The trials and tribulations of building a phase-sensitive detector with an Arduino microcontroller

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Original Goals

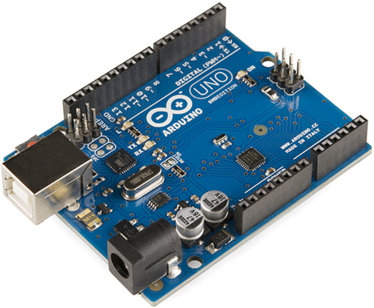
- Use Arduino as a tool for teaching about phase-sensitive detection.
- To do so with only the Arduino, a computer for display purposes, and passive external components (resistors and capacitors)

Why PSD?

- Phase Sensitive Detection (PSD) is the basis of many techniques in physics and engineering
    - Homodyne detection
    - Interferometry
    - Lock-in amplifiers
- Black boxes are useful for application work, but not so much for pedagogical purposes
- Software PSD allows students to peek into the black box.

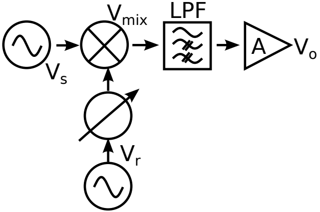
Why Arduino?

- Cheap
- Popular
  - Lots of support
- Simple programming environment
  - Perhaps too simple, IDE has very poor debugging tools.
- Works well with Processing, which is a free and powerful language for visualization
- Both Arduino and Processing are platform agnostic: Windows, Linux, OS X, Raspberry Pi...



Arduino picture from Sparkfun CC-BY-2.0

PSD Basics



Mathematics of PSD

$$V_{mix} = V_s V_r \left[(\cos(\omega_s - \omega_r)\, t - (\phi_s - \phi_r) \right]$$

$$V_o = A \frac{V_s V_r}{2} \left[\cos(\phi_s - \phi_r) \right]$$

Restrictions

- $\omega_r = \omega_s$
- V_s and V_r have no DC offset

What do we need? Can we do it?

Needed features

1. Generate reference signal.
2. Adjustable phase to maximize signal.
3. Get signal into Arduino
4. Mix signal and reference and filter the results
5. Display results

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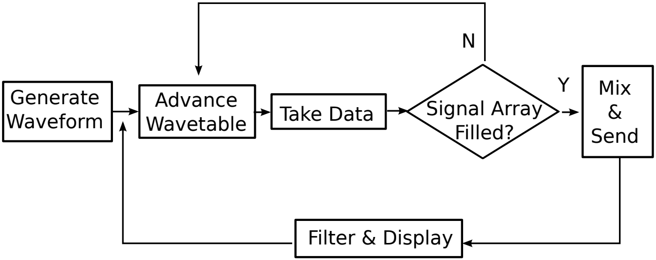
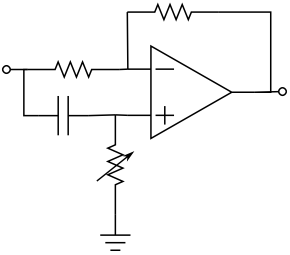
Issues

1. Arduino has no analog out
2. Shifting phase is difficult to do internally
3. Positive voltages only
4. Limited variable memory on Arduino
5. Need to use serial over USB to Processing

Flowchart

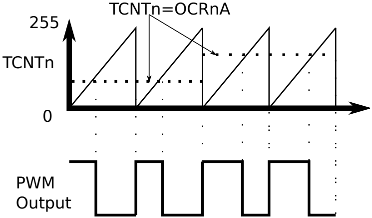

Generate Waveform
Advance Wavetable
Take Data
Signal Array Filled?
N
Y
Mix & Send
Filter & Display

Phase Manipulation



- Need to be able to shift phase to maximize signal
- All-pass phase shifters work, but require a bit more hardware external to Ardunio
- Software solutions difficult to implement
- Use two phase detection.
  - $V_I = V_s \times \cos(\theta)$, $V_Q = V_s \times \sin(\theta)$
  - $R = \sqrt{V_I^2 + V_Q^2}$
  - $\phi = \tan^{-1}(V_Q/V_I)$

