Design of a 4-bit Digital to Analog Converter

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***Abstract* - A Digital to Analog Converter (DAC) takes a binary, digital input signal and converts it into an analog form, allowing for applications in A/V signal processing, motor control, and automotive infotainment systems. While a variety of DAC architectures allow for slight variations in features and approach, our paper offers a low cost, simple DAC solution with 16 bits of data and documentation of the development process to support Cal Poly's educational objectives. With an arduino as the CPU, we connected an AC source to an analog-to-digital-converter (ADC) to sample a 1khz sine wave with a 5V peak-to-peak voltage and 2.5V offset. The ADC translated this wave form into a 4-bit digital value which was then processed by our custom-designed DAC to reconstruct the analog signal. This report encapsulates the entire development process from the initial LTspice simulation to final testing, development, and analysis offering a comprehensive resource for understanding DAC technology.**

Keywords - DAC

I. INTRODUCTION

A DAC is an electronic circuit that converts digital signals into analog signals. They can do this by taking binary bits and transforming them into an analog voltage/current [1]. DACs are most prevalent in video signal processing, motor control, telecommunications, automotive infotainment, and control systems. They have become an irreplaceable part of the modern era [2].

There are several variations of DACs for different applications. The string DAC consists of 2N equal resistors which each correspond to a specific digital input code which generates an analog output signal [3]. Another example is the MDAC [4] (Multiplying DAC) which combines a string DAC with an operational amplifier to adjust the output voltage based on the digital input code. All these DACs share the similar objective of transforming a digital signal into an analog signal. However, each DAC has its own features and methods of achieving that goal.

This paper offers a low cost solution for simple DAC applications and contributes to the education objectives of Cal Poly by allowing for hands-on application of theoretical principles. Throughout this project we incorporate general introductory information for electronics and manufacturing with our experience building the circuit and the lessons we took from it. With our results, others can troubleshoot from our documented failures and compare their results to improve the quality of their work.

This paper will follow the development process of our circuit. We will begin by examining the LTSpice model and simulation of our 4-bit DAC. This is followed by the process of creating our PCB schematic and board layout to be fit for manufacturing. Finally, we examine our testing procedure for ensuring proper PCB functionality and our findings from the process.

II. 4-BIT DAC DESIGN AND SIMULATION

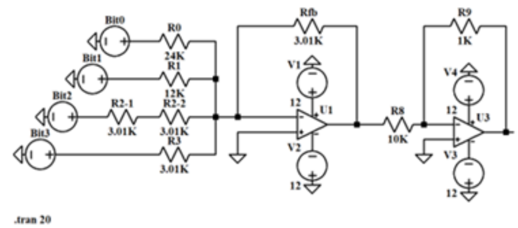

Figure 1. LTSpice Schematic

We used LTSpice to design an initial schematic of our DAC, shown in Figure 1. The placement of the components was not arbitrary by any means. We used 4 inputs for our DAC, representing 4 bits, allowing for 16 discrete input combinations. By using a two stage op amp configuration, we can vary the output voltage using a sum of the input voltages weighted by bit value. The first stage of our DAC is an inverting summing amp which weights the input voltages against a feedback resistor to give each bit its own discrete voltage value. The feedback resistor has a value of 3.01kΩ, while the four bits resistor values from 0 to 3 are: 24kΩ, 12kΩ, 6.02 kΩ, and 3.01 kΩ. As Bit 3 is the most significant bit, it has a feedback/ input resistance ratio of 1, while 2 has a ratio of ½ and bits 1 and 0 have ratios of ¼ and ⅛ respectively. Thus, Bit 3 causes the greatest increase in analog voltage while Bit 0 causes the least.

