# RC Car

6.101 — Spring 2016 — Final Report

Andrés Salgado-Bierman, Alex Oliva, and Ebenezer Nkwate

May 13, 2016

# Contents

# List of Figures

# 1 Abstract

**Remote-controlled cars began appearing in homes as early as the 1960s. The first versions were implemented using bang-bang control, allowing the cars to go abruptly left, right, or straight at a single speed. As these cars became more sophisticated, the analog, single-speed, remote-controlled cars eventually were replaced by digital, variable-speed, radio-controlled cars.**

**This project presents an alternative to radio-controlled communication: the fiber optic cable. It makes use of analog technology to implement a variable speed and variable direction car that is fully battery-operated on both the controller and car ends using a single fiber optic cable to communicate between the two.**

# 2 Introduction

The main project goal is to provide a simplistic model of a complex system. Hence we use readily available parts such as resistors, op-amps, npn and pnp mosfets. Also, the mechanical layout simply consist of using the breadboard was the body, attaching lazer-cut acrylic wheels surrounded by a rubber band to increase friction. Our aim is to provide savvy minds interested in building their own RC cars the ability to do so with as little complexity as possible.

This approach inherently means it becomes more challenging to provide reasonable control with only basic components and hence an interesting reason why we decided to tackle this.

# 3 Design Overview

This project consist of two main components: A transmitting controller circuit and a receiving driving car (Figure 1). Each of these two parts has part of a communication medium. In this case, an optic fiber. Therefore this project comprises of three main modules. A controller circuitry to generate signals to be transmitted, a communication medium to transmit the generated signals from controller to car and the motor circuitry to transform the received signal into a voltage able to drive the motors.

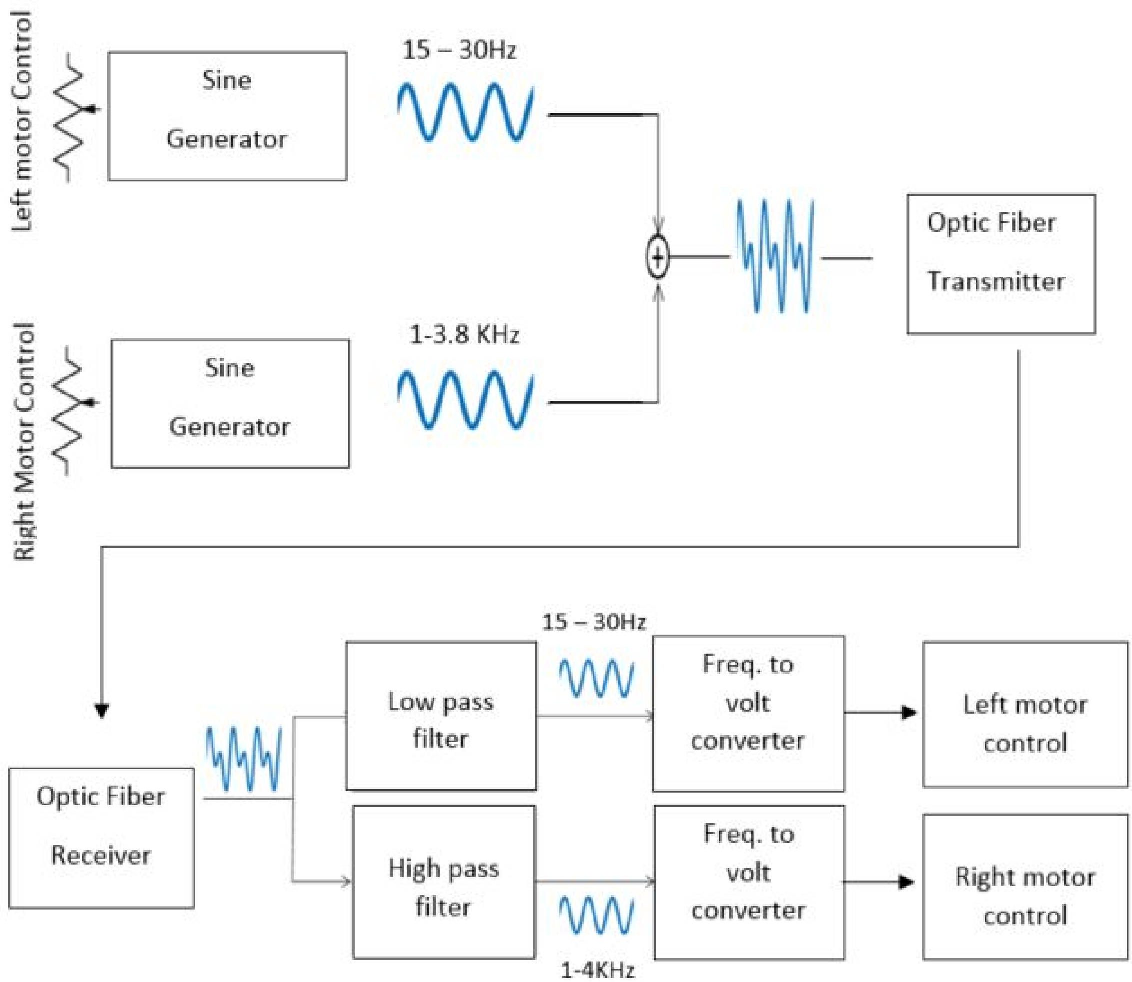


Figure 1: System Overview: Transmitting controller above and Receiver car below

# 4 Module Descriptions

## 4.1 Controller

The controller consist of two sine waves superimposed on each other (Figure 1). These two waves are of different frequencies. A lower frequency range of 15-30hz and a higher frequency range of 1.8Khz to 3.8Khz. The frequency range is achieved by changing the pot's resistance. In order not to let the resistance at that point be zero, the pot is placed in series with a resistor. If the resistance is zero, the output signal becomes zero. In addition, when the pot is being tuned, the peak-peak value of the sine wave changes. Hence after finding a suitable range: A large range which offers ample voltage for all frequencies within it, the pot was placed in parallel with a resistor that enables it to use its whole range but still stay in within that range. This is possible because the lowest resistance along that path is the value of the series resistor and the largest value is the Parallel combination of the pot max value and the resistor. This voltage range provides for the array of speeds the motor can spin at and hence is valuable if made large. However, due to the simple design, there is a limit to the achievable range. In addition, the frequencies are placed at two decades apart to enable easy separation. Although the signal during the time of this design was not modulated, the low frequencies make it easier to modulate. As frequencies in the hundreds of kilohertz can be used.

