Content:

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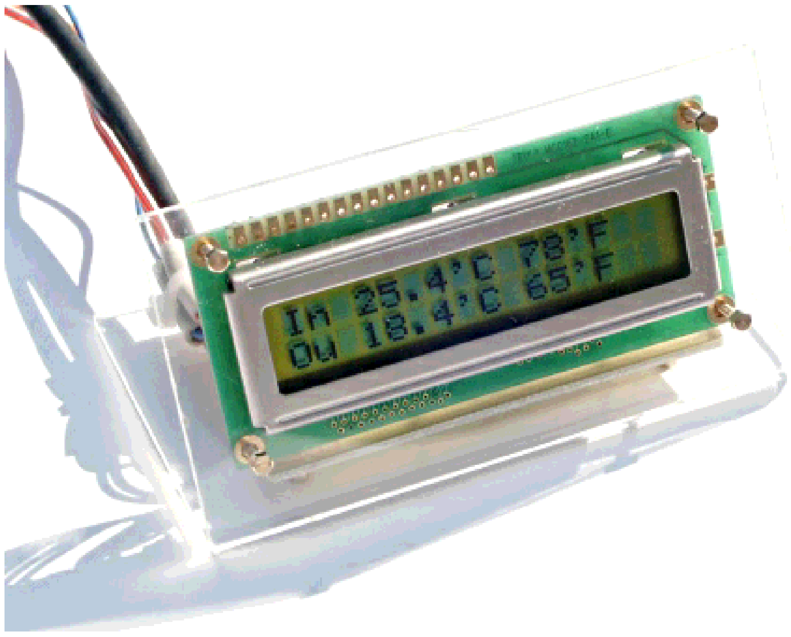
A simple digital thermometer



Abstract:

This is an update of two articles which I wrote in 2005 about a small digital thermometer. The circuit seems to be very popular because it is so simple and still has a very useful and practical application. It is the perfect circuit to get started with AVR microcontrollers.

This updated article replaces the articles from 2005 and simplifies the software as well as the hardware. The original documents from 2005 are linked at the end of this article in case you still need them.

This thermometer can be used as a standalone thermometer with LCD display or it can be read out with a PC running Linux, Windows, MacOSX or solaris. BSD Unix and others are probably also possible to use for reading the temperatures. No special drivers are needed.

The hardware described here can be ordered from http://shop.tuxgraphics.org

Introduction

When you use such an advanced device as a microcontroller to measure analog or digital signals then you want of course interfaces to evaluate the data or send commands to the microcontroller. In all the articles presented here in the past we always used rs232 communication with the UART that is included in the microcontroller. The problem is that this requires an additional MAX232 chip, 4 extra capacitors and an external crystal osciallator for the microcontroller. In any case it is a lot of extra parts..... and we can avoid them!

We go here for connectivity via I2C because it is reliable and really easy to build. The amount of data to transfer between PC and microcontroller is very small (just a few bytes). Speed is therefore no issue at all.

The LCD display is optional. The software is written such that it is identical for the hardware with and without the LCD display.

What is I2C?

I2C (prounouce "eye-square-see") is a two-wire bidirectional communication interface. It was invented by Philips and they have protected this name. This is why other manufacturers use a different name for the same protocol. Atmel calls I2C "two wire interface" (TWI).

Many of you might already be using I2C on their PCs without knowing it. All modern motherboards have an I2C bus to read temperatures, fan speed, information about available memory.... all kind of hardware information. This I2C bus is unfortunately not available on the outside of the PC (there is no physical connector). Therefore we will have to use something else.

How I2C/TWI works

The datasheet of the Atmega8 (see references) has actually a very detailed description starting on page 160. I will therefore present here just an overview. After this overview you will be able to understand the description in the datasheet.

On the I2C bus you always have one master and one or several slave devices. The master is the device that initiates the communication and controls the clock. The two wires of this bus are called SDA (data line) and SCL (clock line). Each of the devices on the bus must be powered independently (same as with traditional rs232 communication). The two lines of the bus are normally connected via 4.7K pullup resistors to logically "High" (+5V for 5V ICs). This gives an electrical "or" connection between all the devices. A device just puls a line to GND when it wants to transmit a 0 or leaves it "High" when it sends a 1.

The master starts a communication by sending a pattern called "start condition" and then addresses the device it wants to talk to. Each device on the bus has a 7 bit unique address. After that the master sends a bit which indicates if it wants to read or write data. The slave will now acknowledge that it has understood the master by sending an ack-bit. In other words we have now seen 9 bits of data on the bus (7 address bits + read_bit + ack-bit):

```
| start | 7-bit slave adr | read_data bit | wait for ack | ... data comes here
```

What’s next?

Next we can receive or transmit data. Data is always a multiple of 8 bits (1 byte) and must be acknowledged by an ack-bit. In other words we will always see 9-bit packets on the bus. When the communication is over then the master must transmit a "stop condition". In other words the master must know how much data will come when it reads data from a slave. This is however not a problem since you can transmit this information inside the user protocol. We will e.g use the zero byte at the end of a string to indicate that there is no more data.

The data on the SDA wire is valid while the SCL is 1. Like this:

```
SDA H -\       /---\     /---\          /---\
    L   \-----/     \---/     \--------/     \------....

SCL H ----\     /-\       /-\     /-\    /-\    /-\
    L      \---/   \-----/   \---/   \--/   \--/   \-....


  | START |      1 |       1 |     0 |    1 |    0 |
```

One of the best things about this protocol is that you do not need a precise and synchronous clock signal. The protocol does still work when there is a little bit jitter in the clock signal.

Exactly this property makes it possible to implement the I2C protocol in a user space application without the need for a kernel driver or special hardware (like a UART). Cool isn’t it?

The plan

As said before we cannot use the PCs internal I2C bus but we can use any external interface where we can send and receive individual data bits. We will just use the RS232 hardware interface of our PC. In other words our communication interface is RS232 but we save the MAX232 hardware, capacitors, etc...

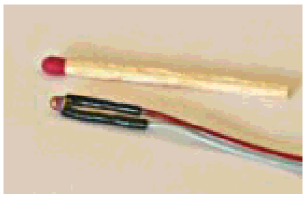
A USB to RS232 converter can be used if you PC does not have a RS232 port.

The LCD display is optional but if you add one then you can use this as well as a standalone thermometer with local LCD display.

The temperature sensor

It is possible to get already calibrated temperature sensors (some of

It is possible to get already calibrated temperature sensors (some of which talk I2C ;-) but they are quite expensive. NTCs are cheaper and almost as good even without individual calibration. If you calibrate them a bit then it is possible to achieve accuracy behind the decimal point.


NTCs are small and cheap with reasonable accuracy

One problem with NTCs is that they are non linear. It is however just a matter of semiconductor physics to find the right formula to correct the non linear curve. The microcontroller is a little computer therefore mathematical operations are not a problem. NTCs are temperature dependent resistors. The value R of the NTC at a given temperature is:

$$R = R_N \cdot e^{B(\frac{1}{T} - \frac{1}{T_N})}$$

where

$$R_N = \text{Value of NTC at } T_N$$

$$T_N = 25\frac{o}{K} + 273K$$

$$B = \text{see datasheet of NTC}$$

$$T = T_C + 273K$$

thus T_C *can be written as*

$$T_C = \frac{1}{\frac{1}{B}\ln(\frac{R}{R_N}) + \frac{1}{T_N + 273}} - 273$$

T or Tc is the temperature value that we are looking for. Rn is the resistive value of the NTC at 25’C. You can buy 4k7, 10K, ... NTCs so Rn is this value.

