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December 17, 2000

Dr. Andrew Rawicz
School of Engineering Science
Burnaby, British Columbia
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Re: ENSC 340 Process Report for an Automatic Tuning Guitar

Dear Dr. Rawicz:

The attached document, *Process Report for an Automatic Tuning Guitar*, summarizes *Perfect Pitch's* ENSC 340 experience. This document outlines the process we endured in designing and completing a device that automatically tunes a guitar as quickly as possible, by mechanically tightening or loosening each string.

This process report includes a high-level and a technical description of the project, plus a description of the problems we encountered, our group dynamics, our conclusions and our recommendations for future work.

Perfect Pitch Instruments is composed of five sharp, creative and talented engineering science students including Gina Millar, Maria Trinh, Aaron Schellenberg, Terrence Yu and Reva Vaze. Should you have any questions or concerns regarding our proposal, please feel free to contact me at (604) 584-8926 or via email.

Sincerely,

Maria Trinh

Maria Trinh
CEO
Perfect Pitch Instruments

Enclosure: *Process Report for an Automatic Tuning Guitar*

Perfect Pitch Instruments

Process Report for an Automatic Tuning Guitar

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Submitted to: Dr. Andrew Rawicz
Steve Whitmore
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Date: December 17, 2000

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1. Project Overview

The goal of our project is to design and develop an automatic electric guitar tuner that would eliminate the hassle involved with tuning a guitar manually. Although tuners exist in the marketplace today, many are handheld requiring the user to pluck a string with one hand, hold the tuner with another hand, and adjust the tension in the strings with another. Clearly too many hands are needed, and the tuning process is unnecessarily time consuming. The few existing automatic guitar tuners cost thousands of dollars, and prove unaffordable for the general public.

Perfect Pitch Instruments' automatic guitar tuner would be installed in a guitar at the time of manufacture. This accessory will be capable of tuning a guitar quickly, and would be suitable for all skill levels ranging from beginner to professional. The tuner can help to ease the learning curve for a novice guitarist or provide a performer on stage with a quick and effective means for tuning their guitar between songs to whatever settings they desire. This implementation will also be affordable to most consumers.

Essentially, the user all but has to pluck the strings on the guitar and the tuning is done automatically. The sounding audio frequencies are conditioned and processed electronically, and are subsequently provided as inputs to a control module. After comparing the pitch of the strings to their desired pitch, the control module adjusts the tension in the strings electro-mechanically. A controlled feedback implementation allows the actuators to be adjusted dynamically while tracking the pitch of the string. The process completes once the strings are tuned to their desired frequencies. Then it is time to rock! The controlled feedback mechanism is diagrammed in Figure 1.

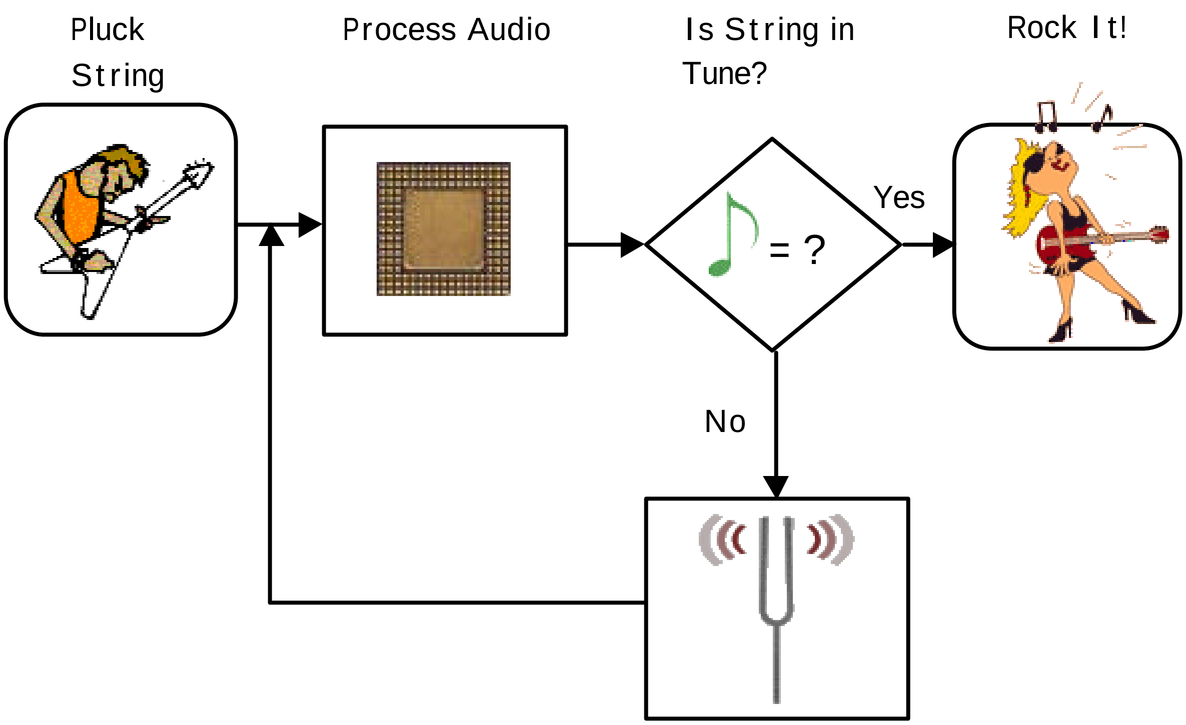

Figure 1. Controlled Feedback Loop

The high-level design used to implement this controlled feedback mechanism shown in Figure 2.

