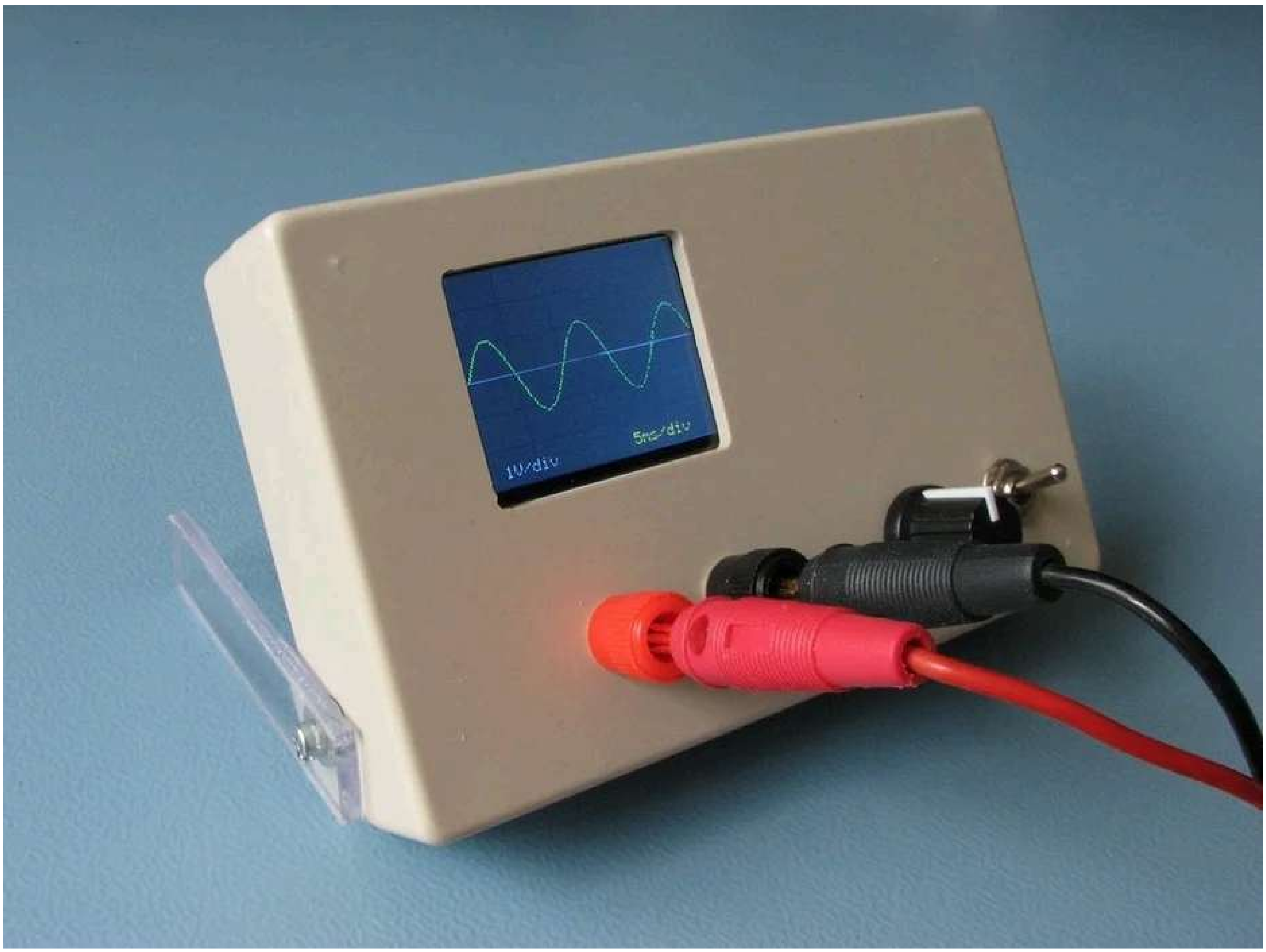
AUTODESK Instructables

Mini Oscilloscope

By WilkoL in CircuitsMicrocontrollers

Introduction: Mini Oscilloscope



This is an Instructable about a mini oscilloscope I made, it isn't anywhere near as capable as a real (digital) oscilloscope (such as my Rigol) but I think it is nice to have. Even more important, I enjoy making things, even when they have no real use. For an example of that, just look at my "tuning fork oscillator".

