

Creating an Audio Integrator

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Particle detectors play a very important role in high energy physics. In this paper I will describe a circuit made in order to detect when particles are being received and alert those around with a light emitting diode and a speaker playing an audio output. This audio output will be dependent on the frequency of the input. I will discuss the schematic for such a circuit and outline each component's purpose and how it is fulfilled.

Motivation

In high energy physics, particle accelerators are used in order to accelerate charged particles to relativistic speeds and then collide them into other particles in order to study the elementary constituents of matter. Fermilab is home to the world's second largest particle accelerator, the Tevatron. The Tevatron is a circular accelerator used to accelerate protons and antiprotons to speeds up to 150 GeV. The stream of protons or antiprotons being accelerated in the Tevatron is called the test beam. The different projects working at Fermilab must split up the use of the test beam. Henry Frisch's projects at the Collider Detector at Fermilab (CDF) receive 4 seconds of the test beam for every minute it is running. As the particles in the test beam reach Henry Frisch's projects they come in a form of pulses of $-0.8V$ charges that have frequencies in the range of 10kHz to 100kHz. It was proposed that we would build a circuit capable of detecting the test beam and alerting those working with the test beam. This would be done with an LED that would light up when beam was being received and a speaker with output frequencies dependent on the input frequency of the test beam.

The Circuit

Designing a schematic became the first task in the building of the circuit. The schematic is broken into two independent branches, sharing only the input pulses received. The top branch of the schematic shows the part of the circuit that received the input and used it in order to drive the LED for the duration of time the pulses were being received. The bottom half of the schematic depicts the portion of the circuit responsible of taking the input pulses and turning them into frequencies in the audible range which will drive the speaker. Below the two halves of the schematic are shown.

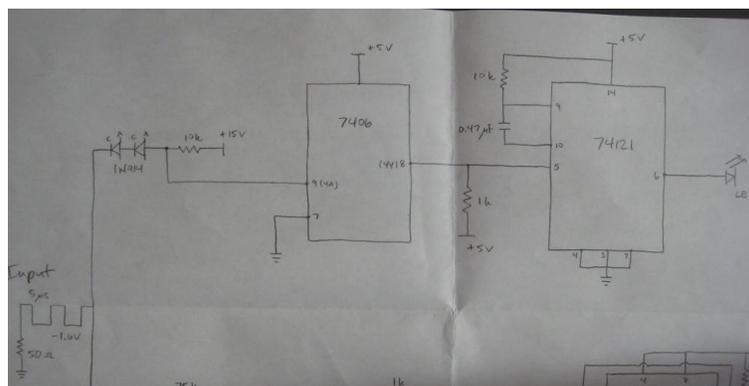


Figure 1: Schematic top half

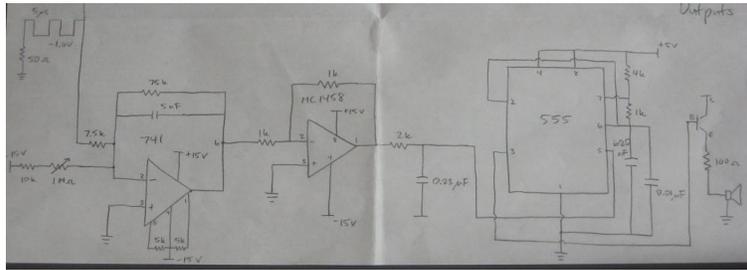


Figure 2: Schematic lower half

Schematic: Lower Half

Integrator

An integrator is used in order to take the input voltage and convert them into a frequency dependent output voltage. An integrator is made using an operational amplifier. Operational amplifiers are circuits with two inputs and one output (usually tied to one of the inputs to create a feedback loop) and they have two rules that govern how they work. First, the output will be as such as to try to maintain a voltage difference of zero across the two inputs. Second, the two inputs draw no current. Using these two rules one can solve for the output voltage of the operational amplifier. Pictured below is the basic design of the integrator.

