RUSSIAN ACADEMY OF SCIENCES
PETERSBURG NUCLEAR PHYSICS INSTITUTE

Multi-Channel Measuring Instrument for Slow Control Systems

P.Kravtsov, V.Trofimov

Gatchina 2007

УДК 621.317.799:681.325

Многоканальный измерительный прибор для систем управления

П.А. Кравцов, В.А. Трофимов

Аннотация

Описано устройство и основные принципы работы прибора для измерения сигналов с датчиков в криогенных и газовых системах. Прибор обеспечивает подключение до 32 датчиков с потенциальным или токовым выходом. Точность прибора составляет 0.004 % от диапазона измерения, который может переключаться в пределах +4 В, ±5 В, +10 В, ±10 В. Дополнительно заложенные в программное обеспечение функции позволяют использовать прибор в качестве контроллера крейта для автономного управления набором устройств. Разнообразие интерфейсов обмена данными облегчает подключение прибора к управляющему компьютеру. Описаны результаты испытаний прибора и опыт его применения.

Abstract

A multi-channel device is described intended for the sensor measurements in cryogenic and gas systems. It provides reading of up to 32 sensors with voltage or current output. The device accuracy is 0.004 % of the measurement scale that can be selected from the range of +4 V, ±5 V, +10 V, ±10 V. Variety of the data exchange interfaces simplifies connection of the instrument to the external control system or computer. Implementation of crate controller function in the firmware allows using the instrument to control a set of various modules with different functions that operates as a single standalone instrument. The results of the device tests are described along with operating experience.

© ПИЯФ, 2007

Introduction

Cryogenic and gas systems [1, 2, 3] always require an automatic slow control systems due to high accuracy of the system parameters that could not be achieved by manual control and long term operation without an operator that needs reliability of the system. Automatic control systems are based on the measuring instruments for the sensor signal conditioning and conversion to the digital form. Generalization of the experimental techniques and experience obtained in various systems allow the development of the versatile set of the modular instruments that could be used to build the slow control system.

The commercial sensors that are typically used in the cryogenic and gas systems could be split into the following groups by the type of output signal:

1. sensors with voltage output (e.g. 0-5 VDC or 0-10 VDC);
2. sensors with current output (e.g. 0-20 mA or 4-20 mA);
3. resistive sensors that require a current source and produce voltage signal (resistance temperature detectors or levelmeters for example);
4. non-resistive sensors that require a current source and produce voltage signal (e.g. Hall probes).

The last two groups need a current source (with small current for RTDs and larger current for the Hall probes). They are usually connected to the measuring instrument with 4-wire scheme, in order to improve accuracy of the measurement or because of the sensor organization (e.g. Hall probe). Therefore these two types of the sensors are usually handled with dedicated measuring devices [4].

First two groups of the sensors have industrial standard outputs and usually do not require such a high accuracy and resolution like temperature sensors. Instead, the measuring instrument for the commercial sensors should have a possibility to measure voltage and current signals with various ranges. A sixteen bit resolution with the accuracy of some least significant bits is generally enough for these sensors.

There is also a concern that measuring instruments for all sensor types should have a possibility to be combined into a common control system. There are three possible system configurations consisting of multiple measuring devices:

1. all devices are working independently;
2. each device is connected to a PC and controlled independently;
3. all devices are combined in a common crate and operate as standalone system or could be controlled by a PC.

The first two configurations are more flexible while the last one has an advantage of reliability, because such a system can support experimental equipment operation with complex algorithms independently of the computer fails.

A special device (DAQ32) was developed for the commercial sensors measurements, which complies with all mentioned requirements. This device was designed on the basis of a modular control system experience for the ISTC #1861 project [5]. It could serve as a standalone device with main control algorithms implemented in the firmware or as a simple interface between sensors or other experimental system components and control computer. Besides, there is a possibility to use this instrument as a crate controller to combine multiple modules into single control system that could be used in turn in standalone or computer-controlled mode.

