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SYSTEM DYNAMICS FILTERING LABORATORY

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I. Abstract

Project 13361: System Dynamics Filtering was conceived as a way to provide the Mechanical Engineering department with a hands-on and interactive laboratory experiment that would introduce the concepts of filtering in its various forms and be accessible and engaging in its completion. The goal was to provide the customer (ME department) with a full suite of hardware and software tools that could be coalesced into a 2 hour activity involving work with hardware audio filters software image processing filters. Providing an easy to grasp yet fundamentally complete understanding of the nature of the various filters was the primary task.

Major design considerations include being storable, easy to maintain, relatively cost efficient, including multiple areas of interaction with the students, and a significant amount of hands-on activities. The hardware component must be robust and relatively user-proof, while still providing ease of access for modification and student engagement. The software portion includes MATLAB based interaction and that is self-contained and straightforward to use. All components of this project are to be usable within the confines of the actual System Dynamics electronics studio classroom, equipped with DC power supplies and computer workstations with standard engineering software and data acquisition capabilities.

II. Technical Introduction

Filters are used in a variety of configurations to perform a multitude of tasks within the engineering world. Whether used to clean up the biomedical signals from an EKG monitor or to select specific frequency bands on a military grade radio, they provide an invaluable tool to today's design engineer in implementing frequency-based solutions. Manipulation of different frequency bands, including the electromagnetic spectrum for radio signals as well as the human range of audible sound frequencies, allows the designer to narrow their range of inputs or selectively determine the desired output.

In general, hardware-based electrical filters can be defined by in terms of their response to alternating current electrical signals in terms of a band of frequencies denoted by either radians per second (r/s) or cycles per second (Hertz, or Hz). The major types of filters used include low-pass, high-pass, band-pass, and band-reject filters. Low-pass filters will pass lower frequencies (defined by a cutoff frequency) and attenuate higher frequencies. High-pass filters do the opposite, passing the highs and attenuating the lows. Band-pass filters select a band of frequencies to pass through, and attenuate all others. Band-reject filters will severely attenuate a specific band of certain frequencies and pass all others.

Software-based image processing filters are used for a variety of applications, and generally include matrix mathematics to manipulate stored image files. These matrix filters (usually 3x3) are applied to every pixel in the image and can radically alter the image, whether it is through sharpening, blurring, or edge filtering. All methods of picture editing use these base techniques, and while abstract and difficult to conceptualize, the results are very obvious to the human eye and easy to digest. In addition to image editing or processing, these techniques can be used for image storage and compression, printing manipulation, and for passing messages within an image among other things.

III. Project Design Overview

The critical customer needs for this project were hardware and software components that demonstrate the power of filters in both domains that are both easy and simple enough to use while still provide maximal learning capabilities and flexibility. The design team settled on an audio signal processor implemented in hardware and an imaging processing Graphical User Interface.

The mechanical and electrical components comprise the main deliverable and fulfill the need for an interactive piece of hardware to complement learning. This hardware assembly includes 5 major components; the case and mounting solution, the interface panel, the printed circuit board, the ISD recording circuit, and the breadboard. The layout of the given components is shown below:

