of 500 ohms. This voltage is processed to read the pressure.

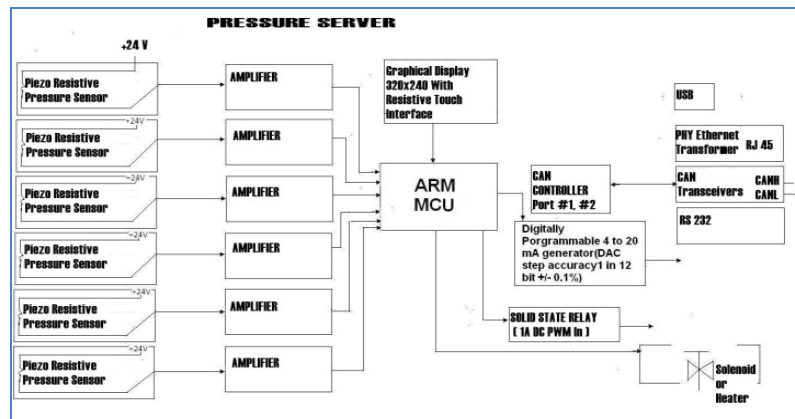


Figure 5 Block diagram of pressure server

The Temperature servers work only with silicon diodes and are used for low temperature measurements in the range of 4.2K to 300K. They differ from the pressure servers only in their current source values and front end amplifier gains. The diodes used are Lakeshore DT470 silicon diodes and excited by a constant current of 10 micro amperes. The block diagram of the temperature server is shown in Fig. 6. As the diode curves are (CURV-10) non linear, temperature corresponding to each voltage point is retrieved using piece-wise linear interpolation technique using multiple equations which is implemented inside the ARM processor.

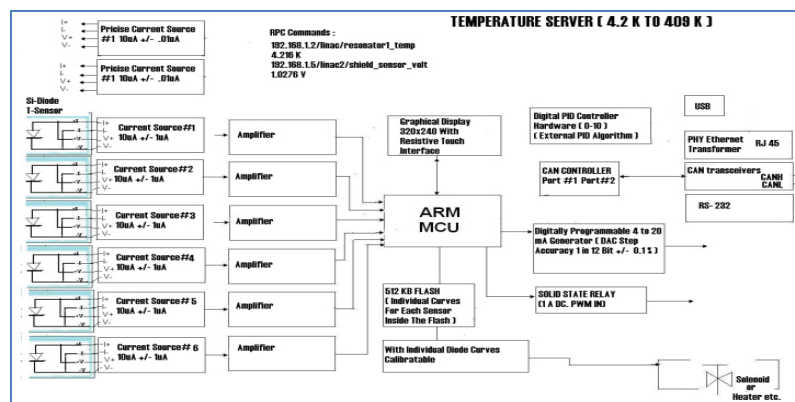


Figure 6 Block diagram of Temperature server

1.5. Cryogenic Tank pressure & vacuum server

This instrument is built with dedicated analog front-end electronics for cryogenic tank temperatures and pressures [-14.7 to +14.7 PSI], vacuum measurements etc. and the digital circuitry to work as globally accessible web servers for remote monitoring of Cryogenic tank. The block diagram of the Tank server is shown in Fig. 7. Here the level of each tank is available in the form of current or voltage format. Therefore necessary gain is added in every channel to reproduce the output. Sometimes it is also possible to mix channels of temperature and pressure within a single device as the transfer functions and gains are set accordingly.

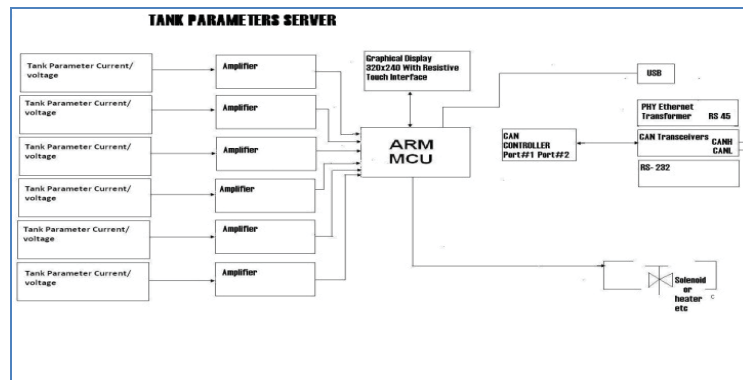


Figure 7 Block diagram for outside tank server

2. Hardware design & manufacturing

The electronic boards were manufactured using the pick and place reflow soldering process. Fig. 8 shows the inside assembly of each unit which has a main mother board and two daughter boards.