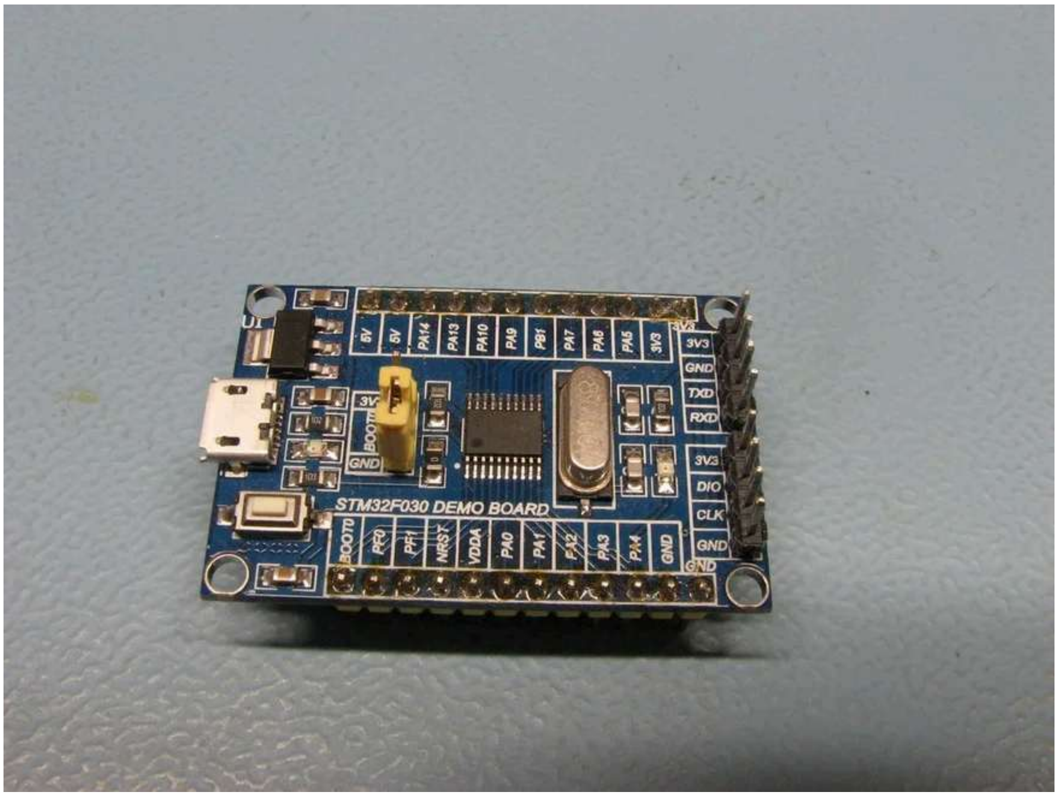
Browsing the internet I came across some simple diy oscilloscopes, usually made with an Arduino or Arduino compatible board but almost always with the Arduino software. The trouble with these is that an Arduino isn't very fast, its ADC isn't either and the Arduino software certainly isn't known for its speed. So some people added a separate ADC to it, which increases the hardware complexity and the total price.

I thought it could be done easier and cheaper and still have a reasonable performance. And I'm a fan of the STM32 series of ARM microcontrollers made bij ST Microelectronics so I picked one of those. I also like to do a project with the smallest, and often cheapest, microcontroller possible but still with acceptable performance.