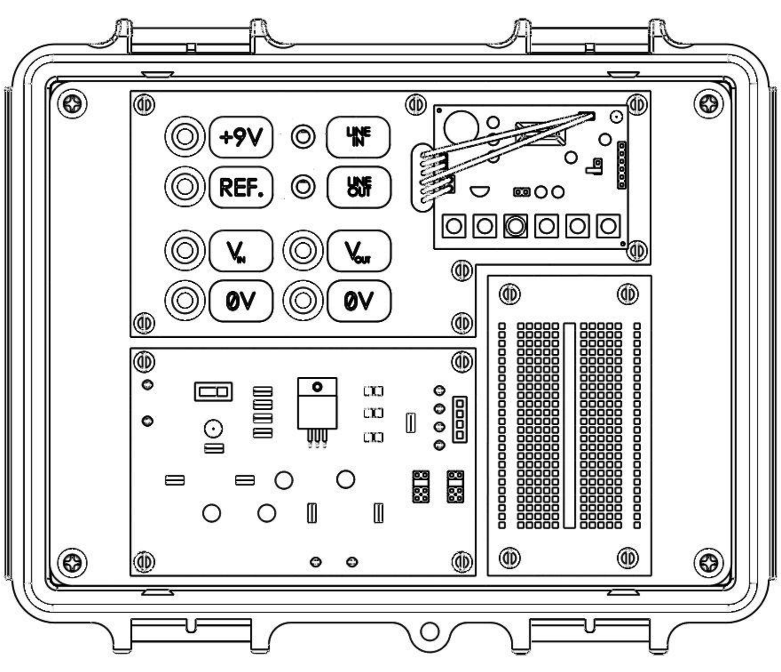

Figure 1 – Major Component Arrangement

The software deliverables consist of several MATLAB script files (M files) that operate a GUI that includes multiple filtering options and associated image sizing and process functions to allow for flexibility of input options. The GUI is simple to use and can easily provide filtered outputs to compare to given inputs and allows for an intuitive approach to explore the various methods of image processing.

IV. Mounting and Casing Specifications

The container and housing solution consists of a commercial off-the-shelf Bud Box made of ABS plastic with pre-drilled mounting holes. The electrical components and routing hardware were mounted to a separate piece of 0.25″ plexi-glass (referred to as the mounting plate) which provides for an isolated mounting solution for assembly simplification. The component assemblies are mounted on stands-offs to the plate which allows for raised access and easy maintenance. The mounting screws are 4-40 ½″with rubber grommets used as spacers on the PCB assembly. The ISD recording board (see section VII) was mounted directly to the interface panel with super glue and strips of rubber to serve as a shock absorbance system and allow for flexibility.

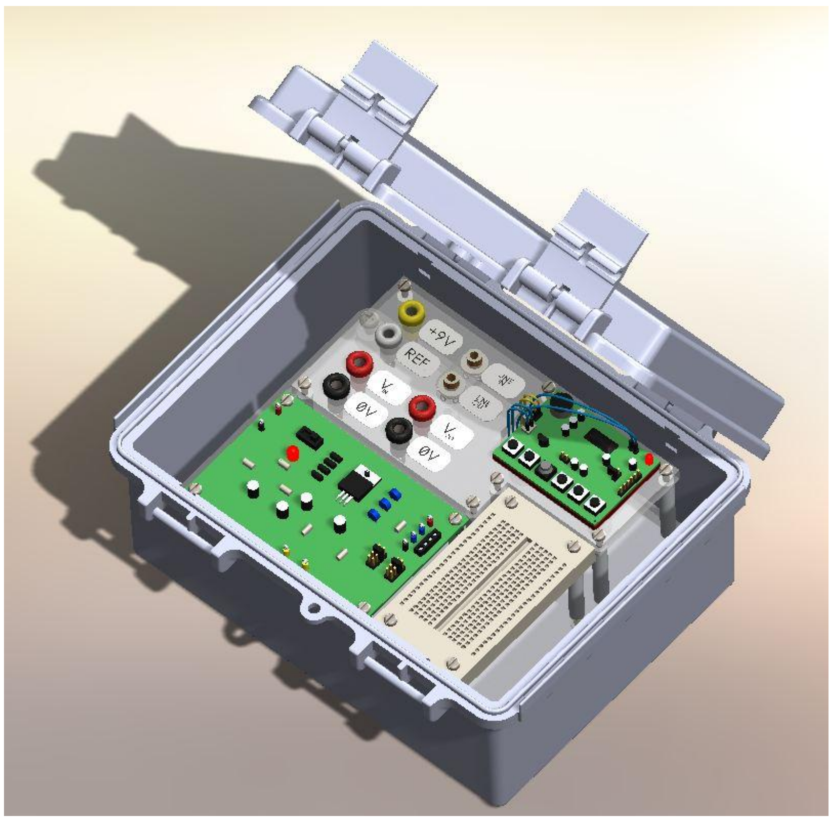

Figure 2 – Proposed Casing Solution

V. PCB Design Specifications

Our printed circuit board consisted of a two-layer (top and bottom) copper trace board with FR4 laminate of 1/16th inch thickness and utilizes only through-hole components, including 6 resistors, 8 capacitors, 4 diodes, a power regulator, and various jumper posts and headers. It consists of four major sections; the power supply module, the built-in analog filter module, and the various harnessing connections to the interface panel and breadboard.

