

design document for

Optical Bass Guitar Pickup

submitted to:

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EXECUTIVE SUMMARY

Early string instruments that resemble the guitar we know today have been dated back to 4000 years ago. The shape was modified through trial and error to obtain a pleasing response from the resonate cavity. George Beauchamp designed the first magnetic guitar pickup in 1928. Since his breakthrough design, several variations have been made. These include humbuckers, passive, active, and hybrid pickups. Despite their wide market acceptance, magnetic pickups have inherent flaws. Magnets are highly susceptible to electromagnetic interference. Using them in musical applications leads to excess noise. String motion is dampened by the magnetic field causing a decrease in the resonance time. The vibration of one string may influence adjacent pickups, called cross talk interference. Sales of magnetic pickups, however, are not hindered by their flaws. The goal of this design is to make an infrared system that produces an accurate, low-noise signal that is representative of the string motion.

Design constraints must be followed in order to provide an acceptable product to the music community. A high signal to noise ratio of 80dB must be achieved to deliver a clean sound to the amplifier. Dynamic range defines the range between the lowest and highest signals that can be produced without distortion. The optics are responsive to string displacement, therefore, the lower strings will produce a louder sound. To avoid sounding too bass heavy, the output must have equal loudness for all frequencies. An output signal of 100mV is determined by instrument cable industry standards. The optical pickup will require a power source, classifying them as "active" pickups. A noninvasive power supply will allow play with or without an AC adapter. While the electronics will be housed inside the guitar, the optics must be exposed to the elements. Some protection is necessary to keep the optics out of the musician's way. Vibrations from the guitar body can affect the optics if they are not mounted properly.

Optical pickups transmit an infrared beam across each string onto a photo-detector. The string's vibration perpendicular to the detector surface modulates the uniform infrared intensity delivered to the detector. A surface mount planer photo diode provides a large detectable surface area at a small size. The pickups must be placed close to the bridge to avoid nonlinear signal response due to the high displacements seen towards the middle of the string. Placing the pickup close to the bridge avoids harmonic nodes for maximum harmonic response. The placement also keeps the pickup out of the guitarist's way. Since the lower strings have a greater cross sectional area, they will have a greater response from the optical system. Each transmitter and receiver pair will be individually biased to produce uniform sound quality across all frequencies. The four signals will be added together and amplified to 100 mV before being sent to an existing amplifier. The use of opamps in the design requires a bipolar power supply. Power will be sent to the ground conductor and another unused conductor of a stereo instrument cable. A coupling device will be designed that allows for the guitar signal to pass through to the amplifier, while the power is being delivered down the same cable.

Optical pickups are currently offered with the purchase of new guitars. Making our design retrofittable to certain guitar models will make it easier for the musician to install new optical pickups onto an existing guitar. Utilizing the instrument cable to deliver power and the guitar signal is a novel approach. While it could be more convenient to not have an extra power cable connected to the guitar, the musician may find a hindrance in being required to use a stereo instrument cable. The output signal will be an accurate representation of the string motion and will not deliver the distortion inherent to magnetic pickups. The musician's acceptance of a clearer sound will determine the success of this product.

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1. PROBLEM

Early string instruments that resemble the guitar we know today have been dated back to 4000 years ago. Historically, the guitar cannot be traced back further than the 15th Century when a small version was created in Spain [1]. The shape was modified through trial and error to obtain a pleasing response from the resonate cavity. The guitar's popularity has fluctuated over time since its incarnation. The desire for a louder guitar drove the development of the electric guitar. In order to have an electric guitar, there had to be a means to 'pick up' the guitar string's vibration to produce an electrical signal. George Beauchamp designed the first magnetic guitar pickup in 1928. Since his breakthrough design, several types have been created to give a greater sound quality. These include humbuckers, passive, active, and hybrid pickups. Magnetic pickups involve the use of permanent magnets to create an electromagnetic field. When the strings are plucked, the vibration of the ferro-magnetic strings changes the magnetic field, which induces a current in the coil of wire surrounding the magnet. The electrical signal from the coil is sent to an amplifier.

Although there are variations, magnetic pickups are widely accepted as the industry standard of signal generation of electric guitars. Musicians desire a high fidelity sound with maximum dynamic range, high signal to noise ratio, increased resonance, and proper harmonic response. Problems with magnetic coils include false harmonics, acoustic feedback, and excess noise. These problems occur because several different factors can interfere with the magnetic field including household electrical wiring, the placement of the pickup, the vibration from other strings, and the number of wire turns in the coils. The string type is limited to ferrous strings when using a magnetic pickup. The string's vibration is influenced by the magnet, causing a misrepresentation of the sought after string motion. Unlike magnetic pickups, optical pickups can provide all of the desired features. Optical pickups transmit an infrared beam across each string onto a photo-detector. The string's vibration through the uniform infrared beam modulates the infrared intensity sent to the detector. An optical guitar pickup detects the string's displacement rather than its velocity, as practiced by magnetic pickups. Since the lower strings have a greater cross sectional area, they will have a greater response. Each string will be surrounded by a transmitter and receiver, which will be individually biased to produce uniform sound quality. Eliminating the magnets from the design has its benefits. Optical devices eliminate 60-Hz interference, which is common with magnetic pickups. This type of pickup gives musicians the option of using nylon or other non-ferrous strings. Interference from external lighting sources can occur, but with proper light shielding the effect will be minimal.

Our pickup will retrofit to any model of guitar and will use a power supply. This would make our product the only active guitar pickup with a power supply on the market. One major competitor, Light-wave Systems, markets their product to guitar manufacturers and does not sell units that can easily be adapted to any guitar. They also use a rechargeable battery to power their optical pickups. Our pickup would be the only one of its kind on the market. The finished product will have a 'clip-on' style with unit models manufactured to fit various types of bass guitars. For example, we could have a model that will fit on certain Fender guitars and another model that will fit on Les Paul and Epiphone guitars. The power supply will be a convenience to musicians. A stereo cable connecting the guitar and the amplifier will be connected to the power supply, which will be connected to the amplifier as well. This allows both AC and DC signals to flow through the same instrument cable. Being the only product of this type on the market would be a considerable advantage.

The creation of a relatively inexpensive optical bass guitar pickup will give musicians an advantage. The optical pickup provides optimal sound clarity by reproducing the string's true

harmonic and the instrument's natural acoustics without interference. A musician can choose to use non-ferrous strings for new and exciting tones. The sensitivity of the optical pickup allows extremely low frequencies to be heard, unlike magnetic pickups.

2. DESIGN REQUIREMENTS

For electric bass guitars, the caliber of sound stems from the device used to pick up the strings' vibration. Two critical factors that influence general pickup design include the spacing between strings and the distance from the pickup to the bridge. Some factors specific to an infrared-based design are the amount of power delivered to the LED's, signal processing circuits, and interference from outside light sources. The optical pickup must work under any condition, and must be adaptable to any bass guitar model. The device cannot move from its original alignment under any circumstances. Also, the optical pickup should be adjustable to any string size and capable of a better sound quality than previous designs.

2.1. Technical Design Constraints

Five technical design constraints must be addressed for the construction of the optical pickup. Table 1 lists the technical design constraints required to meet industry standards and a musician's preferences.

Name	Description
Voltage	The output voltage of the rms signal will be 100 mV.
Power	The LED will be driven between 30-40 mA for maximum power.
Operational Behavior	The pickup placement will be experimentally determined depending on the operational behavior.
Signal-to-Noise Ratio	A signal-to-noise ratio of 80 dB or greater will be achieved.
Transmitter-Receiver Placement	The transmitter and receiver will be placed $\frac{3}{4}$ " from each other.

Table 1. Technical design constraints for the optical pickup.

2.1.1. Voltage

The output signal of the bass guitar must be a signal of 100 mV rms in order to meet industry standards [2]. Regardless of the type of active pickup used, all guitars must output a signal of 100 mV rms for compatibility with audio amplifiers. This output will be generated from the receiver circuit that will convert a current source to a voltage source.

2.1.2. Power

The power supplied to the LED must be enough to ensure that the amount of infrared light received is far greater than any other light source. The pickup will be powered from a wall outlet that will give a total of 120 Vac. In order to achieve maximum power, the LED must be driven between 30-40 mA [2]. After this current is transmitted through the receiver circuit, a voltage of 100 mV rms will be obtained and sent to the amplifier.

2.1.3. Operational Behavior

Table 2 lists a range of frequencies most likely to be detected on each string. If noise exists in the signal outside of these frequencies, then a filter will have to be designed to remove it. Optimally, the transducer will only detect the string's movement and not receive any outside interference that will cause this kind of noise.

String	Low frequency cut-off (Hz)	High frequency cut-off (kHz)
1 st (E string)	20	15
2 nd (A string)	33	15
3 rd (D string)	43	15
4 th (G string)	58	15

Table 2. Range of detected frequencies for each guitar string.

2.1.4. Signal-to-Noise Ratio

The optical pickup measures the string's displacement based on the amount of light intensity detected by the photo-diode receiver. Each string contains a signal-processing unit that is biased based on its photo-diode signal to ensure the highest signal-to-noise ratio and to ensure a suitable dynamic range (no clipping). To achieve optimal sound quality, a signal-to-noise ratio of at least 80 dB, the standard ratio of a good signal, is required.