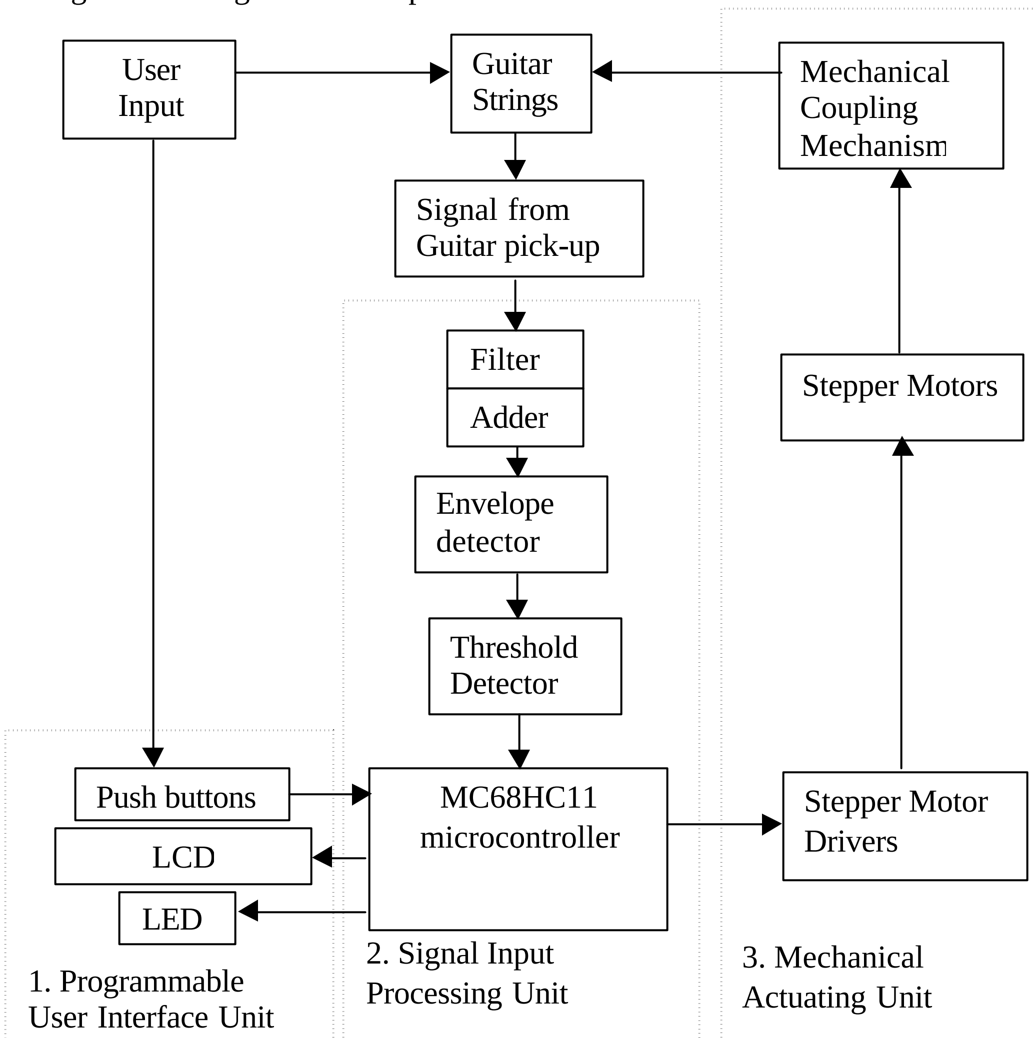

Figure 2. System Overview

The entire system is composed of three main modules:

1. the programmable user interface unit
2. the signal input processing unit, and
3. the mechanical actuating unit

The interactions between each of these modules work to achieve the controlled feedback mechanism as shown in Figure 1. The user programs the string settings using the Programmable User Interface Unit (1) and then plucks the guitar strings. The signal from the plucked string exits the guitar via the guitar pick-ups. The Signal Input Processing Unit (2) then processes this signal. The deviation of this signal from the ideal signal will determine the actuating message sent by the MC68HC11 microcontroller to the Mechanical Actuating Unit (3). The motors will either tighten or loosen the guitar strings (depending on the message from the microcontroller) via the mechanical coupling mechanism. The LCD and LED are also updated by the microcontroller for monitoring by the user.

2. Technical implementation of solution

2.1 User Interface Unit

Due to the nature of our project the user interface is made as limited as possible so as not to clutter up the body of the guitar. A visual representation of the user interface is shown in Figure 3.

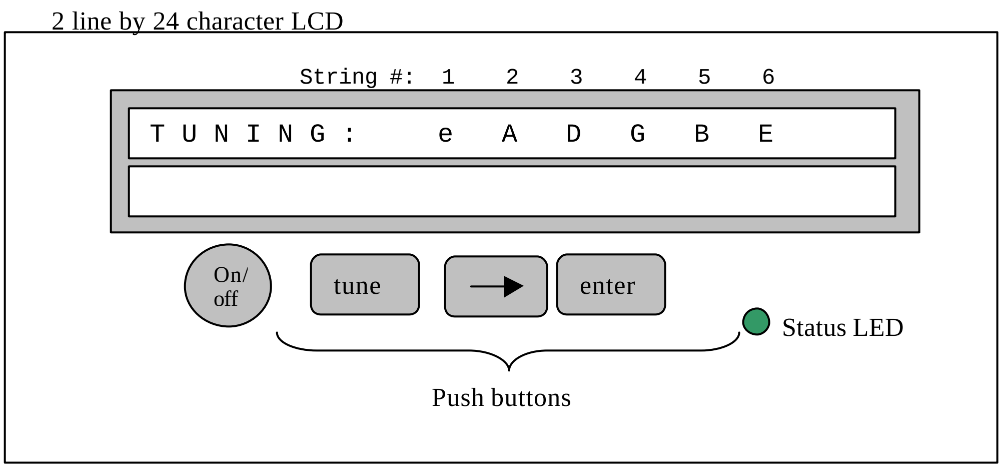

Figure 3. Visual Representation of User Interface

The controls that the user has at her disposal are the following:

- 1 On/Off switch - System power button and Emergency Stop button
- 1 “Tune” button - Toggles between Tune/Not Tune modes
- 3 programming push buttons – Used to program system settings
- 1 - 2 Line by 24 character LCD display – displays feedback for the user
- 1 Bi-colour LED - Indicates tuning status:
  - Green – string is tuned within specification,
  - Red – String is not within specification and needs to be re-plucked.

