OCT Probe Driving Circuit for Use with ThorImage

Brian Frost, Spring 2020

1 Introduction

A former PhD student, Nathan Lin, developed a prototype of an optical coherence tomography (OCT) probe for measuring vibrations in the cochlea. While the prototype functioned, there were a number of quality-of-life issues regarding its use alongside the ThorImage user interface, which provides valuable visual feedback while using the Telesto 3 bulk optics OCT system. When using the bulk optics, the user can change the width of the scan being taken through ThorImage; this was not the case with the original probe interface, wherein the scan width was controlled in hardware by a potentiometer. This lead to confusing visual feedback in which the aspect ratio was often displayed incorrectly to the user. Moreover, to determine the actual field of view, the user had to tap the probe's control signal, read its amplitude on an oscilloscope and convert this amplitude to a distance by hand.

We present a simple circuit which allows the user to control the probe field of view through ThorImage only. This circuit significantly reduces the workload for the experimenter by removing the complex field of view adjustment previously implemented. It also makes qualitative analysis easier on the fly, as the aspect ration of the image shown in ThorImage is faithful to what is actually being captured by the probe.

2 Properties of the Control Signal

2.1 Output of the Telesto

The vertical-direction galvonometer control signal from the ThorLabs Telesto is accessed through a coaxial port at the back of the device. The galvonometer scan position is linearly related to voltage, so the control signal for a B-scan is more-or-less a sawtooth wave. However, the device also implements "flyback", in which a high-voltage signal is sent to the galvonometer for a short time (known as the "flyback time") at the start of each period. Background scans are taken during the flyback period, and the high-voltage signal ensures that the mirrors are pointed away from the sample when these backgrounds are recorded.

More quantitatively, the default B-scan period is 134 ms, and the flyback time is set to 2 ms through configuration files. The relationship between voltage and position is about 130 mV/mm. It is important to remember that the shot speed in ThorImage does not control the B-scan period, but rather the rate at which A-scans are recorded. This means that increasing this rate will have no effect on the period of the galvonometer signal.

It is **VERY** important to recall that the vertical galvonometer signal is being tapped – this corresponds to the "x" direction in older versions of ThorImage and the "y" direction in newer versions. To achieve the maximum signal, we want the B-scan to be taken entirely vertically, which requires an angle of 0 or 180 degrees in the older version of ThorImage, and an angle of 90 or -90 degrees in the newer version of ThorImage. It is foolproof to simply take a vertical B-scan in ThorImage and ignore the coordinate names.

Figure 1 shows a sample of what might be read on an oscilloscope as a B-Scan is being taken. For the sake of visualization, a large field of view is chosen. The voltage scans from positive to negative, which corresponds to an angle of -90 degrees in the newer version of ThorImage. In the case of an antiparallel B-Scan of the same space, the voltage would sweep from negative to positive. The center of each B-scan is at the origin with respect to ThorImages coordinates, which means the voltage sweep will have a midpoint of zero.

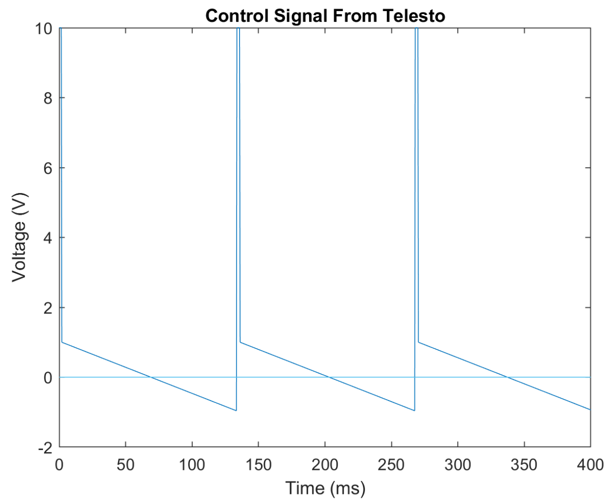

Figure 1: Sample output of the Thorlabs Telesto, where the angle in ThorImage is set to -90 degrees and the field of view is set to about 15 mm – far larger than is possible, but used for an easily visualized example. The field of view is centered at the origin.