The circuit

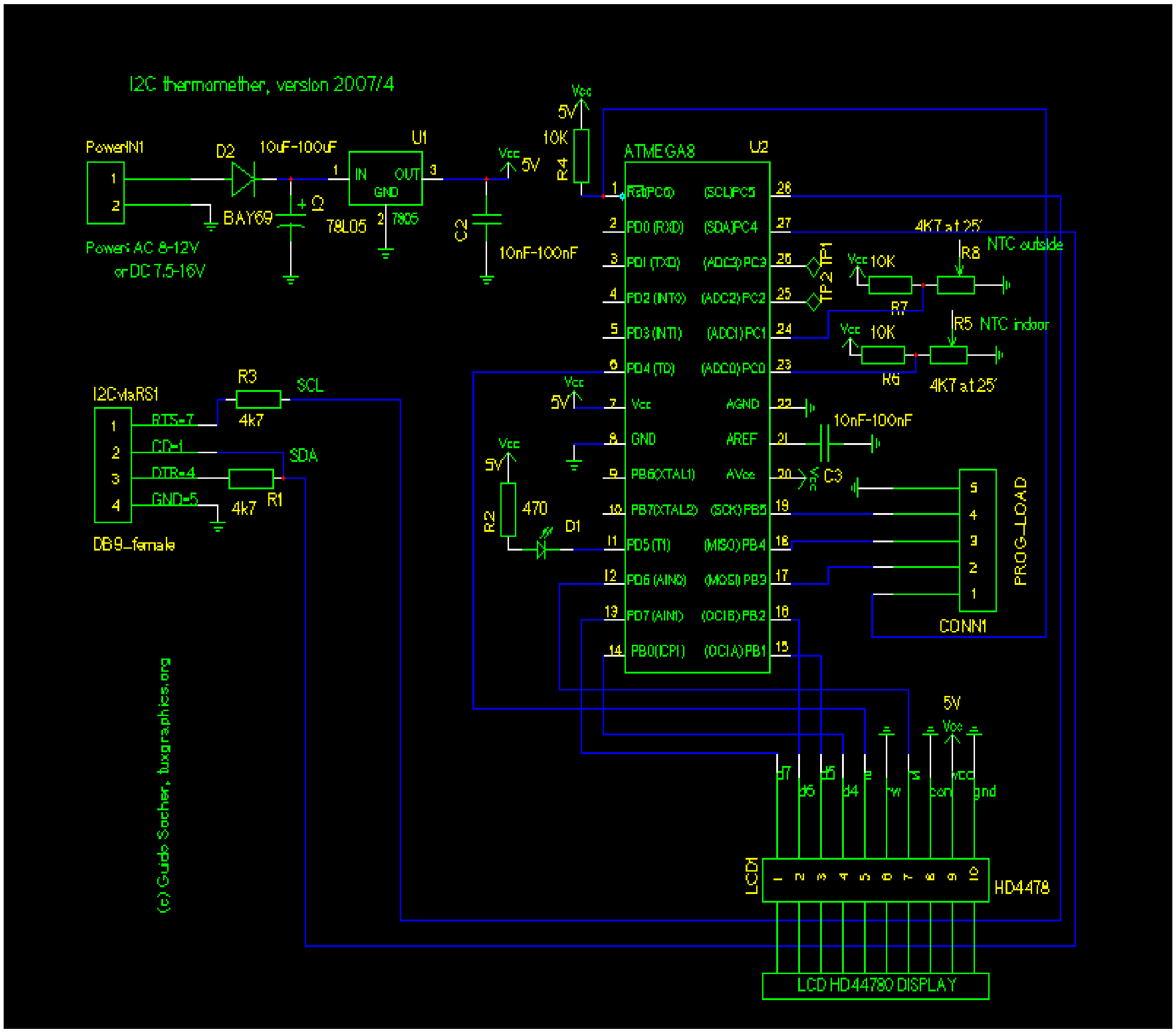
Most of the components are actually for the power supply part. We need a stable reference voltage for the NTCs otherwise the temperature readings will not be accurate.

There is also an LED connected. It does not cost much and is really useful for basic debugging and initial hardware test. The hardware test program test-led.c just causes the LED to blink and is part of the software package (see download at the end of this article).

The analog to digital converter in the microcontroller is used to measure the voltage on the NTC which will then be converted into a temperature value.

The Atmega8 has two options on what is used as a reference voltage for the analog to digital converter. It can use either the 5V (AVcc) or an internal 2.56V reference. For the inside temperatures we will not need a temperature range which is as big as for the outside sensor. +10’C to +40’C should normally be sufficient. We can therefore use the 2.56V reference when we measure the indoor sensor. This gives very high accuracy as the 1024 possible digital values are then spread over only 0-2.56V that is we get a resolution of 2.5mV (more accurate than most digital voltmeters!).

The CD-pin on the RS232 is an input line and it is connected to SDA on the I2C bus. We use it to read data from the microcontroller. DTR and RTS are output lines. When the PC puts data-bits on the SDA line then it just toggles DTR. The I2C-master (here the linux PC) controls the SCL (clock) line. In other words the clock line is an output line on the rs232.