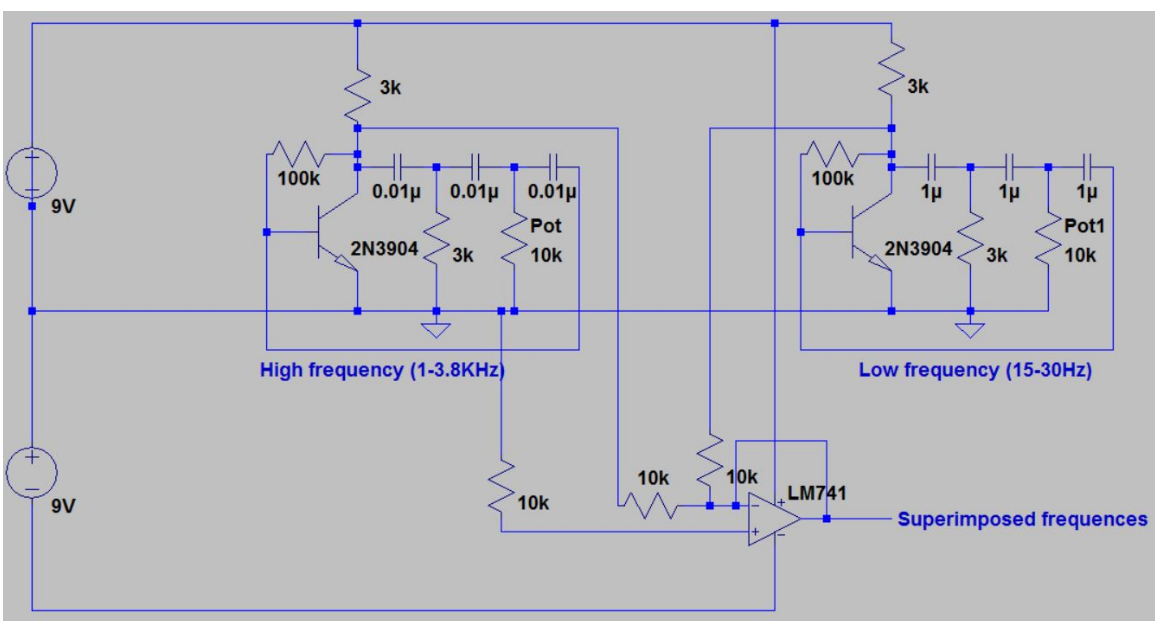


Figure 2: Controller Signal Generation and Signal Super-positioning

## 4.2 Communication

After the controller generated a signal containing information to control both wheels of the car, it needed to be properly transmitted to the car. This was done using a fiber optic cable. Figure 3 shows the overview of the transmission and reception process. The pre-transmission circuitry shrunk the signal and offset it to a level useable by the light-emitting diode (LED) of the fiber optic cable with a small resistor in series. After the signal was transmitted via light and received by the photodiode on the car, a transimpedance amplifier (TIA) was used to reliably convert the received light/current into a voltage level. The two sine waves generated in the controller circuitry were then extracted using a single-pole low pass filter and a double-pole high pass Sallen-Key filter. These signals were then transferred to the car.

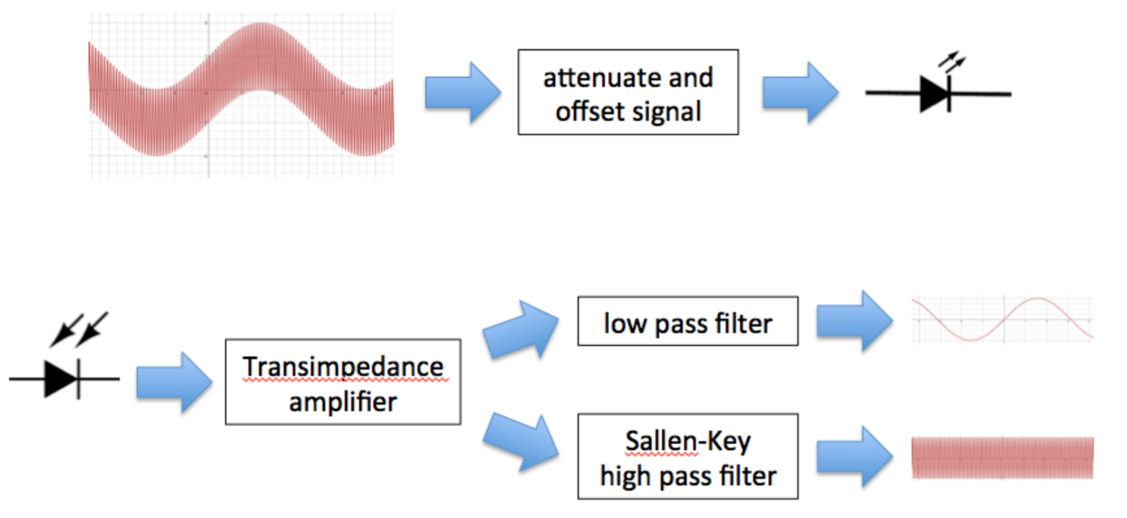


Figure 3: Overview of Transmission and reception process

With a 100 ohm resistor in series with the LED, it was experimentally determined that the LED performed approximately linearly over input voltages from 1.2V to 3.0V. To fit the input signal into this region, the signal was attenuated with a gain of 0.91 and offset by approximately -0.82V. This was done by using an inverting summing op-amp configuration as seen in the first op-amp configuration in Figure 4. The 100k pull-up resistor acted as a 90k resistor in series with a 10k resistor, equivalent to a 0.9V input to a summer, offsetting the voltage by -(9.1k / 10k) * 0.9V = -0.819V. Because the inverting summer produced a negative output, the signal was then passed through a unity gain inverter to produce a positive reflection of the signal (second op-amp configuration in

Figure 4. In order to minimize power losses while simultaneously not introducing large amounts of noise into the signal, 10k input and feedback resistors were used. Afterwards, this signal was pass through the 100 ohm resistor in series with the LED.

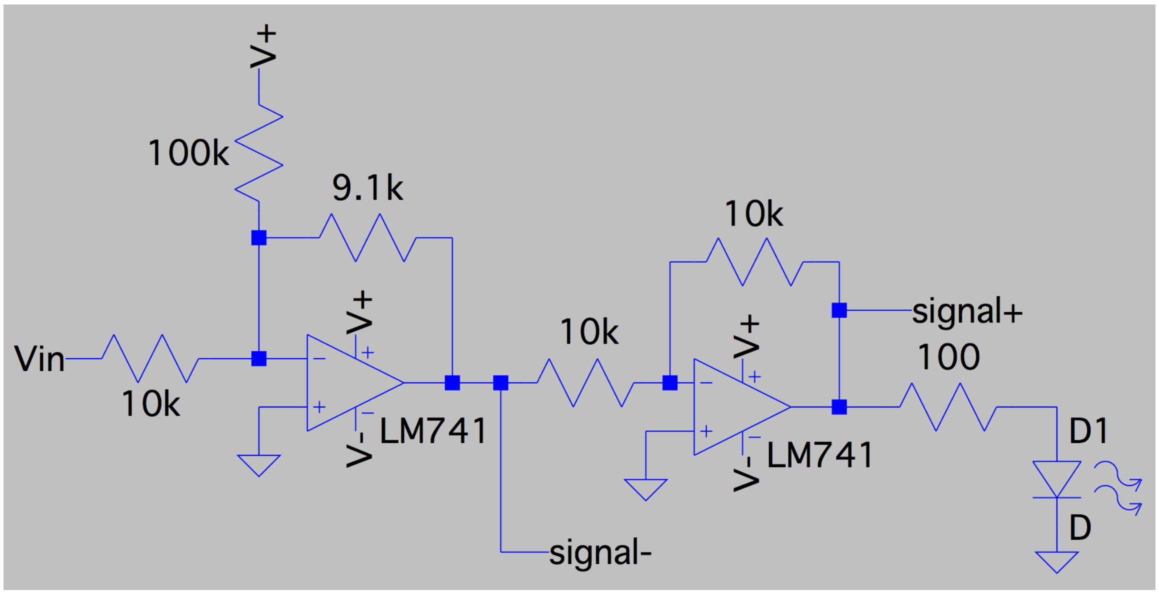


Figure 4: Transmitter Schematic

After the optical signal was transmitted through the fiber optic cable and received at the photodiode, the signal was received as a current on a scale of tens of uA. This was then amplified using an op-amp TIA with an Rm value of 100k (first op-amp configuration in Figure 5). After discovering that the low-pass and high-pass filters distorted the output from the TIA, a second op-amp buffer was inserted between the TIA and the filters (second op-amp configuration in Figure 5). Then a simple, single-pole low pass filter was used to separate out the lower 15-30Hz frequency range. A high-pass Sallen-Key double pole filter was used to separate out the higher 1-4kHz frequency range. These separated sine waves were then passed to the car circuitry.