EDIT: Code is now available on GitLab

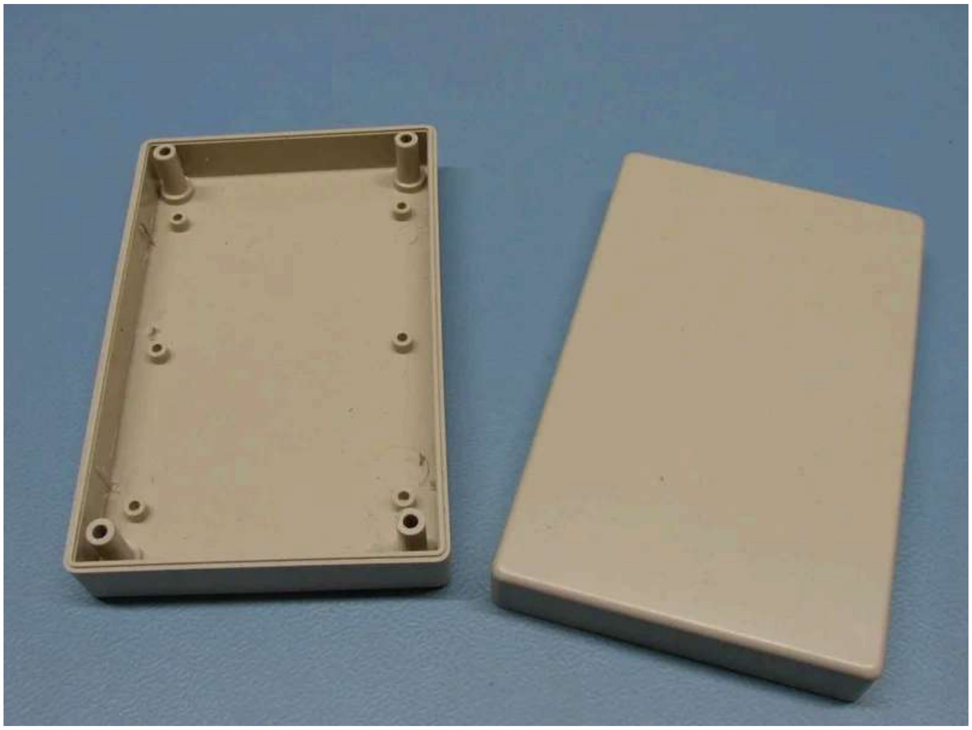
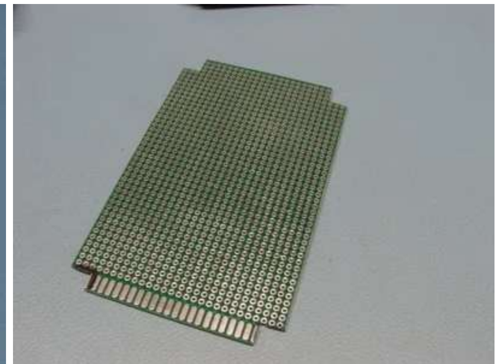
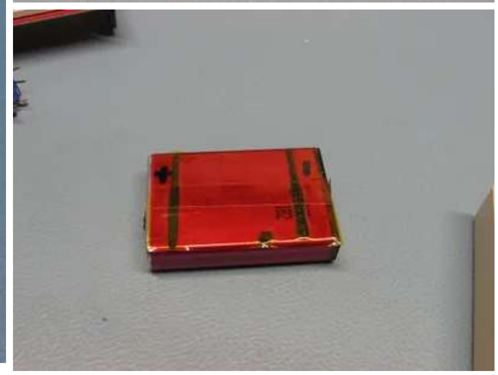
https://gitlab.com/WilkoL/mini-oscilloscope