Circuit diagram. Click on the diagram for a more detailed view in PDF.
Note: The LCD display is optional. Just connect nothing if you do not want to use the LCD display.

Putting everything together

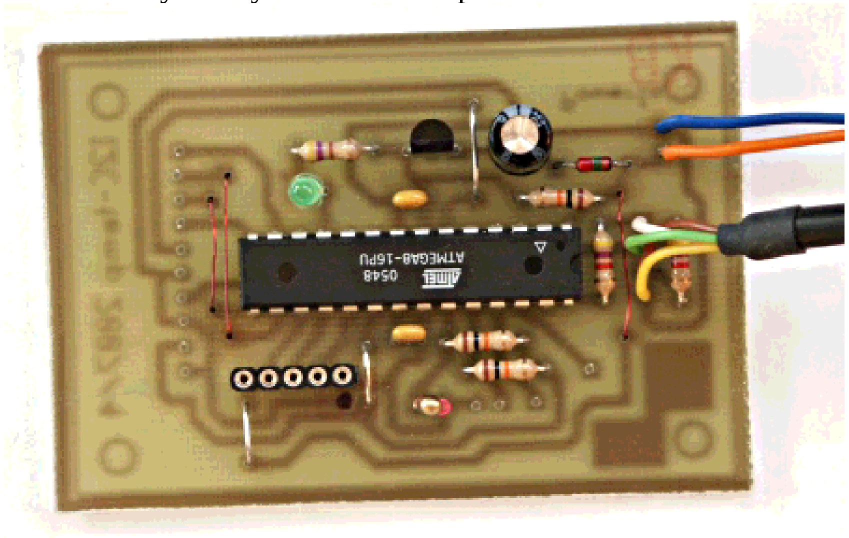
When you assemble the circuit then pay attention to the parts where polarity is important: Electrolyte capactitors, the diode, 78L05, LED and the microcontroller.

Before you solder the microcontroller onto the board you should verify the power supply part. If this does not work you will not only get incorrect temperature readings but you may also destroy the microcontroller. Therefore connect external power (e.g a 9V battery) and verify with a voltmeter that you get exactly 5V on the socket pin of the microcontroller. As a next step connect the circuit to the rs232 port of your linux PC and run the porgram i2c_rs232_pintest with various combinations of signals.

```
i2c_rs232_pintest -d 1 -c 1
i2c_rs232_pintest -d 0 -c 1
i2c_rs232_pintest -d 1 -c 0
```

This program sets the voltage levels on the RTS (used as SCL, option -c) and DTR (used as SDA, option -d) pins of the rs232 port. The rs232 port has voltage levels of about +/- 10V. Behind the Z-diode you should however measure only -0.7 for a logical zero and +4-5V for a logical one.

Insert the microcontroller only after your circuit has passed the above tests.



The complete circuit without LCD display

Using the I2C communication

Download (see references) the linuxI2Ctemp tar.gz file and unpack it. The I2C communication is implemented in 2 files:

```
i2c_avr.c -- the i2c statemachine for the atmega8
i2c_m.c   -- the complete i2c protocol on the linux side
```

I have given the atmega8 the slave address "3". To send the string "hello" to the atmega8 you would execute the following C functions:

```
address_slave(3,0); // tell the slave that we will send something
i2c_tx_string("hello");
i2cstop(); // release the i2c bus

on the microcontroller side you would receive this "hello" string with
i2c_get_received_data(rec_buf);
```

Very easy. Reading data from the microcontroller is similar. Look at the file i2ctemp_avr_main.c to see how it works when the temperature readings are done.

How warm is it?

To compile and load the code for the microcontroller run the following commands from the linuxI2Ctemp package directory.

```
make
make load
```

Compile the two programs i2c_rs232_pintest and i2ctemp_linux

```
make i2c_rs232_pintest
make i2ctemp_linux
```

... or just use the pre-compiled versions in the "bin" subdirectory.

To read temperatures simply run:

```
i2ctemp_linux
```

... and it will print indoor and outdoor temperatures. To make this data available on a website I suggest to not directly run i2ctemp_linux from the webserver because the i2c communication is very slow. Instead run it from a cron job and write from there to a html file. An example script is included in the README file of the linuxI2Ctemp package.