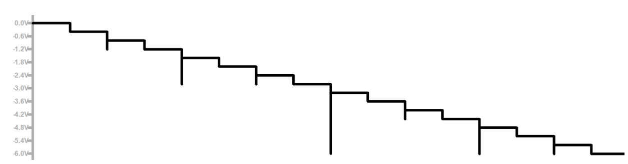

Figure 2. LTSpice Simulation of U1 Output

However, as shown in Figure 2 the output from the first stage of the DAC produces negative voltages. In order to correct the inversion and amplify the output voltage we added a second Op Amp as an inverting amplifier with a feedback to input resistance ratio of 10/1. Therefore, the final output, shown in Figure 3, is a stepped positive output that increases in voltage according to the binary total with 1/10th the voltage as the first stage.

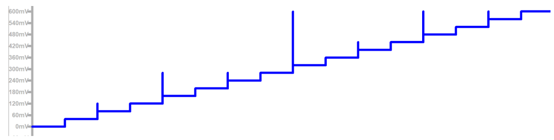

Figure 3. LTSpice Simulation of U2 Output

III. PCB Design

In this section describe your PCB design. Include your Eagle schematic, your BOM (quantity, part description, part name, unit price) , and your Eagle board layout. Give all Figure/Table labels and captions and describe and refer to them within the text. Figure labels go below figures, table labels go above tables. Put figures and tables in text boxes (with no border) to make them easy to move around the document.

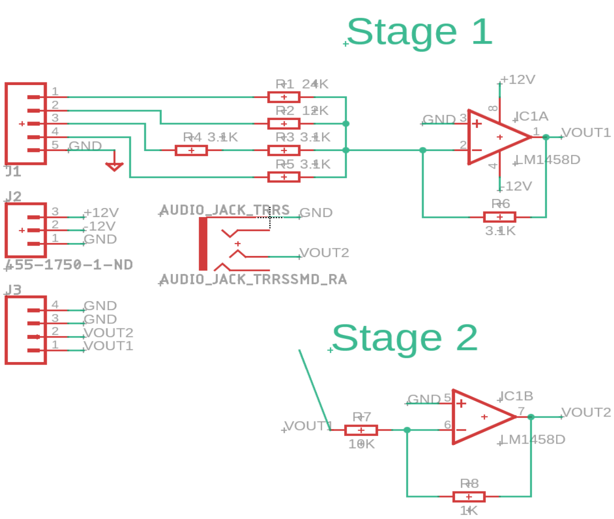

Figure 4. EAGLE PCB Schematic

We used Eagle in Autodesk Fusion 2.0.1 [5] to design the PCB for our 4-bit DAC circuit. We began by creating the schematic shown in Figure 4. To minimize production costs through our manufacturer OSH Park we opted to keep our PCB to a 1" x 1" square. In order to reduce size we used 1206 size surface mount components for all resistors and other surface mount components. The circuit is powered by a three pin header for the +/- 12V rails and ground. A 5 pin header receives the four DAC inputs and allows for a common ground to the Arduino. Finally, a 4 pin header connects the 2 outputs and allows for an oscilloscope reference ground point.

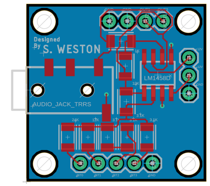

Figure 5. EAGLE 2 Layer PCB Board Layout

From the schematic, we generated a 2-layer PCB board layout as shown in Figure 5. First, we placed the components, starting with the pin headers and audio jack in order to make the future board connections as simple as possible. Then, we placed the op amp in a central location with the resistors around it. The resistors were oriented to limited trace length, minimizing the amount of interference on each signal. After optimizing placement, the traces were all routed manually to minimize the trace length, while ensuring perpendicular trace to pad connections and minimizing acute angles and the associated risk of acid traps.

A ground pour was used on the bottom layer of the board to decrease impedance with the added benefit of dissipating heat and reducing the complexity of traces by allowing for direct via connections to ground close to the relevant pads. Finally, we added mounting holes to the corners of the board to allow it to be mounted to a 3D printed enclosure. After routing the design, we used EAGLE's design rule check tool with the design rules file provided by OSH Park to make sure the routed design met all the necessary fabrication specifications.