General layout of the device

The DAQ32 device (Fig. 1) is designed for industrial sensors measurements. It is equipped with 32 analog input channels with common selectable input voltage range. The signal from the sensor comes to analog filter (Fig. 2) with optional current shunt (Rs) for the current sensor connection. Current shunt installation allows one to accommodate the particular channel for the measurements with the current output sensor.

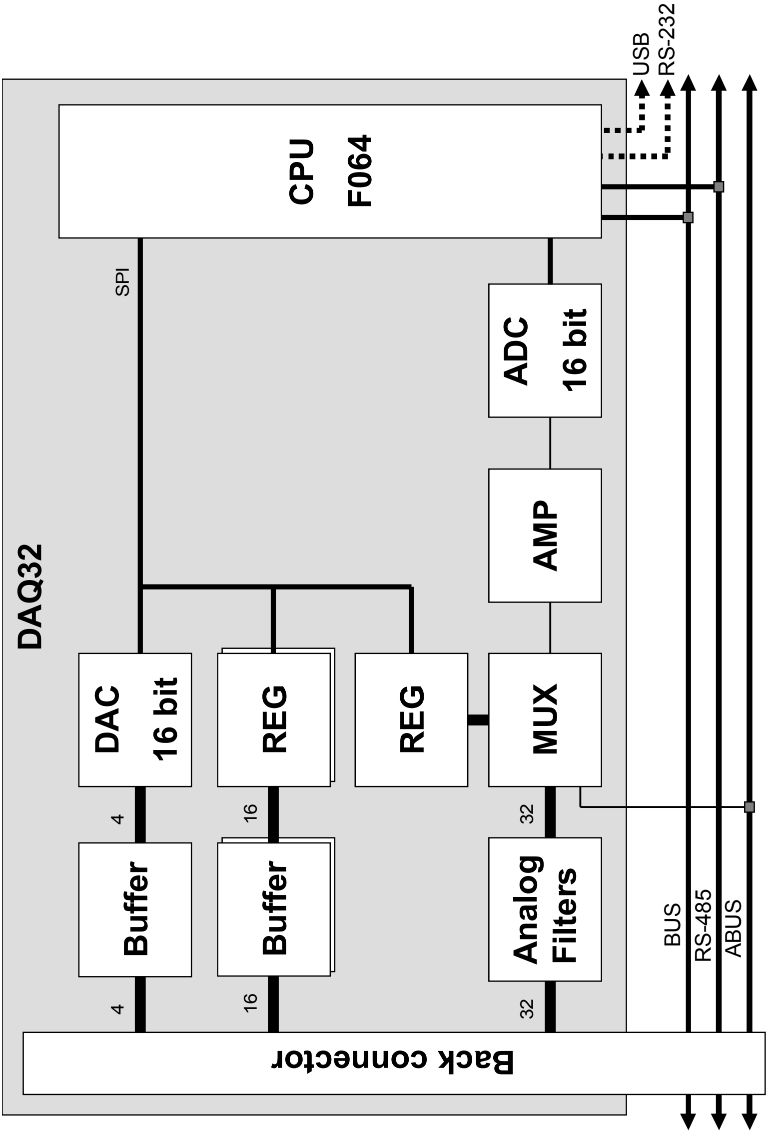

Fig. 1. DAQ32 simplified diagram.

Voltage signals from the sensors or from the shunts are multiplexed using two sixteen channels multiplexers[1], buffered with amplifier[2] and converted to a digital form using the 16-bit ADC[3]. All analog signals are routed through the back connector[4].

The device is equipped with four analog output channels from the 4-channel 16-bit DAC[5] that are buffered and amplified in the quad high precision operational amplifiers[6]. All four signals are connected through the back connector. Also, 16 buffered digital outputs are provided for the actuating devices control, e.g. valves and compressors in the gas systems or heaters in the cryogenic systems. These signals also are routed to the back connector.