The LCD display

For the LCD display we use a HD44780 compatible display as it was already used in previous articles. These displays are very easy to use in combination with microcontrollers because you can send them ASCII characters.

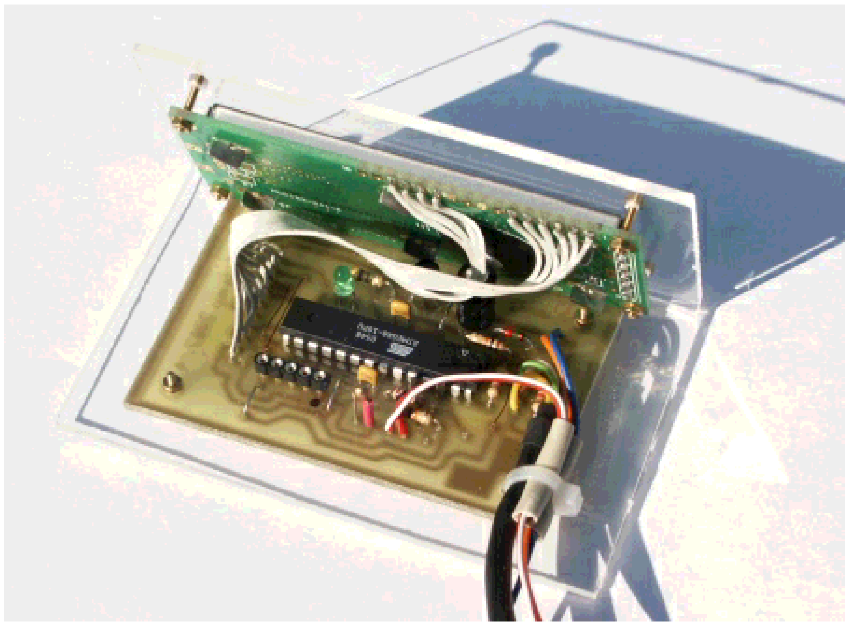
I use the same LCD driver code as in all previous articles. The files which implement this LCD driver are lcd.c lcd.h and lcd_hw.h. They are in the package which you can download at the end of this article. The interface for this code is really easy to use:

```
// call this once:
// initialize LCD display, cursor off
lcd_init(LCD_DISP_ON);

// to write some text we first clear
// the display:
lcd_clrscr();
lcd_puts("Ok the LCD");
// go to the second line:
lcd_gotoxy(0,1);
lcd_puts("works!");
```

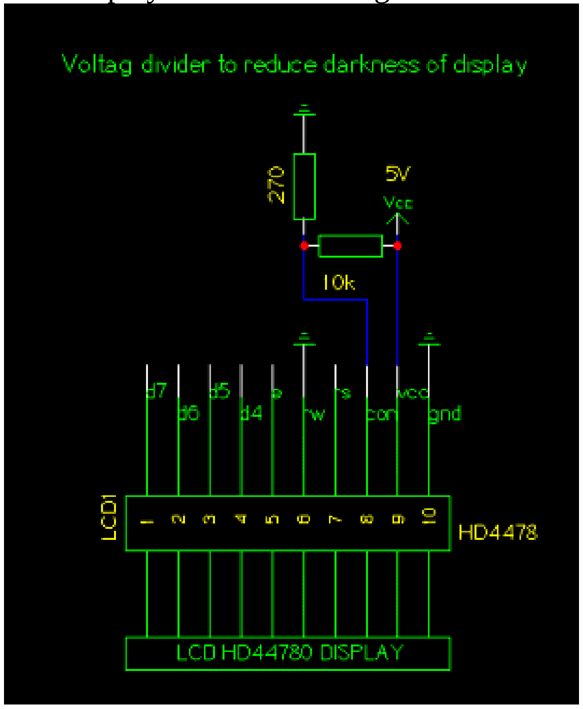
The software is written such that it works with both 16x2 and 20x2 LCD displays.

There is also a test-lcd.c program which can be use to test the LCD display. After loading the corresponding test-lcd.hex file into the microcontroller you should see "=OK=" on the display.