Step 1: Microcontroller: STM32F030F4



The smallest I have is the STM32F030F4, on Ebay usually sold as an development board. Inside this microcontroller there is a decent ADC, it can do a conversion in 1us. The results of the conversions can be read from a register but, and that is very important here, also transfered via DMA to any place in memory making the process very fast and without loading the cpu. In this microcontroller there are the usual timers, it has SPI and I2C, a RTC, a USART and 2 Watchdogs. Of course you cannot use all peripherals at the same time as this version of the STM32F030 has just 20 pins and some of those are used for things as power, reset, crystal, programming and boot-selection. To program the microcontrollers made by ST Microelectronics you need a tool called the STLink-V2, available via Mouser, Farnell and others, a cheap clone of it is available on Ebay and others. The STM32F030F4 board is sold for less the 3 euro and the STLink-V2 for a similar price. If you have an official development board made by ST Microelectronics themselves such as a "Nucleo-board" there is a STLink-V2 on it that can be snapped off of it. That's what I did and I put it in a small plastic box.

Step 2: Part List

- plastic box (12 x 8 x 3 cm)
- perfboard (double sided prototype board 8x12cm)
- STM32F030F4
- TSSOP20 to DIP board
- ST7735s 1.8 inch TFT display
- lithium-ion battery
- HT7333 3.3V low dropout regulator
- MCP6021 opamp
- 8 MHz crystal
- rotary encoder plus knob
- powerswitch
- banana terminals
- lithium-ion charger board
- several resistors and capacitors, nylon spaces, nuts and screws

Step 3: Tools Software and Documents

Tools

- soldering station
- solder 0.7mm
- solder wick
- flux
- some wire
- side cutter
- glasses and loupe
- drill
- multimeter
- oscilloscope (:-))
- STLink-V2
- coffee

Software

- STM32IDE (integrated development environment)
- STM32CubeMX
- STLink Utility
- LowLayer library (not the HAL !)
- library for ST7735s TFT (ported to STM32)
- Notepad++
- Kicad (for schematic only)
- Spotify (for background music)

Documents

- STM32F030 datasheet
- STM32f030 reference manual (RM0360)

Step 4: Preparation

As usual I start all projects on a breadboard. Unfortunately the STM32F030F4 development board is too wide to be used on a single breadboard. And it is too narrow to be used on two breadboards connected together! The solution to this is to remove one of the power rails from a breadboard, then it fits like a charm. (see picture)
But as I tried to fit all the parts in the plastic box I found that the STM32F030F4 board was a bit too big. So on the pcb I went for a bare chip and therefore I had to add the other components such as decoupling capacitors, crystal, low dropout voltage regulator myself. A TSSOP20 chip is way too small for me to use as it is, so I soldered it on a TSSOP20 to DIP board. It isn't very easy to do but with patience, a steady hand glasses and a loupe it is possible. I have done it several times with TSSOP20 and LQFP48 chips without real problems. You will also need flux and (in my case) solder wick to remove any shorts.

BTW, I don't intent to design a PCB for this project as I will make just one of it.

Step 5: Specifications

The TFT screen has a resolution of 160 x 128 pixels, that means that the X-axis (timebase) needs 160 ADC samples. The ADC needs a minimum of 1 us per sample and I think that 10 waves of a signal of such a small screen is at the limit of what is useful. This means 16 pixels per waveform. As the ADC needs about 1us per sample that's 16us, that's a waveform with a frequency of 62500 Hz. That's not much when you are used to a real 100 MHz digital oscilloscope, but it is enough for audio, led-projects, and more low frequency experiments.
In the end I could not even get the ADC do 1.000.000 conversions per second so I settled for 800.000. The time-base therefore goes up to 40us/division. With 5 divisions on the screen it means 200us per full screen. A 5 kHz waveform then fills the whole screen and I think the limit of usefulness is around 50kHz. On the lower end I decided that 200ms/division (1 second/screen) was a nice time, so then a 1Hz signal uses the entire width of the screen.