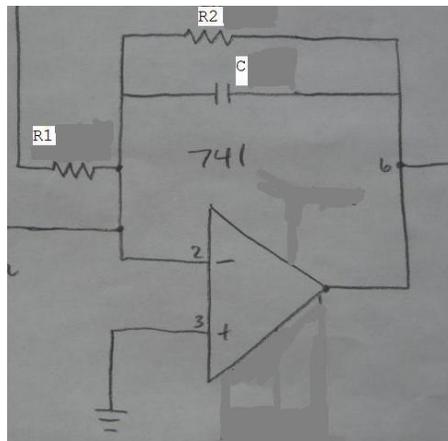


Figure 3: Basic schematic of our integrator

Solving the circuit for the output voltage yields a system of four equations:

$$I_{in} = \frac{V_{in}}{R_1}, I_{in} = i_1 + i_2, V_{out} = -R_2 i_1, i_2 = -C \frac{dV_{out}}{dt}$$

This system of equations yield the following equation:

$$\frac{dV_{out}}{dt} = -\frac{V_{in}}{R_1 C} - \frac{V_{out}}{R_2 C}$$

This equation, along with the initial condition $V_{out} = 0$ when $t = 0$ can be solved to give the equation

$$V_{out} = \frac{1}{R_1 C} e^{-\frac{t}{R_2 C}} \int_0^T e^{\frac{\tau}{R_2 C}} V_{in} d\tau$$

For this circuit the input voltage is a sequence of square pulses and this integral can be solved exactly for each square pulse, yielding two solutions depending on the time regime of the solution. T is the width of

each pulse, and from the beginning of the pulse until time T ($t < T$) the solution is:

$$V_{out} = \frac{V_{in}R_2}{R_1} e^{-\frac{t}{R_2C}} \left[e^{\frac{t}{R_2C}} - 1 \right]$$

This formula corresponds to the charging of the capacitor in the integrator. In the time regime $t > T$ until the beginning of the next pulse the solution has the form:

$$V_{out} = \frac{V_{in}R_2}{R_1} e^{-\frac{t}{R_2C}} \left[e^{\frac{T}{R_2C}} - 1 \right]$$

This formula corresponds to the discharging of the capacitor.

Using Matlab these solutions were plotted in order to demonstrate the output voltages dependence on the resistor in parallel with the capacitor (R_2), which is the component directly responsible for the discharging behavior of the capacitor. This behavior is important as it adds another control to the level of the output voltage of the integrator. The difference level of output voltage due to changes of the input frequency is very important in the circuit. However, it is desirable to be able to limit this difference between the minimum and maximum output voltages. As R_2 increases, the maximum height of the integrated pulse decreases, which will lower the average value of the overall integration. By decreasing this height the difference between the minimum and maximum will be decreased. This is important as the output voltage will need to be in a certain range to operate the voltage to frequency converter later on in the circuit. In the graph two output voltages are shown, each with the same exact parameters except for the value of R_2 . The output voltage plotted that reaches a smaller maximum voltage has a value for R_2 that is 10 times greater than the output voltage plotted on top. This plot is shown below.

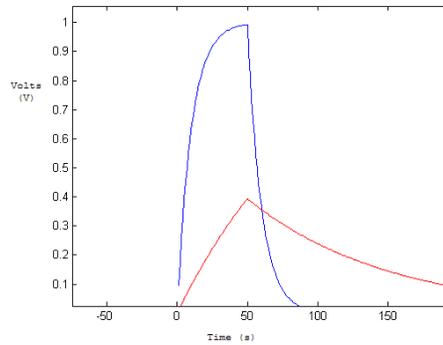


Figure 4: Output Voltage Vs. Time plot.

Using a simulation program a simulation was made of the integrator with all of the exact parameters in place. This simulation produced a simulated screen of what would be seen on the oscilloscope with the input pulses and the output voltage displayed. This simulation is shown below.

