Designing a two-channel data acquisition front-end board for a particle physics cosmic ray muon detector

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Abstract

At Brookhaven National Laboratory our group mission is the construction of a cosmic ray particle detector array. Our goal is to construct and place more than one hundred standalone detectors across New York State schools and colleges for gathering information about subatomic particles showers over vast area. Every detector consists of three main components: polyvinyl toluene plastic scintillator plate, photomultiplier tube, and data acquisition board. My part of the project is to prototype and develop the data acquisition (DAQ) board. The DAQ board is an embedded system consisting of various electrical components that can read and manipulate analog voltage values and report them for further data processing. The circuit board amplifies the electrical signal caused by subatomic particle and holds the acquired signal for a necessary period of time to communicate with the Arduino board.

Introduction

Photomultiplier tube(PMT) is the source of the electrical signal to data acquisition board. Each PMT has a cesium based photocathode which converts incident photons into electrons via the photoelectric effect; internal electrodes held at high voltages convert these electrons into a pulse of current (20ns average) which is fed into the data acquisition board. I used LTspice to generate a generic PMT pulse and to simulate the circuits board.

Overall system

What does data acquisition board consist of:

1. Preamplifier-Multiplies the signal
2. Comparator-Filters the noise (discriminator)
3. AND gate- Confirms particle presence
4. Shaper, Peak Detector and Buffer- Detects the peak of the signal
5. Monostable multivibrators- Detain and delay output signal
6. Sample and Hold- Holds the data for Arduino board reading

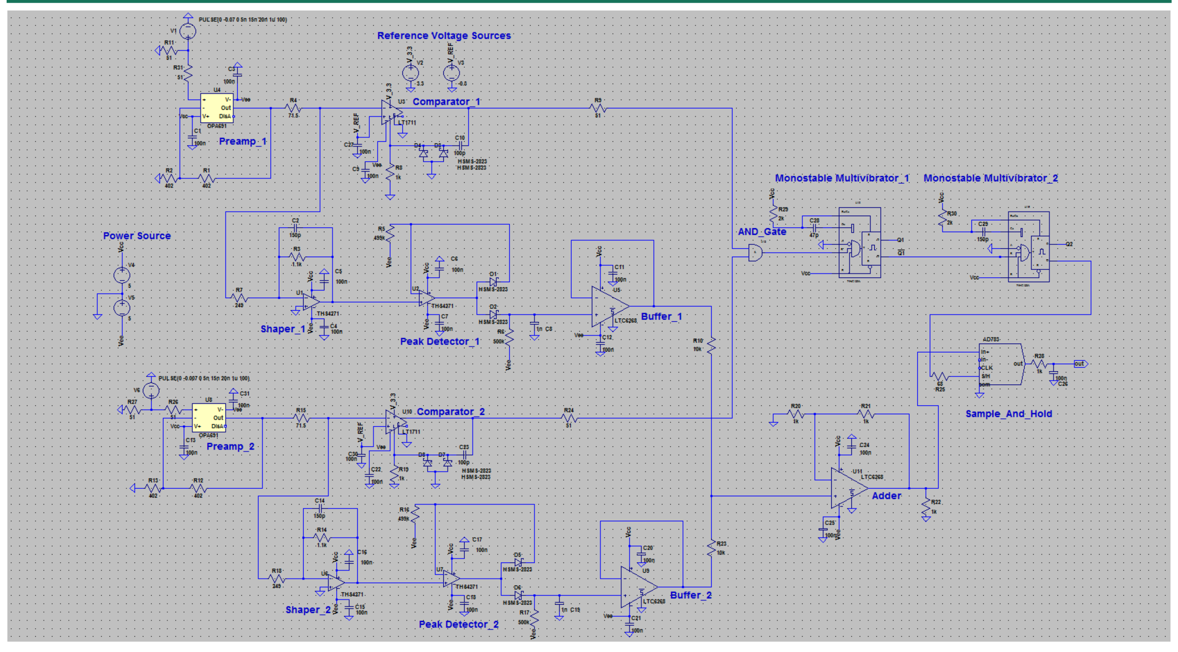
Updates

The major update that was made to this design includes a two-fold digital logic component. The new component increases the accuracy and reliability of the recording data.