The device is controlled by a high speed 8051-family CPU[7] working at 22.1184 MHz. These microprocessors are fully compatible with 8051 development tools that allow using of existing infrastructure to design the device. They also have some advantages in comparison to original 8051 family, e.g. in-system programming, debugging, and flexible integrated periphery.

The CPU has onboard 64 kB of in-system programmable flash memory and 4 kB of data memory. Besides, it supports the optional installation of an external 128 kB data memory. The CPU is equipped with two serial interfaces that makes possible to use one of them for host computer interface and second for the internal crate bus. There are several options (selectable by onboard jumpers) of computer communication interface: USB, RS-232 serial interface, full-duplex RS-485 serial interface. A special watch-dog circuit integrated to the CPU is used to protect the instrument from the firmware fail. It resets the CPU in 47 ms if the software hangs.

---

[1] MPC506, Burr-Brown products, Texas Instruments Incorporated.
[2] AD711 precision operational amplifier, Analog Devices Inc.
[3] ADS7813, Burr-Brown products, Texas Instruments Incorporated.
[4] DIN C 96-pin connector.
[5] DAC7634, Burr-Brown products, Texas Instruments Incorporated.
[6] OPA4277, Burr-Brown products, Texas Instruments Incorporated.
[7] C8051F064, Silicon Laboratories Inc.

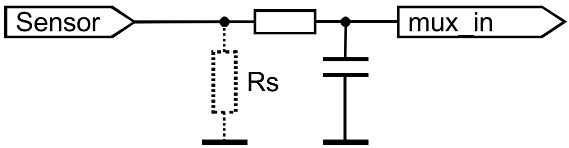

Fig. 2. Analog filter with optional current shunt.

The internal bus interface is used for the data exchange with the crate controller or slave instruments during the crate mode working with other devices in the crate. The DAQ32 instrument is developed in the standard EURO 100x160mm module size.

The firmware for the DAQ32 device was written in C language and provides all basic operations like reading the ADC, control the DAC signals and digital output drivers, and data exchange via communication interface. A Proportional-Integral-Derivative (PID) regulation algorithm was implemented in the firmware independently for every channel allowing for controlling the particular DAC signal using the selected ADC channel.

Measurements accuracy

The DAQ32 instrument provides measurement of up to 32 analog sensors. The range of the onboard 16-bit ADC could be selected using jumpers from the following options: -10 ÷ +10 VDC; 0 ÷ +10 VDC; -5 ÷ +5 VDC; 0 ÷ +4 VDC. These modes cover most of the industrial sensor signal ranges. The current shunt for the current sensor connection has to be chosen in accordance with the selected ADC range.

The firmware provides averaging of every analog channel measurements with adjustable number of samples. The averaging of the ADC samples helps to suppress the measurement noise, but increases the total measurement time required for 32 channels (Table 1). Table shows that DAQ32 instrument provides the measurement of all 32 channels fast enough for the requirements of the slow control systems.

Table 1. Number of samples for averaging and total measurement time.

Number of samples	Total time, ms
1	8
8	16
16	25
32	45
64	78
128	150
255	280

A special measurement mode ("accumulation mode") was implemented in the firmware for investigation of the signal transient processes and effect of multiplexing. In this mode, the instrument acquires the ADC with averaging by specified number of samples and stores every averaged reading in the data memory. The accumulated history of the signal could then be read and processed by computer software. This allows investigation of processes with time resolution of 35 µs that is impossible for usual successive reading of ADC samples by a computer. It also enables the estimation of the measurement accuracy for various averaging numbers.