The ADC converts the voltage on its input referenced to 3.3V (Vdd). You can choose the resolutions 12, 10, 8 and 6 bits and the lower you go, the faster the conversions are. As the TFT screen has an Y-axis (vertical resolution) of 128 pixels (7 bits) it isn't needed to have the ADC do better than 7 bits, but a 7 bit resolution isn't available, so it is set to 8 bits. The least significant bit will be discarded by a shift-right of 1 bit.

Attenuation is required to be able to measure a bit more than 3.3V the ADC is capable of, amplification if you want to measure smaller signals than that, and it would be nice to be able to measure a negative voltage too. This means either to have a positive and negative powersupply or to have an offset added to the input voltage. Because I wanted to use just one battery and keep the device as simple as possible, the offset-method was chosen. This means that the ground-terminal of the input is not connected to ground at all, it is connected to the offset voltage, this I call the virtual ground. It also means that you have to use this oscilloscope battery powered.

The oscilloscope has just one sensitivity: 1 Volt / division. I did think of adding an amplifier and an attentuator with small relais or a digital potentiometer. But the relais I have need at least 5V to work and the digital potentiometer was too noisy to be useful. Of course you can add an amplifier and/or attenuator to it, just put it in front of the input. Next, the oscilloscope shouldn't put a big load on the circuit you are measuring. Most oscilloscopes use 1 Mohm, and so does this one. You can use a real 10x probe with it, that will increase both the voltage range and input impedance tenfold, but you may also have to add frequency compensation with a variable capacitor. I haven't tried it.

The analog bandwidth of an oscilloscope needs to be a high as possible, as a rule of thumb, at least 10 times the frequency you want to measure. After all, a squarewave of just 10 kHz has many harmonics and you need to have at least 90 kHz bandwidth to see the ninth harmonic. Said another way, if you try to see a squarewave of 10MHz on a 10 MHz oscilloscope you will see very little squarewave but mostly a sinewave of 10 MHz. Here a bandwidth of 500kHz would be enough, but more is better. I used an opamp with a gain/bandwidth product of 10MHz a Microchip MCP6021, for the simple reason that I have some in stock. If you want to use another, remember it needs to work at 3.3V.

With an offset from 0V to 3V the acceptable voltage on the input goes from -6V to +6V. But always with a maximum top-top value of 6V! So either from -6V to 0V via -3V to +3V up until 0V to + 6V. Good enough for most Arduino project you may have, and if needed, doubling the input resistor from 1Mohm to 2Mohm will also double the voltage range.

The trigger level can be set anywhere on the screen, that means that it can be set from almost -6V to almost +6V. But it actually has nothing to do with any voltages at all, only with the position of the trace on the screen. It also only acts on the rising edges of a signal. If you want you can add the option to trigger on a falling edges as well, add it to the source, I didn't think it was necessary.

The last specification I want is that the Lithium Ion battery can be charged via a small board with a mini-usb connector. At first I wanted to use a 18650 size lithium ion battery but it was too big, now a small rectangular battery is used, it has the same dimensions as a (dumb)phone battery Samsung and others used in their phones but it i twice as thick. Just use any lithium ion battery you have and that fits. As long as the nominal voltage is 3.7 volt it is fine.

In short these are the specs

- input resistance
- 1Mohm sensitivity
- 1V/div timebase 200ms/div...40us/div
- input voltage -6V...+6V
- trigger level any level on screen
- battery powered

Step 6: Hardware and Schematic

Well, just look at the schematic, it is pretty simple. If you use a STM32F030F4 on the development board there is very little to do besides the connections to the display, rotary encoder and the opamp. Even the voltage regulator is on the board!
I did not use the development board because I was afraid it wouldn't fit in the plastic box. I use the microcontroller soldered on the TSSOP20 to DIP board. Because this DIP board sits rather high above the PCB I can place many parts, such as the crystal and some capacitors, under it. And the lithium ion battery fits nicely under the display :-)

Step 7: Inner Workings

TFT-library
First of all I needed to get the display working. Fortunately for most standard displays there are ready-to-use libraries, but I couldn't find one for this display and a STM32 microcontroller. The one I ported to STM32 was made for Arduino (made by Sparkfun? Adafruit? Someone else?). I don't remember and I didn't keep the original source or the name(s) of the original makers when I ported it to STM32, sorry about that.