The power supply module contains diode polarity correction, an LM7805 5 volt power regulator, an LED indicator light for operation notification, and assorted filtering capacitors. The input voltage to the PCB is 9 volts, and can be supplied with a laboratory DC power supply (intended supply method) or through a 9 volt battery and adapter. The four diodes are arranged to correctly route the power polarity even when the device terminals are hooked up in the reverse configurations, which prevents damage to the board through improper wiring. The voltage losses across the diodes required a higher input power supply, but as 9 volts is standard, that was not an issue. The regulator takes an input voltage of approximately 7.4 volts (2x diode drops) and converts it to a steady 5 volt output for the ISD and connection to the breadboard for various uni-polar op-amp configurations.

The analog filter components are laid out according to the general circuit diagram configurations seen in a standard schematic, as this helps the students connect the conceptual and theoretical side of the topic to the actual implanted devices. They consist solely of resistors and capacitors in standard first order low-pass, high-pass, and band-pass configurations. The band-pass filter is actually a cascaded low-pass and high-pass filter instead of an alternate and more confusing (albeit more efficient) topology, which maintains the conceptually intuitive model previously established. Jumper posts JP1 and JP2 are used to select which signal path is to be used for the output audio (built-in filters, breadboard configuration, etc).

The routing on the PCB is its main function and serves to power the recording circuit and connect to the breadboard and interface panel. Standard 0.1 inch pitch jumper posts are used to connect with female to male wires on the interface panel, allowing a semi-permanent assembly configuration. A four way female SL connector interfaces with the breadboard, as this allows the use of generic laboratory wires to and from the adjacent breadboard. The connections to the ISD recording circuit are simply female to female wires that connect on the same jumper posts as before, and allow for detachability and isolation of the circuits during assembly.

VI. Interface Panel Design Specifications

The interface panel provides a stable and space-efficient means of interacting with the hardware filter module, as it isolates all the major connection points and allows for easy routing and wiring which freed up space on the circuit board. There are 4 major connection points on the interface panel, including the DC power supply connections, the audio line-in and line out jacks, the function generator in banana jacks, as well as the oscilloscope banana jacks. SchmartBoard female to female wires provided the majority of the wiring solutions, and the pins on the ISD and PCB were selected/designed to be compatible with them in mind.

The power supply jacks are yellow (power) and white (ground) banana jacks that are directly related to the coloring scheme on the Instek DC power supplies that are used in the electronics studio classroom where the laboratory activity is held. This reduces wiring complexity the students would encounter and allows for a color-coordinated approach for simplicity.

The audio interface section consists of 2x 3.5 mm audio jacks, with one each for input and output. These are standard headphone size jacks, and are designed to accommodate mono signals. For design simplicity, only one channel of a stereo input/output is used, as this still reasonably demonstrates the desired filtering concepts. A 3.5 mm male to male cable is included with the lab kit, as this allows students to plug in directly from a smart phone or computer and stream audio or music; this provides for excellent material to demonstrate filtering characteristics.

The function generator in and oscilloscope out jacks provide a means to interact with the other lab hardware, as pure tones could be inputted through the function generator or the filtered and unfiltered outputs could be viewed on an oscilloscope. This allows for another level of interaction and provides flexibility in designing experiments to be conducted with the hardware. The line in audio jack is directly wired to the function generator (with a similar configuration for the audio out and oscilloscope jacks), so only one can be used at any given time, which must be observed. The oscilloscope out can be used in conjunction with any of the other inputs and outputs, as it provides minimal load on the circuit.

VII. ISD Recording Circuit Specifications

The ISD-1760 circuit board is a general solution to the problem of recording and playing back audio content. It is a self-contained and total package, with an on-board microphone, amplifier, and recording circuitry. As a whole, it allows for processing of feed-through audio signals that can come from a majority of standard electronic devices, balances them, and then passes them to the board with the right level of amplification to be filtered when the correct jumper is applied. The recording function allows the user to record any voice or sound at the push of a button and is extremely simple to operate. This provides an option for groups with no external audio devices to provide sound to process.