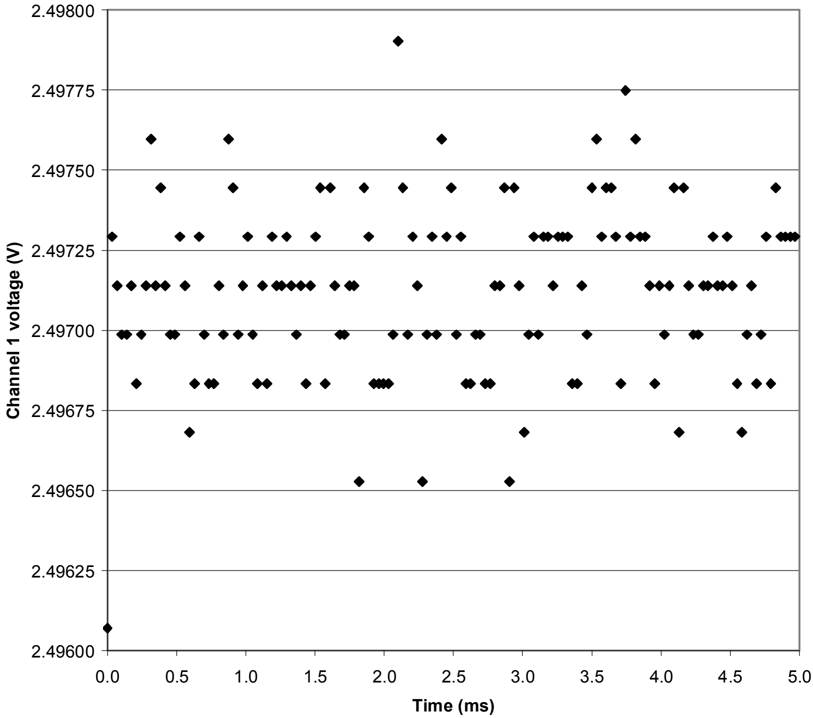

Fig. 3. Channel 1 signal behavior in accumulation mode. No averaging is used.

Typical transient behavior of the channel voltage after switching the multiplexer is shown in Fig. 3. The instrument was set to continuously measure grounded channel 31, then it was switched to channel 1 connected to the external +2.5 V reference and measures it in the accumulation mode. No averaging was used in this measurement. It is clearly seen from this chart, that transient processes of the multiplexer switching are much faster than ADC conversion. Even without averaging first ADC sample is only 1mV below the average measurement level. To suppress this small discrepancy, a 135 μs delay was implemented in the normal mode after switching the multiplexer.

Three analog input channels (1, 3 and 5) were connected to the external +2.5 V reference source for the accuracy measurements. For the investigation of current signal interference 14 channels (even channel numbers 0÷26) were connected to +5 V with current shunt installed for each of these channels. Current shunts were chosen to 301 Ω to provide 16 mA current through every shunt. Besides, other 11 channels (odd channel numbers 7÷27) were also equipped with current shunts with possibility to connect them either to +5 V or to ground. This was done to check the influence of high currents (11·16 = 176 mA) in analog circuits to other channel measurements.

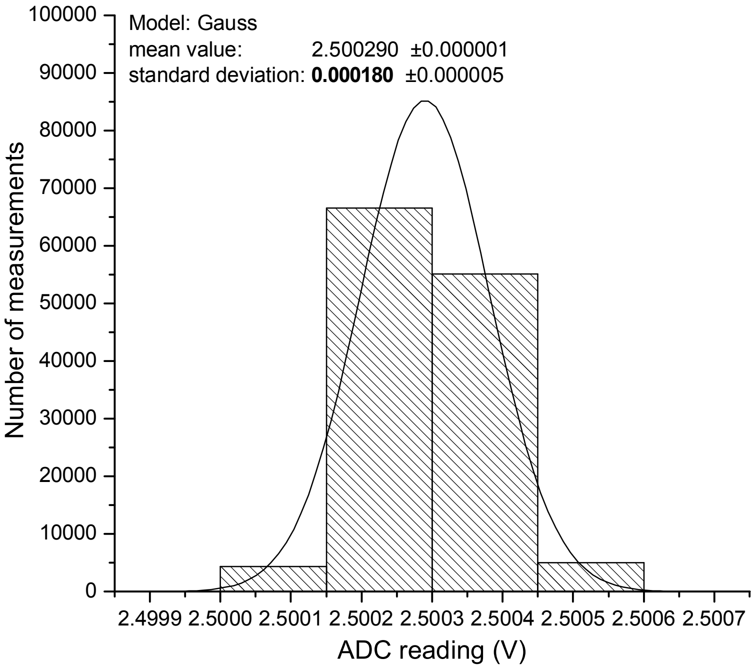

Fig. 4. Signal distribution as measured with three channels.