- So all the honours for the ST7735 library go to the makers, whoever they are -

After porting it to STM32 I found that the display isn't very fast. Luckily it uses SPI and you can make SPI go rather fast on this microcontroller. But still I needed to send the least possible data to it to keep the refresh rate of the display reasonable. I haven't measured it but I think, at the shortest timebase setting it is around 15 to 20 Hz. On the longest timebase setting (200ms/div - 1 second/screen) you will notice that the refresh rate isn't 1 Hz, but just 0.5 Hz! I'll explain that later.

The really, really bad Rotary Encoders Second, the rotary encoder needs to be read. This caused most problems for me, not that I didn't know how to do this, it is just a simple quadrature signal. No, it turned out that all 10 of the encoders I bought (Ebay) were of such poor quality that I needed not only to do software debouncing but also debouncing in hardware. And still I cannot turn the knob all too fast as it will miss pulses. Normally I do software debouncing only, as it doesn't need anything extra, no pullup resistors, no capacitors, but in this case they were very much needed.

ADC and DMA The most important thing is getting analog data in. As I said, the ADC does an 8 bit conversion in about 1us. It is started by a timer (TIM3) that runs continuously and sends pulses to the ADC according to the curent timebase setting. The lowest rate (200ms/div --> 1 second/screen) is 160 Hz. So the ADC does 160 conversions per second, filling the 160 pixel screen in 1 second. The highest rate is 800 kHz, so the screen is filled in 160*(1/800.000) = 200us. If only the display and software were that fast! Then you could have a refresh rate of 5 kHz. (any old analog scope does that without breaking sweat)

Instead the data from the ADC is transfered to an array: adc_buffer[] in memory. This is done with DMA, witch means that the cpu of the microcontroller is not needed to do that, it can continue with whatever it is doing. This makes storing the data very simple and fast. When the DMA is ready with the programmed number of values it needs to transport, it sets the TC-flag (transmission complete) and triggers an interrupt. The interrupt itself doesn't do much, it just clears the TC-flag and sets a variable called "token" as a signal to the main routine telling it that there is data ready to be displayed. The ADC continues conversions and the DMA keeps transporting those results to the adc_buffer[]. So no matter what else there is going on inside the microcontroller, there is a never ending stream of values coming into adc_buffer[].

Triggering As said, the display is 160 pixels wide so only 160 values are needed to show a complete waveform. The adc_buffer[] actually contains 320 samples. So the DMA stores 320 values in it before it triggers a TC interrupt. This is done because the triggering is done in software. And as it is very unlikely that the first value in the adc_buffer[] is the place where the triggering should be. We have to find the place where that point is. So 320 values are read and in the first 160 of these the actual trigger point is searched.

What is done is that in the adc_buffer[] the trigger point is found by checking if the value is at the trigger value en if the next value is just above it. This works quite well, but you need a bigger buffer than the actual display size is. I tried with double the size and quadruple the size, but that made very little difference, so I stuck to 320.

This too is the reason that the refresh rate on the lower timebase settings is slower than you might expect. As I mentioned before when you use the 200ms/div setting, one screen full of data takes 1 second, but because double the amount of conversions is done, it takes 2 seconds. On the faster timebase settings you will not notice it that much.

Step 8: The Code

MAIN.C
because the conversions never stop, the values in adc_buffer[] will continuously be overwritten, on the fastest timebase setting this will happen to all values every 400us. To prevent displaying wrong data, the first thing the main routine does is, making a copy of adc_buffer[] into display_buffer[]. A little later it also copies the same data in erase_buffer[]. This is done because erasing the entire display takes "forever". What is done now is: the previous waveform (green) is overwritten by exactly the same waveform in black at the next round, just before the new one is displayed.