2.2 Desired Probe Control Signal

The probe does not use a galvonometer, but rather a piezoelectric scanner. The piezoelectric also relates voltage to position linearly at about 1 μm/V. The probe does not take background scans in the way that the ThorLabs system does – it cannot divert the optical signal away from the sample due to simple physical constraints. Instead, background scans are taken manually before experiments. Due to this, the large spike in the ThorImage signal is not useful – in fact, it is detrimental to the probe's performance. The probe cannot fly back instantaneously without significant ringing, as a result of the less physically constrained mechanism which controls the probe's scanning.

When driving the probe, we must (i) remove the high-voltage spike; (ii) reduce ringing by "smoothing" out the flyback transition; (iii) correct the amplitude of the Telesto signal so that the probe has the desired field of view. To implement all three of these tasks in simple, small and cheap hardware, we simplify the problem as much as possible – we assume that the angle in ThorImage is always vertical, and that the scan center is always at the origin.

These simplifications are not, in fact, restrictions. The probe's angle, for example, is a function of the probe's physical orientation, and is not available for control electrically. As for the probe's offset, this is similarly dependent on the probe's physical orientation and we have decided to implement it in hardware by turning a potentiometer.

3 Design

As stated in the previous section, our circuit must complete three tasks – (i) removing the spike; (ii) smoothing out the flyback transition; (iii) correcting the amplitude. Of these, the simplest is (iii), as the Telesto output and probe input each have linear voltage-distance relationships. At the Telesto, a motion of 1 micron corresponds to a voltage of 0.13 mV, whereas at the input to the probe, a motion of 1 micron corresponds to a voltage of 1 V. This means that the circuit must have an overall gain of about 7,700.

As for task (ii), it is clear that a lowpass filter will smooth out the flyback transition, but the high-voltage spike incurs a problem here. Although the spike has high frequency components, its amplitude is so high that we cannot easily attenuate it with a filter alone without also attenuating our desired signal. It is also important to note that aggressive lowpass filtering could incur a significant phase shift, which is undesirable; if the signal at the probe is out of phase with the signal from the Telesto, the B-scan in ThorImage will be off-center, and may regester A-scans from the flyback period as proper signal.

However, if we first complete task (i), and remove the high-voltage spike, we can then apply a less aggressive lowpass filter and smooth out the transition without incurring a huge phase shift or attenuating our signal. Thus, once we have completed task (i), tasks (ii) and (iii) are completed simply by a first-order lowpass filter and a fixed-gain amplifier.

Removing the spike proves to be surprisingly complicated, however. Naturally, one would imagine that a clamping circuit may be useful, but it is not clear what the clamping voltage should be. In fact, as different fields of view have different signal amplitudes, we cannot clamp at a fixed voltage (the correct clamping voltage for a small field of view will filter out signal at larger fields of view). We must thereby implement a *dynamic clamp*, which will clamp the signal at a certain voltage as a function of the field of view.

As is illustrated in Figure 1, the negative component of the Telesto output is unaffected by the spike. With a negative half-wave rectifier, we can extract only this component of the signal – a single half-period triangle. The peak value of this triangle is what we would like to use as our clamp voltage. We realize that the average value (i.e. the DC component) of this signal is related to this clamp voltage by a constant factor. We can determine the clamp voltage in hardware by using a lowpass filter to obtain the DC component, and amplify it by the necessary constant.

The DC value of the half-wave rectified signal with height A is given by

$$V_{\mathrm{DC}} = \frac{1}{T}\int_0^{T/2} A(1 - 2t/T)\, dt = A/4$$

So to get the clamp voltage A, we just need to amplify the DC value by 4.

The incoming signal is first amplified, then split into two paths. The first path rectifies the signal, filters and amplifies it to determine a clamp voltage. In the second path, the signal is clamped as determined by the first path's output. The signal is then low-pass filtered to smooth the transition. After this, the signal enters a summing amplifier which does not offer any amplification – instead, a potentiometer controlled by the user adds a DC value to the signal. Lastly the signal is to be fed into a 20 x amplifier piezoelectric driver, which only safely takes signals between -9 V and 9 V.

We have two clamping elements to ensure the signal is in this range, then feed the output into the piezoelectric driver.

The block diagram shown in Figure 2 gives a high-level view of what is being done by the circuit, as described above. The operation of each of these blocks is described in the following section, and the schematic can be found in Appendix I.