All the device servers were grouped together and wall mounted in the proximity of the sensors & actuators before it was connected to the network switches.

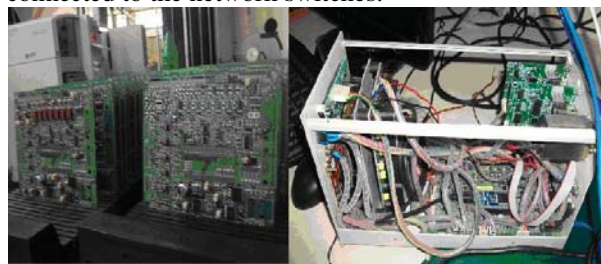


Figure 8 The main-printed circuit boards- Type I & Type II(left) The inside view of device-server with two daughter boards vertically mounted (right)

3. The cloud compiler based Firmware

A series of Http GET commands are firmware coded to generate the complete command set required for each device. Each command is made meaningful to recognize the action to be performed. Because it is a web IDE, one can log in to it from anywhere and carry on from where you left off, and moreover, you are free to work on Windows, Mac, iOS, Android, Linux, or all of them. Every device has a USB port provided at the front-panel for reprogramming. Every device has a firmware coded static ip address in the range of 192.168.1.XX, that gets displayed on the front-panel VFD display every time the device is rebooted.

4. Operator Interface design

The GUIs for operator interface were developed in windows operating system. The user interface software, which currently runs as operator panel under LabView® included the following features

- 1) 50 selectable online trends each with a history duration of 24 hours
- 2) Data logging program for infinite duration
- 3) Alarm windows audible and non-audible
- 4) Daily log of every action in 10 secs time interval readable in EXCEL

5) User friendly graphical interfaces with pop-ups/dialog boxes

A health monitoring utility has been added to test the health of each device periodically and report to users.

The Main screen of User graphical interface for control and automation is shown in Fig. 9.

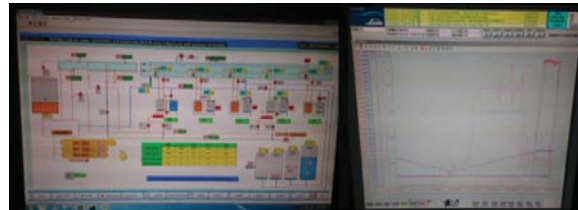


Figure 9 The Main screen User graphical interface for control and automation & 24 hr. trends

5. Installation and Experimental results

At present Twenty six(26) numbers of device-servers have been built and installed in a private cryogenic LAN. Each device IP is configurable as static or dynamic. Remote rebooters are added in each device to reboot the servers in case of emergency. All control loops can be running at a fast rate inside the embedded loop. All actuators attached to the device can be taken to emergency mode of operation locally by using precise pots and switches in the front-panel. A changeover from local mode to PC mode is very smooth. Cloud compiler based development system is employed. Therefore one accesses the compiler and programs online and downloads onto the device. One doesn't need extra Programmable logic controllers or similar control devices, as all control functions are embedded in embedded http server concept. Touch interface is used to add user-friendly unlimited key functions. It has a 4x3 keypad, spi character display, USB o/p, rs232 o/p, Ethernet o/p, CAN o/p etc. It also has two daughter boards: wherein the one works like IP DAC for manual, auto, PID operations and the other works as a stable rebooter. These two boards run stable http servers and can be programmed independently of the mother board.

6. Conclusions

This paper basically describes the designing a group of intelligent cryogenics instruments with built-in embedded http servers to eliminate the use of extra control crates like PLC or VME or CAMAC in a control network¹². This hardware model is useful for all kinds of sensors and actuators, not necessarily only for cryogenic applications. The concept can be expanded for the instruments to talk one-another without a human or computer intervention. All the reported instruments are presently installed and continuously under use with the cryogenic distribution system of Inter university Accelerator Center¹³, New Delhi for last two years.

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