The initial LCD screen shows the standard strings settings for the guitar. The user can change each string from the standard tuning by moving the cursor (using the → button) to highlight the desired string, and then pressing by “enter”. Once the user has done so, a list of possible pitch settings for that particular string is made available, from which the user can again select, using the → and “enter” buttons again. The cursor loops around to the beginning of the display if it reaches the end of line.

Once the user has chosen the chord settings, she must press the “tune” button to ready the tuning system. Once a string has been plucked, the mechanism will be activated. The user can pluck any string, and the cursor on the LCD will highlight the string being tuned. Once each string has been tuned successfully, the LED will turn from red to green.

For any reason, the user can abort the tuning process by pressing the On/Off button at any time.

Figure 4 shows how the LCD, the push buttons and the bi-colored LED are all connected to the MC68HC11 microprocessor.

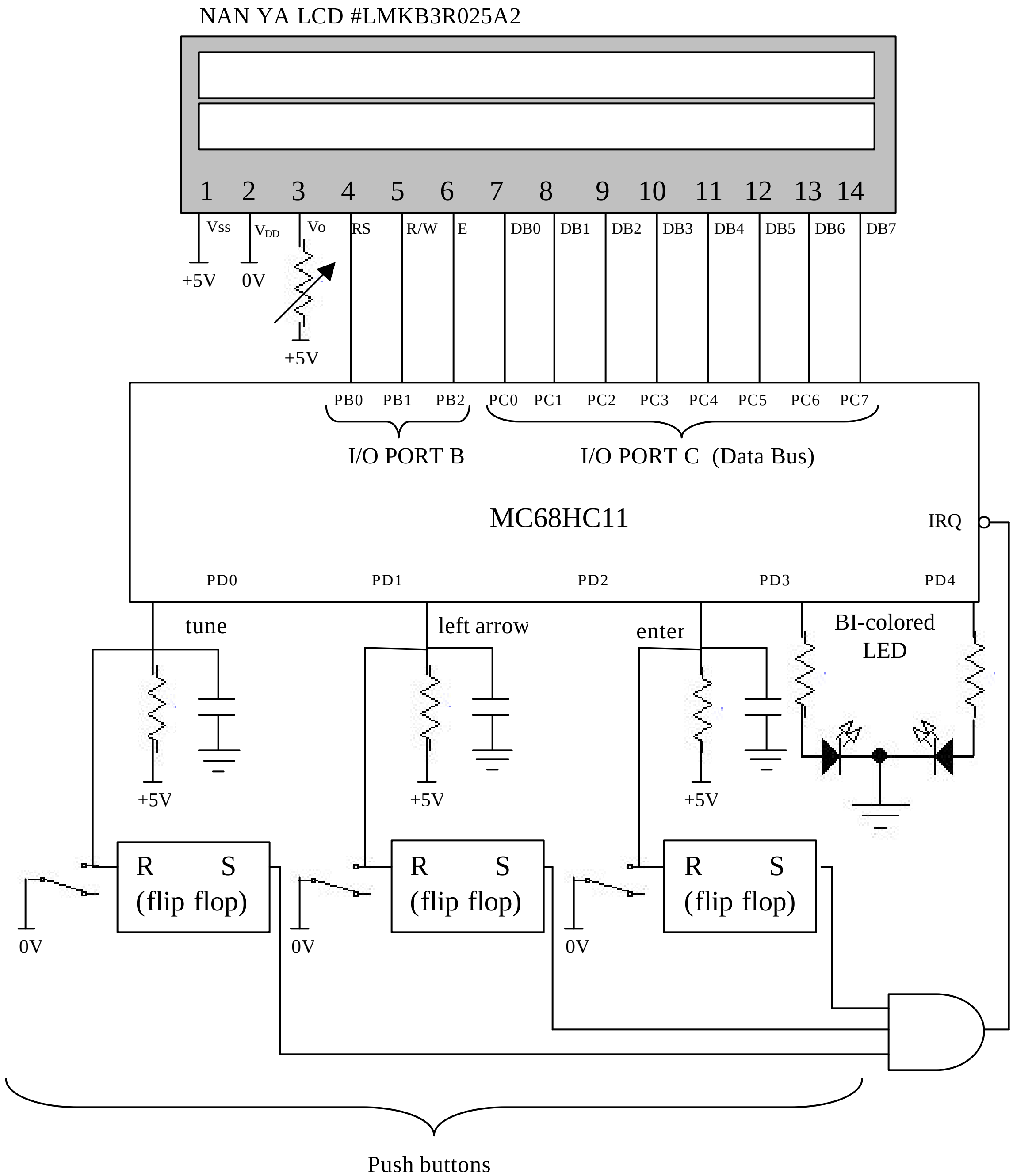

Figure 4. Hardware Implementation of the User Interface

The LCD requires all of the microprocessor's Port C I/O pins to deliver and receive 8-bit words, plus three more pins from Port B for its enable, read/write and RS lines. The push buttons are tied to Port D pins, and are debounced using RS flip-flops, and they trigger the IRQ interrupt line via an AND logic gate. Our design specifications intended 4 push buttons, but to save I/O lines, we were able to eliminate one (the ← button). The bi-colored LED is tied to lines 3 (red) and 4 (green) on Port D.

