SOFTWARE DEVELOPMENT FOR INTEGRATED CONTROL SYSTEM OF DC MAGNET POWER SUPPLY

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Abstract

To enhance the system reliability and maintainability, an integrated DC magnet power supply control board is designed to effectively consolidate several control functions into a unified whole. A Raspberry Pi Compute Module, a STM32 micro-controller, an Intel CPLD as well as other functional ICs, such as energy measurement IC, ADCs and DACs, are embedded into a single board. The software implementation handles the control logic and communications among these ICs. An EPICS IOC runs inside the Raspberry Pi deals with the EPICS communication towards our main control network while the micro controller aggregates hardware status information from ICs and reports them to the IOC. The CPLD is mainly used for the interlock signal processing. The communication protocol design between those parts and programming practice experiences are introduced in this work.

INTRODUCTION

About 200 power supplies for the steering magnets are used at the KEK injector linac to support a stable beam operation. A newly design of the steering magnet power supply control system replaces the old PLC based system with a new Raspberry Pi (RPi) based control system to decrease the difficulties of the EPICS (Experimental Physics and Industrial Control System) integration as EPICS is the standard framework of the control system at the injector linac. This system has started to operate since 2020 [1].

The first version of the Raspberry Pi based DC power supply control system has been reported in paper [1, 2]. Nevertheless, lack of self monitoring feature, high coupling between different modules and ungraceful cable connections have become a major concern of the control system during the long term accelerator operation. The second version is thus developed to address those concerns.

The Raspberry Pi Compute Module (RPi CM), the STM32 micro-controller (MCU), the Intel Complex Programmable Logic Device (CPLD) as well as other monitoring ICs are embedded into a single PCB board to meet our requirements. The configuration of those monitoring ICs are controlled by the STM32 MCU.

CONTROL BOARD

To improve the functionality of the DC power supply control system, several new modules are introduced in the new control board. The layout of the control board is shown in Fig. 1 and the change of modules is shown in Fig. 2. The 24-bit ADC (LTC2380) and 20-bit DAC (AD5791) are reused because they are proved to be effective and accurate to control the magnet power supply during the accelerator operation.

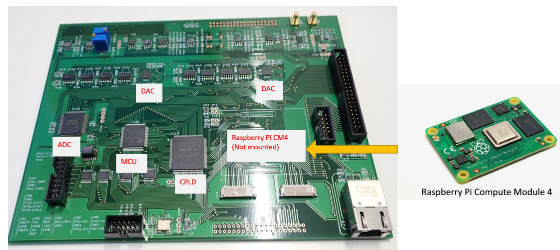

Figure 1: The layout of new control board.

The main controller is changed to the RPi CM4 which is specifically designed for industrial and embedded applications. It is built with the same ARM processor as the Raspberry Pi 4 so that the software of the first version control board can be mostly reused. We also benefit from the flexibly of RPi CM4 by deliberately removing unnecessary IO interfaces, like HDMI and audio ports, to reduce the risk of bus interference.

The Arduino Mega board is substituted by the STM32G474 device because the MCU can provide more General-purpose input/output (GPIO) Pins (up to 107), which makes it possible to monitor many on-board signals. And the MCU is capable to operate at a frequency of up to 170 MHz. The MCU has 512 KB FLASH to storage the data and 128 KB RAM to run the program [3]. The SPI and UART controller inside the MCU are used to communicate with other modules.

Main controller	Raspberry Pi 4B
Sub controller	Arduino Mega 2560 R3
ADC	LTC2380-24 (24 bit)
DAC	AD5791 (20 bit)

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Main controller	Raspberry Pi CM 4
Sub controller	STM32G474-QE
ADC	LTC2380-24 (24 bit)
DAC	AD5791 (20 bit)
Logic control	MAX V CPLD 5M570Z
ADC	ADS8686S (16 bit)
DAC	DAC81416 (16 bit)
Power metering	ADE9078

Figure 2: The change of modules in new design.

The on-board signal monitoring is implemented by using a 16-channel, 16-bit ADC module (ADS8686S) and two daisy-chained 16-bit DAC modules (DAC81416) [4, 5]. The DACs are responsible for outputting the signal threshold while the ADC monitors whether the on-board signals sit between the thresholds. Besides that, the ADE9078 power

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metering IC allows the control board to perform a highly accurate power and energy measurement [6].

The on-board signals act as one kind of interlock signals and are examined by the MAX V CPLD. The CPLD ensures the flexibility of interlock signal processing because the modification and upgrade of the interlock logic can be easily achieved by reprogramming the CPLD rather than redesigning the control board.

SOFTWARE IMPLEMENTATION

The systematic diagram of the new architecture is show in Fig. 3. The EPICS IOC runs inside the RPi module controls the magnet power supply the same way as the former design.