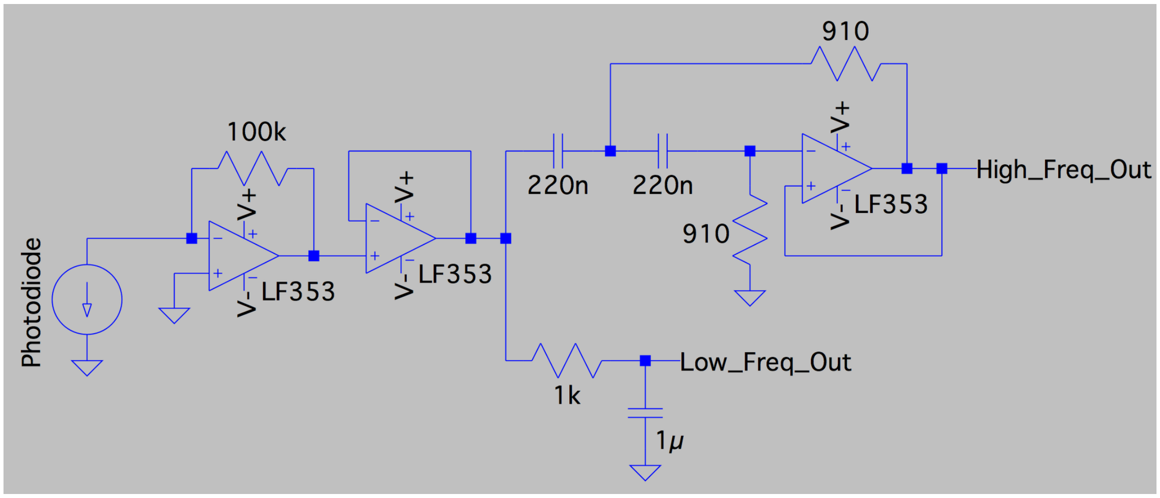


Figure 5: Receiver Schematic

The initial design was intended to use FM transmission to wirelessly pass the signals to the car. The transmitter design (as seen in the left half of Figure 6) used an LC tank to create the carrier frequency. The goal was to transmit the signal at around 10MHz. However, this required a very small inductor value of around 0.1uH (created just a few turns of wire without a core). This posed several problems. Simulations of various configurations with this inductor value showed that the output signal was always very small, often at the level of single mVs. In reality, this would result in the signal being completely hidden by noise. Furthermore, our design was not finished in time to be able to create a PCB. This meant that even if we successfully created a 10MHz LC tank, parasitic capacitances in the breadboard would shift this value dramatically and unpredictably. One solution several groups implemented in the past was using a crystal oscillator. This would allow us to reliably create a carrier frequency, even at lower frequencies such as 200kHz, to transmit our signal. However, time constraints presented problems in ordering this component and it was ultimately decided to switch to using a fiber optic cable.

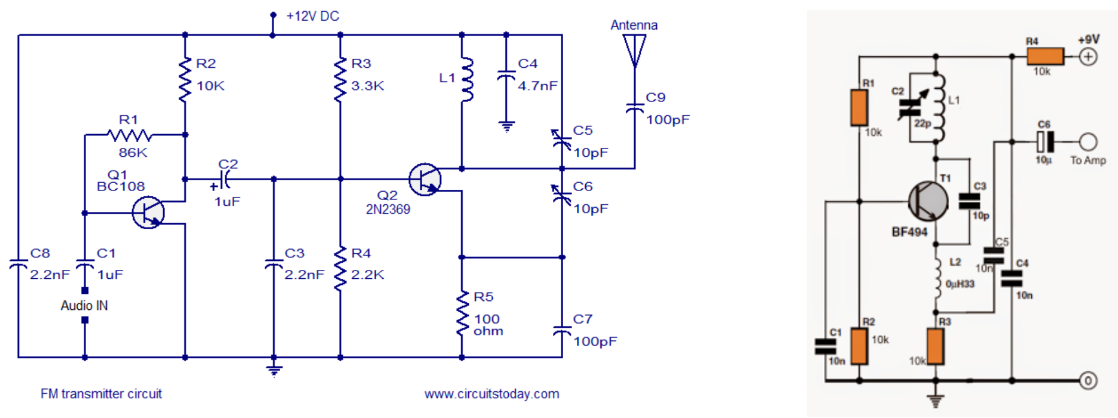


Figure 6: FM Communication Design: Transmitter (Left) and Receiver (Right) Circuits[1][2]

After switching to the fiber optic cable, it was decided to use a simple AM transmission circuit to allow for multiple channels later on. The signal+ and signal- signals from Figure 4 were used to power a phase-shift oscillator circuit configured to generate a 104kHz signal, as shown in Figure 7. This was transmitted through the fiber optic cable, TIA, and buffer as is the case with the actual implementation. However, in the AM transmission version, the signal was then passed through a 71kHz to 122 KHz band-pass filter and then through an envelope detector, as seen in Figure 8. The envelope detector was created using an op-amp precision diode and a low-pass filter to demodulate the signal and shift it back down to the 15Hz-4kHz range. In the end, this circuit was not used either because the modulation circuit did not precisely modulate the carrier frequency, so the demodulated signal was too distorted to use.