Creating a Reference Signal

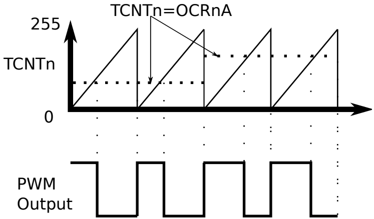


Picture adapted from J. Thompson, MAKE vol. 35

Timers and Interrupts Part I

- The ratio of PWM on to off determines an average "DC" signal
- When register TCNT1 reaches OCR1A PWM goes low
- When TCNT1 overflows PWM goes high again

Creating a Reference Signal



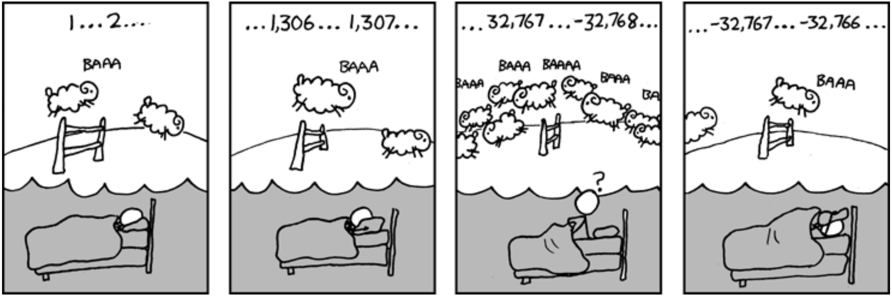
Picture adapted from J. Thompson, MAKE vol. 35

$$f_{ref} = \frac{\text{TCNT2 rate}}{\text{OCR2A value} \times \text{wavetable length}}$$

Timers and Interrupts Part II

- Need fast timer2 and regular timer1, which outputs PWM
- When timer2 reaches OCR2A:
  - Update OCR1A from wavetable
  - read signal at AnalogIn
- When timer1 counts up to OCR1A, PWM goes low
- When timer1 overflows PWM goes high again

Signal Input

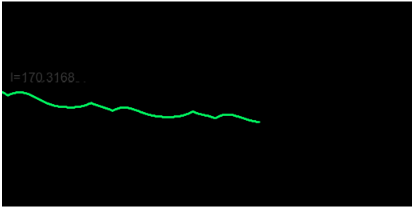


XKCD comic 571 "Can't Sleep"

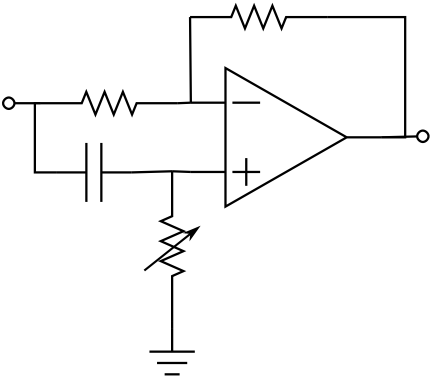
Signal Input

- Arduino can only have positive voltages at its inputs or outputs
  - Integer overflow when mixing
  - Necessary DC offsets makes phase indefinite
- Need to run ADC as fast as we can so as to to interfere with reference generation.
  - Setting pre-scalars and registers can get sampling rates of 50k samples/sec. Not bad for a 30 board!
  - ADC has 10 bit resolution with adjustable V_{ref}, so resolution on the order of a millivolt is possible

Display



In-phase channel as phase is changed



What we accomplished

- Built and tested a working two-channel phase-sensitive detector
- Learned techniques that can be used for other micro-processor based instruments
- Published on github under GPL v3 license

Still to do

- Characterize detector (noise, internal phase shift, etc...)
- Clean up display
- Explore other memory options on Arduino
- Use in an application

For Further Reading I

- The programs!
  https://github.com/HartwickChaosLab/Arduino-Phase-Sensitive-Detector
- Arduino
  http://www.arduino.cc
- Processing
  http://processing.org
- Moding the Arduino ADC
  https://sites.google.com/site/measuringstuff/the-arduino
- J. