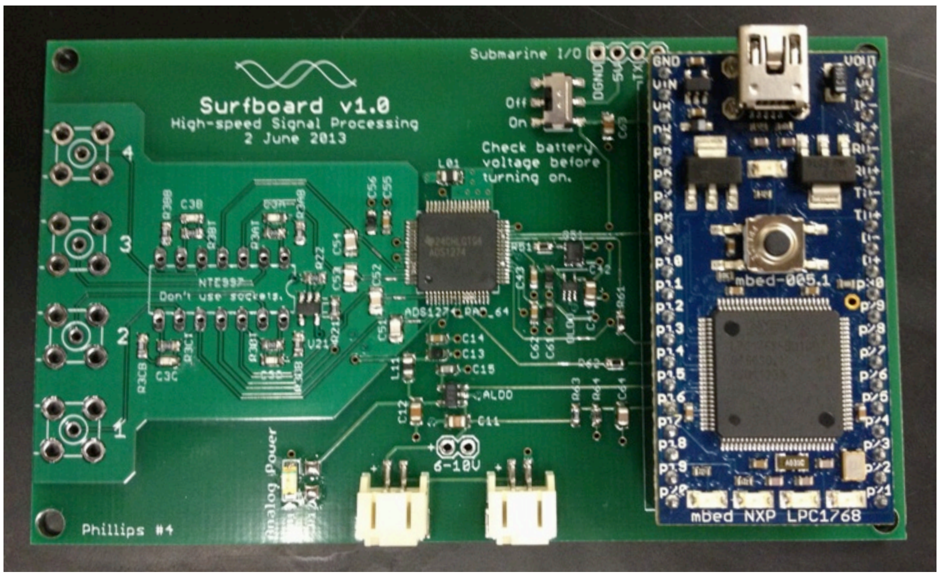

Surfboard: A High-Speed Digital Signal Processing Platform

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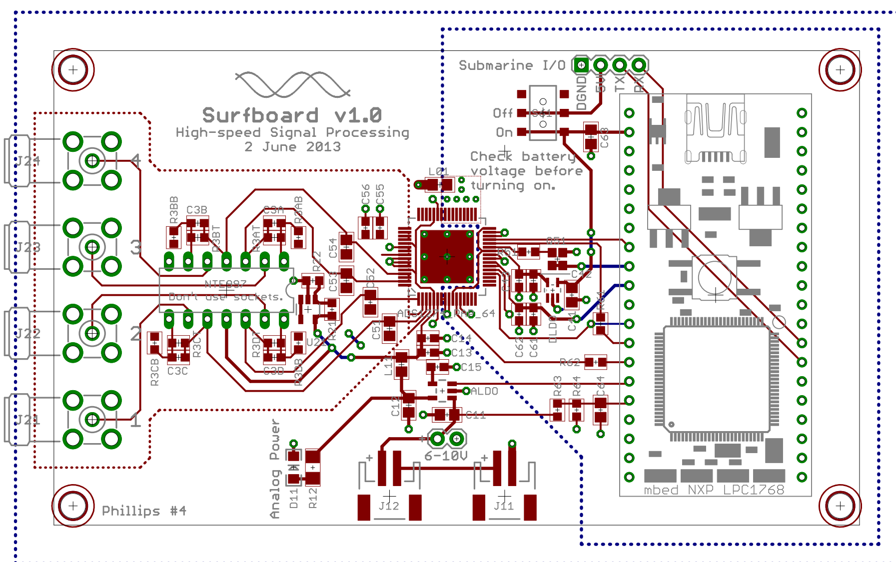
AP Physics