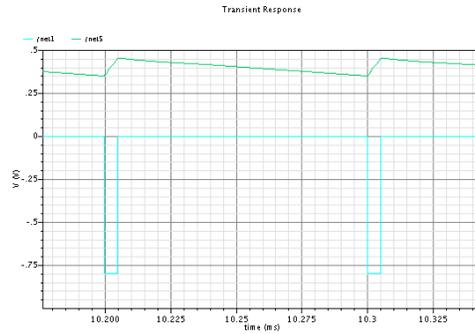


Figure 5: Simulated oscilloscope showing Input Voltage and Output Voltage Vs. Time

The bottom line shown is the input and the top line is the output voltage. As seen, the output behaves as the formulas predict it should. The most important aspect of this to see is the average voltage level the output is at. As the input frequency between 10kHz and 100kHz this average level will change, rising monotonically as the frequency increases. This behavior will be very important later on in the circuit.

Inverter

The output of the integrator then goes into an inverter that inverts the output voltage. This is necessary in order to obtain the correct behavior from the voltage to frequency converter later in the circuit. An inverter is another example of what can be done with an operational amplifier.

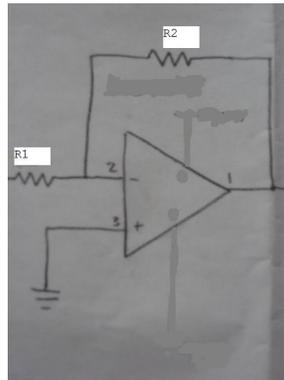


Figure 6: Basic inverter schematic

Using the same techniques for solving circuits with operational amplifiers in them described above, one ends up with the following relations:

$$I_{R_1} = \frac{V_{in}}{R_1}, I_{R_2} = \frac{V_{out}}{R_2}$$

Since no current can go into the input, these two currents must add to zero, and this gives us the desired relation:

$$\frac{V_{out}}{V_{in}} = \frac{-R_2}{R_1}$$

By selecting resistors with the same value, as we have, one gets output voltage that has the opposite sign of the input voltage.

RC Filter

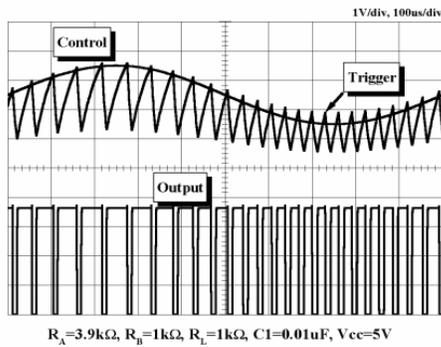
A low pass RC filter is placed after the inverter in order to smooth out the output of the integrator. The high frequency responses (the rises and falls seen that corresponded to an input pulse) seen in the integrator output gave bad responses from the voltage to frequency converter. The easiest way to deal with this problem was to just eliminate the high frequency responses of the integrator. A low pass filter solved this problem in the circuit, as it only allows the steady average output voltage level that is important to pass. This behavior can be seen from the formula that relates the output voltage of a low pass filter to the input voltage and the frequency, shown below.

$$V_{out} = \frac{V_{in}}{[1 + \omega^2 R^2 C^2]^{\frac{1}{2}}}$$

As seen in the formula, as the frequency increases, the output voltage will decrease.

Voltage to Frequency Converter: Ne555

A voltage to frequency converter, the one in the circuit being the Ne555, then takes the output voltage given to it and outputs pulses a certain frequency which will be in the audible range and drive the speaker. The Ne555 gave many problems, mostly due to the lack of information given by the manufacturer. Shown below is the only information in the datasheet of the Ne555 for the role it is meant to fill. This data was found to be unreliable and instead it was chosen to take data and graph it. This data is plotted to the right of the graph provided in the datasheet, shown below. A power supply was connected supply directly to the Ne555 and measured the output frequency given as a function of the input voltage. This was done for several values in between the minimum and maximum allowed input voltage ($1.6V < V_{in} < 5V$).



