Real time capable control design with increased life expectancy for research purposes

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Abstract. A new, freely programmable, scalable control system for academic research purposes was developed. The intention was, to have a control unit capable of handling multiple PT1000 temperature sensors at reasonable accuracy and temperature range, as well as digital input signals and providing more powerful output signals at 230V AC than conventional control units. To take full advantage of the system, control-loops are run in real time. The whole system runs independently of a personal computer. The two on-board RS232 connectors allow to connect further units to use more sensors or actuators or to connect other laboratory equipment, as required. To allow usage for long-time experiments, systematically electronic components with low failure-in-time (FIT) rate have been chosen in order to achieve high life expectancy. This paper describes the third prototype, which now provides stable measurements, and an improvement in accuracy compared to the previous designs. A rough estimation about the expected mean time between failures is given. As test case, a thermal solar system to produce hot tap water and assist heating in a single-family house was implemented. The solar fluid pump was power-controlled and several temperatures at different points in the hydraulic system were measured and used in the control algorithms. The hardware design proved suitable to test several different control strategies and their corresponding algorithms for the thermal solar system.

1. Introduction

When preparing experiments in the test and education laboratories, again and again we encountered similar situations: Deciding which control is the most suitable for the intended specific application. When setting up test benches in the field of air conditioning, more temperature sensors, than standard control systems usually offer, were needed. When setting up the thermal solar energy field test system later described, more sensors were needed, more input channels were needed. For planned future tests more powerful outputs to drive electric valves and mixer motors at 230V will be needed than the systems we looked at could offer at a price that is suitable for unsponsored, independent research. Many of the conventional controls offer relay outputs. These are great for high currents, but not suitable for power control in a mix of pulse width modulated- and leading – edge manner we intended.
The commercially available smaller control units were designed with few input channels and few output channels on board. Additional input/output modules are expensive. The larger commercial control units had enough input/output channels but were financially out of reach and did not offer the capability to be freely programmable.

2. Yet another free programmable control unit?
In order to prepare several experiments for student’s lab courses, the same above described difficulties arose.

Additionally none of the available systems was completely free programmable. Real time response times in the millisecond range we could not find. But for fast process control the short response times of control loops are essential. To realize short control loops free programmability is necessary.

The open source control boards like the Arduino and raspberry families are built-up on a modular basis which is great to test ideas and strategies on the desk. But for test benches intended to run for several years, we had objections concerning the lifetime. And the fine granular modularity of Arduino and raspberry input/output modules doesn’t make mounting “on-site” an easy task.

So we decided to see if we can build a system that serves our needs and gives our students a good chance to learn how control systems can be built with little resources.

3. Goals of the new design
As goals of the design we defined to have, in contrast to the first version with sixteen temperature inputs, only ten PT1000 temperature inputs to save space on the board. Additionally we wanted to have six inputs at mains voltage of 230V, up to sixteen semiconductor outputs at 230 Volts to power single phase motors.

To be able to modify parameters on-site without the need of a PC, an additional, but optional board was designed to have a small text display (four lines at sixteen characters), eight input buttons and eight LEDs for indication purposes.

A second filter stage at the analog input ports should be added to further reduce the influences of electromagnetic interference (EMI) and hum when long sensor lines are connected. The length of the sensor lines could exceed twenty meters.

To allow timed actions a hardware real time clock (RTC) was added.

4. Safety and reliability considerations
In the laboratory test bench controls are switched off most of the time, so reliability issues that come along with “runtime-hours” are usually insignificant. Functional safety has been taken into account. A risk analysis has been performed. In case of air conditioning the controlled equipment doesn’t cause harm in case of a malfunction. No safety measures have to be included.

In the considered case of the air condition test bench the electronic equipment was assumed to be mounted in a place inside the housing where temperatures are relatively high during use. Mounting in a cooler area inside the housing was avoided due to expected condensation problems.

The control application for the solar field test has need for safety, since the solar fluid pump must not run when the collector is filled with steam. If fluid is pumped into the hot collector in this state, a steam explosion is likely to occur.

Hot temperatures although, are known to reduce lifetime of electronic components and likely cause earlier malfunctioning behavior of a device.

To keep the risks low, a big design goal was to minimize malfunction behavior caused by component wear.

To allow easy repair the PCB layout was decided to be fitted on two layers of copper.

5. Conceptual approach
The block diagram in Figure 1 is derived according to sections 3 and 4.
5.1. Explanations of intended functions
In Figure 1 the main functional units are shown as defined in previous sections.
In addition the 230V galvanic isolated parts are marked yellow-green to symbolize that care must be taken to ensure the clearance and creepage distances in the layout according to [7]. The violet block indicates the optional display- and button unit (man-machine-interface, MMI).
Not shown are additional RAM and real time clock.