2.1.5. Transmitter/ Receiver Placement

The alignment of the transmitter and the receiver is one of the most crucial elements of this design. The receiver must fit between the body of the guitar and the string, while allowing room for string vibration. The transmitter has to be placed so that there is a gradient of light on the detector. The distance of the pair from the bridge must be determined to achieve the best possible dynamic range of the received signal.

2.2. Practical Design Constraints

The physical design constraints include the cost of components, size of the unit, and proper interfacing with amplifiers and other guitar electronics.

Constraint Type	Name	Description
Economic	Cost	The estimated production price for the pickup is \$50.
Durability	Physicality	The optical design will contain a metal plate that will be able to withstand outside disturbance without harming the receiver.
Manufacturability	Size	The physical dimension will be $3\frac{5}{16}$ " x $2\frac{11}{16}$ " x 1".
Health and Safety	Safety	The optical pickup should not pose any safety issues if used correctly.

Table 3. Practical design constraints for the optical pickup.

2.2.1. Economic

An important feature of our optical bass guitar pickup is its affordable price. Our objective is to create a product that will output a better quality of sound at a more reasonable price than current optical pickups. The estimated production price for this device is \$50.00 and the estimated sale price is \$200.00. The sale price was formulated based on the uniqueness and scarcity of the optical pickup.

2.2.2. Durability

The power supply and a metal enclosure will help sustain the reliability of the optical pickup. Because the power supply ensures a constant DC voltage source, constant draining and charging of a battery is eliminated. For protection, the optical pickup will have a metal enclosure to guarantee that the product will not be damaged during use. This protector will also ensure that no ambient light will interfere with the transmitter and receiver pairs. With proper usage, the optical pickup should last a lifetime

2.2.3. Manufacturability

The distance between the first and second strings ('E' and 'A') is $1 \frac{1}{32}$ " , but the distance between all other strings is 1 inch. The distance influences the alignment of the transmitter/receiver pairs, which affects the clarity, dynamic range, and harmonic response. The optical pickup will have dimensions of $3 \frac{5}{16}$ " x $2 \frac{11}{16}$ " x 1". This size allows the musician to retrofit the optical pickup to their bass guitar with the proper alignment and distance of the transmitter/receiver pairs.

2.2.4. Health and Safety

Some components of the device may be hazardous if exposed or used improperly. For consumer protection, the optical pickup will have a National Electric Manufacturers Association (NEMA) 1 standard, which ensures that debris will not come in contact with the components of the optical pickup. This standard also ensures that consumers do not come in contact with electronic components.

3. APPROACH

3.1. Hardware Design

Hardware design considerations encompass the transducer, amplifier, and tonal control circuitry. Successful completion of this project requires the production of an electrical signal that accurately represents the mechanical energy of a vibrating bass guitar string. Transducers commonly used for this task come in the form of the magnetic pickup. Given the drawbacks associated with electromagnetic detection, another means has been investigated and deemed appropriate. Our design relies on an infrared transmitter and receiver pair to provide an electrical signal from the string's displacement. Accurate detection provides clean inputs to the signal processing stage of the hardware design. Primary concerns addressed with signal processing include: compensation for the amplitude difference between the responses of each string, user volume control, and tone control. The block diagram shown in figure 1 illustrates the various hardware components necessary for an optical pickup system.

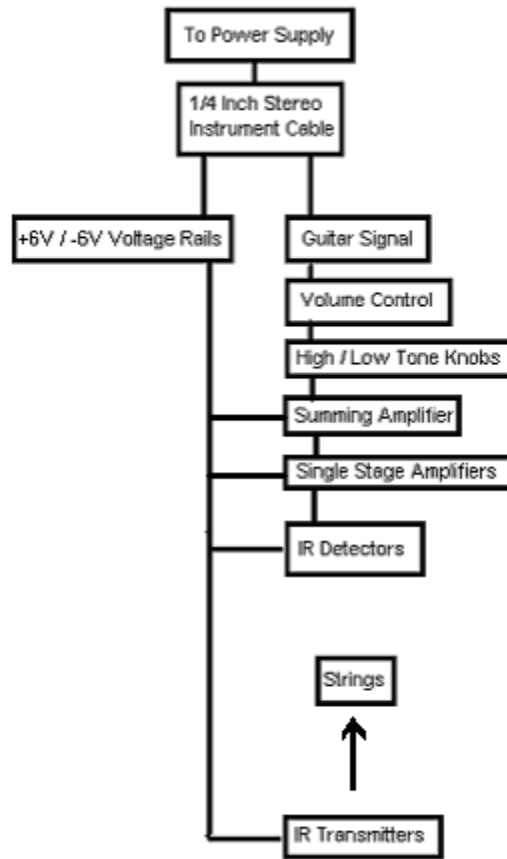


Figure 1. Hardware block diagram of the transducer and signal processing circuitry.

3.1.1. Bipolar Power Supply

In order to allow a single output signal from the guitar, the signals of all the strings must be combined. This is accomplished by designing a summing amplifier using an opamp. Since the opamp requires voltage rails, a bipolar power supply is absolutely necessary. A unipolar power supply would be sufficient for this design if a transistor design for the summing amplifier were used instead. Since the components of a transistor design are too large and more costly, an opamp with a bipolar power supply is more practical. Table 1 indicates the advantages and disadvantages of the unipolar versus bipolar power supply.

Unipolar	Bipolar
<ul style="list-style-type: none"> • Accepts any 1/4" mono cable • Requires transistor design 	<ul style="list-style-type: none"> • Requires stereo cable • Allows opamp design option • Consumer inconvenience

Table 2. Advantages and disadvantages of power supplies.

The design of the power supply is based upon the load constraints which includes $\leq \pm 6V$ for the opamp and the transmitter/receiver pairs. Figure 2 shows the schematic of the bipolar power supply.

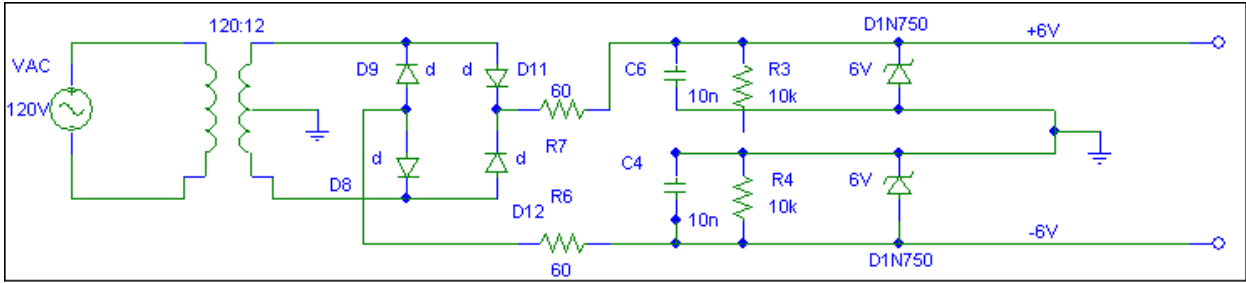


Figure 2. Bipolar power supply schematic.

3.1.1.1. Center-Tap Transformer

In order to obtain the positive and negative rails of the bipolar power supply, a center-tap transformer is necessary. The basic design of the center-tap transformer include a primary side, which inputs an AC voltage source, and a secondary side, which outputs an AC voltage source grounded at the center. The center-tap allows a positive and negative voltage source to be obtained, thus providing usage for an opamp. The transformer allows a 120 VAC input source on the primary side to be electrically isolated from the 12.6 VAC output source on the secondary side. The center-tap splits the secondary winding to allow $\pm 6V$ for the voltage rails. The power rating of the transformer depends on the current per half cycle produced by a half winding on the secondary side [4].

3.1.1.2. Full Wave Bridge Rectifier

The full wave bridge rectifier utilizes the positive and negative cycle of the AC sine wave, unlike a simple full wave center-tap rectifier that utilizes only the positive half cycle. Although the full wave center-tap is more efficient, the full wave bridge rectifier allows the use of a smaller transformer at a more efficient rating [5]. The full wave bridge rectifier is thus necessary for the bipolar power supply.

The full wave bridge rectifier uses four diodes to prepare a positive and negative input AC signal to be transformed into a positive and negative output DC signal. The packaged full wave bridge rectifier used in this design has a rating of 4 amps and 50 volts since the filter design draws heavy surge current [4]. The packaged bridge rectifier is also less costly than four separately purchased diodes. Figure 3 shows the output waveform of the positive and negative half cycle of the AC signal [6].

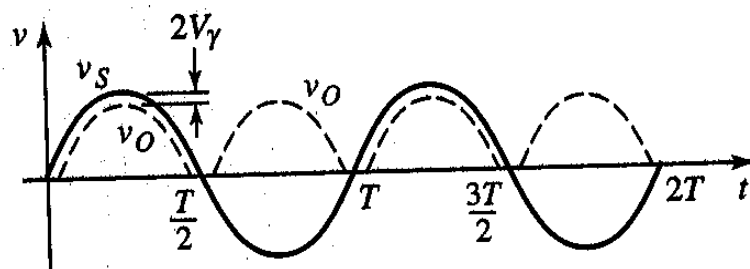


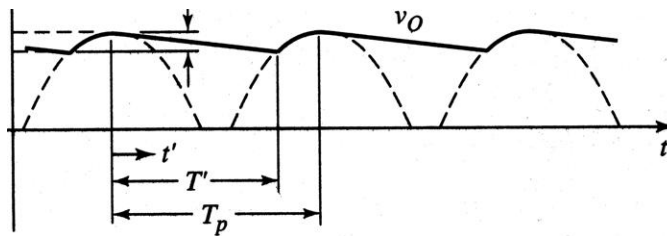
Figure 3. Waveform of output and input voltages of the bridge rectifier.