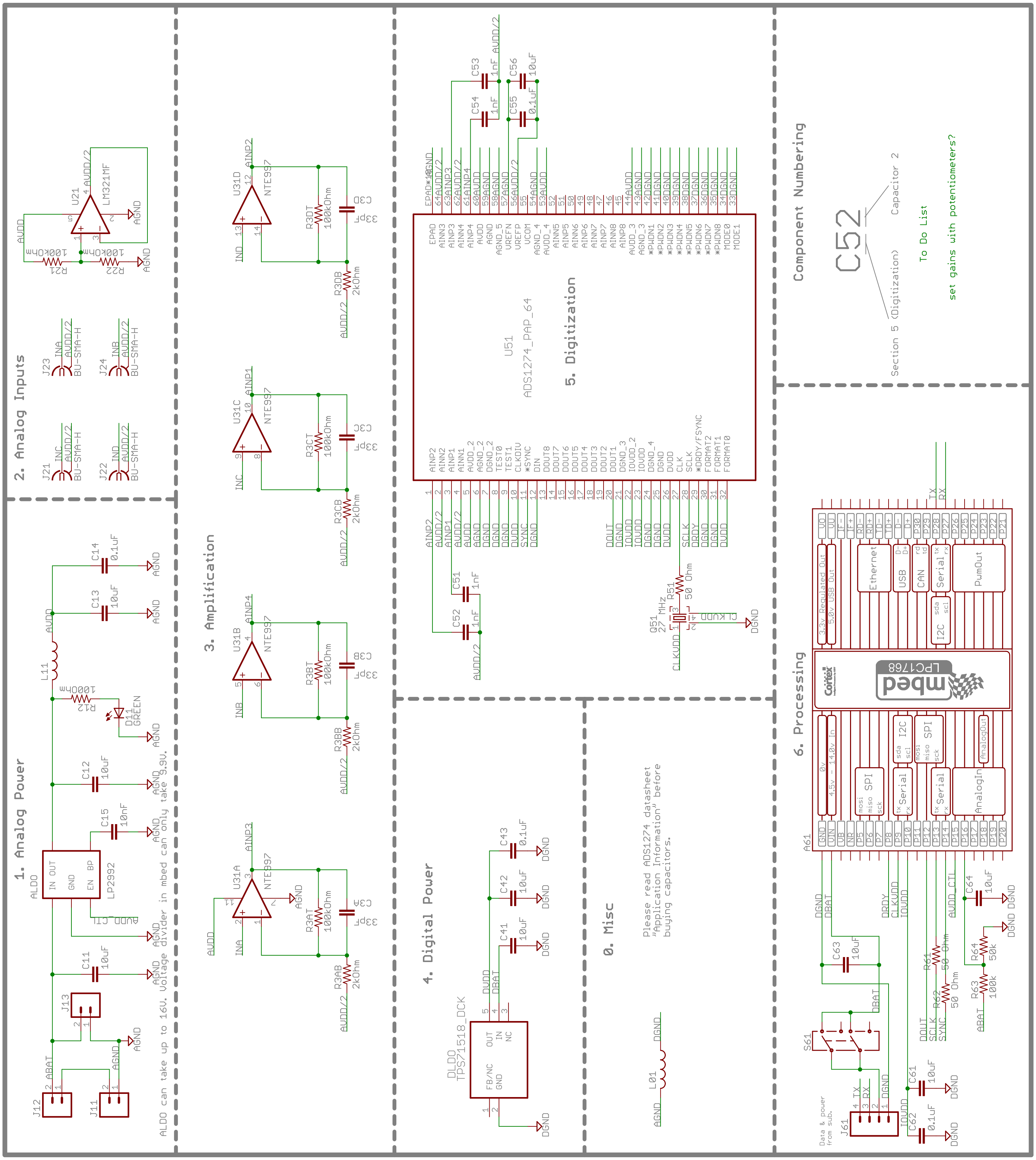
Introduction

AUVSI Foundation, the nonprofit outreach arm of the Association for Unmanned Vehicle Systems International (AUVSI), created an international college-level student competition in 1998 to increase interest in autonomous underwater vehicles. In 1999, students at Amador Valley High School entered their AUV in the 3rd annual AUVSI AUV competition. Since then, our robotics team has consistently performed better than many college teams.