5.2. Details of selected hardware functions
The digital multiplexers are connected with SPI lines to the Microcontroller.
The multiplexers are structured in a way that allows the reading of the input signals at the same time the outputs are written. Transmitting and receiving of one byte on the SPI bus is done by the built-in USART of the microcontroller. This allows fast Input and Output transitions of the multiplexed input and output signals at relatively low microprocessor operation time.
The real time clock is connected to normal input/output pins of the Microcontroller and operated by SPI protocol implemented in software.
As Controller system we decided to use the Atmel MEGA128 “AU” version. With its 5Volt technology and integrated clamping diodes it is electrically very robust and relatively tolerant to electromagnetic interference (EMI) [1].
To reduce power consumption and self-heating, the Microcontroller runs at only twelve Megahertz. This frequency is sufficient for all of the tested functionality, including the dimming of the LCD-backlight by pulse width modulation (PWM). To enhance reliability, a ceramic resonator is used instead of a quartz. The reduced accuracy in resonator frequency, compared to a quartz, limits communication speed on the RS232 interfaces to approximately 56k baud.
Figure 2. Top view of the main control board.
Legend: yellow: 230Volts domain, blue: analogue domain

Figure 3. Bottom view of the main control board, colours see Figure 2
5.3. Power supply
To supply the whole system with energy a switching wall plug is used at 7Volts output. To bring these 7 Volts down to the 5V system voltage, a linear voltage regulator is used. This simplifies the handling of EMC filtering and at the very low currents used enhances reliability compared to switching regulators.

To give a rough estimation of power consumption, Table 1 shows the main energy consumers.

| Power supply component | Current consumption (in mA) |
|------------------------|-----------------------------|
| Microcontroller AT Mega128 AU | About 3mA with output pins low |
| 230V switches (solid state relays) | Each about 8 mA on DC-side in activated state |
| LCD backlight LEDs | About 160 mA at full power, dimmed about 100mA |
| Overall current consumption | The measured values were below 200mA with eight power outputs in “on”-state and display backlight dimmed. |

5.4. The analog PT1000 temperature measurement circuit
The experiments carried out showed, that the temperature stability of the measurement electronics is far better than expected.

However, the absolute accuracy had to be adjusted manually for each temperature sensor.

The test scenario with the air condition showed that at and below zero degrees Celsius accuracy is not as good as the simulations resulted in. We suppose, that the multiplexer circuits introduce injection currents that influence the measurements in a negative way. Future redesigns will take into account these effects by simulations [5].

The specified temperature range is -30°C to approximately +170°C. Using analog signal conditioning circuits similar to the ones described in [3,4] turned out in our constellation to give relatively large errors and offsets. Experiments have shown that more accurate measurements can be obtained when using oversampling techniques [5] and omitting large signal conditioning circuits. For all measurements the built-in ADC of the microcontroller was used. Massive filtering is needed to handle the noise picked up by long measuring lines. Shielded lines did not significantly reduce the effect.

Wiring was decided to be carried out as two lines per sensor. The change in resistance is much greater than the resistance induced by the wiring as well as the change of the wiring’s resistance with temperature. Four line measuring was not implemented due to limited space on the PCB.

5.5. The display unit
The display unit consists of a two-layer PCB with large ground plane (Figure 4) and eight mechanical pushbutton switches. (Figure 5)

These “old fashioned” mechanical switches give an immediate “click”-sound feedback when pressed. This is important in combination with the slow display update rate of one per second.

Measured at the number of activation events during the lifetime of the control, these SMD switches are not a lifetime limiting factor. In figure 4 close to the lower left corner of the PCB an unused double row header can be seen. This is an intended design alternative to have the choice of which HD44780 compatible display module to use.

The non-graphical character display was chosen due to several reasons:
- If graphics are needed, a PC can be connected by RS232.
- The capabilities of the eight bit controller were not intended to be used to the outmost extent.
- The limited RAM of the controller is used to store variables and measurement results for later download by a PC.
Figure 4. Bottom view of the display board, mounted to the backside of a housing lid

Figure 5. Front view of the display board. LEDs are hidden under the top cover
6. Reliability estimation according to SN29500
According to ISO 61709 a reliability calculation using the FIT rates of Siemens standard SN29500 was carried out. [6,7,8]

The result is an estimated rate of 1313 FIT, which equals an MTBF value of approximately 86 years. Calculation was done for the main board including 8 solid state relays for the digital output. Not included in these calculations is the display-board.

According to the fact, that the display board does neither have an own voltage regulator nor a microcontroller, the only part that may contribute to a non-negligible fit-rate is the four-lines of sixteen characters HD 44780 compatible display which is replaceable by almost any similar type.

7. Conclusion
In our Test scenario with the solar collector it could be shown, that the reliability and functionality is well suited to operate equipment for research purposes. The reset function by watchdog usually should not have to do anything. It occurred, that systematic programming failures sometimes lead to a watchdog reset. As simple the function of the on-chip watchdog is, it turned out to help a lot to ensure the intended and safe functioning of the overall control behavior, resolving “dead-locks” by restart.

As a side effect of the design process we have seen that complex projects like this can be well done with free software. In this case we used TinyCad for the schematics and FreePCB for the board layout. [9, 10]

8. Outlook
Further improvements will be to increase the absolute accuracy of temperature measurements. The practical experiments have shown that exact temperature measurement is a very important point in maximizing solar energy gain.

Especially at low temperature differences e.g. at cloudy weather solar energy gains can be achieved whereas with less precise measurement the system must be stopped much earlier. Depending on the weather conditions, on many days no gain can be realized at all with unprecise measurement – especially when heating support is an intended function during the winter months.

For future improvements the focus will be to enhance absolute accuracy and to make the temperature inputs more flexible, for example by supporting standard 4-20mA industry transmitters.

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