The measurements of the three channels connected to the reference were put together and analyzed. The distribution of the measured reference signal is shown in Fig. 4. The measurements were carried out with averaging by 16 samples, total scanning time of 32 channels 25 ms.

Reference channels were interlaced with +5 V channels with current shunts. Obviously, the channel interference is negligible. Reference signal samples are spread within two least significant bits of the ADC with the standard deviation of 0.18 mV.

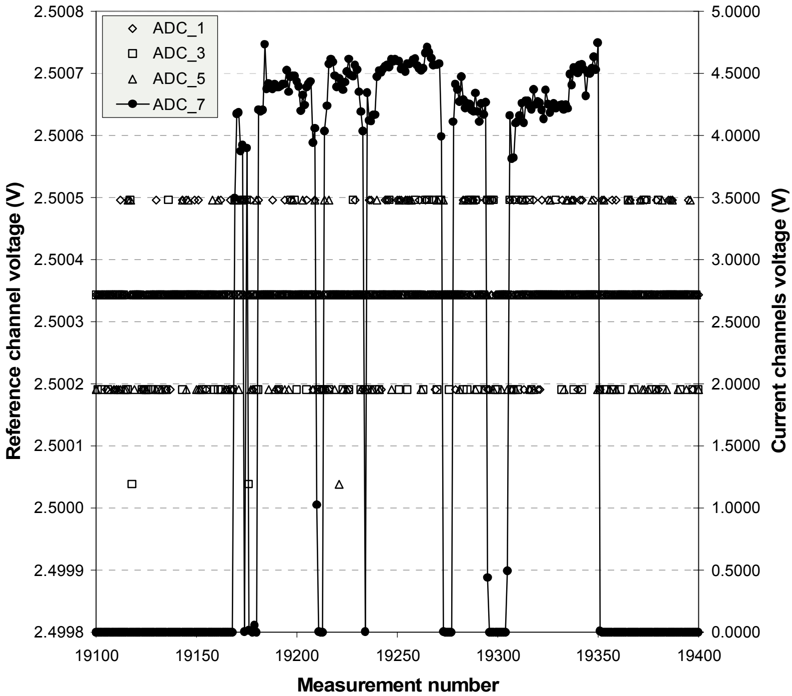

Fig. 5. Influence of the high currents on the reference measurements.

The impact of the high current in the analog circuits upon the reference measurements was investigated with intermittent connection of the eleven channels to +5 V and ground, producing the intermittent current of 176 mA in the analog filters (Fig. 5). The distortion of the reference channel measurements is less than ADC resolution and could not be seen in the chart.

Communication protocol

The DAQ32 instrument is equipped with two serial communication channels. One is used for data exchange with the host computer, second is dedicated to internal crate bus interface. Host computer interface could be converted into one of the following options: RS-232, RS-485 (full duplex) or USB. A simple CMOS serial interface is used for the crate bus.

The communication protocol is the same for both serial channels. It is based on usual request-answer scheme with 5 bytes binary packets exchange. This protocol is used in a number of devices enabling the versatile computer software development. The requests (commands) are sent by a host device (computer or crate controller); answers are sent by the slave device with correct address.

Table 2. 5-byte packet format.

Byte	Description
1	Bit 7 – read/write bit. Bit 7 = 1 corresponds to write command and bit 7 = 0 – read command. Bit 6 – special command flag. If bit 6 = 1, packet contains special command. Bits 5÷0 - device address. Should be equal to the preprogrammed device address or packet will be ignored otherwise.
2	High byte of 16-bits address field.
3	Low byte of 16-bits address field.
4	Data byte.
5	XOR-sum of first 4 bytes. B5=B1^B2^B3^B4. If it is not correct XOR-sum, packet is ignored.