3.1.1.3. RC Filter

The filter design of the power supply is an RC filter. The capacitor is used to filter out a large portion of the sinusoidal signal produced from the AC source. The capacitor value is chosen according to the amount of ripple voltage that is desired in the circuit. The ripple voltage is defined as V_r and the peak output voltage is V_m . Since we desire a small ripple such as 0.2, the capacitor value can be adjusted as follows [6]:

$$C = \frac{V_M}{2fRV_r} \quad (1)$$

The capacitor charges to its peak voltage and then discharges through the resistor. As shown in figure 4, this discharge is shown in the straight line slope from the sinusoidal signal [6]. This voltage discharge is restored through the diode current. The resistor value is defined as the output resistance, which is chosen by the desired output current.



Output voltage of a full-wave rectifier with an RC filter

Figure 4. Output voltage of the RC filter.

3.1.1.4. Voltage Regulation

In order to obtain a regulated DC voltage output following the low pass filter, a voltage regulator is necessary. Either a shunt regulator or a linear regulator can be used for this design. Table 2 indicates the uses of a shunt regulator and linear regulator [4].

Linear Regulation	Shunt Regulation
<ul style="list-style-type: none"> • Varying loads • High output applications 	<ul style="list-style-type: none"> • Maintains constant loads • Not practical for voltage changes • Inexpensive

Table 2. Linear regulation vs. shunt regulation.

The shunt regulator was chosen for this design instead of a linear regulator because of its practicality in using just a zener diode. In order to regulate the voltage, a rated zener diode of 6.2 volts was chosen. The series resistance (R_s) for the zener diode was calculated using the following formula [7]:

$$R_{series} = \frac{(V_{out} - V_{zener})}{I_{zener}} = \frac{7.4 - 6.2}{20mA} = 60\Omega \quad (2)$$

V_{out} is determined to be the voltage from the secondary side of the transformer, V_{zener} is the rated value of the zener diode, and I_{zener} is the rated value of the zener diode. The power rating of the series resistance is $\frac{1}{4}$ watt.

Future power supply upgrades will include a linear regulator that will eliminate the ripple voltage that is in the shunt regulator. The ripple voltage obtained in the shunt is about 0.48, which is slightly higher than what is required for this design. Therefore, the linear regulator will be an integral part in making the bipolar power supply design more efficient.

3.1.1.5. I/O Cables

The guitarist typically uses a 1/4" mono cable to connect directly from the guitar to the amplifier. For the inclusion of the power supply and the power coupler, one 1/4" stereo cable will be needed to connect the power coupler to the guitar and one 1/4" mono cable to connect the power coupler to the amplifier. Figure 5 displays the connection of the power supply to the guitar.

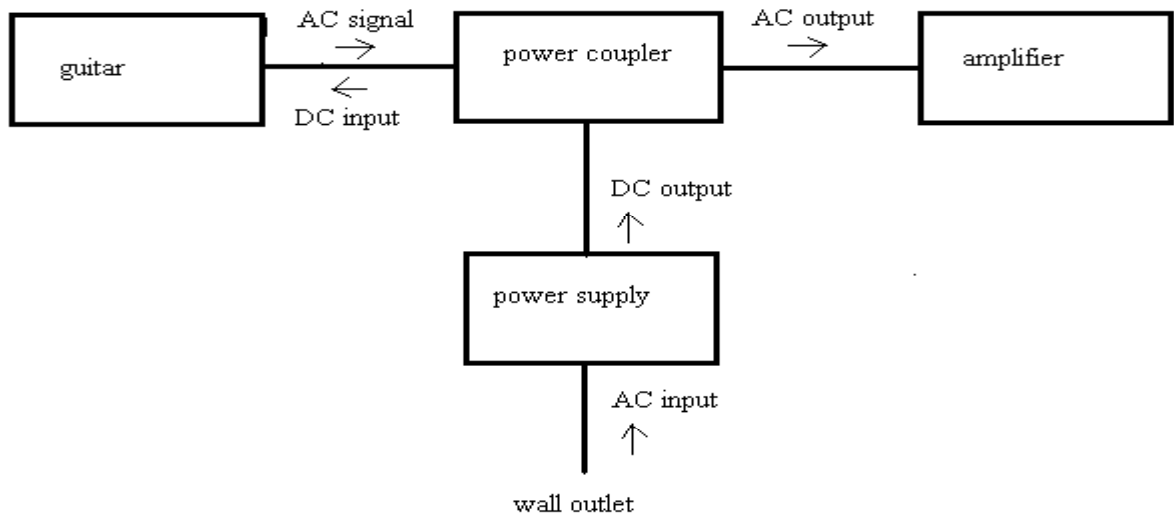


Figure 5. Block diagram of I/O cables.

3.1.2. Power Coupler

Frequent battery changes plague the users of active guitar pickups. A goal of this project is to eliminate these battery replacements. We will provide bipolar power to the guitars internal electronics using the required 1/4" inch instrument cable. A mono cable is standardly used to connect guitars to their amp, but two conductors will not be enough to provide power and signal. The ideal cable would contain four conductors: one each for the positive and negative DC supply, one for the guitars output signal, and one as a ground. Stereo cables have three conductors, which will allow one conductor to carry both the AC signal and one of the DC voltage rails. Output signals are capacitively-coupled to the positive DC rail. Linear regulation makes sure that the DC supply is free of the added guitar signal before powering the guitar's circuitry. This output coupling and linear regulation will take place in the guitar. Further capacitive coupling prevents the DC from entering the external amplifier input. This final coupling as well the connections to the bipolar power supply is housed in the power coupler.

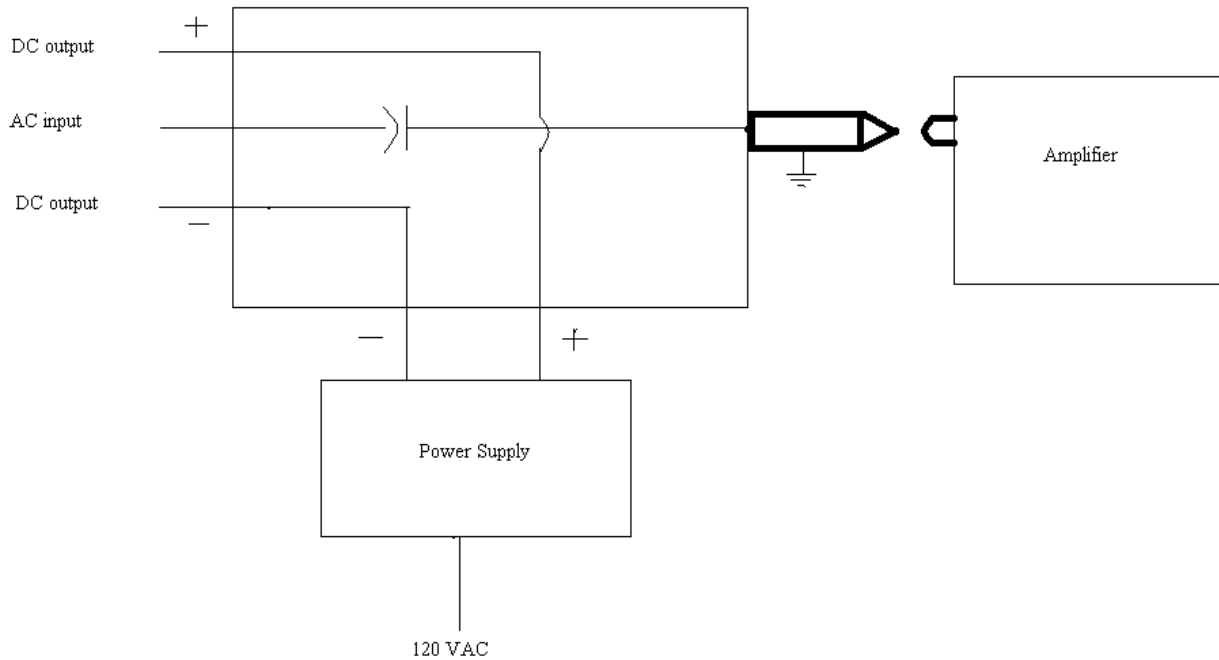


Figure 6. Block diagram of power coupler.

3.1.4. Transducer

A transducer is defined as any device that converts one form of energy into another. Transducers serve many functions in our everyday lives. Microphones create an electrical signal from the movement of a diaphragm under the influence of sound waves. The diaphragm is a transducer; converting sound waves into mechanical vibrations. The electronics within the microphone serve as another transducer, converting the mechanical vibrations into an electrical signal. Sensors that deliver an electrical signal based on detected temperature, pressure, humidity or other environmental factors are widely used in robotics, the automotive industry and industrial automation. These sensors are integral in providing control systems with the data needed to effectively monitor the overall system performance [8].