Waveforms of pulse position modulation

Figure 7: Information provided by the Ne555 datasheet

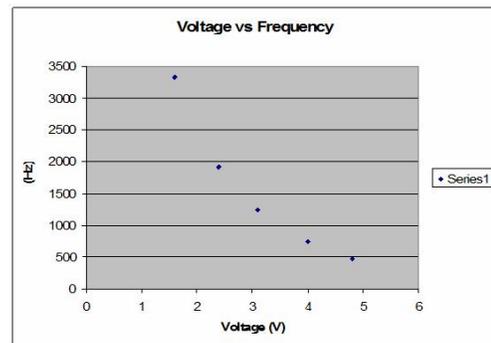


Figure 8: Graph of Output frequency Vs. Input Voltage

It was decided that the optimal range for input voltage was between 2 to 4 volts. It can be seen in Figure 8 that in this region the output frequency is monotonic, which is important for the desired purposes. Being in this region will also keep us within the operating range of the Ne555. It can also be seen in this graph that the output frequency is higher at lower input voltages. This caused a problem for the circuit as low input voltage of the Ne555 corresponds to low output voltage of the integrator, and thus low input frequency of the input pulses. The inverter became necessary as a solution to this problem, as it flips the output of the integrator. By inverting the integrator output the integrator output now matches what the Ne555 needs in

order to get our desired frequency response. However, adding the inverter also created another problem, as the output of the integrator would then be too negative to drive the Ne555. This was solved by adding a potentiometer, or variable resistor, into the integrator circuit. There is a -15V power supply attached to a 10kΩ resistor and then the potentiometer (max value of 1MΩ) which is then attached to the input not tied to ground. The potentiometer can be tuned anywhere between 0 and 1MΩ, allowing one to inject more current into the integrator. This injected current would move the height of the output voltage, and thus the integrator was tuned to give the correct range of output voltages. Adding these two components allowed the circuit to have the monotonic output that mimicked the input as desired.

Transistor and Speaker

The final component of this part of the circuit is a transistor before the speaker that amplifies the current going into the speaker. This is necessary because the output current of the Ne555 alone would not be enough to drive the speaker. By using a 3 pin, npn transistor one is able to amplify the current from the Ne555 by a factor of 100. The transistor used has 3 legs, and this kind of transistor has 3 rules that govern how it operates. The collector leg must be tied to a higher voltage than the emitter leg. The base-emitter acts as such that current can only flow from the base to the emitter leg. Finally there are max values for the current in the base, current in the collector, and voltage across the collector and emitter legs that must not be exceeded. When these conditions are met we end up with the condition:

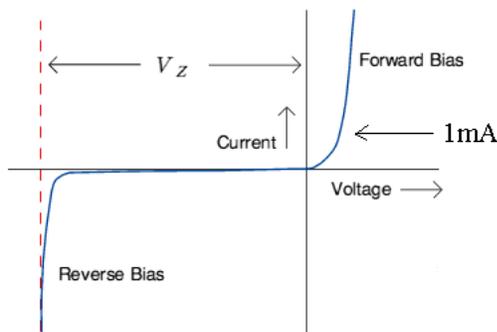
$$I_C = \beta I_B$$

With $\beta \approx 100$. With this amplified current, the output of the Ne555 makes it to the speaker and creates the audio output.

Schematic: Upper Half

Silicon Diodes

The first part of the upper half of the schematic is 2 silicon diodes in series, responsible for raising the input pulse voltage to a level that can trigger the next component. In diodes, current can only pass from the anode to the cathode. Depending on the current through a diode, there will be a voltage difference between the anode and the cathode. The behavior of diodes can best be explained using a graph of the current vs. the voltage, shown below.