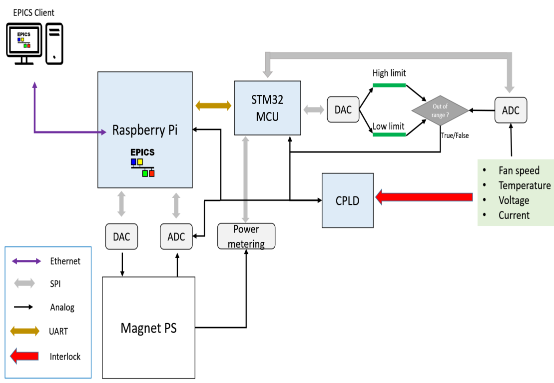
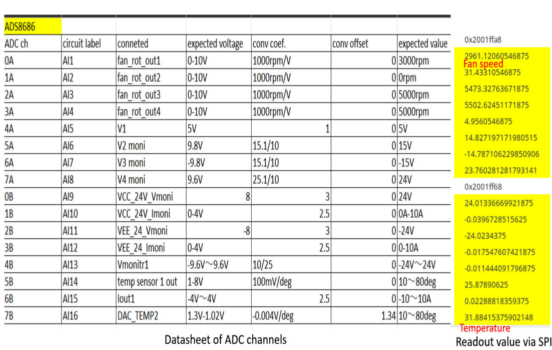


Figure 3: The software schematic diagram.

On-board IC configuration

To properly utilize the on-board monitoring IC, several commands must be transferred to the registers inside the ICs via the SPI interface. The Hardware Abstraction Layer (HAL) API provided by the STM company is used to configure the SPI controller and transfer frames between MCU and ADC/DAC ICs.



ADS8686							
ADC ch	circuit label	conneted	expected voltage	conv coef.	conv offset	expected value	Readout value via SPI
0A	AI1	fan_rot_out1	0-10V	1000rpm/V	0	3000rpm	2961.12060546875
1A	AI2	fan_rot_out2	0-10V	1000rpm/V	0	0rpm	31.43310546875
2A	AI3	fan_rot_out3	0-10V	1000rpm/V	0	5000rpm	5473.32763671875
3A	AI4	fan_rot_out4	0-10V	1000rpm/V	0	5000rpm	5502.62451171875
4A	AI5	V1	5V	1	0	5V	4.9560546875
5A	AI6	V2 moni	9.8V	15.1/10	0	15V	14.827197171980515
6A	AI7	V3 moni	-9.8V	15.1/10	0	-15V	-14.787106229850906
7A	AI8	V4 moni	9.6V	25.1/10	0	24V	23.760281281793141
0B	AI9	VCC_24V_Vmoni	8	3	0	24V	24.01336669921875
1B	AI10	VCC_24V_Imoni	0-4V	2.5	0	0A-10A	-0.0396728515625
2B	AI11	VEE_24_Vmoni	-8	3	0	-24V	-24.0234375
3B	AI12	VEE_24_Imoni	0-4V	2.5	0	0-10A	-0.017547607421875
4B	AI13	Vmonitr1	-9.6V～9.6V	10/25	0	-24V～24V	-0.011444091796875
5B	AI14	temp sensor 1 out	1-8V	100mV/deg	0	10～80deg	25.87890625
6B	AI15	Iout1	-4V～4V	2.5	0	-10～10A	0.02288818359375
7B	AI16	DAC_TEMP2	1.3V-1.02V	-0.004V/deg	1.34	10～80deg	31.88415375902148

Figure 4: The readout value of ADS8686S via SPI.

The on-board monitoring ADC measures the fan speed, temperature, current and voltage value. The MCU then collect these data through SPI and convert the raw data to engineering value. The results of converted data are shown in Fig. 4.

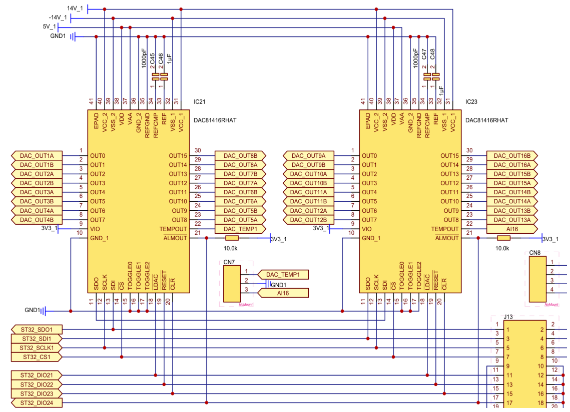


Figure 5: Two DACs are connected in daisy-chain.

To save the GPIO pins of the MCU, two on-board monitoring DACs are connected in series to form a daisy-chain connections. The diagram is shown in Fig. 5. The SPI communication software are also capable to support this kind of scheme.

Before measuring the power and energy using the ADE9078 IC, additional gain calibration is necessary to acquire accurate results because the sampling capacitors inside the ADE9078 vary device to device [6]. By applying a known nominal voltage to the IC, the measurement value by the ADE9078 is read via SPI. Then the voltage gain can be acquired by comparing the expected value and measured value. With the help of KIKUSUI PCR2000WE AC Power Supply module and HIOKI PW3390 Power Analyzer, the voltage gain calibration is performed and the experiment data is recorded in Table 1. Figure 6 shows the parameters of AC power measured by the Power Analyzer. The voltage gain under such case is 2.023.