Magnetic pickups are widely accepted as the premiere form of transduction for electric guitars. Magnetic pickups consist of a permanent magnet creating an electromagnetic field surrounding a small section of string and coils of wire. The magnet is wrapped with wire so an induced current will be present when the magnetic field is disturbed. At rest, the flux through the magnet is constant. When the strings are plucked, the vibration of ferro-magnetic strings disrupts the magnetic field lines creating an alternating flux through the magnet. The coil delivers the oscillating current indicative of the string motion. Amplitude of the electrical signal is proportional to the velocity of the string through the magnetic field. Other factors influencing magnetic pickup response include: string thickness, magnetic permeability, strength of the magnetic field, and displacement between the magnetic pole and the string.

Since George Beauchamp's breakthrough single-coil passive pickup design, several alterations have been created to deliver varied sounds. These pickup types include active, humbucker, and hybrid pickups. Since early amplification relied on vacuum tubes, greater signals from the passive pickup were necessary to deliver the desired output. Compromises between quality and sensitivity were soon realized. Placing the magnets closer to the string or using stronger magnets

increases the output at a cost. String vibration is dampened by the magnetic attraction between the string and the pickup. Typically, magnetic pickups decrease the length of note sustenance by this inherent physical quality. Using too strong of a magnet can create false harmonics or double notes. Additional windings of the coil wire also give an increase in the output. Excess windings increase the pickup's impedance, posing problems with treble loss through long cables. Similar compromises are made when selecting the coil wire gauge. Active pickups typically have a lower number of coil windings, delivering a small signal with low impedance. The small signal is amplified by an on-board active preamp while maintaining the low impedance. Long cables can be driven by low impedance pickups without noticeable treble loss. Single-coil pickups are sensitive to magnetic fields generated by transformers, fluorescent lamps, and other sources of electromagnetic interference. Interference manifests itself through hum and noise. Dual coil or "humbucking" pickups consist of two separate coils that are 180° out of phase. Common-mode signals that radiate into both coils with equal amplitude are canceled out, eliminating much of the undesired interference.

An infrared-based transducer responds to the guitar string's vibration by producing an electrical signal representative of the string displacement. The transducer consists of a small source infrared emitting device (IRED) and an infrared sensitive photodiode. Orientation of the emitter and receiver is such that string vibration occurs directly between the two.

The diode's ability to permit current flow in one direction and block the current flow in the opposite direction stems from the junction of two different semiconductor materials. A junction between an n-type material with an excess of electrons and a p-type material with an excess of holes gives the desired effect. Free electrons from the n-type material attempt to move towards the positive charge of the p-type material. At the same time, positively charged holes from the p-type material try to move to the n-type material. The electrons and holes recombine in the vicinity of the p-n junction. This recombination of electron hole pairs removes all charge carriers surrounding the junction. Establishment of a carrier free region, or depletion zone, prevents electron flow unless sufficient forward bias is applied. Connecting the n-type region to a negative voltage source and the p-type region to a positive voltage source can cause the electrons in the depletion region to be freed if the voltage is sufficient. A continuous combination of electrons and holes at the junction allows for a constant current to flow through the diode in this forward biased mode. Connecting the diode in the opposite manner widens the depletion region. The reverse biased mode does not allow charge to flow across the p-n junction [8].

Light emitting diodes are constructed of the same p-n junction as regular diodes. When a sufficient forward bias voltage is applied, a combination of electrons and holes occurs at the junction. Each combination is associated with an energy level reduction releasing some quantity of electromagnetic energy. It is desirable for the energy level reduction to be great enough to release energy in the form of a photon. The frequency of an emitted photon is dependent on the semiconductor material. Achieving various colors is done through careful manipulation of the compounds used [9].

Unlike elementary silicon used in semiconductor fabrication, IREDs are made from two elements of groups III (e.g., Al, Ga, In) and V (e.g., P, As) of the periodic table. Emission in the near infrared range between 800 nm and 1000 nm limits the selection of materials to GaAs and

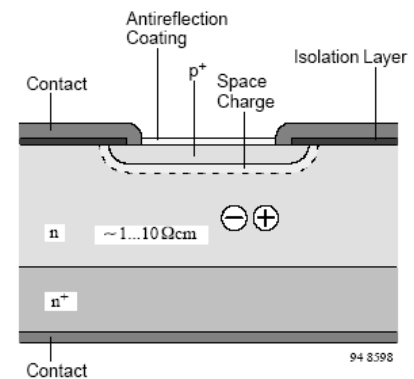


Figure 7. Photodiode construction with p-n junction.

crystals made from a combination of pure GaAs and AlAs compounds. Most IREDs are made from GaAs with a bandgap of 1.40 eV [10]. Common chip structure is shown in figure 11. The bandgap between the conduction and valence bands directly determines the wavelength of emitted photons. Devices fabricated with higher bandgap energies require greater energy for recombination to take place. These higher recombination energies correspond to a higher energy of the emitted photon. The relationship of photon wavelength to the bandgap energy level is shown in equation 11 [11].

$$\lambda(\mu m) = \frac{1.240}{(E_g(eV))} \quad (3)$$

The heart of the pickup lies within a photovoltaic device that responds to a fluctuating intensity of infrared radiation caused by the moving string. Photodiode construction consists of a similar p-n junction as used in IREDs, except the top p-type layer is very thin. The thin p-type layer can be seen in Figure 12. The thickness of the p-type layer depends on the wavelength of radiation of which detection is desirable. A depletion region exists around the junction just as in regular diode operation. The depletion region of a photodiode is where the device is most sensitive to radiation. Light absorption in the active area leads to the formation of an electron-hole pair. The newly created pair separates; electrons move toward the n-region and holes move toward the p-region. The result is a generated current that is dependent on the intensity of light incident on the detector surface. This migration of electrons and holes to their respective regions is known as the Photovoltaic Effect [8].

The vibration of the string must be analytically proven to have a direct effect on the receiver response. Two hypotheses were developed to explain the theoretical operation of the optical transducer. Detection of the string motion perpendicular to the sensor face is outlined by the first hypothesis. A gradient infrared radiation pattern is transmitted across the string onto the photodetector surface. The string's distance from the emitter determines the amount of light that reaches the receiver. As the string moves closer to the source, the amount of radiation reaching the detector is diminished. Increasing the distance between the source and string will lead to an increase in the amount of radiation at the detector. The second hypothesis predicts how the string motion parallel to the detectors surface is detected. The gradient nature of an IRED's radiant intensity delivers a linear distribution of radiation across the detector. Linear distribution across the detector allows for a distinction to be made between displacements parallel to the detector surface. The string's vibration through the gradient infrared field delivers a linear fluctuation of photon energy to the photodiode [8]. Evaluation of the emitter's gradient intensity provides a description of the intensity pattern at the detector surface. Conventional surface-emitting LEDs are usually defined as Lambertian sources. A Lambertian source is any light source that obeys Lambert's cosine law. Lambert's cosine law applies when the source has intensity directly proportional to the cosine of the angle from which it is viewed. Figure 8 illustrates the relationship between intensity and the viewing angle, thus creating a spherical radiation pattern [8].

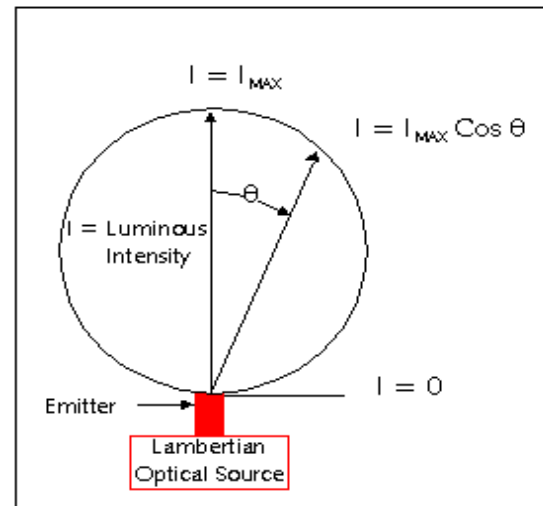


Figure 8. Lambertian distribution relationship.

Before analyzing the two hypotheses, certain LED measurement issues must be addressed. A key concept defining the relationships between different measurement geometries is that of the solid angle, or steradian (Ω or W). A steradian is defined by the solid angle, with its vertex at the center of a sphere, required to remove a spherical surface area equal to the square of the radius of the sphere. Equation 12 shows the relation between the solid angle and the area of the enclosed spherical surface area (da_s).

$$dW = \frac{da_s}{r^2} [W / sr] \quad (4)$$

Trigonometric laws define the size of the projected spherical cross-sectional area as:

$$da_s = dA \cos(\theta) \quad (5)$$

IRED specifications for the amount of emitted radiation are defined as radiant intensity (I). Radiant intensity is a measure of radiometric power per unit solid angle, expressed in watts per steradian as shown.

$$I = \frac{d\phi}{dW} \quad (6)$$

Photodiode response to intensity levels is specified through irradiance (E). Irradiance is a measure of radiometric flux per unit area, or flux density, typically expressed in W/m^2 , defined as:

$$E = \frac{d\phi}{dA} [W/m^2] \quad (7)$$

Determining the detector's response requires the conversion of radiant intensity to irradiance. Several substitutions must be made before reaching a direct equation to convert the measurements. Substituting the projected spherical cross-sectional area da_s into the solid angle definition yields:

$$dW = \frac{(dA \cos(\theta))}{r^2} \quad (8)$$

Substitution of the incremental solid angle value into the radiant intensity definition and solving for $d\phi$ leads to the following:

$$d\phi = \frac{(I dA \cos(\theta))}{r^2} \quad (9)$$

Finally, the evaluation for $d\phi$ is inserted into the definition of irradiance. This equation simplifies to the form:

$$E = \frac{(I \cos(\theta))}{r^2} \quad (10)$$

This equation can be integrated for an explicit evaluation of irradiance incident on the detector surface, due to a certain radiant intensity for a given range of angles [8].