The complete circuit with LCD display

The LCD display has a contrast pin. Connecting this pin to GND results in maximum darkness of the display. The total darkness off the display depends however very much on the make of the display, the viewing angle and power supply voltage level. A change of 0.2V results already in a noticeable change of display darkness. In most cases it is quite OK to connect the "CON" pin directly to GND.

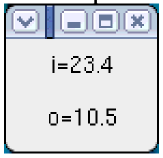
If that gives however a too dark display then add a voltage divider as shown here:



Since the CON pin is normally directly next to the VCC pin the easiest solution is to solder the 10K resistors directly to the display and insert the 270 Ohm resistor in the wire that goes to the CON pin.

A little GUI

For those wo would like to have GUI on their desktop I made a really simple gui. It consists just of 2 labels which are used to display the two line output of i2ctemp_linux command (the i2ctemp_linux is the command which read the temperatures from the circuit via I2C):



```
i=23.4
o=10.5
```

Now we have a really cool thermometer. With a lot of possibilities:

- You can read the temperature locally from the display
- You can have a little GUI on your desktop
- You can write values with a cronjob to a log file to get long term statistics

I will now use the rest of this ariticle to explain a bit the internals of the software.

Makeing temperature data available on the web

You should not run i2ctemp_linux directly from the webserver. It is too slow. Instead add a contab entry which runs a script to generate an appropriate webpage e.g every 15 minutes:

The script to run from contab:

```
#!/bin/sh
webpagefile=/home/httpd/html/temp.html
echo "<h2>Local temperatures</h2><pre>" > $webpagefile
i2ctemp_linux | sed -e 's/i=/inside  /;s/o=/outside /' >> $webpagefile
echo "---------" >> $webpagefile
date >> $webpagefile
echo "</pre>" >> $webpagefile
```

Copy the i2ctemp_linux program to /usr/bin and run the above script e.g from a crontab entry which looks like this (load a file containing this line with the command crontab):

```
1,15,30,45 * * * * /the/above/listed/scriptfile
```

How it works: Analog to digital conversion

The Atmega8 supports two modes. In the continous mode it permanently measures the analog signals and just triggers an interrupt when the measurement is ready. The application software can then use this interrupt to quickly copy the result from two registers into a variable.

The other mode is the so called single shot mode. Here only one conversion is done. The single shot mode is still pretty fast. Including the setup time of the required registers before and the reading out you can still get 100 conversion per second. This is more than fast enough for us. So we use this mode because it is easier to use in functional programming. We just call a function and it returns the ADC values.

The Atmega8 has analog input pins ADC0 to ADC3. In addition to this there are the pins AGND (analog ground, connected to normal ground), AREF (the reference voltage) and AVCC (connected to +5V).

During analog to digital conversion the analog signal is compared with AREF. An analog signal equal to AREF corresponds to a digital value of 1023. AREF can be any external reference between 0 and 5V. Without the use of an external reference you can still do precise conversion by either using an internal reference (2.56V) or AVCC. What is used is decided in the software via the REFS0 and REFS1 bits in the ADMUX register.

The analog to digital converter can convert one of the input lines ADC0-ADC3 at a time. Before you start conversion you have to set bits in the ADMUX register to tell the chip which channel to use.

A simple analog to digital conversion would then look like this:

```
unsigned char channel=0; // measure ADC0
int analog_result;

// use internal 2.56V ref:
ADMUX=(1<<REFS1)|(1<<REFS0)|(channel & 0x0f);
// ADCSR: ADC Control and Status Register
// ADPS2..ADPS0: ADC frequency Prescaler Select Bits
// ADEN: Analog Digital Converter Enable, set this before setting ADSC
ADCSR=(1<<ADEN)|(1<<ADPS2);

//  start conversion
ADCSR|= (1<<ADSC);
while(bit_is_set(ADCSR,ADSC)); // wait for result
adlow=ADCL; // read low first !!
adhigh=ADCH;
analog_result=((adhigh<<8)|(adlow & 0xFF));
```

As a software designer you must watch out that you read the lower 8 bits first as the microcontroller has some locking mechanism to simulate "atomic" reading. After this we have the analog to digital conversion result available as a number in the analog_result variable. This can the be used elsewhere in the program. Very easy.