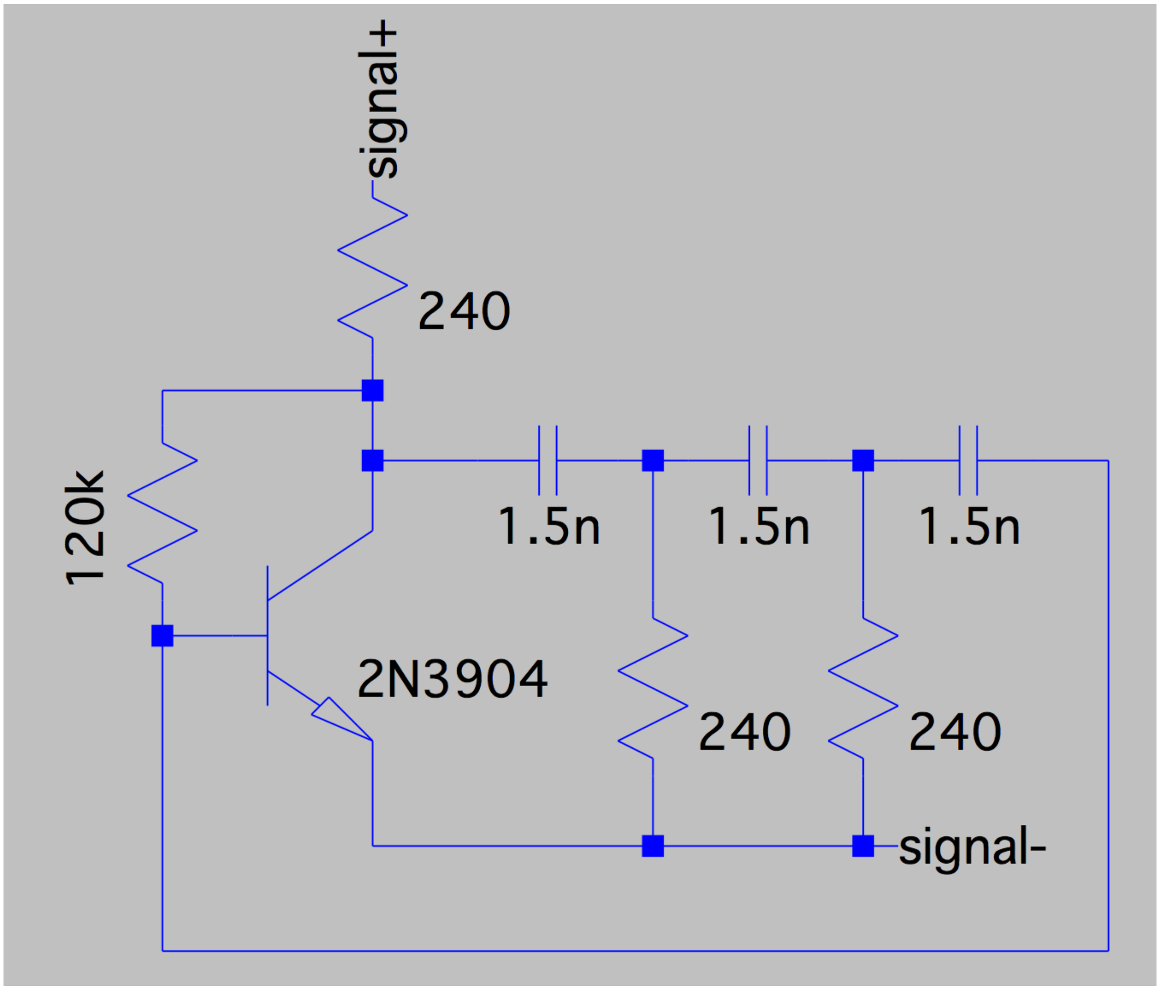


Figure 7: Phase Shift Oscillator For AM Modulation

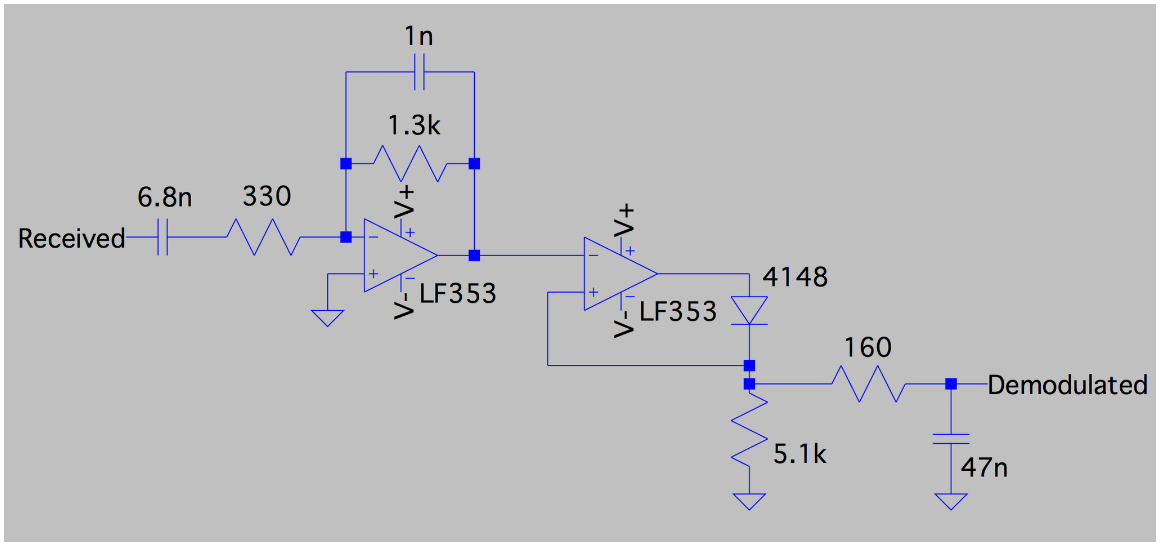


Figure 8: Signal Demodulator

## 4.3 Car

### 4.3.1 Car System Overview

The goal of the car circuitry was to use the two recovered frequency signals to variably control the speed of two motors. Each motor was controlled independently with full reverse at one end of the frequency band, full forward and the other, and no motion in the middle, with variable speed based on frequency all the way from full reverse to full forward. By controlling each motor independently we created a tank drive that allowed the car to drive forward, drive backwards, and turn. When one motor moved faster than the other the car would turn.

The circuits to control each motor were quite similar, with only slight adjustments made for the two different incoming signals. The way one motor control circuit works is first it converts the incoming frequency signal to a new signal at that same frequency that operates reliably with the frequency to voltage converter. A frequency to voltage converter is used because the variable output voltage can be used to control the pwm of a motor driver and thereby the motors speed and direction. It was then necessary to adjust the voltage outputted by the frequency to voltage converter to a 0 to 9 volt range. This reverence voltage was compared against a sawtooth function to generated a square wave with a duty cycle controlled by the reference voltage. This square wave then drove the motors. A delay circuit was used to avoid shoot through when switching the mosfets in the

H-bridge. Finally and H-Bridge was used to control the motor.

#### 4.3.2 Signal Adjustment

To understand the design of the signal adjustment we must first look at the input requirements of the frequency to voltage converter. The frequency to voltage converter is operated from 0 to 9 volts. A voltage is generated on the output of the frequency to voltage by means of a charge pump (Figure 10). When the input of the frequency to voltage converter goes low a capacitor charges up, and when the input goes high the capacitor discharges. This difference between high and low controls how much charge is pumped with each cycle. Since the amplitude of the input signal varied, the best input signal for us to obtain a consistent frequency to voltage conversion was therefore a rail to rail square wave at the given frequency.

Converting the incoming signals to rail to rail square waves required two steps: first adjusting the level of the signal, and second passing it through a comparator. Each of the two incoming signals required different initial adjustment (Figure 9). The low pass and bandpass filters that recovered the two control frequencies for the cars operated from -9 to +9 volts. The low frequency signal was entirely below 0 volts, so it was passed through an inverting op-amp to bring it into the 0 to 9 volts range. The high frequency signal oscillated around 0 volts so it was passed through an adder op-amp to give it a dc offset of 4.5 volts. The adjusted signals were passed through a 311 comparator with a voltage reference set by a pot. The pots were adjusted with the use of the oscilloscope to the middle of the incoming sine waves. The output was then put through an op-amp buffer to protect the signal from the current the frequency to voltage converter used.