Diode I-V Curve

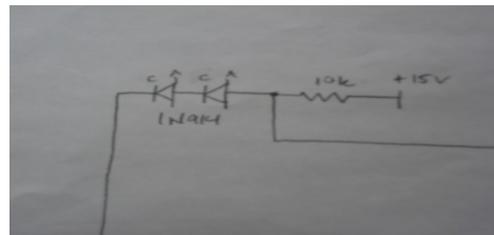


Figure 10: Schematic of diodes

Figure 9: Graph depicting the behavior of diodes

In the forward biased region, the region of importance for the circuit, voltage asymptotically approaches a max value of 0.6V, first achieved at a current of about 1mA. Therefore with a current of approximately 1mA flowing through a diode, the anode will be 0.6V more positive than the cathode. In this configuration, the circuit has two diodes in series in such a way that going from the left side of the schematic one first sees the first diode's cathode then anode, then the next diodes cathode then anode. Tied to the second diode's cathode is a voltage source of +15V and a 10kΩ resistor, feeding the diodes a current of 1.5mA traveling from the right to the left of the schematic. This means that the voltage on the right end of the two diodes in series will be 1.2V higher than the left side. This creates the bump in voltage for the input pulses, traveling from left to right across the diodes. The -1.6V pulses are raised to -0.4V, and the 0V portions between each pulse is raised to 1.2V. The pulses are -1.6V and not -0.8V as mentioned above because of NIM standards. These will be discussed later.

Logic Inverter: 7406

The next component in the upper half of the schematic is a logical inverter, the 7406, with the purpose of logically inverting the input pulses and trigger the next component. The series of diodes was necessary to get the input pulses to have a voltage higher than the trigger threshold of the 7406, which is 0.8V. The logical inversion of the 7406 is such that the 1.2V portion which corresponded to the spacing in between the pulses will not trigger the next component, and the -0.4V input pulses which will not set off the trigger will. To understand this we must look at a specific part of the internal workings of the 7406.

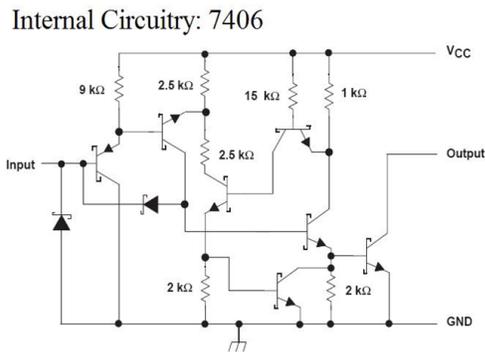


Figure 11: Internal circuitry of the 7406

Closed Transistor

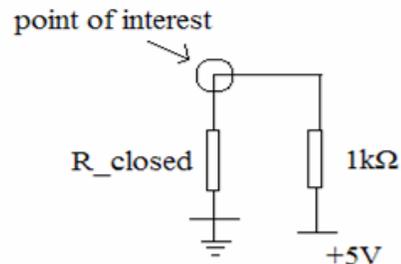


Figure 12: Schematic including the point of interest where the measured voltage will either trigger or not trigger the next component

Figure 11 on the left shows the internal workings of the 7406. The only portion that needs to be discussed is the transistor on the lower right hand corner. This transistor has 3 legs: one that accepts the input from other parts of the 7406, one that is tied to ground, and one that is tied to the output of the 7406. The leg tied to ground is the important one. The transistor can be thought of as a switch to be open or closed. When it is closed, depicted above in Figure 12, the leg tied to ground is connected and acts as a resistor with resistance on the order of $10 \sim 100\Omega$. The current flowing through the loop can be calculated as $I = \frac{5V}{(1k + R_{closed})\Omega} \approx 0.5mA$. This will give a voltage at the point of interest of $V = 0.5mA * R_{closed} \approx 0.05$ to $0.5V$. The trigger will be closed when the 7406 is receiving the 1.2V portion of the pulses, and this will not be enough to trigger the next component. When the transistor is open, it is acting as if the leg connected to ground has resistance on the order of $10^5 \sim 10^6\Omega$, and therefore one can act as no current is flowing through that leg. Since there is no current flowing there is no voltage drop across the 1kΩ resistor tied to the

+5V source and thus the point of interest will have a value of +5V. This will be enough to trigger the next component, which triggers at +1.5V.