The protocol consists of two main commands: read instrument memory byte and write instrument memory byte. It could contain also some special commands that are specially described for every device. The device sends 5-byte answer for every 5-byte command, if device address field in this command is correct. The packet structure is shown in Table 2.

One special command is accepted by all instruments, with byte 1 = 0x41. In response to this command the device sends the memory area from zero address to the address specified in the command (bytes 2:3). This command is the fastest way to get all information from the device, being 10 times faster than usual 5-byte packets exchange.

Communication speed could be programmed using a special command. By default 115.2 Kbit/s speed is set. Usually read or write access to the device memory using this protocol takes not more than 2ms for every byte at 115.2 Kbit/s.

The versatile communication protocol simplifies the data exchange with the instruments, reducing transmitting of any variable to the device memory access with simple byte transfer. Memory map is different for every device and is specially described as well as additional commands. Byte ordering of multi-byte variables is little endian, high byte has low address. The memory map of the DAQ32 instrument is shown in Table 3. It could vary depending on the instrument application, with implementing additional control algorithms that defined by experiment or slow control system requirements.

Table 3. Memory map of the DAQ32 instrument.

Address	**Length (bytes)**	**Type**	**Name**	**Description**
0x0000	2	word	WDCount	Watch-dog resets counter. Should be 0 or small value and not increase. This counter resets to 0 at every "cold" start, i.e. power-on procedure and increases at every watch-dog CPU reset.
0x0002	1	byte	Flags1	Internal bit flags.
0x0003	1	byte	Flags	Internal bit flags.
0x0004	1	byte	xDevAddr	Device address.
0x0005	1	byte	ClockLoad	Internal timer counter.
0x0006	1	byte	MUXADDR	Internal multiplexer address.

Address	Length (bytes)	Type	Name	Description
0x0007	1	byte	ADCchan	ADC channel number. Device will measure only this channel (0÷31) or all 32 channels if ADCchan>31.
0x0008	1	byte	AVGCount	Number of samples to average. No averaging occurs if = 0. Default value is 0x10.
0x000A	2	word	ADCDelay	Delay between multiplexer switching and ADC conversion. Default value is 0x100.
0x000C	1	byte	ADCchanH	ADC channel number for accumulation mode.
0x000D	1	byte	DO1	Digital outputs control byte.
0x000E	1	byte	DO2	Digital outputs control byte.
0x000F	1	Byte	ID	Device ID = 0xA1. It is NOT device address.
0x0020	64	word	ADCval[32]	Sensor values in 2-byte integer format.
0x0060	8	word	DACval[4]	DAC values.
0x100	32			Crate controller internal variables.
0x120	16	struct	Slave[4]	Slave information structure with device address (byte), status (byte), and memory size (word) for every slave device.
0x130	64	array	ZCmd	Ring FIFO buffer containing the control commands for the slave devices.

Address	Length (bytes)	Type	Name	Description
0x170	64	struct	PID[4]	PID regulation structure with PID coefficients, process variables and setpoint.

Bus interface

The communication protocol of the crate bus is the same like protocol of the host computer data exchange. Crate controller functions are implemented in the DAQ32 device and include periodical poll of all programmed slave instruments installed in the crate. The crate controller keeps the slave device address, status and memory size to be read during the poll. Device status contains information about communication errors of the particular slave device and is used to stop the data exchange with the slaves that are not responding. The specified memory range of every slave instrument is read into a special area of the crate controller memory and becomes available for subsequent reading by the host computer.

In addition to periodical poll of the slave devices, the control functions are implemented in the crate controller firmware. There is a special ring FIFO buffer for the slave commands that could be filled either by the host computer or by the crate controller software. The commands from this buffer are sent to the slaves between the polls.