The ADPS register (ADC clock pre-scaler bits) must be set such that the clock frequency divided by the pre-scale factor is a value between 50 and 200 KHz. The division factor is 2^ADPS (two to the power of the ADPS bits value). The above setting (ADPS2=1, ADPS1=0, ADPS0=0 = decimal 4 -> 2^4 = 16 -> division factor = 16) is good for a clock frequency of 1MHz.

The Atmega8 has several possibilities for reference voltage selection. The reference voltage is compared against our analog input voltage. It is the voltage that corresponds to a digital value of 1023.

REFS0=0, REFS1=0	use external AREF, Internal Vref turned off
REFS0=0, REFS1=1	AVCC with optional external capacitor at AREF pin
REFS0=1, REFS1=1	Internal 2.56V Voltage Reference with (optional) external capacitor at AREF pin

An optional capacitor on the AREF pin can be used to suppress noise and stabilize the AREF voltage (in case you switch between differnt voltage levels: remember that it needs time to charge the capacitor).

How it works: I2C communication, Atmega8 part

I explained already in the beginning of this article how this I2C protocol works. Let’s now have a look at the software. The Atmega8 has hardware support for I2C communication. Therefore you do not actually need to implement the protocol. Instead you need to implement a state machine. This tells the Atmega8 what to do next. Here is an example:

An I2C packet with our own slave address was received. The Atmega8 will now call the function SIGNAL(SIG_2WIRE_SERIAL) with the status code 0x60 (for other events we would get other codes).

--> We must now set a number of registers to tell the Atmega8 what to do next. In this case we will tell it: receive the data part and acknowledge it.

When the actual data was received we will get called with status code 0x80.

--> Now we read the databyte and tell the Atmega8 to acknowledge the next data byte if it comes.

When the communication is over we get a status code 0xA0 (stop condition) and we can tell our application that a complete message was received.

The whole state machine for the I2C slave mode and all possible states are explained in the datasheet of the Atmega8 on page 183 (see link in reference section at the end of the article).

Transmitting data is very similar. Have a look at the code!

How it works: I2C communication, Linux side

First a word about the hardware. Even though I2C is a bus we only use a point to point connection between one slave and the Linux PC as I2C master. We can therefore save the pullup resistor as long as the slave can still pull down the line without causing a short circuit. We just put a 4.7K resistor into the line.

The voltage levels must be adjusted. The voltage levels on the RS232 side are +/- 10V. This would be too much for the Atmeag8 but it has also an internal over voltage protection diode. We limit with the 4.7K resistors the current so much that it is sufficient to relay that protection diode for over voltage protection.

The Linux I2C software implements basically a complete I2C stack. This is because I wanted to have a little command line utility which does not need any special library or kernel module. It should just work on its own.

If you look into the file i2c_m.c (see download) you can see that really every I2C message is build bit by bit.

To generate the "bits" we must toggle the physical pins on the rc232 interface. This is done with ioctl calls:

```
        // set RTS pin:
        int arg=TIOCM_RTS;
        ioctl(fd, TIOCMBIS, &arg);
```

... or to produce a zero:

```
        // clear RTS pin:
        int arg=TIOCM_RTS;
        ioctl(fd, TIOCMBIC, &arg);
```

If you want to port this stack to a different OS then you just change these lines. The rest is plain C and independent of the operating system.

How to mount the outdoor sensor

The outdoor sensor must be protected properly against rain (and sun). You can try to wrap it into some plastic but I don’t recommend this. No matter how tight you tie it, water will eventually come in and stay in there. The NTC is quite robust and it does not matter if it gets a bit humid as long as it can dry again. Use a up-side down mounted tablet tube which you leave open at the bottom. This way any water will be able to get out again.

Conclusion

I am now using the thermometer for 2 years and I really like it because you can read it out directly on the display and you have the possibility to store all the data on your PC. You can view it there, draw graphs do statistics. Really cool.

The I2C protocol requires very little extra hardware and is optimized for transmitting or receiving small amounts of data. That is exactly what we need when we want to communicate with our own microcontroller hardware. It is really a very nice solution!

References

- **Software, documents and future updates: Download page for this article**
- shop.tuxgraphics.org the online shop where you can get all the needed components.
- The old 2005 articles (this article is based on those and replaces them):
  - 2005-02: A digital thermometer or talk I2C to your atmel microcontroller
  - 2005-03: Part 2 -- A digital thermometer or talk I2C to your atmel microcontroller

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