IV. PCB Assembly and Testing

Figure 6. Bill of Materials

Part ID(s)	Quantity	Type	Value	Cost
R1	1	SMD 1206 Resistor	24 kΩ	$0.10
R2	1	SMD 1206 Resistor	12 kΩ	$0.10
R3, R4, R5, R6	4	SMD 1206 Resistor	3.1 kΩ	$0.40
DAC PCB	1	OSH Park	~~NA~~	$5.00
Dual Op-Amp	1	LM358	~~NA~~	$0.44
Audio Jack	1	Surface Mount	~~NA~~	$0.97
Total	-	-	-	$7.01

The total cost for our PCB worked out to $7.01, itemized in Figure 6. We received all the electronic components from the Cal Poly Student Project Lab and ordered the PCBs from OshPark, a budget PCB fabricator. The PCB fabrication also resulted in 2 spare boards. The DAC was assembled in two stages, beginning with reflow soldering of the LM-358P and

SMD resistors. Next, we hand soldered pin headers and the audio jack, as reflow soldering would melt their plastic enclosures. The final PCB can be seen in Figure 7.

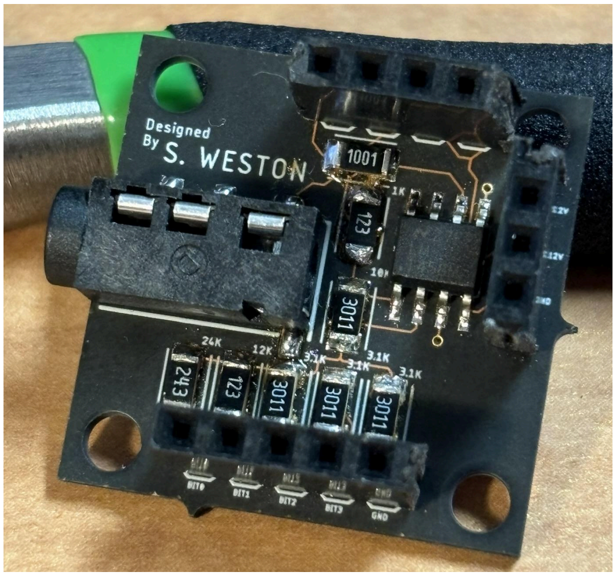

Figure 7. Assembled PCB

However, when tested the PCB would not output consistent signals, regardless of input. After testing individual sections of the circuit using a continuity tester we determined that the issue was a faulty 3 pin header. After replacing the 3 pin header the final circuit was functional. We powered teh board with a +/-12V supply and checked the board's proper operation using a binary counter. As shown in Figure 8, our output for the first OP Amp matched the predicted values from the simulation.

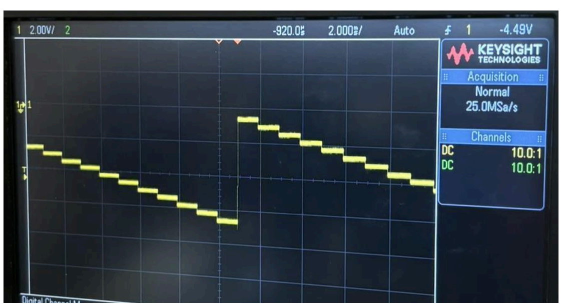

Figure 8. PCB Output with Binary Counter Input

The scoped values are compared to the simulated values in the following table**, Figure 9.**

Bit Input	Simulated Value (mV)	Real Value (mV)
0000	0	1620
0001	-401	1512
0010	-802	1246
0011	-1203	768
0100	-1600	432
0101	-2000	230
0110	-2402	50
0111	-2803	-178
1000	-3200	-480
1001	-3601	-750
1010	-4002	-1250
1011	-4403	-1550
1100	-4799	-1630
1101	-5201	1620
1110	-5602	1403
1111	-6000	1298

The outputs of the real circuit are all shifted up by an offset of approximately 1.5V, causing the output signal to reflect a waveform oscillating above and below ground. However, the intervals between the steps remain the same, showcasing the implementation of the binary logic.