In the previous data acquisition board, every signal source channel was compared to discrimination threshold and if the strength of the signal was bigger than set threshold the board would count this signal as a result of sub particle interaction. Due to the fact that photomultiplier tube has internal noise, which sometimes can overcome the discriminating threshold, this setup has a potential for misleading data. The new design is significantly more reliable as it relies on coincidence signal of two PMTs.

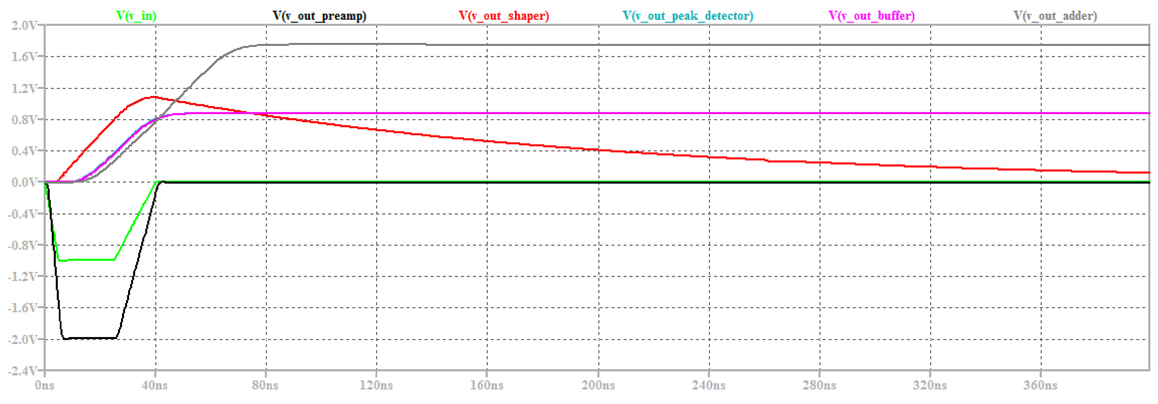
In an improved particle detector apparatus, two scintillator counters, each with its own PMT, are stacked one above the other such that incident muons go through both counters within a very small window of time.