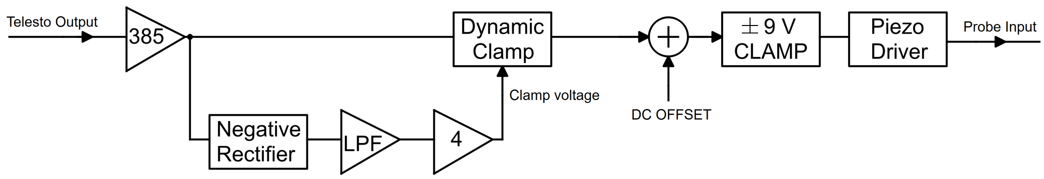

Figure 2: Block diagram of the designed circuit. All blocks consist of one or more op amp blocks, described in detail in the "Op Amp Blocks" section of this document.

4 Op Amp Blocks

The first amplifier is implemented using a standard non-inverting op amp topology, as seen in Figure 3. The gain of this block is $1 + (R_2/R_1)$.

The negative rectifier can be seen in Figure 4. This circuit effectively works as any half-wave rectifier would, but uses an op amp to reduce the diode drop by a factor of the op amp's open loop gain. For our purposes, a 0.7 V drop would be far too much to sacrifice (in some cases, it would delete our entire signal), so the use of an op amp is necessary here.

The filters and the inverting amplifier in the rectifier path use the standard inverting amplifier topology shown in Figure 5. The gain of this block is $-Z_2/Z_1$. In the case of the amplifier in the rectifier path, Z_2 and Z_1 are resistive and should have a ratio of 4. In the case of the lowpass filters, Z_2 is a parallel RC combination, where the cutoff frequency is given by $f = \frac{1}{2\pi RC}$. To ensure unity gain from the filter, Z_1 is a resistor with the same resistance as that in the RC combination.

Clamping and negative clamping blocks, as shown in Figures 6 and 7, respectively, work just as standard clamping circuits but implement op amps. Much like in the rectifier case, the diode drop is reduced by a factor of the op amp open loop gain, which is critical.

The signal summation uses a standard summing amplifier topology as shown in Figure 8, where all resistors are chosen to have the same value so as not to introduce gain.

5 Implementation

The circuit was prototyped on a solderless breadboard. After its operation was validated, a PCB was laid out in KiCad, and the layout and final product can be seen in Appendix II. The list of parts used can be seen in Appendix III.

Potentiometers are used instead of resistors in many places to ensure that the correct amount of amplification is being provided. To check that these potentiometers are set correctly, four BNC connectors are present. Connector J2 reads the output of the first amplifier, which can be used to

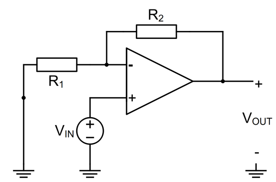

Figure 3: Noninverting amplifier block

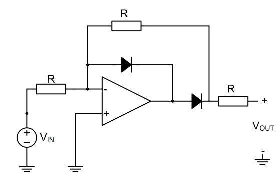

Figure 4: Negative rectifier block

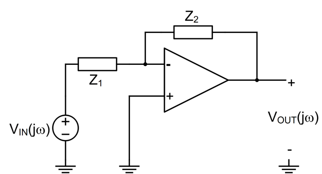

Figure 5: Inverting amplifier and filter block

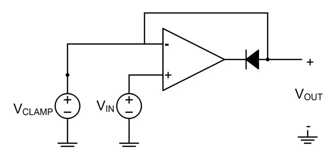

Figure 6: Standard clamping block

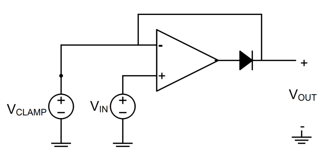

Figure 7: Negative clamping block

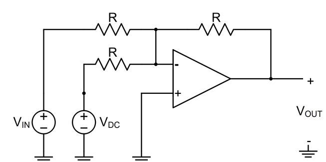

Figure 8: Summer block

ensure the first amplification stage is working as desired. Optimally, this first amplifier should amplify a 360-micron field of view Telesto output to a ±9 V signal (disregarding the spike). Connector J3 shows the clamp voltage, which should be about 9 V at a 360-micron field of view. Connectors J1 and J4 are the input and output, respectively.

The potentiometers RV5 and RV6 clamp the voltage at the output between -9 V and 9 V. These can be tested by observing the output at large fields of view.

A ±15 V power supply is used. The PCB is about 6.5 cm × 9.7 cm, and was ordered from PCBMinions. 741 op amps were chosen due to their ease of availability, and although they offer sub-par slew rate, this is entirely unimportant for our low-frequency application. Surface mount passives were used.