The competition, now called RoboSub, is designed to simulate real-world tasks for autonomous submarines. The final obstacle involves navigating to an audio beacon located at the bottom of a swimming pool. This platform puts us closer to completing that task by providing a passive low-pass filter, four-channel operational amplifier (op-amp), analog-to-digital data converter (ADC), and an mbed Microcontroller for software filtering and processing.



Actual-size image of the Surfboard circuit board. The dotted lines represent boundaries of copper pours. Soldermask and bottom silkscreen layers are disabled for clarity.


1. Analog Power
ALDO can take up to 16V. Voltage divider in mbed can only take 3.3V.
2. Analog Inputs
3. Amplification
4. Digital Power
0. Misc
Please read ADS1274 datasheet "Application Information" before buying capacitors.
5. Digitization
U51
ADS1274_PAP_64
6. Processing
Component Numbering
C52
Section 5 (Digitization)
Capacitor 2
To Do List
set gains with potentiometers?

System Overview

Signal Input

The board accepts input from four coaxial SMA connectors, which were chosen because they are smaller than BNC connectors. The insides of the connectors carry the output signals of four Reson TC4013 hydrophones, referenced to a virtual ground of 2.5 V to accommodate input requirements of the ADC. The virtual ground is generated by a high-current op-amp. The signals I'm interested in are 20 to 30 kHz sine waves at 2.5±40 mV.

Signal Conditioning

The signals are connected to the noninverting inputs on the NTE997 quad op-amp.[1] The op-amp's output is connected to the inverting input through a resistor divider to amplify the input with a gain of 50 (to give approximately 2.5±2.5 V, which lets us use the full 24-bit resolution of the ADC). In additional, a 33-pF capacitor is connected in parallel with the top resistor of the voltage divider to form a low-pass filter with a cutoff around 35 kHz. This helps filter out high-speed digital noise that may have entered the system.

Digitization

The ADS1274 from Texas Instruments is a 4-channel analog-to-digital converter.

ADC Power and Ground

To reduce noise, analog power is provided by two single-cell lithium-polymer batteries[2] connected in series. The power is regulated from 7.4 V nominal to 5 V with a low-dropout regulator (LDO) and then filtered through a ferrite chip with low DC resistance to remove any high-frequency noise that may have entered the circuit.

Digital power (DVDD) is provided through an LDO as well. IO power (IOVDD) is provided by the mbed so that the logic levels of the ADC and the ARM CPU will be the same.

There are no switch-mode power supplies on this board because the switching noise might reduce signal quality. This is also why AVDD is not provided by the switch-mode power supply in the sub.

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[1] I chose this op-amp because the robotics team had a few of them left over from a previous experiment. In the future, this could be replaced with four single op-amps to avoid running the signals near each other. Surface-mount op-amps are preferred because their traces are shorter and don't interrupt the ground plane.

[2] The board is designed to take a 9-volt battery as well, which may be needed in an emergency.

The submarine ground is connected directly to the digital ground (DGND) through the Submarine I/O connector. To prevent different ground voltages and other nastiness that can destroy components, the analog ground (AGND) is connected to DGND through another ferrite chip. Hopefully, there is not a large voltage drop across the ferrite. As a last resort, a 0-Ω link or jumper wire can be soldered in its place to connect them directly.[3]

Sampling Clock

The ADC requires a clock signal on the CLK pin to set the sampling rate. With a sampling clock of 27 MHz, the ADC will take 105,469 samples per second (SPS). This requires that it be put into high-speed (low-resolution[4]) mode. On this board, the clock is provided by a semiconductor oscillator, which was chosen for its small package size.

Amplified Signal Input

The op-amp's outputs are connected to the positive inputs on the ADS1274 analog-to-digital converter and the 2.5-V virtual ground is connected to the negative inputs.[5] The ADC digitizes the difference between the positive and negative inputs.