These fundamentals can be applied for an analysis of the hypotheses through the integration of equation 11 with respect to theta (θ). Setting test specifications that apply to both cases ensures that the results are comparable. It should be noted that the calculations are only performed for the positive angles under the assumption of symmetry. The low E string is considered under scrutiny. With a diameter (d) of 0.24 cm, the E string is the thickest string on the bass guitar. Increased thickness leads to increased displacement and electrical response. A separation distance (l) between the IRED and photodiode is set to 1.27 cm. It is assumed that the string is located at the midpoint between the transmit-receive pair. Radiant intensity of 1.6 mW/sr is set as the worst case IRED intensity scenario. A final assumption must be made concerning maximum string displacement. The maximum displacement of half the string's width is applied to both hypotheses.

The total irradiance within the angle of half intensity is calculated in the absence of any string.

$$E = \int_0^{2\pi/3} \left(\frac{I \cos(\theta)}{r^2} \right) d\theta = 0.859 \text{ mW/cm}^2 \quad (11)$$

The amount of irradiance blocked by the string is deducted from the total irradiance of 0.859 mW/cm². The extremes of string displacement will be considered for each case. The results are compared for determining the method that provides a higher dynamic range. The blocked angle (θ_B) for a given geometry is determined by the trigonometric function as shown in equation 10. Since the stationary string instance is the same for both cases, it is calculated first. Only the positive angles are calculated; therefore, only half of the string is seen in its stationary position. For that reason, the width is divided by two in equation 10.

$$\theta_B = \tan^{-1} \left(\frac{d/2}{(l/2)} \right) = 0.187 [\text{rad}] \quad (12)$$

Evaluating the irradiance integral from 0 radians to 0.187 radians determines the amount of radiation blocked by the stationary string.

$$E = \int_0^{0.187} \left(\frac{I \cos(\theta)}{r^2} \right) d\theta = 0.184 \text{ mW/cm}^2 \quad (13)$$

The overall irradiance minus the irradiance blocked by the stationary strings yields a constant 0.675 mW/cm² present at the receiver.

Our first hypothesis theorizes that the string motion perpendicular to the sensor face is detected by the varied shadow sizes created therein. The maximum response for this configuration occurs when the string is displaced 0.12 cm away from the source. The blocked angle for this case turns results in 0.157 radians. Evaluation of the irradiance integral from 0 to 0.157 radians determines the minimum amount of irradiance blocked by the string. The integral evaluates to 0.155 mW/cm². The resulting maximum irradiance is 0.704 mW/cm². The minimum response of perpendicular detection is 0.12 cm displacement towards the source. The blocked angle for this case results in 0.229 radians. Evaluation of the irradiance integral from 0 to 0.229 radians determines the maximum possible value of irradiance blocked by the string. The integral evaluates to 0.225 mW/cm². The resulting minimum irradiance level results in 0.634 mW/cm². The difference between the maximum and minimum irradiances is 0.07.

Our second hypothesis accounts for the detection of the string motion parallel to the face of the photodiode. The maximum displacement of 0.12 cm off center yields a blocked angle of 0.361 radians. Evaluation of the irradiance integral from 0 to 0.361 radians gives the maximum irradiance blocked by the string. The integral evaluates to 0.350 mW/cm². The corresponding

minimum irradiance at the detector surface is 0.509 mW/cm^2 . The difference between the maximum and minimum irradiances is 0.125.

Not only has the fluctuation in irradiance been shown, but it can be seen that the second hypothesis delivers a higher dynamic range. The dynamic range provided by the detection of the string motion parallel to the sensor surface is 179% more responsive. Laboratory experiments confirm the preliminary analysis. With an optical transducer in place and the output monitored on an oscilloscope, a much greater dynamic range is observed when the string is displaced parallel to the sensor face when compared to the perpendicular motion.

Alignment was identified as a key issue from the beginning. A symmetrical configuration of radiant intensity on the photodetectors results in a mirrored response as the string moves in both the positive and negative directions. In order to avoid this potential loss of signal data and concurrently optimize the dynamic range, the infrared emitter must be placed slightly off center from the string and detector.



Figure 9. Impulse response of magnetic pickup.



Figure 10. Impulse response of optical pickup.

3.1.5. Transducer Signal Amplification

The signal coming from the transducer needs to be amplified to 100mV rms . This is the standard signal strength for an active guitar pickup. Each string has its own emitter-detector pair and the output level from this pair is determined by the magnitude of the string's displacement, the

diameter of the string, etc. Due to these variances, it is necessary to have a separate amplifier with a unique gain for each string. This is done to insure that the signal from any one string does not overpower the others, leading to a uniform sound across all frequencies. Developmental control over the gain of each string allows trouble free combination of all four signals. The amplification needed is quite small with voltage gains ranging from about 1.5 to 2.5. This should have as little distortion as possible. To fit inside the body of a guitar, the circuitry must meet the spatial design constraints of the guitar's body.

Two options were considered to provide this amplification: single stage (one transistor) class A amplifiers (common-emitter/source configuration) or operational amplifiers.

The single transistor amplifier idea is based on the “Zen Amplifier” work of Nelson Pass as shown in figure 11 [11].

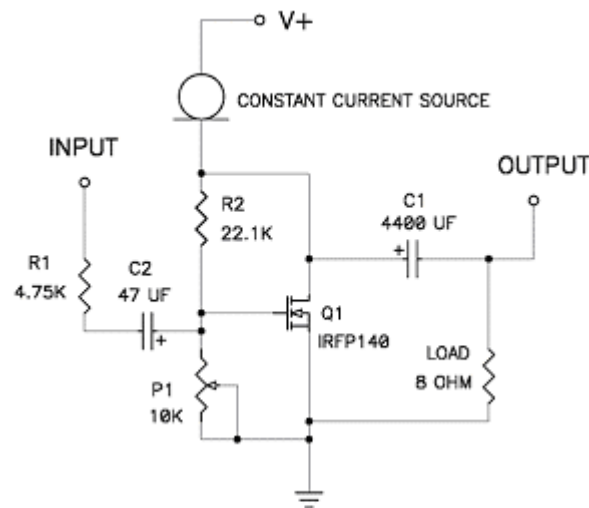


Figure 11: Nelson Pass Simplified “Zen Amplifier.”

These amplifier configurations show how one can achieve good sounding audio amplification with just a single amplifying element. Assuming a common-emitter (source) style configuration, the choice between MOSFETs and BJTs must be made. The determining factor of this decision was transconductance, since voltage gain is linearly proportional to the transconductance of the element. For BJTs, the transconductance (g_m) is the DC collector current divided by the threshold voltage or [12]:

$$g_m = I_C / V_T \quad (15)$$

for MOSFETs, g_m is determined by the following equations

$$I_D = k * (V_{GS} - V_T)^2 \quad (16)$$

$$g_m = 2\sqrt{k * I_D} = 2 * k * (V_{GS} - V_T) \quad (17)$$

where k is a constant based on the channel width and length of the MOSFET [12].

The transconductance of the FET is based on the square root of the drain current (I_D from equation 2 and 3), while the BJT's transconductance is based on just the collector current (I_C from

equation 1) [12]. This results in FETs having a transconductance an order of magnitude lower than BJTs meaning that FET amplifiers would be easier to fine tune and more likely to give the required low voltage gains [12]. After choosing FETs over BJTs and assuming a common-source configuration, the amplifier would have their gains controlled by a simple voltage divider between the voltage rails and the gate. Figure 12 displays the schematic:

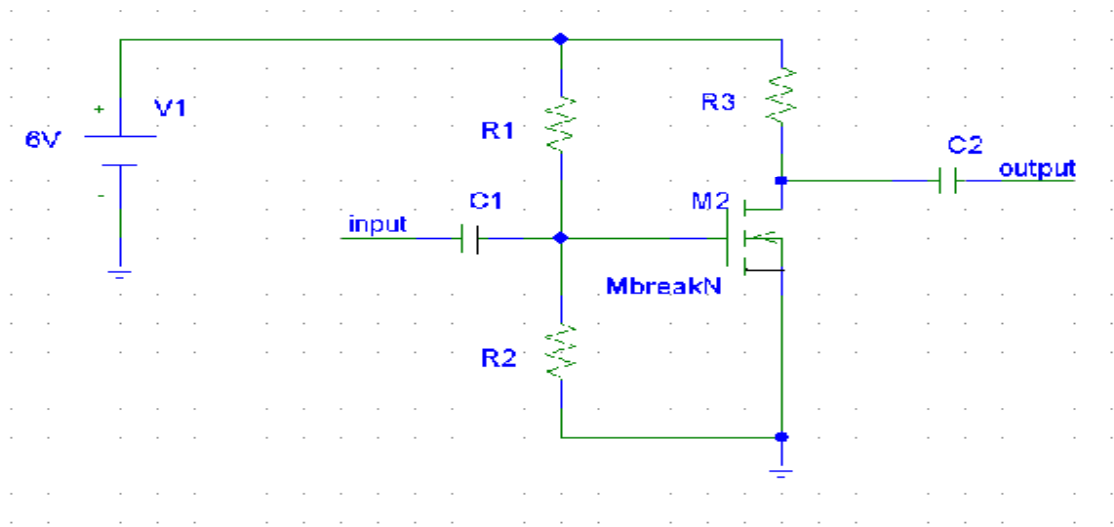


Figure 12. Sample Class A common-source amplifier using n-channel enhancement mode MOSFET.