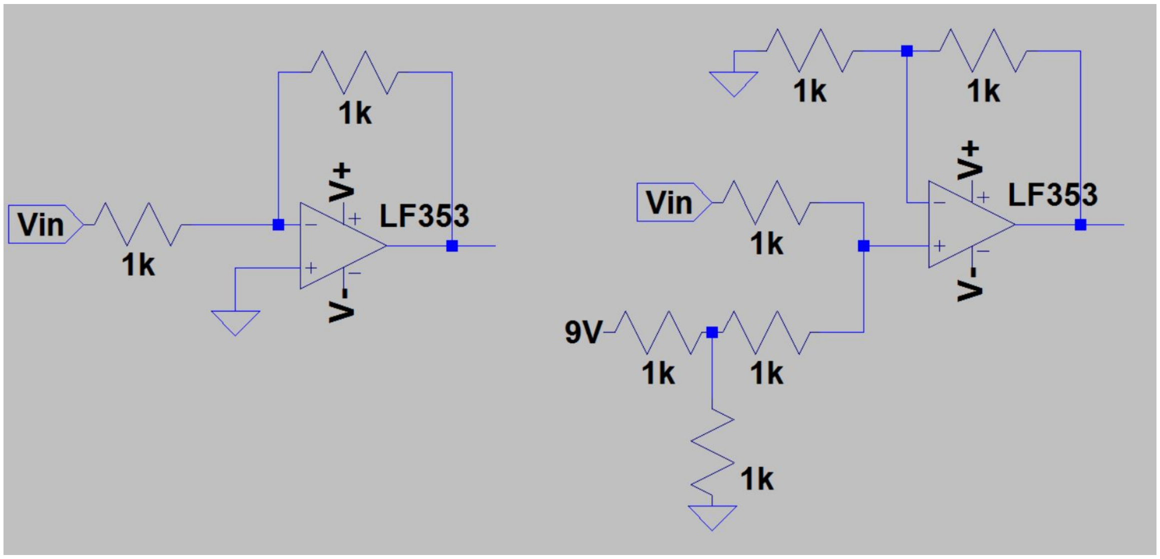


Figure 9: Signal Adjustment

#### 4.3.3 Frequency to Voltage Converter

The operation of the frequency to voltage converter is mostly described in the section above. The size of the first capacitor determines how much charge is pumped with each cycle. To obtain a reasonable voltage range smaller capacitors work better at higher frequencies and larger capacitors at lower frequencies. For the low frequency range C1 was 3.3$\mu$f, and for the high frequency C1 was 33nf. The pumped charge then enters an RC filter to give a steady voltage to the next circuit.

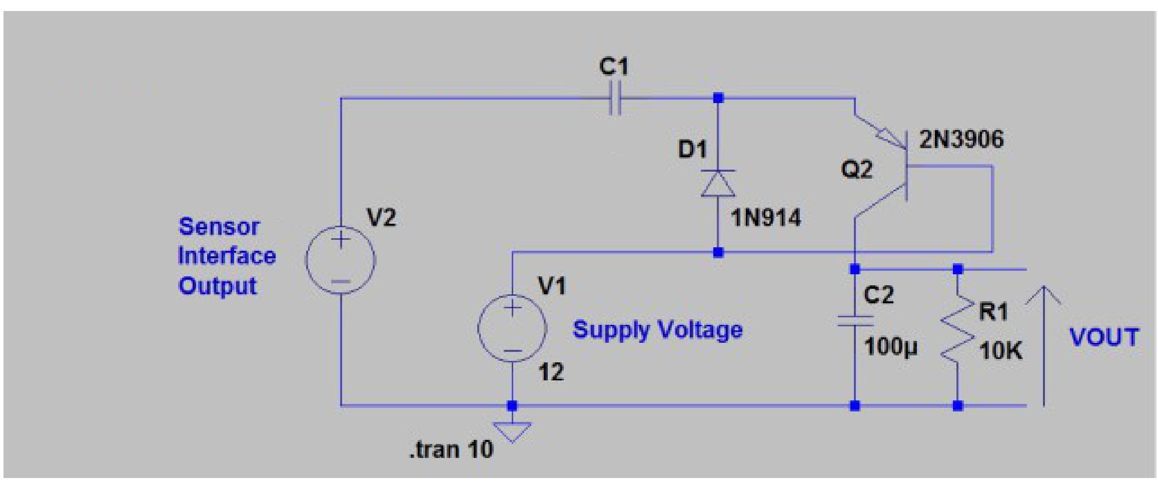


Figure 10: Frequency to Voltage Converter

*figure modified from http://mathscinotes.com/2014/03/a-simple-frequency-to-voltage-converter/

#### 4.3.4 Voltage Adjustment

The frequency to voltage converter gave around a 1 volt range with a dc offset. This was passed through a difference op amp with gain to bring the signal to a 0 to 9 volts range.

#### 4.3.5 Voltage to Duty Cycle

To create a variable duty cycle square wave the voltage from the frequency to voltage converter was compared against a sawtooth function. The sawtooth function was generated with an astable op-amp oscillator circuit (Figure 11). A high frequency relative to our perception of the movement of the motors was chosen for the sawtooth so that the motion of the motor would appear smooth. This is because the dc motor is basically a low pass filter of this driving square wave. We see less ripple at higher frequencies.