Appendix I – Circuit Schematic

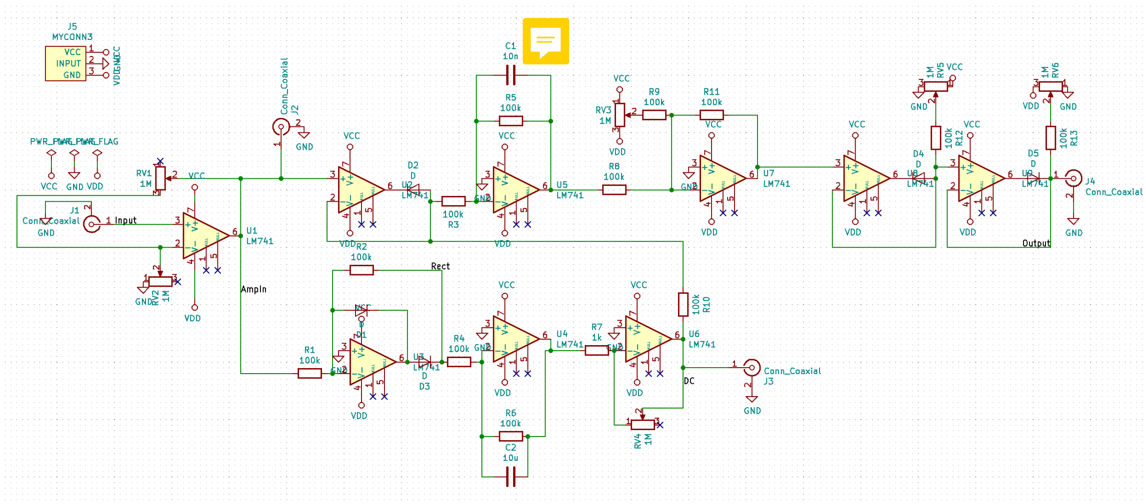

Figure 9: Schematic of the designed circuit, made in KiCad.

Appendix II – PCB Images

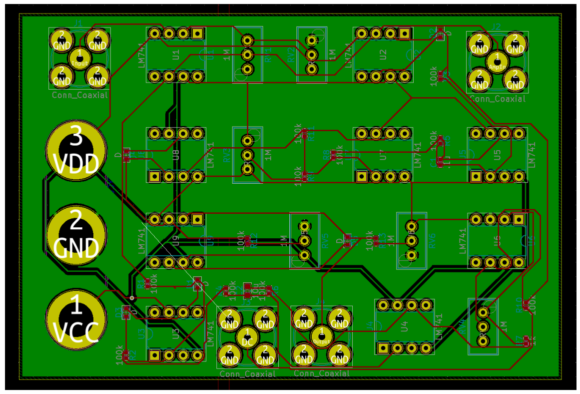

Figure 10: PCB layout of the designed circuit, made in KiCad. The PCB is 6.502 cm × 9.652 cm, or 2.56 in × 3.80 in.

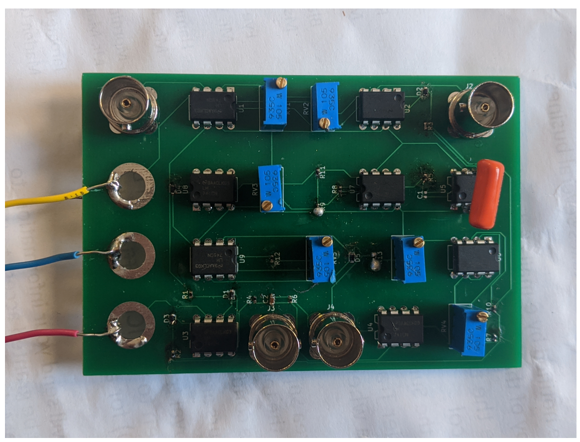

Figure 11: The physical PCB, with components soldered on.

Appendix III – Parts List

Component	Part Number	Quantity
BNC Connector	A97581-ND	4
1 MΩ Potentiometer	490-2877-ND	6
Diode	1N4148WTCT-N	5
Op Amp	LM741CNNS/NOPB-ND	9
10 μF Capacitor	490-13248-1-ND	1
10 pF Capacitor	399-7746-1-ND	1
100 kΩ Resistor	P100KJDKR-ND	11
1 kΩ Resistor	P1.0KJCT-ND	1
Piezoelectric Driver	Piezo Systems EPA-008	1