Schematics

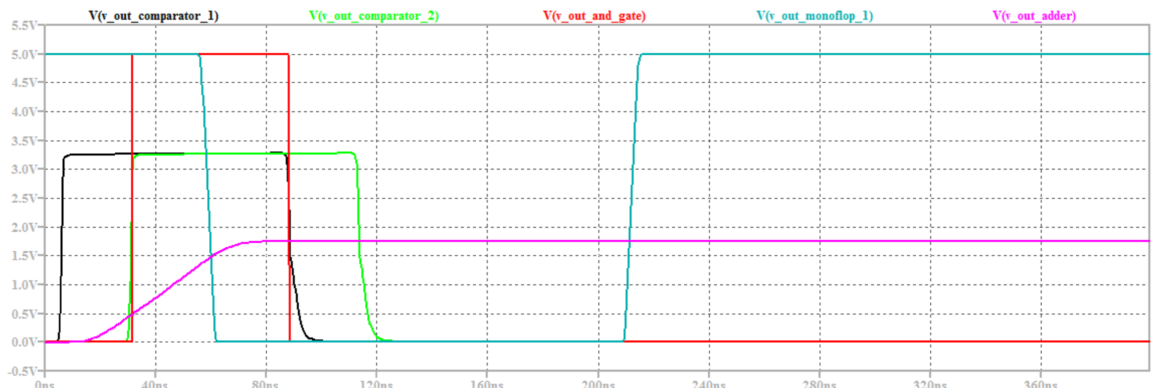


Simulation

A complete simulation of all the circuit components is presented below. On the first set of waveforms we can observe the path of the analog signal to sample and hold unit. The waveform in green represents a generic PMT pulse going into the circuit. Next, pulse doubles its value due to the gain of two on the preamplifier(black waveform). After passing through the shaper the pulse is inverted and stretched(red waveform). The peak of the pulse is held after crossing the peak detector component (blue waveform, but it is overplayed by buffer). Buffer copies the peak detector pulse(pink waveform). In the end, when two pulses from different channels are added after adder component we can observe that the value got stabilized(grey waveform).



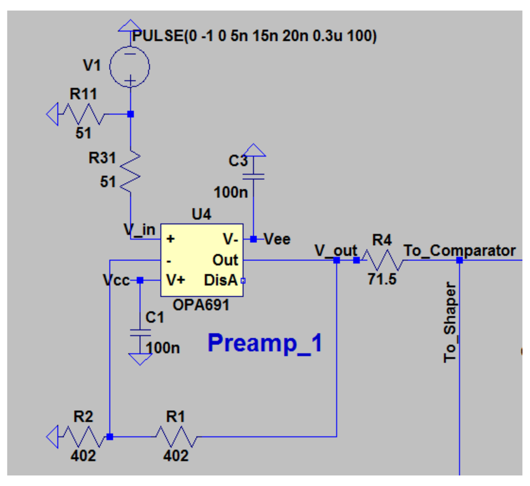
On the second set of waveforms we can observe the path of the digital signal to sample and hold unit. The waveforms in green and black represent comparators output signals. The next stage is AND gate.(red waveform). AND gate output is fed into monostable multivibrator_1, and we can see it's reaction signal in blue color. Due to computing power constrains I could not simulate the signal from the second multivibrator. However, you can observe that result on the right side of the poster. The final circuit component before sample and hold(SaH) unit, monostable multivibrator_2, will react to the first monostable and rise high for 250ns, giving enough time for SaH to detect stabilized voltage value of adder(pink waveform). Later this value will be send to Arduino board and raspberry pie and saved in the data base.

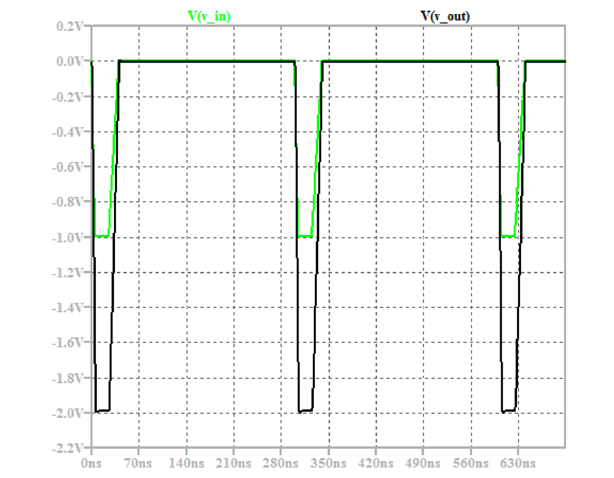


1. Preamplifier

The Preamp receives a signal from Photomultiplier tube sent through the BNC-50 Ohm connector, processes it and then sends the signal out to the Shaper and the Comparator. This part of the data acquisition circuit board is used to amplify the input pulse. To accomplish this we use a non-inverting amplifier circuit. To calculate the gain for such a circuit the following formula is used:

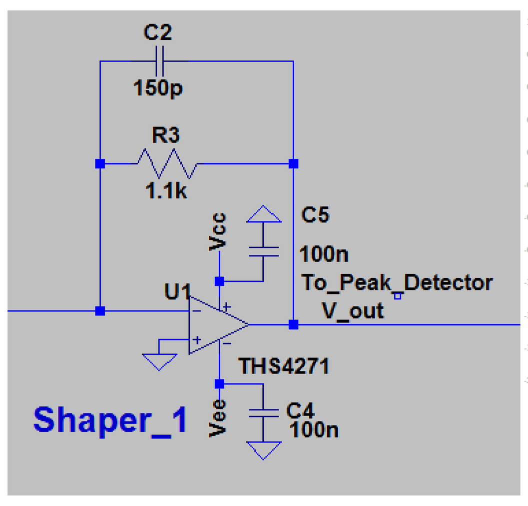
$$G = 1 + \frac{R1}{R2} = 1 + \frac{402}{402} = 2$$

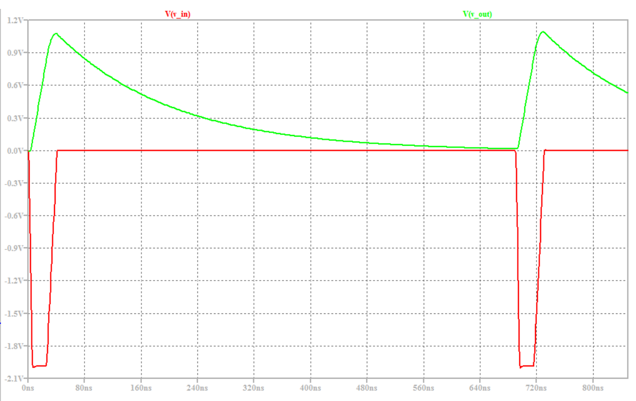




Shaper

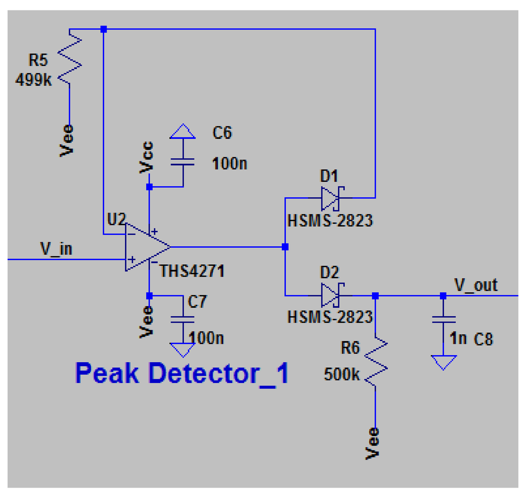
The Shaper is part of the Peak Detector. The shaper sub circuit is used to stretch and invert the signal for the upcoming peak detector circuit.