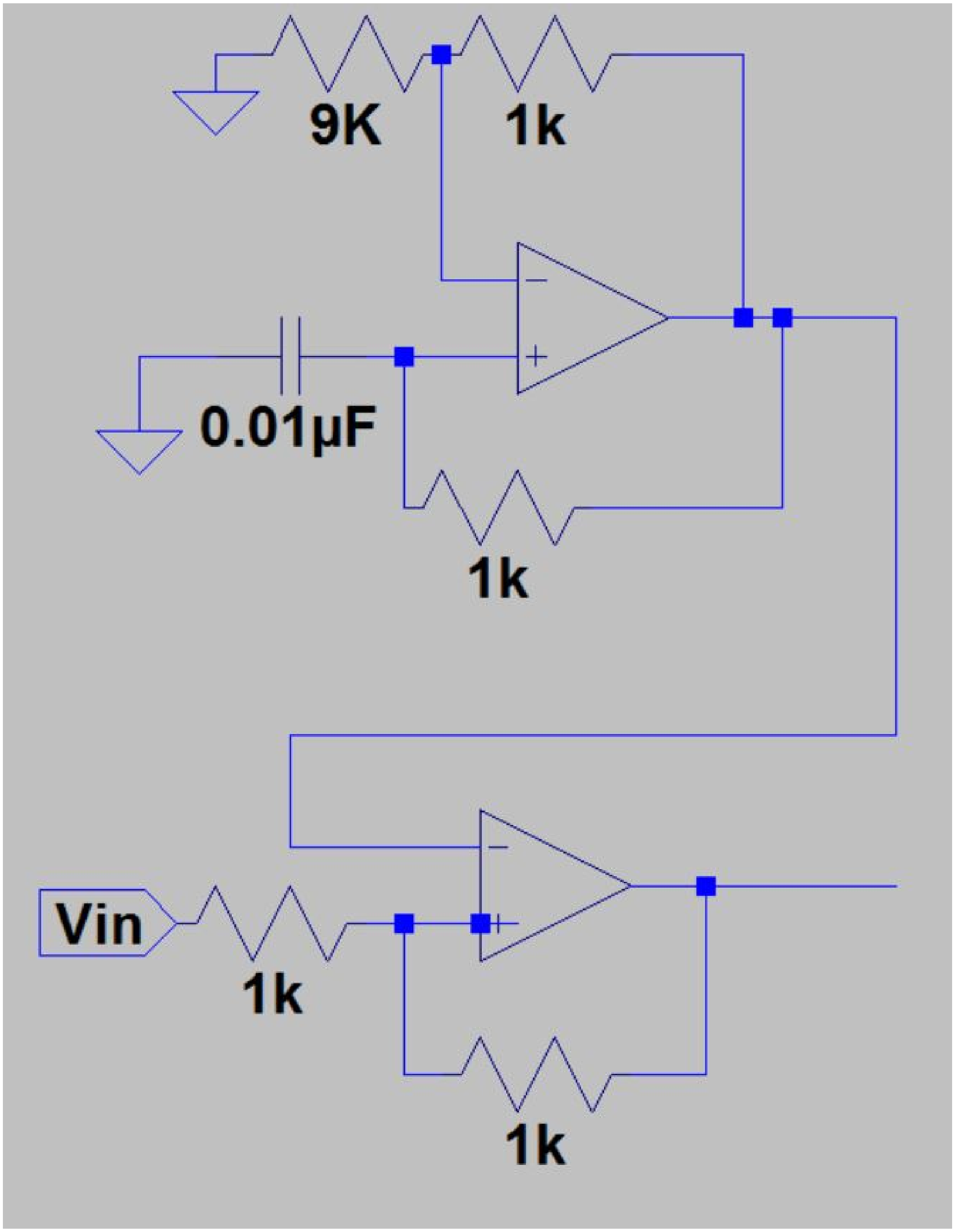


Figure 11: Voltage to Duty Cycle

#### 4.3.6 Motor Driver

We could have purchased a motor driver IC, but opted to build the circuitry ourselves to learn about the specific design challenges of driving motors. An inverter chip was used to generate timing delays. This chip took a 5 volt supply. We provided 5 volts with a linear regulator, but a better long term design for a battery powered device would use a switching power supply to obtain higher efficiency.

**Delay and Switching Signal Generator** A delay is used to have a brief period when all the mosfets on the H-bidge are off as they switch. This is needed to avoid shoot through. The rc circuit with the signal diode sandwiched between two inverters adds a delay in the order of nano seconds (Figure 12). The signal diode determines whether the delay is on the rising or falling edge of the square wave. Two signals are created one with the delay on the rising edge and one on the falling edge. The inverse of these signals is also taken. The signals with the delay added to the low portion of the signal are sent to the n-channel mosfets, as these mosfets turn off when the signal is low. The signals with the delay on the high portion of the signal are sent to the p-channel mosfets as these mosfets turn off when the signal is high.

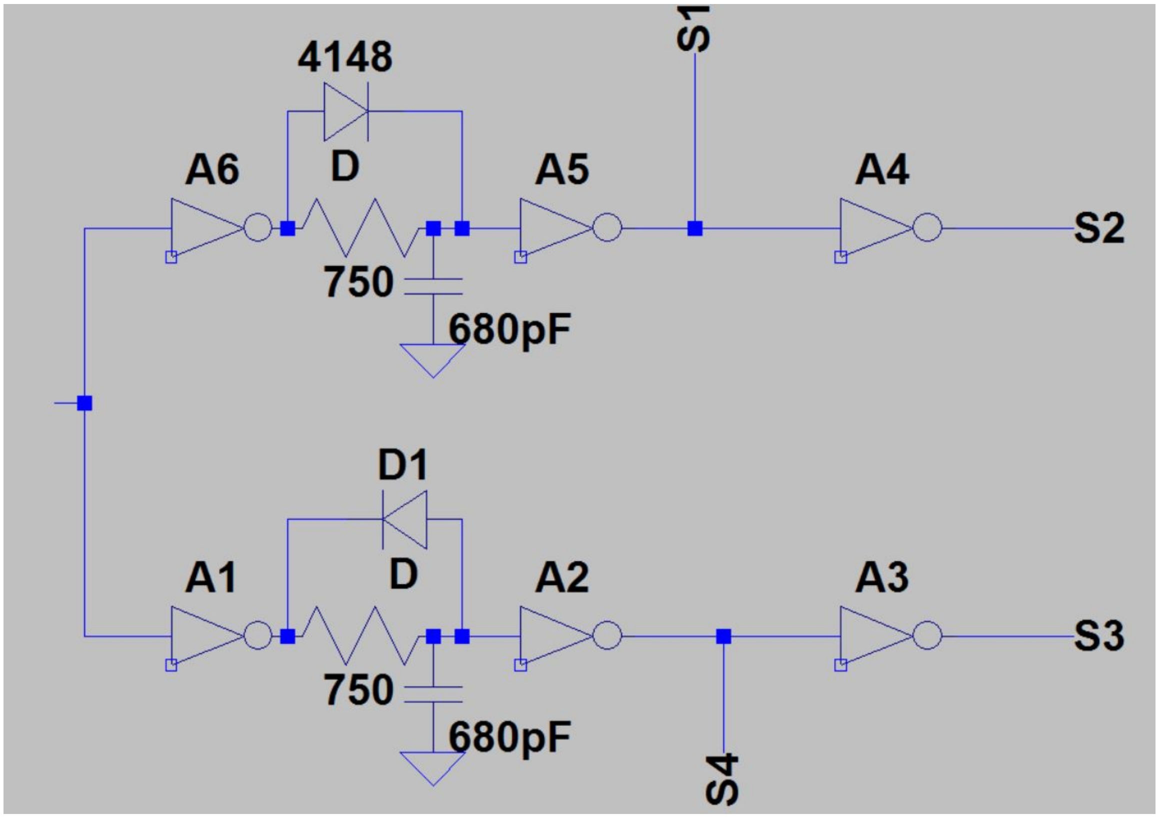


Figure 12: Timing Delays

**H-Bridge and Motor** The design of our H-bridge is standard. However one of the p-channel mosfets is connected not to Vcc but to the Vcc through the switch controlled by the distance sensor (Figure 13). This is so that the forward direction of current can be turned off when you reach a wall. Anti phase lock drive is used to drive the motor (switching between forward and reverse current).