2.2 Signal Processing Unit

A block diagram implementation of the Signal Processing Unit is given in Appendix A. The unit processes the input signal from the guitar pickups in two parallel operations. The entire process relies on "beat detection", and consists of frequency resolution and frequency to voltage conversion. The need for two parallel units will soon become apparent.

2.2.1. Frequency Resolution of Input Signal

To resolve the frequency of the input signal, we have implemented the following components

1) Modulator
2) Filter
3) Envelope Detector
4) Limiter

Modulation involves adding a *Reference Square Wave* to the *Input Signal*. The modulated signal then passes through the clock tunable low pass filter (having a cuttoff frequency close to the desired string frequency) to remove harmonics from the input signal, as well as from the additive square wave. The output of the filter is a modulated signal with a sinusiodal envelope having a frequency equal to the difference between the *Reference Square Wave* and the *Input Signal*. To detect this envelope, we have implemented an envelope detector consisting of a simple diode, and RC circuit. The DC component of the signal if removed through a coupling capacitor. The output of the envelope detector is then fed to a limiter circuit that squares up the input signal as long as its amplitude is above a predetermined threshold level. Thus the limiter output is a square wave with constant amplitude, and frequency equal to the difference between the *Reference Square Wave* and the *Input Signal.*

2.2.2 Frequency to Voltage Conversion

Since we want to determine if the string should be tuned up or tuned down, we need to have two parallel units as is shown in the block diagram. The frequency *of Reference Square Wave #1* is set slightly lower than the desired frequency and the frequency of *Reference Square Wave #2* set slightly above the desired frequency.

The limiter outputs are connected to the input compare channel of the MC68HC11 microcontroller. The microcontroller is configured such that it generates an interrupt and every time a zero crossing on the input signal is detected. The interrupt service routine latches the local timer value into memory, and thus the frequency of the limiter output signal can be measured. If the frequency of the signal of Limiter #1 is greater than the frequency of the signal of Limiter #2, we conclude that the string needs to be tuned down and vise versa. The microcontroller now knows which direction the motors should turn in, and by what amount.

2.3 Mechanical Actuating Unit

2.3.1 Guitar and Bridge

The electric guitar we selected is a 3 pick-up guitar (2 single coil, 1 Humbucker) complete with a Kahler floating bridge (similar to a Floyd Rose). After some preliminary design work, it was decided that the most suitable way to interface motors to the guitar strings for our purposes is to use a pre-manufactured floating bridge.

The most common embodiment of the floating bridge is the patented Floyd Rose Floating Bridge, in which the entire bridge pivots about two vertical posts aligned across the body of the guitar (i.e. perpendicular to the strings). The term "floating" refers to the fact that the bridge is held in place by the counter-balancing forces of the six tensioned strings, which travel along the top of the body, and 2-3 tensioned springs traveling underneath the body Figure 5. The two pulling forces cause the bridge to balance in a somewhat horizontal position. A lever attached to the bridge (often called a tremolo bar or whami bar), permits the guitarist to pivot the bridge around the vertical posts by exerting torque on the lever. This causes a change in string pitch, as the tension in all strings is either increased or decreased.

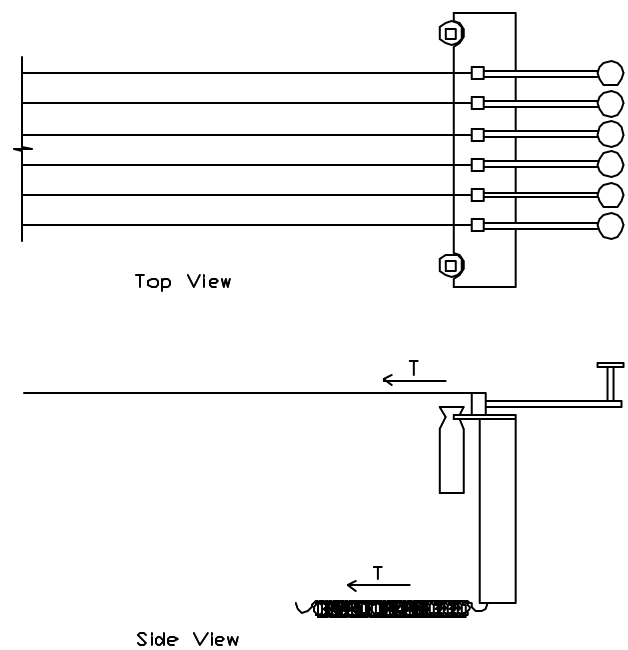

Figure 5. Floating Bridge

The guitar strings tend to go out of tune when repeatedly subjected to strains caused by the yanking of the tremolo bar. In order to reduce the susceptibility of the strings to de- tuning, a locking nut, consisting of a simple clamping mechanism is installed at the top of the guitar neck. This clamps the strings in place so that the tuning pegs in the head of the guitar do not unwind. When the nut is locked, however, the guitarist is unable to tune her guitar using the conventional tuning pegs, therefore, a secondary set of tuning pegs, called “fine tuners” are installed on the floating bridge itself, allowing the guitarist to tune her guitar after the nut has been locked.

We interfaced our motors to these fine tuners. Some of the advantages that these tuners provide are: (1) a mechanical advantage, provided by levers and screw drives, that significantly reduces the torque requirements of our motors (see Figure 6), (2) no holding torque is required to keep the string at the desired tension, and (3) they eliminate the complicated task of designing our own string tensioning mechanism. One disadvantage to this solution, however, is that we are limited to the tuning range of the fine tuners, which varies from 5 semitones for the low E string to 2.5 semitones for the high E string.