Board Design Notes

Based on the layout suggestions in the datasheet, filtering capacitors are connected to the analog inputs near the ADC. Small resistors are connected digital inputs to the ADC to reduce ringing. The soldermask on important traces is exposed to facilitate debugging.

Processing[6]

I chose the mbed NXP LPC1768 (mbed Microcontroller) over a dedicated digital-signal-processing (DSP) chip. The mbed is fast enough to process data and I already have experience writing software for it.

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[3] The datasheet says that everything should use a single ground plane, so using a jumper is closer to what they recommend.

[4] This term isn't completely accurate, but it's what the ADS1274 datasheet uses. Low-resolution means the digital filters in the ADC average fewer samples per output sample (less supersampling).

[5] I didn't use the VCOM pin on the ADC, which also generates 2.5 V, because it is created by an internal resistor divider and may sag if the current is too high. This could distort our signal since everything is referenced to the virtual ground.

[6] The software changes all the time. This section may not be accurate by the time you read it. Always read the source for the most accurate information: the truth is in the code.

Activation

The mbed receives power from the submarine's 5-V rail. Upon power-up, it checks battery voltage and waits for a "run" command from the submarine.

Power Supply Sequencing and Start-Up

To meet the ADC's specific timing requirements, the mbed uses its DigitalOut (GPIO) pins to sequence the power-on of the devices on Surfboard. If ADC inputs are driven before the ADC's internal power-on reset is triggered, the ADC can be damaged.

This is a summary of the power-up sequence:

- Turns on AVDD (by controlling the enable pin on the LDO) and IOVDD (directly powered by a DigitalOut pin, which can source up to 40 mA of current). Wait a few milliseconds for the power-on reset. This step also turns on the op-amps, which is technically not OK. However, it is impossible for the op-amps' output to rise faster than AVDD, so we should be fine.
- Turns on the sampling clock. Waits 11 ms[7] for the output to settle before data are valid.
- Drives the $\overline{\text{SYNC}}$ pin to logic low (voltage high) to reset the ADC. The ADC datasheet recommends synchronizing the outputs this way to reduce aperture error, which occurs when samples in different channels are not taken at the same time.

During this time, the mbed will also set up the direct memory access (DMA) controller, the SPI bus to the ADC, and the serial lines to the submarine.

Upon receiving a command from the submarine,[8] the mbed will run those steps in reverse to shut the board down safely. Then, power can be removed from the mbed.

Data Input

The mbed Microcontroller receives serialized data from all four channels over an SPI bus by using DMA. The DMA controller stores data received over SPI into memory without intervention from the CPU, enabling the CPU to complete other tasks. (The sample rate so high that, without DMA, there most of the CPU time would be spent receiving data.)

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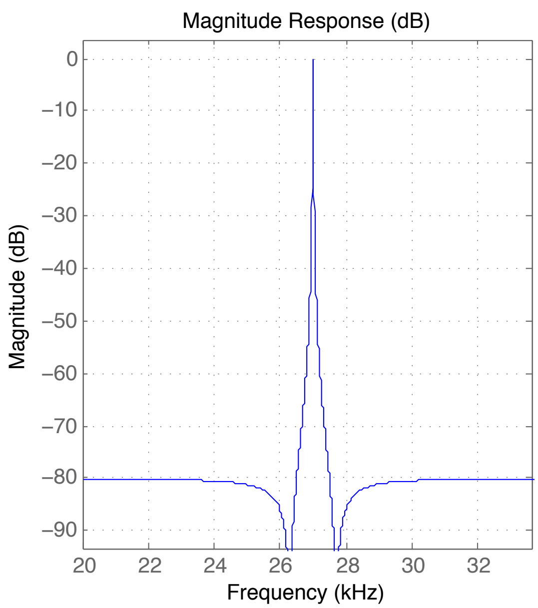
[7] 2^{18} CLK cycles + 129 conversions

[8] The shutdown sequence is not run when the mbed is switched off. If this causes issues, I can add a shut-down button that the mbed can read to the next revision of this board.