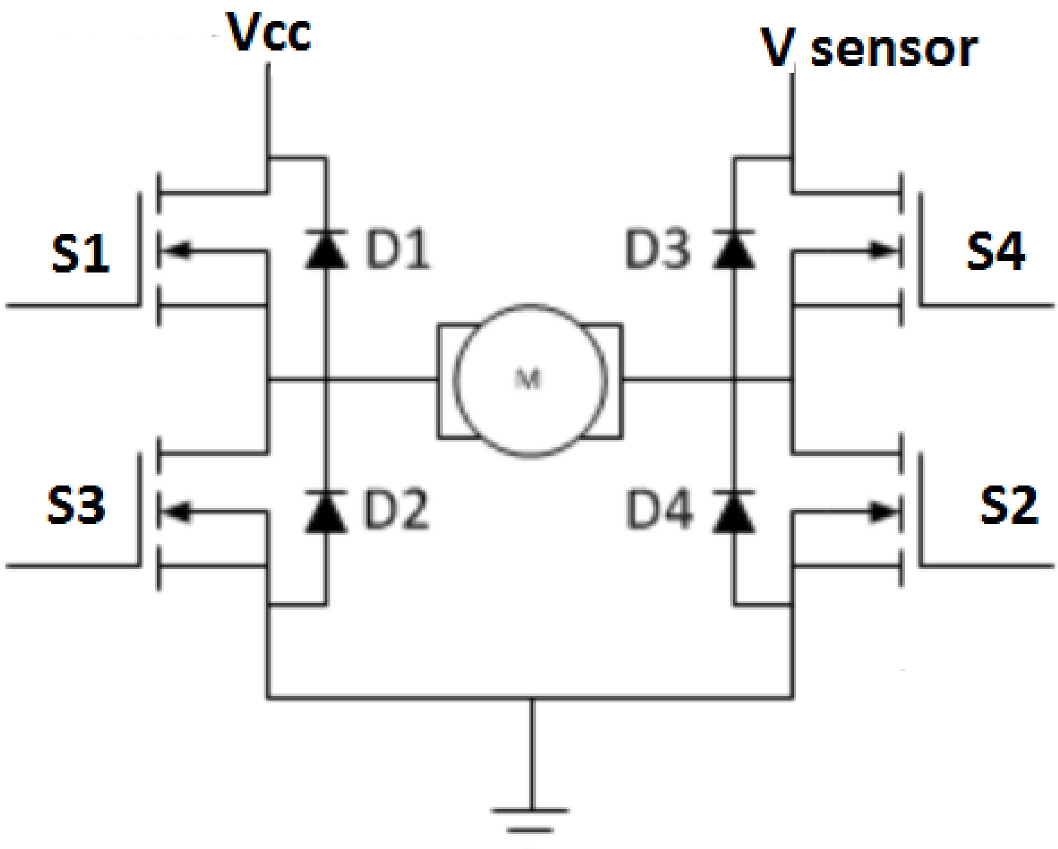


Figure 13: H-bridge

### 4.4 Mechanical Design of the Car

Two low power high torque dc motors with attached gearbox and D shafts were mounted on an aluminum plate. The body of the car consisted of three connected breadboards for the car's circuitry. The motor plate was fixed to the bottom of the breadboards with velcro for easy removal when working on the circuit. A sliding contact was also attached with velcro at the front center of the car. The contact was cut from acrylic. Wheels for the two motors were also cut from acrylic with axles holes to mount on the d-shafts as a press fit. A rubber band was glued to the outside of the wheels for traction. During operation of the vehicle a weight was placed on the car between the wheels to increase their traction with the ground.

## 4.5 Direction Indicator

LEDs were also added to indicate when the car was turning. The voltage levels for both the left and right frequency-to-voltage converters were buffered and sent through a differential amplifier with a gain of 2 (Figure 14). This difference could then be compared to a certain threshold in order to provide a voltage output to light an LED if the difference was sufficiently low (turning left) or sufficiently high (turning right). By using this difference method, the LEDs are still able to indicate turning even if both wheels are moving forward, or if the wheels are moving backwards but the face of the car is still significantly turning.

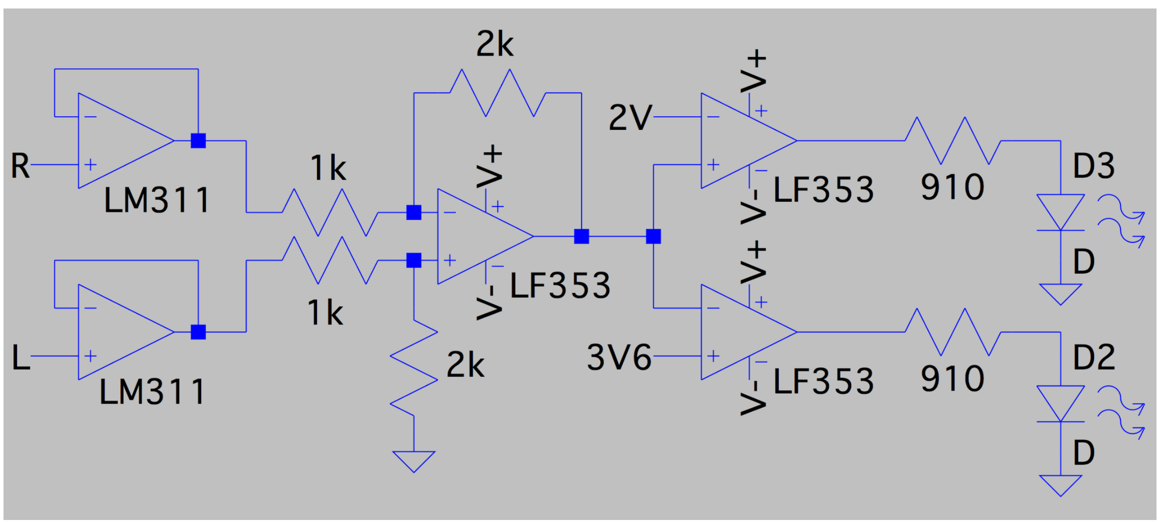


Figure 14: LED Schematic To Indicate Turning

## 4.6 Collision Control

A light sensor requiring a 5V input is used to determine how close the car is to an obstacle. Since only 9V batteries are used, the 5V is gotten by using a linear regulator (7805). This light sensor can be modeled as a light dependent resistor. Hence when exposed to light, its output voltage is low and when blocked, its output voltage increases. connected via a voltage follower to separate it from the rest of the circuit is connected to an op-amp used as a comparator. The sensor is connected to the negative input of the comparator so that when it is high, it drags the output of the comparator to the negative rail hence turning on the p-channel mosfet. (Figure 15) This mosfet is then used to power the motor's forward direction source. Therefore preventing the motor from moving forward when an object is placed in front of it. The positive input of the op-amp by design has a pot controlling the threshold (V threshold) because it enables the user to control how close the car has to be in order to stop. The present value is placed at 2.2V and causes the car to stop when an object is about 5cm in front of it. The light sensor's voltage varies from 0.1V, exposed to light, to 3.8V when closed. Unlike a photo resistor however, if you completely close the light sensor, it registers a very low voltage hence using the data-sheet adds value.

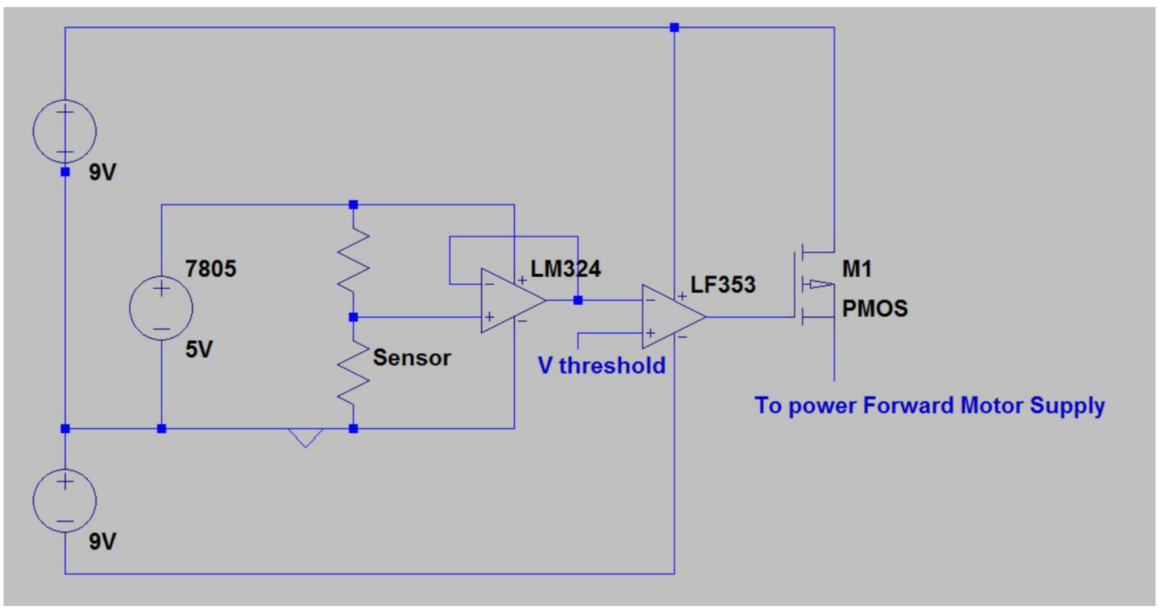


Figure 15: Collision Control Schematic

# 5 Testing

First to verify if the concept will work, the motors are tested with a PWM signal to ensure that they can work at variable speeds.