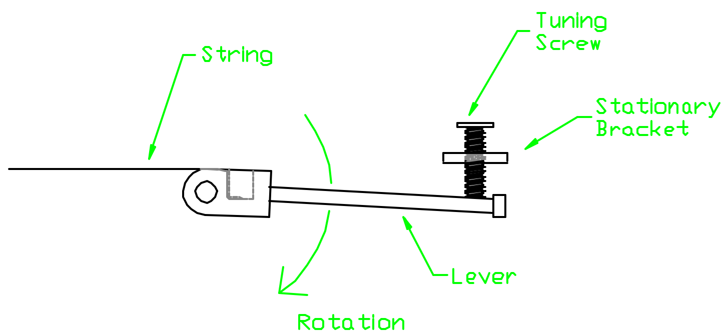

Figure 6. Fine Tuner (Side View)

2.3.2 Mechanical Coupling

This mechanical device couples the motor power to the floating bridge via the fine tuners. For each string, we replaced the fine tuning peg shown in Fig 2 with our own shaft coupling device Figure 7

The new threaded shaft is coupled to the motor shaft by way of a simple belt and pulley system Figure 7. By adjusting the ratios of the pulley radii, we can add further mechanical advantage to the system by making the radius of the secondary pulley larger than the primary (motor) pulley.

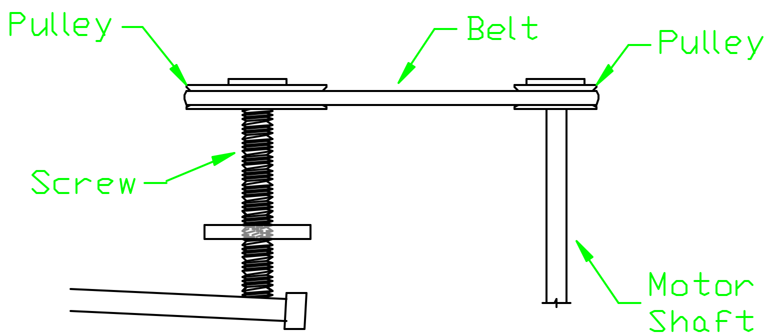

Figure 7. Coupling Device

2.3.3 Motors

The torque requirement of the coupling mechanism is a maximum of 0.033 Nm. The best motors we could afford (common 5.25 floppy-disk drive motors) provide about 0.05 Nm of torque. We will install three motors in the body of the guitar. We intended to install all six motors (one for each string), but found that the best motors we could afford were too big to all fit on the guitar. Still the electrical system is designed to accommodate up to six motors.

We will route out a cavity in the back of the guitar to install the motors, with the drive shafts poking out of the top of the guitar body near the floating bridge. The guitar body is approximately 1 ¾" thick and 3 ½" from the back of the bridge to the end of the guitar.

The fine tuners on the Kahler floating bridge are not perpendicular to the horizontal plane of the guitar body; rather they are tilted 5° - 10° from the perpendicular axis. This posed an additional complexity when mounting the motors, however, this was overcome by using angles spacers between the motor and the mounting surface. This way the motor shafts and tuning shafts are parallel, as shown in Figure 7

2.3.4 Driver Circuitry

One of the most challenging issues with the motor control system was the lack of I/O pins on the HC11. In order to minimize the number of pins that the motor drivers require, we used a multiplexer to distribute the signals between the four H-bridges. This was possible because only one motor is required to be moved at a time. By using a high torque control sequence in which two of the signals are complements of the other two, the number of pins the number of pins was further reduced. The result was that only two signals were required to be generated by the microprocessor in addition to the multiplexer control and the enable lines. Figure 8 shows a high level diagram of the motor control circuitry.

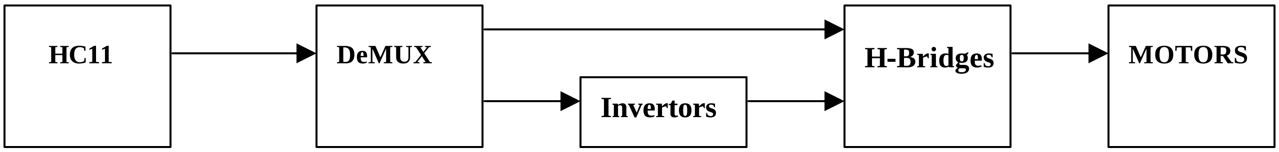

Figure 8. Motor Control System

2.3.5 Power Supply

The automatic guitar tuner will run off of a standard wall socket power supply using a 120VAC to 24 VDC adaptor. The required voltages for different components (i.e. 24VDC for motors, 5VDC for LCD, microprocessor, etc.) are obtained by stepping down the 24 VDC using voltage dividers and regulators.

3. Problems encountered

3.1. Technical issues

3.1.1 The Microcontroller

We chose the Motorola HC11 as our microcontroller for several reasons. One of the reasons was that, at the time, the HC11 met all our project requirements. While working with the chip, issues arose that had to be dealt with before the project could continue. One problem is that the switched capacitor filters we are using to filter out the harmonics of the different guitar strings needed a high frequency clock. The frequency had to be one hundred times the frequency of the desired break frequency, a frequency that the HC11 could not produce.

3.1.2 Digital vs. Analog Signal Processing

The first month of the semester was spent in deciding on the proper signal processing strategy. We debated quite a bit on the pros and cons of digital versus analog processing. Each had their advantages and disadvantages but we finally settled on an analog design largely in part because none of the group members had any previous digital experience, but also in the interest of time. Had we used digital methods, certain parts of our project would be greatly simplified. For example, using digital techniques, filtering of the input signal would have been easier to implement, and we wouldn't need the switched capacitor filters thereby reducing the size of our design. However, we saw several websites in which other people had implemented a guitar tuner (nothing like the one we are) using digital techniques, and they either failed in their endeavors, or found other more technical challenges related to the digital nature of their algorithm. In the end, we are pleased with the results that we are getting using the analog circuitry, and are glad that we chose this route.