This option would be least costly of the two, but would require more space when building the circuit. This design will also require grounding to the body of the guitar, which could cause problems.

The second option considered was operational amplifiers. The use of operational amplifiers simplifies both the design and the fine tuning/troubleshooting of the amplifier. Since the op-amps are being used for small gains (and are being inverted again at the summing amplifier), they can be designed in a simple inverting configuration [6].

Since a bipolar power supply is being used, space conservation is crucial, and remaining under budget is necessary, inverting op-amps would be ideal to provide the necessary small signal gain. Since the signals were to be summed by another op-amp, the actual gain values could be set so that the signals had the best dynamic range. This was done by using 25k potentiometers as the feedback resistance. After adjusting the potentiometers the following levels were measured:

String	Voltage (mV)
E	400
A	192
G	144
D	128

Table 3. Measured outputs by string.

3.1.6. Summing Amplifier

The signal from each guitar string must be combined to a single signal before its output to the amplifier. In order to achieve this, a summing amplifier is necessary. Industry standard for guitar outputs is around 0.1V rms, but can vary from guitar to guitar. The output signal of each guitar string is set so that after the passive filter currently used the signal is around 100mV. Due to the voltage drop across the passive filter the output was set to -1.2 volts. The input resistors and the feedback resistor must be properly selected by using the following formula [6]:

$$V_o = R_f * V_1 / R_1 + R_f * V_2 / R_2 + R_f * V_3 / R_3 + R_f * V_4 / R_4 = -1.2V = -1.2V \quad (18)$$

Based on the measured values of V1 through V4 the following scaling factors for each string were determined:

String	Voltage (mV)	Scaling Factor	Resistor Value
E	400	1	100k
A	192	0.48	47k
G	144	0.34	34k
D	128	0.32	32k

Table 4. Scaling factors for summing amplifier.

3.2. Software Design

Software aspects of this project center on the liquid crystal display (LCD) unit that conveys relative tone and volume levels to the user. A microcontroller monitors the high frequency gain, low frequency gain, and master gain circuits for any changes in the output levels. Signal processing of the guitar's signal is done through dedicated analog hardware, bypassing any software interaction. Output will not be delayed by the microcontroller and LCD initialization.

3.2.1 Use Cases

Graphically defining successful user operation in comparison with an ill-fated scenario brings up main hardware and software objectives. The intended user interaction with a product places constraints on both hardware and software components of the design. Prediction of unstable cases involving incorrect user operation or device failure increases the scenarios in which proper device functions are possible. The graphical use case, utilizes bold vertical lines to represent the user and device, in this case a bass guitar. User manipulation of the device controls is shown as blue arrows pointing towards the guitars. The device's response and current status is in represented as red arrows pointing towards the user side. Possible cases are easily observed when presented in a direct cause and effect manner. Proper software reaction under normal use is defined by the sunny day use case shown in figure 13. A welcome message is displayed on the LCD immediately following microcontroller initialization indicating the guitar has been successfully powered on. The message will remain on the LCD for two seconds or until an output level is changed. Adjusting tone or volume controls activates the LCD if it has turned off. The leftmost digit indicates if the high tone, low tone, or master volume is being altered by displaying an 'H', 'L', or 'V' respectively. Output level of the control under user manipulation is displayed by a bar graph on the remainder of the LCD. The display is turned off in absence of any further changes for the next five seconds.

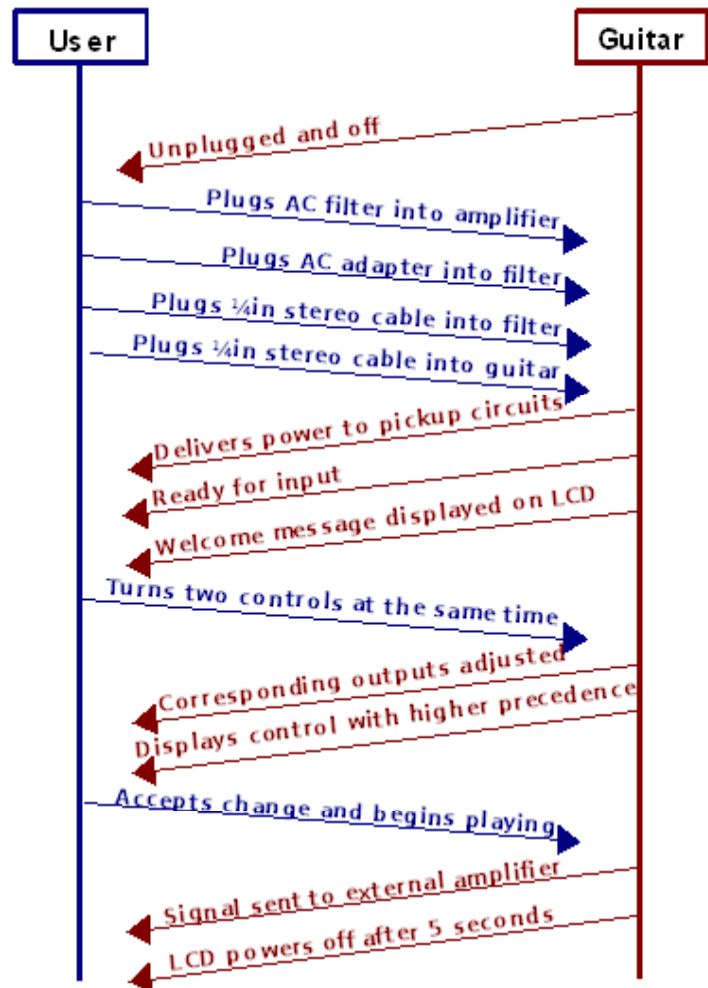


Figure 13. Rainy day use case illustrating interaction between both hardware and software components of the project and the user.

Illustration of usage leading to possible device malfunction is displayed in the rainy day case of figure 13. Many situations exist that could lead to undesired pickup performance. Extremes in temperature and humidity are obvious factors that determine whether successful operation is

possible. Excessive airborne contaminants such as dust and pollen could also prevent the desired high fidelity output. Despite its name, our rainy day case assumes that the device is used in a climate that permits functionality. The device's response under excessive humidity, dust, and temperatures are not confronted

by this case. Possible user interaction is evaluated in search of situations that may lead to undesired LCD output. The rainy day case examines the guitars response when more than one control knob being turned at a time. If the user begins adjusting a control while another control is being used, the display shows the levels of the most recently modified control. Precedence over which control gets displayed, in the event that two controls begin adjustment at the same time, is set in software. Top display priority goes to the master volume, followed by the high tone and low tone.

Use case evaluations provide guidelines for functional device operation, as well as events that could disrupt operation. Anticipating and understanding how undesirable results are culminated brings forth awareness of possible shortcomings. Awareness of weak points in a design determines safeguards to prevent malfunction. It is not possible to consider all configurations of weather and user interaction. Through extended anticipation of various problems, a more reliable product is developed.