After DMA puts data into a buffer, an interrupt is called to perform some preliminary processing. This converts the data from a serialized buffer of 24-bit little-endian integers to parallel buffers of 16-bit big-endian integers. The third byte of each integer is discarded, and the first and second bytes trade positions. This routine may be rewritten in assembly if better performance is needed.

Band-Pass Filter



An 4th-order infinite impulse-response (IIR) filter is used to attenuate signals with a frequency other than the one we are looking for. (The competition organizers will announce the pinger's frequency before each run.) Each output value is computed as a weighted moving average of the input and previous output values. This means that, in theory, an impulse (a signal of 1 followed by zeroes) would last forever, giving it an "infinite" response.

Filters are designed in MATLAB, so the filter taps (coefficients) for each possible frequency are precalculated and stored for use on demand.

Output of Results

The timestamp of each signal is sent to the submarine via UART (serial), where it is used as the input for a hyperbolic positioning algorithm. If more CPU cycles are available, the pinger's relative position can be computed on Surfboard and sent instead of timestamps.

Manufacturing

Because the component placement in this design is so dense, it's tedious to solder with an iron. I used solder paste through a stencil and a hot plate to attach the components.

Solder Paste Stencil

The solder paste stencil was cut from a sample of 5-mil clear mylar film from TAP Plastics. I generated a PDF of the stencil design from my PCB design by isolating the top layer. To prevent bridged apertures, I shrank all pads by 4 mil in Adobe Illustrator. The stencils were cut on the mylar setting with the power at 35%. Next time, I should experiment with different power levels to avoid bridging stencil apertures on the ADC's tiny pins.

I used solder paste that had been expired by about 3 months. Though it reflowed fine in my testing, I found that it did not stick to the board well because the flux had evaporated.

Pick and Place

I used a pair of very fine tweezers to pick up components and place them onto the board. The components did not stick well to the paste either, leading to alignment issues when they refused to get off my tweezers.

Soldering

The Corning hot plates we use in chemistry labs actually have very accurate temperature regulation, making them suitable for reflow soldering. I heated the hot plate to about 220 ºC. I placed the PCB onto the hot plate and waited for the solder paste to melt. Then, I carefully removed the board and set it on the lab bench[9] to cool.

I soldered through-hole components, such as the quad op-amp, using an iron.

Flux Removal

I gently scrubbed the board in hot water with an old toothbrush to remove flux residue. The flux in this paste isn't no-clean, so it's strong enough to corrode metal over time.

Testing

I connected the analog inputs to the headphone jack on my phone one by one while playing a high-pitched sine wave.[10] I then read the digitized signal using the mbed.

Conclusion

Surfboard provides the hardware platform needed to complete the pinger task in the RoboSub competition. As the team is active during the summer, I will no doubt improve Surfboard's hardware and software as described throughout this paper.

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[9] The table material our school uses resists burns and conducts heat, making it a pretty good heatsink.

[10] Consumer audio chips don't go beyond 20 kHz because that is the limit of human hearing. You need a real function generator to test the full frequency range of Surfboard.

Grading

In-Class Work: 51/51

I worked every day in class, whether it was making progress toward the project, understanding mixed-signal design, or learning about signal processing.

Project Evaluation: 45/49

This is the most complex project attempted in AP Physics this year. Though it is an electrical engineering project, it relies on many concepts from the electricity and magnetism portion of AP Physics: alternating current, crosstalk, semiconductors, capacitance, resistance, and Ohm's law, to name a few. It is not fully functional, but that is something that will be improved over time. The difficult part of understanding the problem to be solved is already done.

Acknowledgement

I would like to thank Daniel Naito for his technical guidance during this project. I would also like to thank Mr. Dennis, the engineering teacher, who spent hours with me experimenting with the laser cutter, and Mo Ohady of Digicom Electronics for donating solder paste.