VIII. Breadboard Specifications

The included breadboard is mounted in a similar fashion to the rest of the components and provides a clean palette with which to paint the wonders of custom filters into the tapestry of understanding. The PCB supplies 4 connection points to the breadboard; +5 Volts, Ground, Signal In, and Signal Out. The power and ground connections are for wiring up operational amplifiers for use in active filter circuits. Note: as the ISD centers all audio signals in the positive voltage range and produces no negative voltage, there is no need for a negative power supply to the operational amplifiers in any possible configuration. The Signal Out connection point provides the unfiltered signal to the breadboard, while the Signal In connector receives the filtered output of the custom filter. The 'Out' and 'In' refer to the signal from the 'perspective' of the PCB, as the signal first comes out of the breadboard, is filtered, and then returns to the PCB to be routed to the output.

IX. Analog Filter Design Specifications

The purpose for providing built-in filters rests upon the comparison basis that can be established with go-to references that the students can use to audibly differentiate the major filter archetypes. Switching between the given low-pass and high-pass gives an easily relatable experience to the student, while the given filters be even be compared to custom made filters on the breadboard. For example, one might use the 1st order RC low-pass filter in a passive configuration on the board and then construct the same pole frequency but with an operational amplifier buffer circuit, or even a two-pole version of the built-in configuration for a sharper cut-off frequency.

The filter poles (in hertz) can be calculated by the following equation:

$$F = (2 * \pi * R * C)$$

where R and C are in given Ohms and Farads, respectively. The poles are calculated regardless of the topology, which is the only characteristic that determines the actual frequency response. The different roll-offs to high or low frequencies depend strictly on the arrangement of the resistor and capacitor with respect to the output. For reference, the built-in filters consist of a low-pass filter with cutoff frequency of 1.6 kHz, a high-pass filter with cutoff frequency of 100 Hz, and a cascaded band-pass filter configuration with a low frequency pole of 500 Hz and a high frequency pole of 100 Hz.

X. Image Processing Design Specifics

The main goal of the software processing section of our design parameters was to demonstrate and facilitate the understanding of two dimensional filtering through image processing. Since MATLAB has many built in functions to do basic image filtering, MATLAB was a key choice of software to use. In the software component of P13316 Filters Laboratory, a user is able to choose from a custom image and apply 4 basic filters. The four filters are High Pass, Low Pass, Gaussian Blur, and an Edge Detection filter. Both the High Pass and Edge Detection methods are similar types up filters, as they target high frequency components of the image. High frequencies in an image consist of sudden changes, such as edges and corners. The Gaussian blur and low Pass filter are two filters that are both approximations of the same type of filter. These remove the high frequency components from the image, thus smoothing the corners and edges of the image.

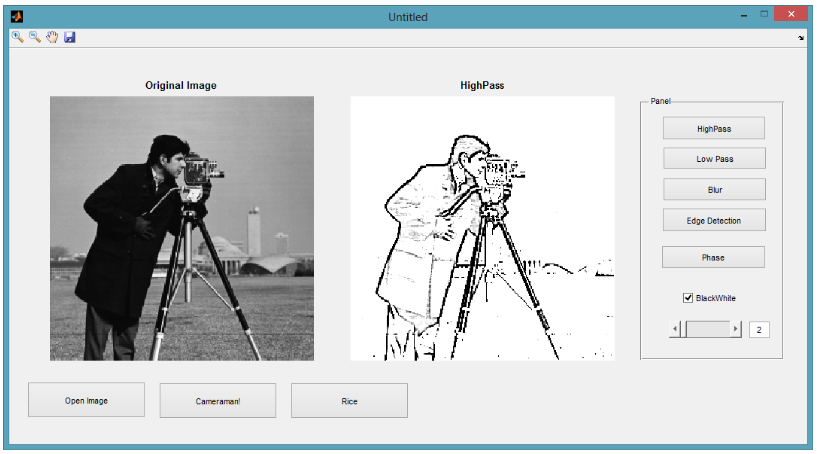

Figure 3 – Software GUI Example Image

The above figure shows the layout of the software GUI. The user is able to pick their own image to filter, or has the option for multiple predefined images. These are stock images in MATLAB, which are commonly used for image processing. The GUI can accommodate both color and black and white images. To help the user visualize the changes, the user has the option in zooming in on the image and converting the color image to black and white. Each pushbutton applies that type of filter to the image. Moving the slider in the bottom right corner, varies the intensity of the filter. This is supposed to represent the equivalent of moving the pole location in the one dimensional case. If this was a color image, the user would have the option of converting the image to black and white by using the Black and white push button.