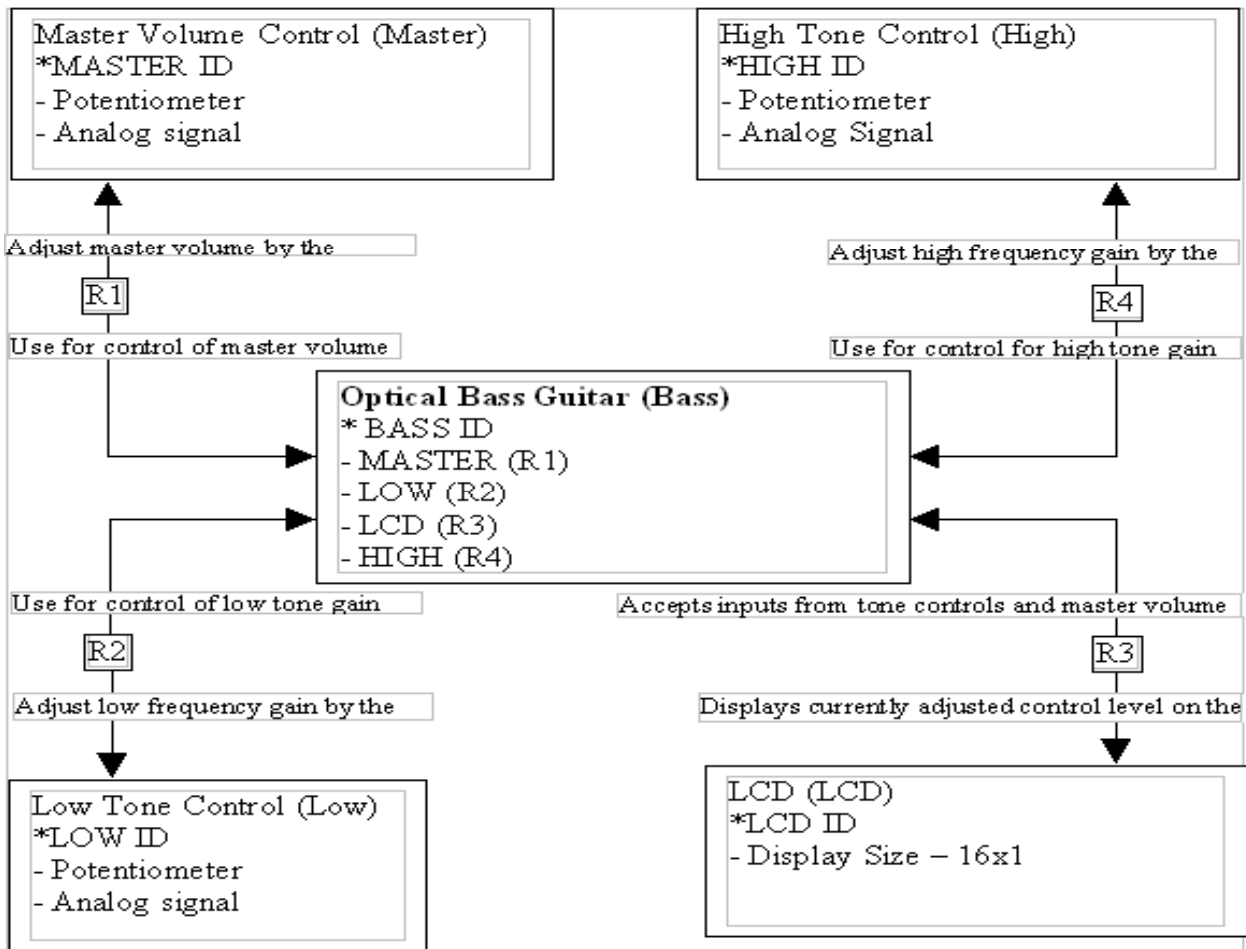


Figure 14. Software information model defining data interaction between inputs and outputs and the microcontroller.

3.2.2 Information Model

Data interactions between hardware components and software are represented through the information model in figure 14. Inputs and outputs crucial to software implementation are defined by their purpose and type. Three analog inputs will monitor the outputs from the master volume control, high frequency tone control, and low frequency tone controls. Potentiometer values determine the attenuation of each variable. The analog-to-digital converter included in the microcontroller converts the signals received from each control into digital signals that may be evaluated by our software. Comparison of the actual input signal to the previous value and the full range of possible values is performed. Results from the comparison determine the size of the bar graph required to accurately convey output levels. The microcontroller output drives the sixteen digit LCD by a digital signal.

3.2.3 Process Model

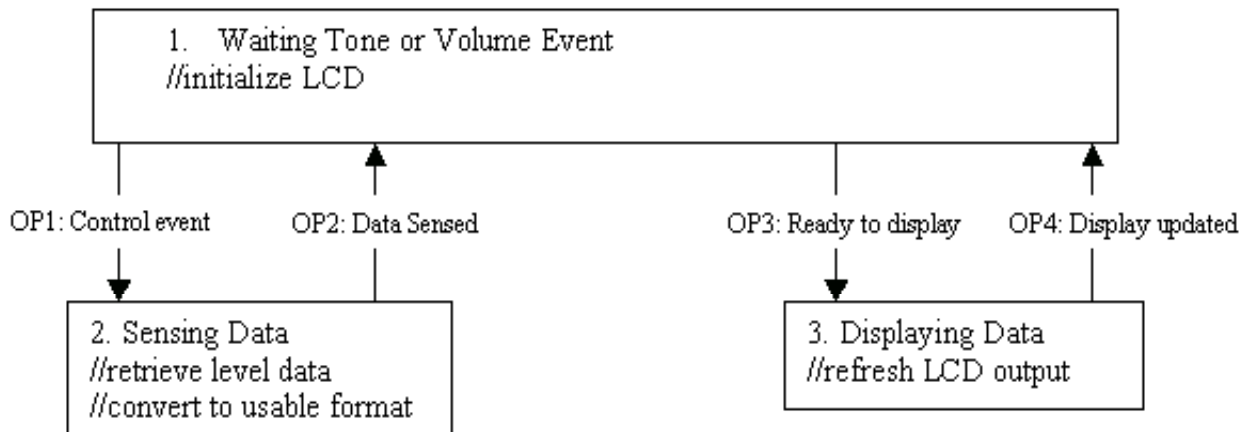


Figure 15. Software process model showing processes involved in the software portion of this design.

The process model for this project gives an indication of the software steps required to translate an analog input signal into a displayable bar graph. In the default state, the microcontroller will be accepting signals from the tone and volume controls. Present signal values will continually be compared to the previous value as well as the upper and lower limits. As an output control is adjusted, the software detects the difference. In the event of a detectable change, the LCD initialization is triggered. With the LCD now active, the microcontroller begins sending the relevant commands to control the display. The bar graph will be updated during the entire time the control is manipulated. Following five seconds without another adjustment, the LCD will be disabled. Deactivation of the LCD is a power saving feature that reduces overall power consumption. The steps outlined by the process model define key software features and the order in which they must communicate to ensure successful interaction.

3.3.3 Physical Model

Software design must be done with the end result in mind. The software physical model in figure 16 is a rendering of the final guitar system. User controls are for master volume, high tones, and low tones are shown as knobs on the face of the guitar. Providing convenient access to the three controls while keeping them out of the musician's way is important to providing a user-friendly product. The controls must be located so that they don't interfere with the playing of the instrument. At the same time, they must be easily accessible for quick adjustments by the user. Ideally the LCD will be located on the top of the guitar body. Guitars are normally suspended from a strap worn across the musician's torso. When played by a right-handed person, the display is in their direct line of sight while looking down at the guitar. Size constraints of the guitar body and LCD unit may lead to mounting the display on the front surface of the guitar body. This location, when compared to the ideal option, would not be as easily observed by the user, but functionality remains.



Figure 16. Software physical model illustrates user controls and output display.

4. EVALUATION

4.1. Test Specification

The Optical Bass Guitar Pickup is a precision device for a sensitive instrument, the bass guitar. This pickup must be able to faithfully reproduce the sounds created by the guitar. These test specifications are designed to ensure that this pickup meets or exceeds the design constraints.

The Optical Bass Guitar Pickup has two key parts: The power supply and the pickup itself. These parts will be tested individually before being tested as a complete prototype.

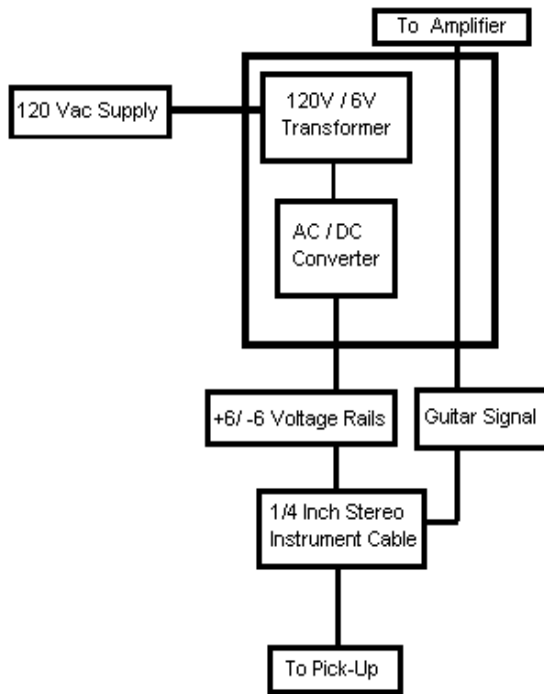


Figure 1. Power Supply Block Diagram.

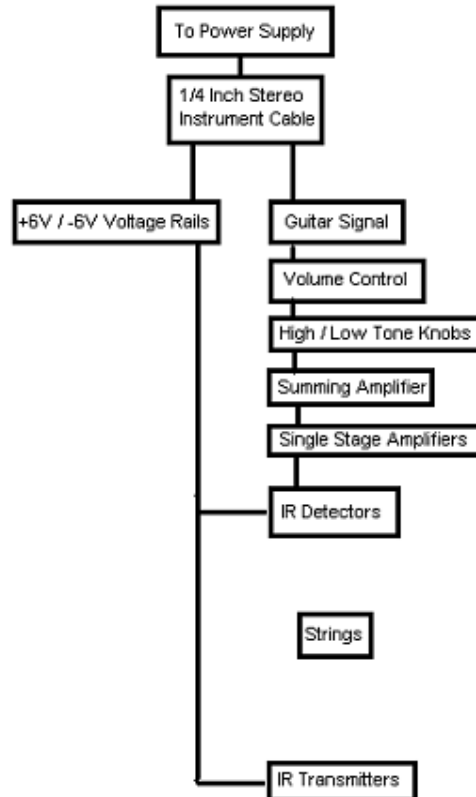


Figure 2. Pickup Block Diagram.