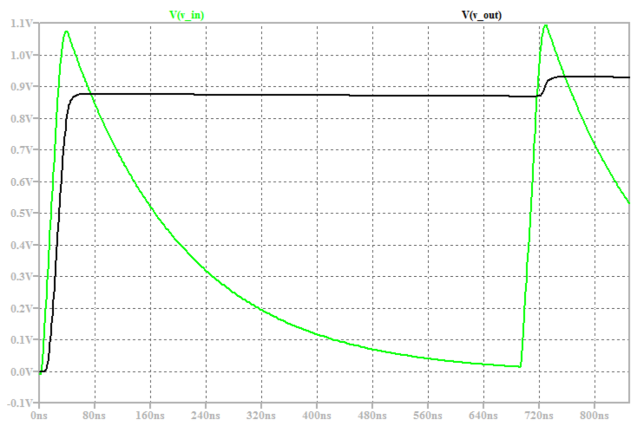




4. Peak Detector

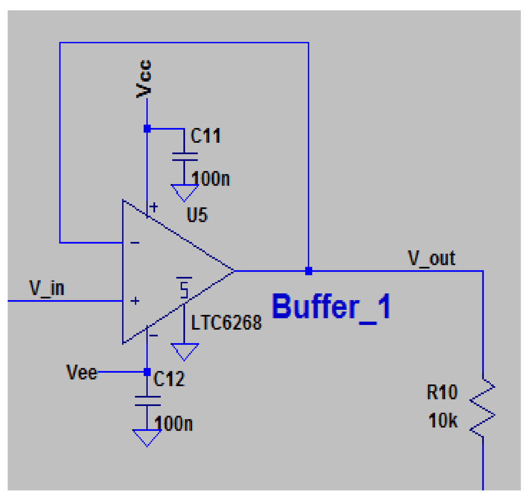
The peak detector purpose in the circuit is to measure the peak amplitude that occurs in a waveform and hold it, giving sample and hold unit enough time to sample the signal.. When the input waveform falls the capacitor, charged by the waveform, retains the peak value and slowly discharges. Adjusting R6 resistor and C8 capacitor on the diagram we can change the discharge time of the peak detector.

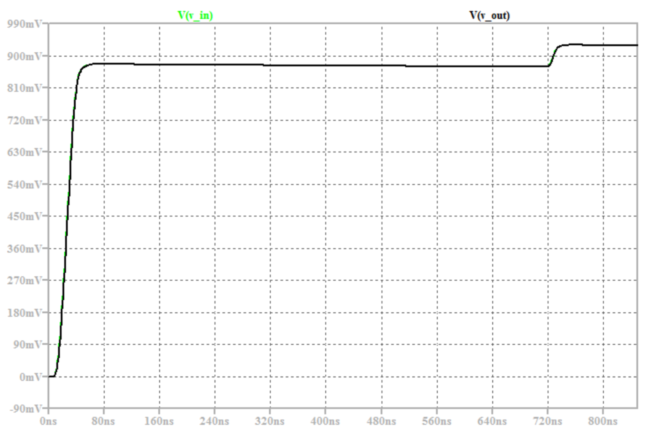




Buffer

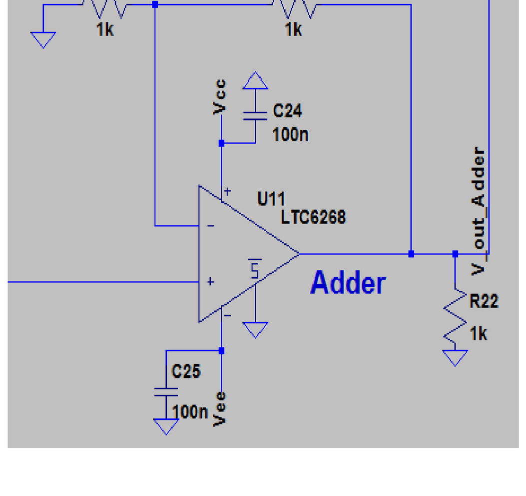
The last part of the peak detector circuit is buffer. A buffer provides electrical impedance transformation from one circuit to another. The aim of this buffer is preventing the signal from peak detector to be affected by currents that the adder may produce. There are two waveforms on the graph but because buffer component completely copies the input signal it overlays it.