V. 4-bit DAC Application

We first applied the DAC to convert a 50 Hz 200 mVpp 0.5V offset sine wave shown below in Figure 9.

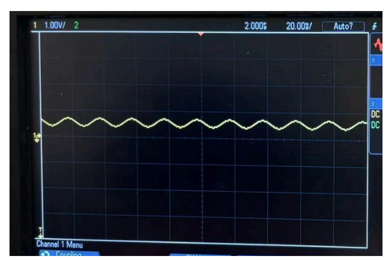

Figure 10. DAC Sine Wave

This waveform near identically matched the input signal, being indistinguishable from the input signal. After a successful first application we applied the DAC to the song Dancing in The Moonloader by Toploader seen below in Figure 10.

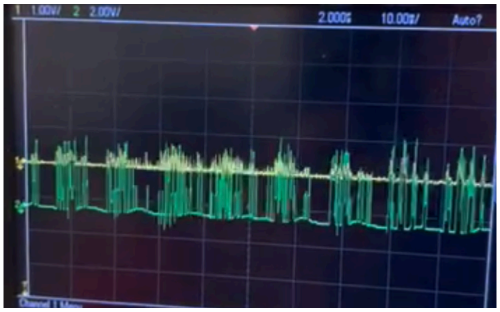

Figure 11. Dancing in The Moonlight Output Wave

We were able to capture low-resolution audio which became simple tones and noises through the songs input to the level shifting circuit's audiojack. To the human ear there was notable noise and some distortion, however the melodies remained distinguishable and the higher notes were clear.

By converting binary inputs into corresponding analog voltages or currents, DACs facilitate a myriad of applications, from video signal processing to motor control, and from telecommunications to automotive systems. However, due to the 4-bit resolution of the input, the output audio had a noticeable reduction in quality. Therefore, for future applications, increasing the bit rate would be a simple solution to noticeably increase the sound quality. Furthermore, eliminating the level shifting circuit and handling the binary signal directly would reduce failure points and added noise.

VI. CONCLUSION

This experiment illuminated the critical role of Digital-to-Analog Converters in the seamless integration of digital technology with real-world analog applications. The exploration of DACs, from the basic string DAC to the more complex Multiplying DAC demonstrates their diverse capabilities and the unique features brought to various technological arenas.

This project offers a low-cost DAC solution that not only meets simple application requirements but also furthers the educational mission of Cal Poly. By melding theoretical knowledge with practical experience, this work stands as a testament to the value of hands-on learning in the field of electronics and manufacturing.

The development narrative of our 4-bit DAC—from the initial LTSpice simulation to the final PCB testing—provides a comprehensive account of the design and manufacturing process. The challenges faced and the knowledge gained have been candidly documented, offering a roadmap for others to follow and build upon.

As we reflect on the journey of creating a functional DAC circuit, the lessons learned extend beyond the confines of this project. Implementations such as improvement of power efficiency and miniaturization of DACs is a necessity as devices continue to shrink in size. It is our hope that this report will serve as a valuable reference for future endeavors in the ever-evolving landscape of electronic design.

ACKNOWLEDGMENT

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REFERENCES

[1] What is a DAC and How Does it Work https://www.electronicshub.org/what-is-dac-and-working/

[2] Demystifying Dacs: What is a DAC? https://www.stozzaudio.com/home/what-is-a-dac

[3] Integrated Analog-to Digital and Digital to Analog Converters. Link

[4] Multiplying DACs. Link

[5] EAGLE PCB Design. https://cadsoft.io/

[6] Digi-Key Electronics. http://www.digikey.com/

[7] Osh Park – An electric ecosystem. https://oshpark.com/

[8] Jeremy Blum. "Tutorial 1 for Eagle: Schematic Design." https://www.youtube.com/watch?v=1AXwjZoyNno&t=1581s June 14, 2012.