The modular nature of the project makes it possible to build components independent of input from other parts of the RC car. Hence allowing all members of the team to work independently and combine parts later on.

At the controller, the output of each phase shift oscillator is tested to ensure it is at the required frequency. Then, the superimposed wave is feed into the oscilloscope and using the oscilloscope's low pass filter and high pass filter functions, the wave form is verified to be of the required voltage and frequency.

The communication medium is tested using a sine wave from the signal generator. The input and output are probed to verify that the integrity of the signal is maintained. Hence input is the same as the output.

The frequency to voltage converter is tested using a square wave from the function generator set to be at the frequency expected from the controller.

# 6 Design Analysis

An analysis of the final version of the RC car provides great insight into how and why certain analog circuits were used. Several design choices provided for a robust car, while others set limits on the cars capabilities.

Using a fiber optic cable as opposed to RF communication provided a much more reliable communication method. Because the power of EM waves falls off proportional to 1/distance$^2$, very powerful signals would need to be transmitted or very low noise circuitry would need to be used at the receiver to extract the signal. Standard commercial toy RC car manufacturers typically use AM or FM communication through carefully designed PCBs and crystal oscillators. FM is sometimes preferred because it is less susceptible to glitches (interference) in urban areas, but both are acceptable for low-cost toy cars. Our design therefore uses an unconventional communication method to overcome the use of PCBs and crystal oscillators. This design choice does provide uses for other types of remote controlled vehicles. For example, had the project been to design a remote controlled submarine for deep sea research purposes, RF communication would not have been an option, as RF communication can only reach a few feet underwater.[1] Fiber optic cables, however, would have been a very reliable option.

One limitation of our implementation of the fiber optic cable was that instead of using a current source to control the LED in the fiber optic cable transmitter, we simply used a resistor in series with the LED and estimated current by assuming a 0.7V drop across the diode. In order to use this method, we needed to test which input voltages performed approximately linearly with the LED before it began to rail. The superimposed sine wave signals from the control were attenuated just enough to cause it to fit well in this region. This meant that if we wanted to add a third signal or implement the controller as FM or AM channels, the gains of the attenuating op-amp would need to be changed. This would have been less of a problem had a current source been used, as the input voltage could have been a much larger voltage range than what was used (approximately 1.2V to 3.0V).

Another limitation of our design was the nonlinear behavior of the sine wave generators in the controller. Because frequency was changed by changing the impedance of one of the resistors, the amplitude inevitably increased with increasing frequency. As a result, the frequency to voltage converters in the car circuitry would not perform linearly with frequency. In order to overcome this obstacle, the sine wave was converted to a square wave railing from 0V to 5V with a 50Also regarding the frequency to voltage converter, the output voltages for the two frequency ranges also were not equal. As a result, the maximum and minimum speeds for the two wheels were not equal. This could have been addressed by adding a non-inverting op-amp to the output of the lower voltage frequency-to-voltage converter. The problem in general could have been avoided by using the original design, which was to have one potentiometer control direction and the other speed. However, the largest advantage of using each potentiometer to control each wheel was that the delay circuit to protect the MOSFETs became much simpler and fewer logic chips were needed to control each H-bridge. Overall, the design provided a functional product with reliable performance. While it had several areas in which it could improve to create a more robust design, it explored new areas of communication and control.

# 7 Lessons Learned

The project changed quite a bit from the first planning phase to the final product. A lot was learned in terms of how to design, build, and test a product. Each process gave insight into what makes a good electronic design. For example, the initial design phase was excellent in building an understanding of how certain analog circuits work, while the building phase showed what physical consequences of certain circuits exist that are not modeled in design software or hand calculations (e.g. parasitics). Lastly, testing the finished product demonstrated what modules work well and what can be improved or restructured for future iterations.

In this particular RC car design, one important lesson was that modules should be built to create a robust design. In case one module does not function properly, there should be alternative methods available to still create a functioning product. For example, although RF communication did not end up working, a fiber optic cable was still able to be used to connect the controller circuitry to the motor circuitry. Planning ahead of time what alternatives were available for each module saved a lot of wasted time and worry when certain modules did not function as expected.

Another important lesson was that physical imperfections that are not modeled in hand calculations or SPICE software are very real characteristics of circuits that must be expected, especially for analog circuitry. For RF communication, parasitic capacitances and inductances severely limited the capabilities of using an LC tank to create a high carrier frequency. For the AM transmission circuit design, if the signal+ and signal- signals were not exactly 180 degrees out of phase, the demodulated signal at the car would be unusable. In theory and in SPICE, this circuit worked very well. However, physical delays and imprecise gains led to the AM transmission circuit being unusable. Similarly, timing issues presented a need for delay circuitry in the H-bridge motor controllers to protect the MOSFETs.

Other important takeaways were how some simple concepts can be enormously useful. The biggest was how frequency domain information stored as simple sine waves can be used in terms of information transfer. By storing speed information in terms of frequency, control commands could be transmitted over RF or fiber optic communication media to create a functional product.

# 8 Conclusion

After several weeks of designing, developing and testing the RC car, a functional product with direction and speed control through modern optical technology was built. The project offered insight into how analog circuity can be implemented to power a complex mechanical system, such as the motors of a car. The process underwent several phases of design: the hand calculation and SPICE design, the physical testing of different modules, the modification of existing modules after testing, and the cohesion of all modules together to form a final project. As a result of the effort put into the product, a fully functional RC car implemented through analog circuitry using basic parts was created.

# 9 Acknowledgments

We would like to thank Gim Hom, the course instructor for having tailored this class over the years. The structure of the course prepared us to take on the final project. The use of sine-wave generators in earlier labs and most of the components used during labs was critical for the final project. Also, the problem sets aimed at improving design thinking and this helped when designing the car's controls

A big thanks to the teaching assistant Elliot and lab assistants Alex, Jason and Yanni. Their help during labs especially in debugging and sharing of their experiences was invaluable and enriching to our overall learning experience. We would like to thank the CIM instructors, in particular, Mary Caulfield for her guidance in adding structure to our report. Finally we would like to thank all the other students in 6.101 for their contribution as we learned together throughout the semester

# 10 Figure Credits

[1] Circuits Today (2012). textitSimple FM Transmitter Circuit [Online]. Available FTP: circuitstodays.com Directory: simple-fm-transmitter-circuit

[2] Homemade Circuits (2013). *Make This Simple FM Radio Circuit Using A Single Transistor* [Online]. Available FTP: homemade-circuits.com Directory: 2013/10/make-this-simple-fm-radio-circuit-using

## 11 Works Cited

[1] PhysLink: Physics and Astronomy Online (2016). *Why isnt radar used underwater?* [Online] Available FTP: physlink.com Directory: Education/AskExperts/ae456