Communication speed of the crate bus is programmable using the following procedure. First, the speed value is written into the crate controller by the host computer. Then it is distributed among the slave devices by a special crate controller command. After this a special interrupt signal is generated on the bus forced all slaves to switch to the new communication speed.

The bus interface provides the reliable data exchange between devices in the crate and allows the crate to operate as a unified standalone instrument.

Calibration

The DAQ32 device was calibrated using Keithley 2700 digital multimeter (KDMM). Keithley readings and ADC samples were interpolated with linear regression. The difference between average Keithley reading and voltage calculated by calibration is shown in Fig. 6. It is obvious that calibration error does not exceed ±0.2 mV that is 0.004 % of the full scale (10 V). This calibration error corresponds to the Keithley multimeter error (0.2 mV at the 10 V scale).

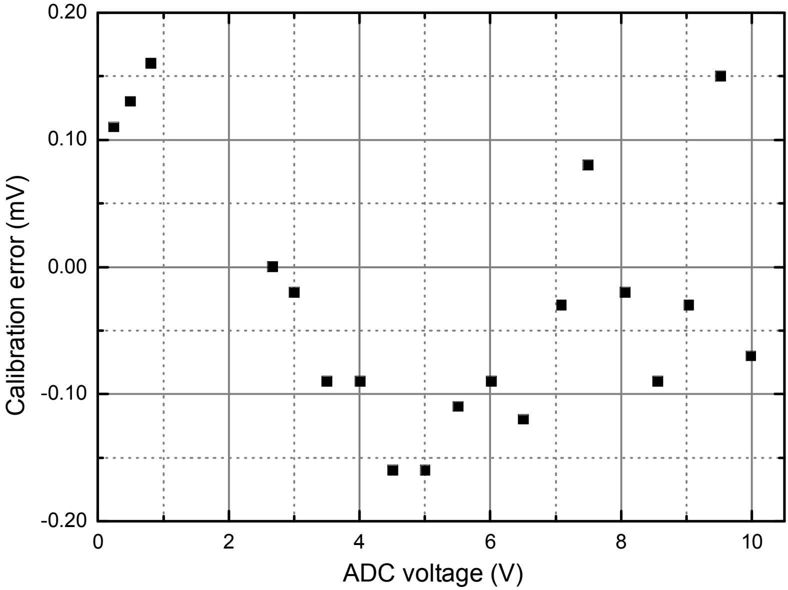

Fig. 6. Calibration error of the DAQ32 device.

The measurement error of 0.004 % is absolutely sufficient for the commercial sensors with typical calibration error not less than 0.01 %. The same calibration error was measured for all ADC ranges.

Operating experience

The DAQ32 instrument was used in the Deuterium Removal Unit (DRU) [2] of the MuCap experiment. It provides the pressure measurements with absolute[8] and differential[9] pressure sensors. Differential sensor was used for the precise measurement of the liquid hydrogen level in the reboiler.

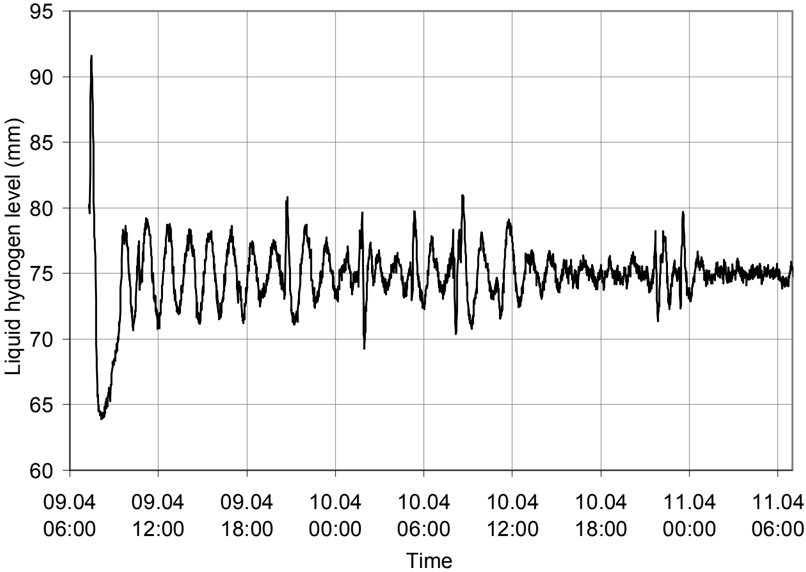

Fig. 7. Liquid hydrogen level stabilization.