3.1.3 Filtering

The clock tunable, switched capacitor low pass filters that we purchased operate with a clock frequency 100 times the desired filter cutoff frequency. Initially, we thought that we could use the HC11 processor to fulfill this requirement, but as it turned out, the processor can't generate clocks above approximately 15kHz. We need to generate clocks up to 32 kHz, which can't be done. So we resorted to building local oscillators using the 555 Timer. Currently, we have an individual oscillator for each string. If we had more time, and had anticipated this problem, we would have built a voltage-controlled oscillator that could be controlled by the microprocessor.

3.1.4 Mechanical Coupling Mechanism

We agonized over the mechanical coupling mechanism for the first two semesters of the semester. Having scant experience in the field of mechanics, we turned to the lab staff (Gary Houghton, George Austin) and the mechanics in the Physics machine shop for their input. George inspired us to find miniature turnbuckles to tighten the guitar strings, just like large turnbuckles tighten ropes on ships. We went to local hobby shops and found some tiny brass turnbuckles, and we built a test jig to see how it would work. It turned out that the turnbuckles could tighten the strings, but they had a tendency to unwind slightly when not held in place, and were therefore not reliable.

Aaron had the idea of using what was already available on the market to give us a mechanical advantage: guitars with floating bridges. The only problem would then be how to interface to the screws on the floating bridge. The mechanics at the machine shop suggested that we implement universal gears, but they are incredibly expensive, and would provide no gear-reduction despite their flexibility. In the end, we ordered the pulleys and spent a great deal of time trying to install them on the guitar, with little yet hindering mechanical problems arising all the time.

The biggest issue was the debate on motors: should we implement 6 motors (one to tune each string) or should we implement one motor with a complicated clutching system? The clutching system would have added a new complexity to the mechanical aspect of the project, and seemed to be less "automatic." So we decided that the most efficient solution would be to try to accommodate 6 motors on the guitar. Due to constraints imposed by the size of the guitar body, we needed to find motors that were small and that generated enough torque to turn the fine tuners. This proved to be a difficult task since we were trying to avoid buying expensive gearboxes and the like to reduce the necessary torque. Finally, we decided on using larger motors and only tune three out of the six strings. We figure that if our algorithm works for three strings, there should be no problem tuning all six strings.

3.2. Financial issues

Table 1 summarizes our expenditures on this project.

Table 1. Expenses

Second-hand Electric Guitar	$300
Actuating Components	$30
Mechanical Components	$200
Electronics	$200
Software development system	$0
Power Supply	$50
Overhead	$50
Total	**$830**

For the most part, our initial budget forecast was accurate. We were able to fund our project through the Wighton Fund, the EESEF and with the initial $50 from the school. We were also prepared to provide a small contribution on an individual basis if needed. As our project stands right now, we have fully utilized the external sources of funding, and we are now starting to burn holes in our own pockets.

3.3. Scheduling issues

Figure 9 outlines the timeline we proposed in September 2000.

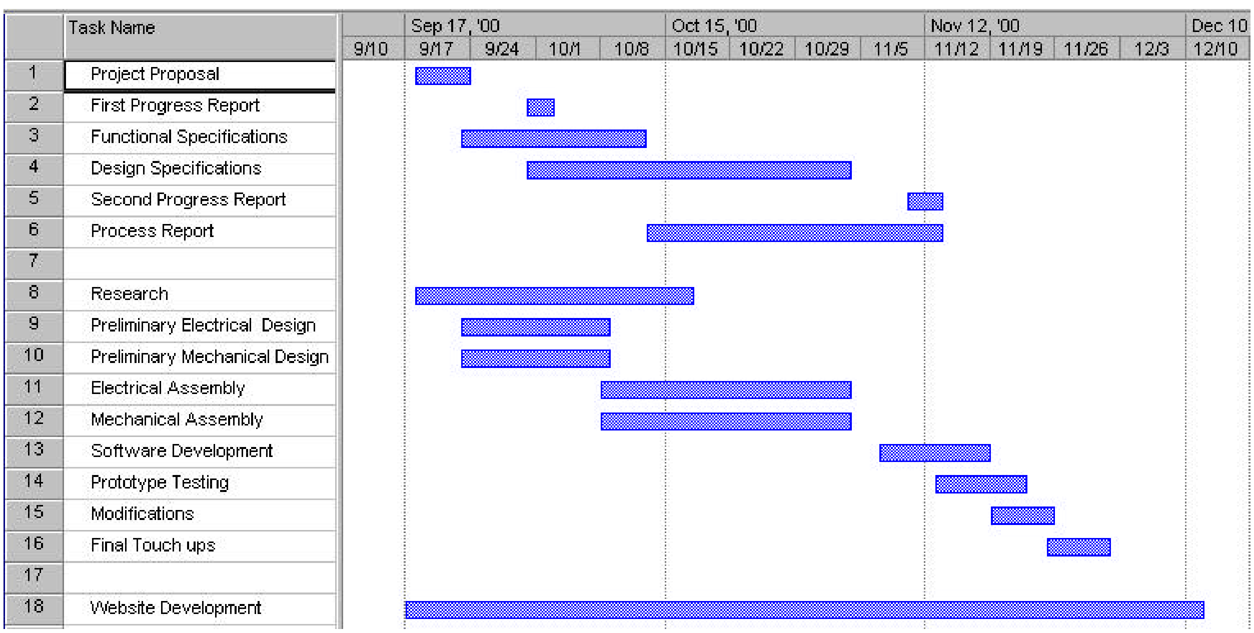

Figure 9. Proposed Timeline in September 2000.