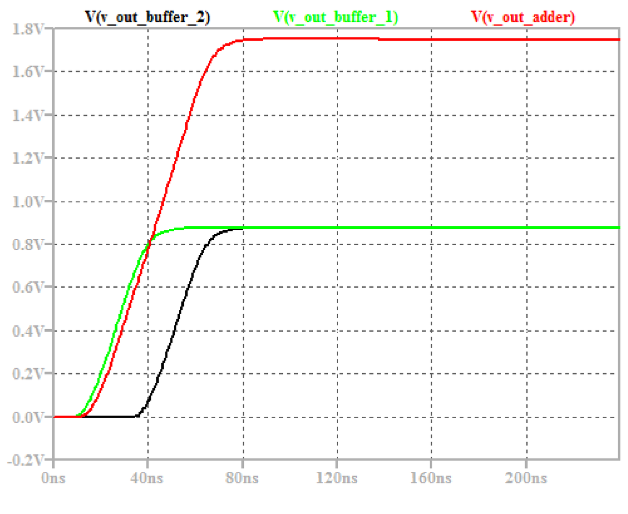




Adder

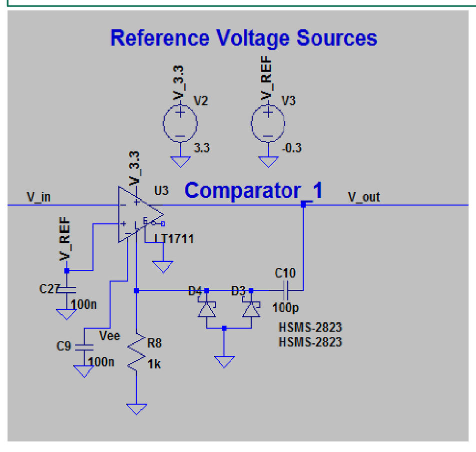
The Adder sub circuit takes in the two signals from their respective buffers and sums their averages, generating one output signal. It has a gain of 1 and does not invert the output signal. I have created a time delay for simulated waveforms, so it is easier to read the graph.

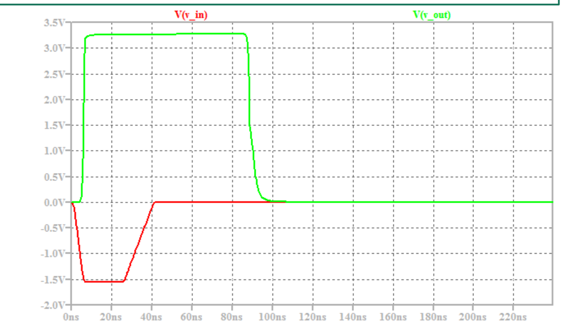




2. Comparator

The discriminator sub circuit is used to set a lower limit on signal amplitude reducing noise, and to output for each PMT pulse a square wave of particular width to be read by coincidence logic. It does this by comparing the Preamp output to a reference voltage

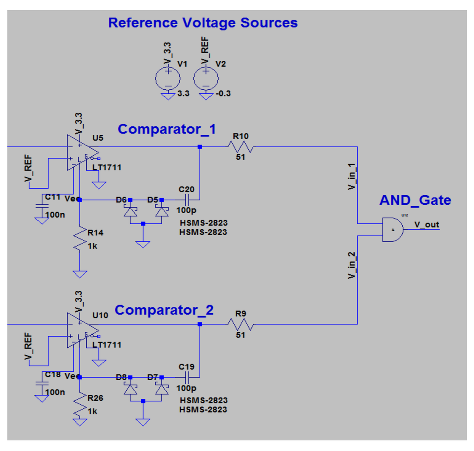


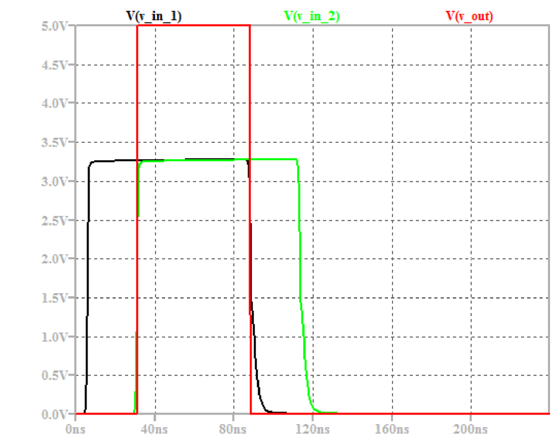


3. AND Gate

The AND gate is a simple digital logic gate that implements logical coincidence. High output 5V results only if two comparators are high. If none or not all inputs to the AND gate are high, a low output results 0V.