4.1.1. Simulation

The following parts will be simulated both individually and as a whole in PSpice:

1. Power Supply
2. Individual Op-Amps
3. Summing Op-Amp
4. Tone Control Knobs and Master Volume Knob

We will test to make sure the power supply reliably provides the power needed at the proper voltage and current levels and that it converts from AC to DC with inconsequential levels of ripple. The amplifiers and the summing op-amp will be tested to make sure they provide the right levels of amplification and that they properly combine the signals of the different strings. The signal from the pickup will be simulated by a variable current source. The tone knobs will be simulated to ensure that they properly act as high pass and low pass filters. The volume knob will be simulated to see if it changes the signals amplitude along a reasonable scale.

4.1.2. Hardware

The output from the pickup alone was tested at different distances from the bridge along the E string (powered by prototyping test bench):

Distance from bridge cm	Voltage (mV)	Clipping (y/n)
1	27	n
1.5	33	n
2	40	n
2.5	49	y
2.2	44	n

Table 1. Various distances for E string.

The individual op-amps were added and the dynamic range of the signal was fine tuned using a potentiometer as the feedback resistance. After fine tuning, the following output voltages were recorded:

String	Voltage (mV)
E	400
A	192
G	144
D	128

Table 2. Measured outputs by string.

These voltage levels were used to determine scaling of the signals for the summing amplifier. The summing amplifier was added and its output signal was fine tuned using the resistance box. The proper resistance was put in place of the resistance box and an average output voltage of 120mV rms was measured.

Recordings were made at this point and FFT transforms were performed using MATLAB to determine frequency range and signal-to-noise ratio.

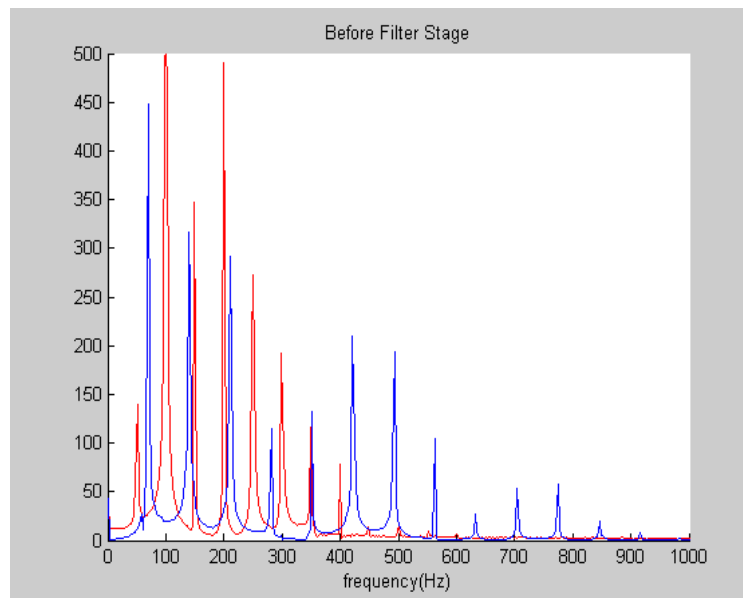


Figure 3. Comparing magnetic pickup output to unfiltered optical pickup output.

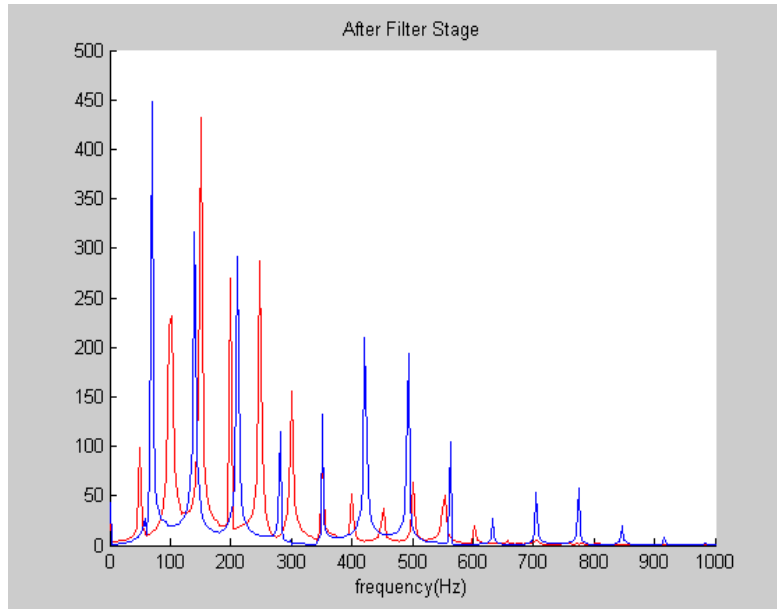


Figure 4. Comparing optical pickup output to filtered optical pickup output.

The power supply's DC voltage out was tested using a multi-meter and the voltage ripple was tested using the oscilloscope. The DC output was tested on a range varying from 115-120 volts to reflect the fluctuation of a wall outlet. Table 3 shows an output of the test results from the power supply.

Test AC voltage	DC output (+)	DC output (-)
115	6.05	6.07
120	6.06	6.11

Table 3. Output from DC bipolar power supply.

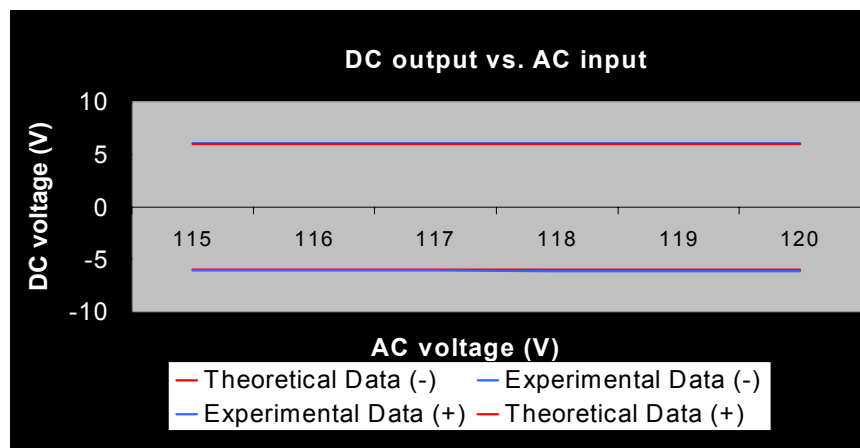


Figure 5. DC output vs. AC input

4.1.3. Software

Tone controls and master volume control will be monitored by a microcontroller. Three analog input pins will monitor the gains for each control as they are manipulated by potentiometers. The microcontroller signals to an LCD bar-graph to display the gain of each control in real-time. Output will be displayed on a 1x16 LCD while the manipulation is occurring and for five seconds following. After five seconds, the display will be turned off to minimize power consumption.

1. Software must be written to convert the analog inputs into LCD signals.
2. The LCD will be monitored for the proper output.
3. The delay timing to turn off the LCD will be measured.
4. This section is incomplete since the design team is still in the testing stage.

5. SUMMARY AND FUTURE WORK

This summer the power supply will be redesigned to include a linear regulator. The current power supply prototype successfully provides $\pm 6V$ with a ripple voltage of 0.48V. The ripple voltage must be even smaller to insure the best possible output signal. A linear regulator will be incorporated into the power supply design to achieve a smaller ripple voltage. The mounting of the transducer pairs will also be improved upon this summer. Currently, the detectors are mounted on one breadboard and the receivers on another. This creates a problem when just one transducer pair needs to be adjusted. The separate mounting will achieve the best possible alignment for each transducer pair, which can be adjusted without affecting the alignment of the other pairs. The filter design will also be improved upon this summer. Currently, the filter does not provide a better frequency response than a magnetic pickup. The filter will be redesigned to ensure the high and low frequencies are equal or better than a magnetic pickup. The power coupler also needs improvement. The current design of the power coupler neglects proper grounding. The new design involves AC coupling of the signal to one of the voltage rails and grounding of the stereo cable sheath to the power supply ground.

Next semester, the components of our prototype will be mounted onto printed circuit boards for packaging. The printed circuit boards will be placed in or on the body of the guitar. The transducers will be tested for various guitar models and with different string gauges. This testing ensures that the pickup can be retrofittable to other guitar models and provide excellent sound quality regardless of the string gauge. The optical signal will continue to be compared to the magnetic signal with recordings (by microphone) out of an amplifier and speaker cabinet.

6. ACKNOWLEDGEMENTS

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APPENDIX A: PRODUCT SPECIFICATION

Optical Bass Guitar Pickup



FEATURES

Sensitive Infrared Detector for High Fidelity Sound

Less Interference Than Standard Magnetic Pickup

Possible Use of Non-Ferrous Strings

Master Volume Control

High/Low Tone Control

Equal Loudness Contour Circuit for Low Volume Compensation

Heavy Duty Shield to Reduce Light Interference and Physical Damage

Bridge Mounted for Optimum Harmonic Response and Maximum Playability

SPECIFICATIONS

FREQUENCY RANGE
10Hz to 15kHz

MOTION DETECTORS
4 Independently biased infrared phototransistors

TONE CONTROLS
+-12dB high and low attenuation

PACKAGE
3 1/2" x 2 1/2" x 1"

INDICATOR
LED power indication

FUNCTIONS
Auto-on when cable is inserted

OUTPUT
100mV rms

CONNECTOR
1/4" Instrument cable

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