The rest of the program is more or less cosmetics, a grid of horizontal and vertical lines is displayed, the current values for sensitivity and timebase. The zero volt line is shown brighter that all others and it moves with the offset. A small line is shown where the current trigger level is. What at the moment is active on the rotary encoder, timebase, offset or trigger level, is shown in yellow.

SystemClock_Config While I was experimenting to get the most speed from the microcontroller I increased the clock far above the official maximum of 48MHz, to 64MHz and even 80MHz. Everything worked without problems even on 80MHz but I didn't want to keep it that high so I reduced it to 64MHz. This is still far outside the specs from ST Microelectronics so the microcontroller *could* malfunction. That said, I doubt it will cause trouble because those specs are what ST Microelectronics say will definitely work in all conditions, from 2.4V to 3.6V and from -40C to +105C. Here it sits on my desk at 25C and with a stable 3.3V, I don't think I will be using it a lot at -40 Celsius.

MX_ADC_Init There is actually one pin left on the microcontroller, I took care that it was PA1 as that pin could possibly be used as a second ADC input. It might be possible to make this into a two channel oscilloscope. But I haven't tried it (yet). At the moment PA1 is configured as an output the I use for a debug-led. Of notice is the setting to circular mode of the DMA to the ADC, so it never stops. The ADC clock is the system clock divided by 4, this is 16MHz and that is also above ST Microelectronis specs. It shouldn't be any higher than 14MHz. Again this works. Each conversion is started on the rising edge of a TRGO signal from TIM3 (see below) The ADC does not produce any interrupts, that is taken care of by the DMA after 320 samples.

MX_SPI1_Init Not much to tell about, except that it works at 16MHz, which is nice with the ST7735 TFT display.

MX_TIM3_Init This timer is responsible for the starting of the ADC conversions. It runs at 64MHz and at each UPDATE, (overflow) it sends a pulse to the ADC via the TRGO output. By way of changing the maximum value of the timer in the register called AutoReloadRegister (ARR) the frequency of the TRGO pulses (the timebase) is changed. This change is done in the interrupt routine of TIM6 (see below)

MX_DMA_Init Just enables its interrupts in the NVIC.

MX_TIM14_Init This one produces a squarewave on PB1 with a frequency of a bit more than 100kHz and a variable pulsewidth. A low pass filter made with a 1k resistor and a 10uF capacitor transforms this in the offset voltage for the opamp.

MX_TIM16_Init Does the debouncing of the rotary encoder and decrements the timeout value. This timer is normally OFF and only started when there is movement detected on the rotary encoder. This movement detection is done via EXTI interrupts on the GPIO connected to the rotary encoder. When running, this timer produces 1000 interrupts per second. When the timeout reaches zero this interrupt routine disables itself and re-enables the EXTI interrupts.

MX_GPIO_Init Sets several GPIO as input and output and takes care of enabling the EXTI on some inputs.

STM32F0XX_IT.C

DMA1_Channel1_IRQHandler Clears it's TC flag and then sets token to 1. This indicates for main.c that there is new data that needs to be displayed.

TIM16_IRQHandler Determines if the rotary encoder button is pressed and if the rotary encoder is turned clock wise or counter clock wise. After that it sets the timebase settings for TIM3, offset settings in TIM14 and the trigger level. It also sets things as what colour the options should be displayed in. The last thing this interrupt routine does is disable itself after a short time (timeout) and re-enable the interrupts for the EXTI (see below).

EXTI2_3_IRQHandler Interrupt for the rotary encoder button. Enables TIM16 for the debouncing and disables itself. Sets timout to 20ms

EXTI4_15_IRQHandler Interrupt for the rotary encoder A and B connection. Enables TIM16 for the debouncing and disables itself. Sets timout to 20ms

Step 9: Video's