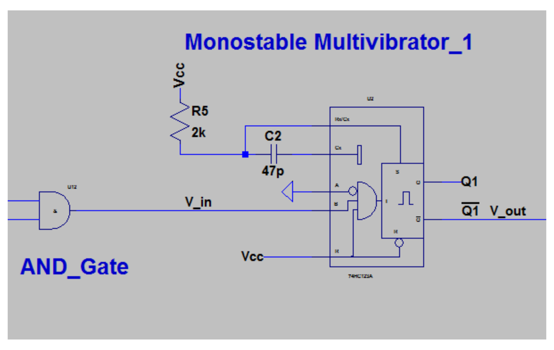
On the graph you can see that AND gate logic output is high only when comparators outputs are high at the same time. This technique will help to eliminate recording of a false counts(PMT noise).



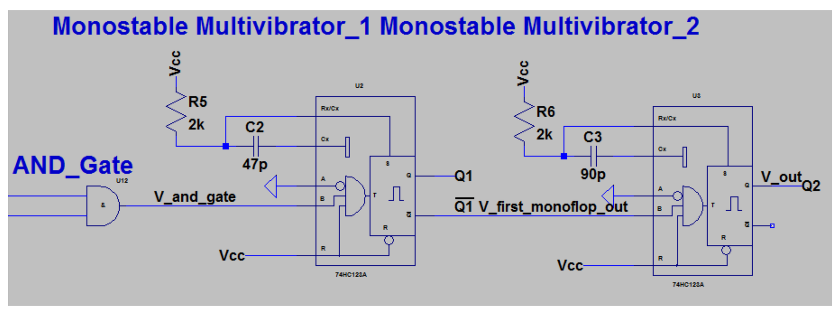


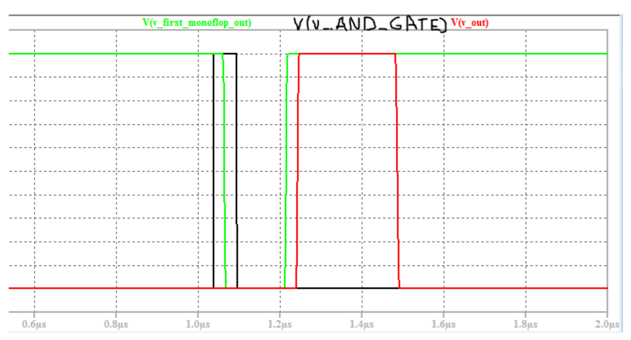
5. Monostable multivibrator

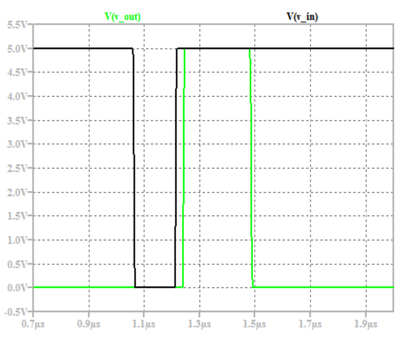
Monostable Multivibrators are used to generate a single output pulse of a specified width. In our design coincidence logic signal +5V initiates a timing cycle in the first multivibrator and causes the output of the monostable to change its state from high +5V to low 0V. At the end of the timing cycle, the first monostable returns itself back to its original (stable) state +5V, however the changing edge(rising edge in our case) triggers the second multivibrator, and causes it to to change its state from low 0V to high +5V for determined timing cycle. The timing cycle of the monostable is determined by the time constant of the timing capacitor, C and the resistor, R. You can observe a working principle of the first multivibrator on the graph below.



Because the signal splits after preamplifier unit, a time delay appears between AND gate signal, digital input, and adder, analog input into sample and hold unit. The purpose of the multivibrators connected in series is to neutralize the delay.







Conclusion

Simulating the circuit board I used models of the real world circuit components available on the market. Although the work was theoretical and a big progress designing the board was accomplished. The next step towards the goal of completing the circuit is to transfer the circuit schematics to another software for layout and prototype printing.

Acknowledgement

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