Monostable Multivibrator: 74121

The next component is a monostable multivibrator, or one shot, the 74121, that when triggered creates a pulse which will turn on the LED, with pulse width determined by an external capacitor and resistor. A multivibrator is a circuit used to implement a two state system. A monostable multivibrator is one that has only one stable state; a trigger will put it into the unstable state for a predetermined amount of time and then it goes back to the stable state. There are two kinds of monostable multivibrators: retriggerable and non-retriggerable. In a non-retriggerable one-shot the one shot is triggered once a HIGH logic state is input and once it is triggered it will not trigger again until after the pulse is over. In a retriggerable one-shot timing begins after the input falls from a HIGH to LOW logic state. No matter what the length of the input pulse, the output will remain high for the predetermined time constant.

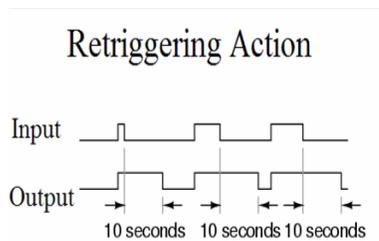


Figure 13: Input and output of a retriggerable one-shot

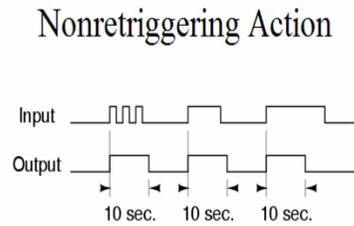


Figure 14: input and output of a non-retriggerable output

The figures above depict the input and output of retriggerable and non-retriggerable one shot. It can be seen that in the retriggerable one-shot timing does not start until the LOW state is reached and in a non-retriggerable one-shot it begins as soon as it is triggered. The 74121 is a non-retriggerable one-shot and was chosen so the output pulse would begin as soon as input was being received.

The width of the pulse is determined by the formula:

$$T_{pulse} = 0.7R_{ext}C_{ext}$$

where T is in nanoseconds, R in kΩ and C in pF. By picking the values of the external resistor and capacitor the time constant is chosen. The time constant was chosen in order to meet a few criteria. The output pulse should be long enough so that it is always greater than the maximum amount of time between any two input pulses. The lowest frequency of input pulses would be 10kHz, so the maximum time between pulses is $10^{-4}s$. The output pulse should not be too long however, as it would be undesirable for the LED to be on for a significant amount of time after the last input pulse. A $10k\Omega$ resistor and $0.47\mu F$ capacitor were chosen to yield a time constant of $3.29 \times 10^{-3}s$. This meets both criteria as it is longer than $10^{-4}s$ and yields a max time only slightly over the 4 seconds input pulses will be received each minute.

NIM

The circuit was then placed into a box that met NIM (nuclear instrumentation module) standards. NIM is the standard that defines mechanical and electronic specifications in experimental particle and nuclear physics. A few additions to the circuit had to be made to fit the NIM standards. First, a 50Ω resistor had to

be tied from the input to ground in order to match the impedance of the input wire to destroy any feedback and preserve the waveform of the input. The NIM power supplies are +6V, +12V, and -12V as opposed to the +5V, +15V and -15V originally designed. The circuit was able to handle the change from 15V to 12V and -15V to -12V, but a diode had to put after the +6V in order to drop the voltage to +5.4V in order for it to operate correctly. The circuit was also tuned to receive pulses of width $5\mu s$. However the width of the pulses received at Fermilab could not be guaranteed to be of this width. In order for the circuit to work the input must first be fed into a discriminator. The discriminator will take the -0.8V pulses and output pulses at -1.6V and width of $5\mu s$ at the same frequency that they are received. The circuit had to be tuned to be able to accept the -1.6V instead of the -0.8V as originally planned. This was accomplished by using the potentiometer in the manner described above.

Conclusion

By using the configuration outlined, one can build a circuit that will alert with output audio and a light emitting diode when input is being received. The circuit is designed for a specific input, but with the correct modifications and tuning the circuit should be able to handle other inputs one may want to have detected.