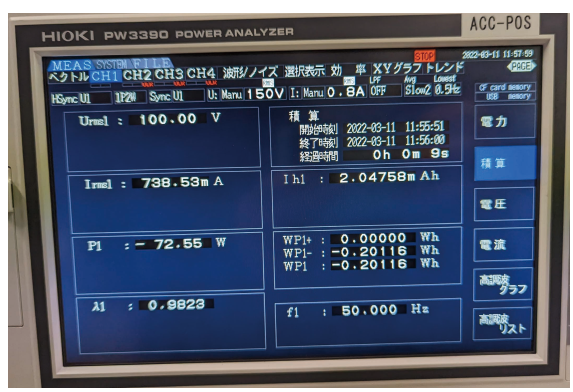


Figure 6: The HIOKI PW3390 power analyzer.

CPLD

There are two major functions of the CPLD. The first is to implement the interlock logic. The other is to provide the ADC sampling clock.

The interlock signals consist of three types, 16 analog lines, 12 digital lines, and 4 external lines. All signals are latched inside using the CPLD logic. If one of these signals

Table 1: Voltage Gain Calibration of ADE9078

Nominal Value	Expected Value	Measured Value
100 V RMS	0.10 V RMS	0.0494 V RMS
110 V RMS	0.11 V RMS	0.0544 V RMS
120 V RMS	0.12 V RMS	0.0593 V RMS
130 V RMS	0.13 V RMS	0.0642 V RMS
140 V RMS	0.14 V RMS	0.0692 V RMS

fail, the CPLD triggers a relay which cuts off the output. The interlock logic can be reset either by a physical push button or by a RPi GPIO output.

The LTC-2380 ADC features an average-N conversions which receives continuously conversion trigger and outputs the averaged results. Consequently, the synchronization logic is achieved using 4 4-bit counters inside the CPLD to provide up to 32768 triggers pulses.

EPICS Integration

All the on-board monitored values as well as the latched interlock signals should be published through EPICS. The UART API between EPICS IOC and MCU is designed based on the EPICS StreamDevice module [7]. The IOC constructs text-based commands using StreamDevice module and sends the commands to MCU.

The MCU is set to receive an amount of data in interrupt mode till either the expected number of data is received or an IDLE event occurs. After checking the start flag and device control byte, dedicated commands are analyzed and sent to targeted IC via SPI. Besides of the basic register read and write commands, several special function commands are provided to reduce the complexity of StreamDevice protocol. The description of UART command is shown in Fig. 7 and the example protocol file for ADC is shown in Fig. 8.

Command description

The command strings are **Text-based**. The *start flag* is `HEY!`.

Special control character is used to select devices

- `DC1` (`0x11` or `0d17` or `^Q`) *device control 1* --------> ADS8686S
- `DC2` (`0x12` or `0d18` or `^R`) *device control 2* --------> DAC81416
- `DC3` (`0x13` or `0d19` or `^S`) *device control 3* --------> ADE9078
- `DC4` (`0x14` or `0d20` or `^T`) *device control 4* --------> Interlock signals

All returned data is appended with terminator of `CR LF`.

After the device selection byte, a command byte follows. Command byte includes,

- Read -> `R`
- Write -> `W`
- Special function -> `S`

Figure 7: The UART API.

SUMMARY

The new software of the new steering magnet power supply control board is developed. Apart from controlling the magnet power supply, it also includes operation status monitoring and energy measurement feature. The STM32 MCU works as a bridge between RPi IOC and on-board ICs.

The UART API between EPICS IOC and MCU provides an easy-to-use template for similar projects. This development process expands the usability of EPICS in the embedded system field.

```
#-----User variables-----#
device = 0x11;
ok = "OK";
#-----User variables-----#

#-----Allowed Register names-----#
# CR, CHSEL, RANA1, RANA2, RANB1, RANB2, SR, ORSA, ORSB, LPF, ID, SSR{0-8}
#-----Allowed Register names-----#


rd {
    out "HEY!",$device,"R:\$1";
    in "%x";
}

wr {
    out "HEY!",$device,"W:\$1:%#x";
    in $ok;
}

# read device ID
sp1 {
    out "HEY!",$device,"S:1";
    in "%x";
}

# set ADC to default configuration
sp2 {
    out "HEY!",$device,"S:2";
    in $ok;
}

# read 16 channel's raw data
sp3 {
    out "HEY!",$device,"S:3";
    in  "%d";
}

# read 16 channel's convertered data
sp4 {
    out "HEY!",$device,"S:4";
    in  "%f";
}

# set to factory mode
sp5 {
    out "HEY!",$device,"S:5";
    in $ok;
}
```

Figure 8: The protocol file for StreamDevice.

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