We found that our proposed timeline was overly ambitious, as we did not foresee the amount of research that was required for this project, and we did not expect the incredible time demands of our other courses. We proposed that the research would be done by the end of October, but it was not actually completed until the end of November. The hardware was the most difficult design aspect, because we had so little exposure to mechanical solutions. We spent the first two months thinking about how to implement the hardware coupling, consulting everyone we knew. The signal processing aspect also required a lot of consulting from faculty members who had many different solutions that we had to ponder the pros and cons of each for weeks. The implementation and testing period was grueling, as new problems arose that hindered our progress and kept us from meeting our deadlines. During December, we were still questioning our design choices, and trying others to see if they would work better. Figure 10 shows the actual timeline we realized in developing our project.

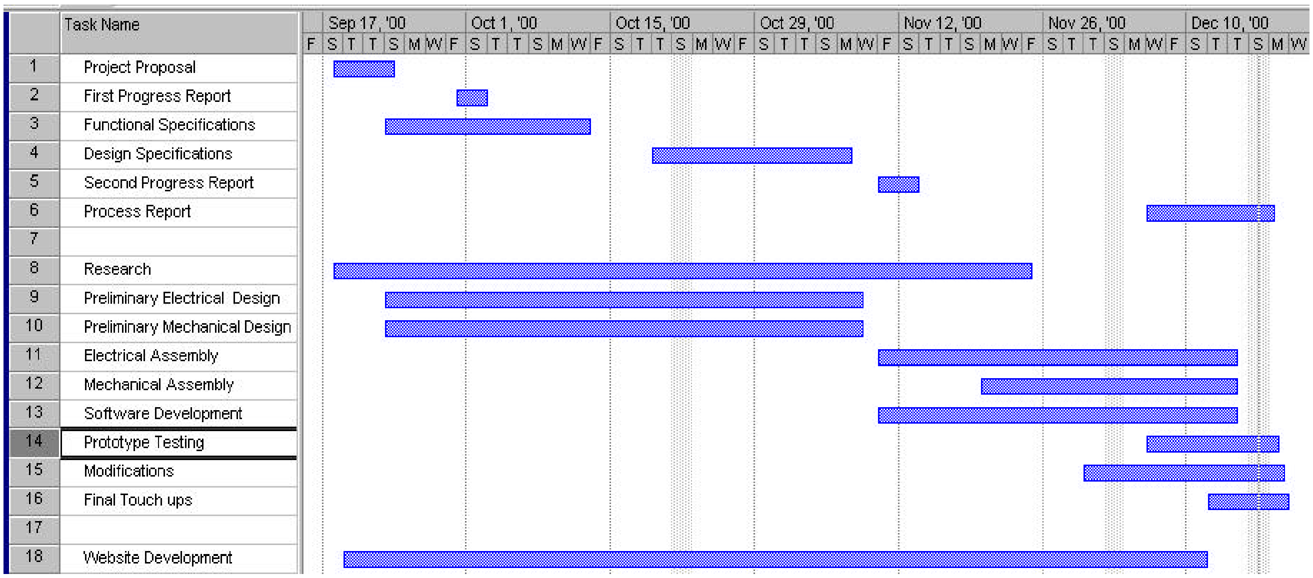

Figure 10. Realized Timeline in December 2000

3.4. Group dynamics issues

The Perfect Pitch Instruments Team worked well together. Group dynamic issues were curbed by the fact that our team members were all rather enjoyable to work with. Early on we chose business titles for all the members, making each other feel important in having a role in the company. In choosing positions, we chose a strong and organized CEO who helped to keep the rest of us on track. Beyond the company titles were the technical roles we would play in building our project. Each of us excelled in different areas, making it easier to entrust certain parts of the project to a certain group member. Reva and Aaron immerged as the signal processing specialists; Terrence became the software guru; Gina put the motor drivers together; Maria built the user interface module; Aaron crafted the mechanical coupling mechanism. But we also helped each other with our respective tasks and learned from each other's skills. Important decisions pertaining to the project were always made at group meetings with all members attending, and everyone always had a say in where the project was heading.

4. What we would do differently

If we had more money, more experience and more time to invest in this project, we would have implemented the following:

1. 6 smaller (yet much more expensive) motors, which are lighter and provide more torque, and which would fit on the guitar body to tune all six strings.
2. A more sophisticated coupling mechanism between the motors and the strings, using expensive universal gears that are more reliable and more flexible to implement. We would also have a custom-made floating bridge on the guitar to suit our implementation.
3. A DSP solution to the signal processing unit, which would have provided quicker and more precise filtering of the pick-up signal. A dedicated DSP would have been very expensive, but would have negated the problems that we encountered with the analog solution. Plus, all six strings could have been strummed and tuned at once. Using a DSP would have also required us to overcome a steep learning curve, as our exposure to digital signal processing has been limited.
4. A better processor, if not a DSP processor, that has a higher clock frequency to carry out all the timing tasks involved. Also, a processor with a more user-friend development system that would have provided more efficient debugging of the assembly code.

We also should have met more frequently during the weekdays to work on this project. As it turned out, we were all bogged down with an unusually heavy and stressful course load that made it almost impossible to dedicate the amount of time we wanted to pour into this project.

5. What we have learned

Maria Trinh, Chief Executive Officer

This project opened my mind to the number of design solutions available to solve the same problem. At first, I had a simple idea worked out in my mind about how we would implement the signal processing problem, but as we discussed the problem, my teammates impressed me with alternate and better solutions, and we even consulted various faculty members for their input as well. Each proposed solution had their own advantages and disadvantages, and I learned that most solutions in life are a result of the careful weighing of tradeoffs, and not because of a lack of a more sophisticated solution.