The liquid level was stabilized using PID regulation algorithm controlling an electric heater in the reboiler (Fig. 7). Level oscillation in the left half of the chart are explained by the tuning the algorithms of joint work of the DRU and CHUPS [3] systems in the circulation mode. A hydrogen gas was circulated through the DRU system using CHUPS facility. Inlet and outlet circulation flow was regulated with two mass flow controllers. The device proved to be very reliable and flexible during all DRU experiments.

---

[8] Keller Piezoresistive pressure transmitters series PAA21. Keller AG für Druckmesstechnik, St. Gallerstrasse 119 CH-8404 Winterthur.

[9] Series 631 Wet/Wet Differential Pressure Transmitter. Dwyer Instruments, Inc. P.O. Box 373, Michigan City, IN 46361, USA. (http://www.dwyer-inst.com)

Conclusion

The DAQ32 device proved to be very stable and reliable during the cryogenic systems experiments. It achieved very good resolution (0.003 % of the full scale) and measurement accuracy (0.004 % of the full scale) with selectable ADC range.

The flexibility of the instrument allows one to connect commercial sensors with voltage or current output. Using of the microprocessor core enables the implementation of additional control algorithms in the device, allowing stand-alone mode of the system control. The control operation is also supported with abundance of analog and digital control channels. Variety of the data exchange interfaces simplifies connection of the instrument to the external control system or computer.

An addition internal crate bus interface with implementation of crate controller function in the DAQ32 firmware allows one to assemble a set of various modules with different functions that operates as a single standalone instrument, with main control function placed on DAQ32 crate controller.

All these advantages make the DAQ32 instrument extremely useful for building the control subsystems of various cryogenic or gas systems. Big number of channels with high acquisition speed enables the development of the control system on a single DAQ32 instrument. For instance, it is possible to control the typical gas system [1, 6, 7] with one DAQ32 device.

Acknowledgments

The authors wish to thank Dr. A. Vasilyev for important design remarks and fruitful discussions. They gratefully acknowledge the MuCap collaboration for their support of the experiments involving the DAQ32 instrument.

References

[1] L. Kotchenda *et al.*, STAR TPC gas system. NIM **A 499** (2003), pp. 703-712.

[2] I. Alekseev *et al*. Experimental Results of Hydrogen Distillation at the Deuterium Removal Unit of the MuCap Experiment. Preprint PNPI-2702, Gatchina (2006) 26 p.

[3] A. Vasilyev, B. Bezymyannykh, V. Ganzha, P. Kravtsov, G. Shapkin, V. Trofimov, M. Vznuzdaev. Cryogenic System for Continuous Ultrahigh Hydrogen Purification in Circulation mode. NHA Annual Hydrogen Conference 2005, Washington, DC.

[4] P. Kravtsov et al., High-Precision Temperature Measuring Instrument. Preprint PNPI-2722, Gatchina (2007) 24 p.

[5] M. Poltavtsev *et al*., Nuclear Polarization of Hydrogen and Deuterium Molecules after Recombination of Polarized Atoms in a Storage Cell. Meeting of the German Physical Society, 2005, Berlin.

[6] L. Kotchenda *et al*., Gas systems of PHENIX central tracking detectors. PNPI Annual Report 1999.

[7] L. Kotchenda *et al*., PHENIX TEC-TRD Detector Gas System. Preprint PNPI-2712, Gatchina (2007) 16 p.