XI. Support Documentation

As the exact scope of this project is only for exploration of the concept and with intent for mass production in the future, support documentation must be provided to allow for the Mechanical Engineering department to reproduce the complete system. This is a crucial part of the project, as the design team is only responsible for the creation of the prototype unit, and exacting technical reproduction is required en masse. The major documentation includes an assembly document, testing verification, an operator's manual, and a lab activities manual.

XII. Conclusions, Recommendations, and Acknowledgements

The testing process proved uneventful, with all of the major requirements being fulfilled. As this project was less about stressing technical specifications and more about relating to the specifics needs of our customer and designing an experience for the students, we had little in the way in terms of testable parameters. Our major considerations were mostly cost efficiency, prompt delivery, and ease of storage and maintenance, none of which have any specific tests required for them. The testing and verification process mostly involves basic and correct operation of the device in a normal operating environment.

During the exploration of this project, several problems were discovered that could lead to further improvements. Multiple revisions were made to the PCB for future development, some of which include extra spacing towards the edges of the board for easier mounting, rerouted speaker connection points for ease of access to the ISD wiring, and modification of test point mounting. These changes allow for a tighter design with easier assembly. Code improvements include the addition of a skeleton filter that can be modified as needed to implement any desired matrix filter within the context of the GUI. The proper framework and formatting is supplied, with generic variables and functions that can be renamed to produce another unique filter. Given the hardware connection possibilities, the output from the board can be sent to a Data Acquisition (DAQ) device that can receive the filter the waveform data and deliver it to the computer for processing. This allows the filtered or unfiltered waveform data to be visualized or manipulated on the PC workstation, which allows for flexibility in laboratory exercise development.

While ordering the project hardware components, it was discovered that the desired case, an ABS Bud Box, was an out of stock item, which meant that it would not be delivered until well after the completion of the project was scheduled. As a result, the decision was made to maintain usage of the existing out of stock box and develop to fit that with the final result of ordering the box when it was available. The out of stock casing solution provided the easiest means of design in terms of limiting modifications and was perfectly sized and priced for the application, and finding an alternate was deemed unnecessary. Assembly modifications were minimized and only a slight delay in physical realization was required to carry through with the current solution.

Our group would like to first thank our faculty guides for providing design suggestions and helping us develop our product in an organized and thoroughly documented manner. Further credit goes to our customers in the Mechanical Engineering department, primarily Dr. Mark Kemspki and Dr. Kathleen Lamkin-Kennard. They provided invaluable insight in sculpting their required solution, and without their diligent input and constant feedback, we would be lost. We would also like to thank Dr. Elizabeth DeBartolo, Dr. Agamemnon Crassidis, Dr. Jason Kolodziej, and Dr. Marca Lam who participated in the design process as well. Special thanks go to Dr. Vincent Amuso and Dr. Sohail Dianat for their technical assistance with the image processing. Finally, our thanks go to Peter Goebel for his continued assistance with multiple aspects of our project.

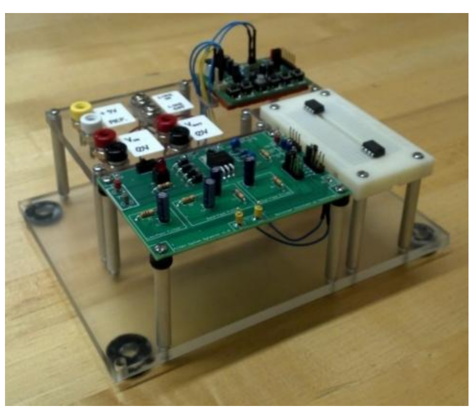

Figure 4 – Completed Assembly (Minus Casing)