I also learned about the natural response of guitar strings, their harmonic components, and how a signal from a guitar pick-up could be filtered in so many different ways to detect its deviation from the desired fundamental frequency.

Technically, I learned how to more effectively debounce push-buttons with R-S flip-flops, how to set up an LCD display, and how to code in this particular HC11 environment. I learned about the possibility of multiplying input frequencies using a PLL. I also learned how stepper motors work and how they should be implemented, and about the many creative ways a mechanical problem can be solved.

I also learned that working with self-motivated and diverse people is key to having breadth and depth in a project. Most of our team members did not know each other too well at the beginning of the semester, but after working on this project, we have become friends and have shared a lot of laughs.

Terrence Yu, Chief Operating Officer

The Top Ten Things Terrence has learned…

10. The inner workings of the HC11
9. Electric circuit design and implementation
8. Assembly language
7. You can’t push on a rope
6. Documents rule!
5. Putting ammeters in parallel is not such a good idea
4. Things always take longer to do than expected
3. Nothing ever works the first time
2. Did I mention assembly language?

And the number one thing Terrence has learned
1. Jimi Page plays a mean guitar

Reva Vaze, VP Engineering Operations

Through the past 4 months of grueling project development I’ve learnt a great deal about teamwork, hardware debugging and guitars. I also learned the importance of proper and effective communication in order to get a job done and on time. Through the circuit design and testing, I was able to use knowledge gained in the classroom, and apply it to a real world application. I realized that coming up with a good design solution is very time consuming even if at first the problem seems trivial. Also, unexpected problems always come up and even though you may not anticipate them, you should definitely be prepared for them.

I enjoyed working with the team, and learned quite a bit from every member. I found that everybody thinks in a different way, and that everybody’s ideas are valuable, each having their unique features. All in all a good time was had, and I would rate this experience with 2 thumbs up.

Gina Millar, Chief Financial Officer

Over the past semester and the duration of ENSC 340 I have acquired skills in a multitude of areas. Technically, as the person responsible for the motor control circuitry and software, I gained an in depth understanding of the practical application of stepper motors. I have also learned the important skill of working closely with a group of people to achieve a common goal.

As I mentioned, most of my technical knowledge was gained in the area of motor control systems. Having no previous experience with motors meant it was necessary to research almost every aspect of motor control that could be relevant to our project. As a result I learned about the stepper motors themselves, their drive circuitry including H-bridges, and about interfacing them with a micro controller, in this case the HC11. It was interesting to see knowledge from both my digital and analog design courses come together in the final design.

Of more importance are the group dynamics and time management skills that I have acquired. Working on an unmonitored project such as this while pursuing a full course load really tests your ability to manage your time effectively. Also, this project allowed me to experience the process of making something as a team. Specifically, of the importance of making decisions as a group, and being patient and understanding with each member of the team.

Aaron Schellenberg, Chief Technical Officer

This project has taught me many things, from technical know-how to general project management and implementation. On the technical side of things, I have learned and refreshed various principles of analog design. Since I haven't yet taken ENSC 425, this project has allowed me to gain some insight into certain analog topics for the first time, such as switched capacitor filters and phase-locked loops, even though we didn't end up using the latter in our final design. This project has also peaked my curiosity as to how a DSP solution would have compared to our analog design and performance. Another key thing I have learned is that simpler solutions are usually better, and that a simple solution in theory does not always turn out to be simple in practice. On the project management side of things, I have learned that it takes very skilled foresight to develop a project proposal that actually gets completed on time and as initially planned. For my next Engineering project, I will definetely consider more carefully certain barriers that could prevent me (us) from completing the project as planned, such as availability and cost of parts, difficulty and feasibility of outlined proposal, and time management. Finally, I have learned that it is possible to have good group dynamics. I believe that our group has functioned well together over the semester, and I would not hesitate to work with my Perfect Pitch teamates again in the future.

6. Conclusions/Recommendations/Future work

There is a large amount of work that has yet to be done in order to make Perfect Pitch's self-tuning guitar a marketable product. Much enthusiasm exists among the members of Perfect Pitch regarding the future of our project, and many ideas are circulating for improvements to be made during a second project course or perhaps as a thesis project.

We believe that future ENSC courses, such as ENSC 429 (DSP), will provide us with the necessary skills to take a more practical approach to our project. We envision a single digital single processor to replace all analog filtering and control algorithms. Additionally, it may be possible to control the six motors in parallel with a high-speed DSP, reducing the total tuning time required for all six strings to under a second. A completely digital solution would be a key step in our ultimate goal to encase all components into the guitar body.

In order to realize this goal, we must select stepper motors that are more suitable for our application. Internet research has shown that significantly smaller motors exist with the necessary torque ratings for our needs, however, these motors are quite expensive and have long ordering lead times, which made them impractical to use for our initial prototype in 340. The mechanical bridge interface must be redesigned in order to bring our product to market, however, since we have a lack of mechanical design experience and know-how, this task would likely be contracted to a mechanical design specialist.

Another possibility for our project is to leave the electronics as an external unit to be used in a chain of guitar effects boxes or “foot pedals”. This popular effects configuration propagates the guitar signal through a series of effects boxes and allows the guitarist to easily select the desired effect (e.g. heavy distortion, echo effect, reverb, etc). Incorporating the tuner electronics into an external box would accommodate the existing usage behaviours of many guitarists.

Many possibilities exist for our self-tuning guitar, and Perfect Pitch Instruments is excited about the future of our project (which will eventually have an actual product name).

Special thanks to Gary Houghton, George Austin, and Patrick Leung for their invaluable help and their patience with our efforts.

Appendix A

Signal Processing Unit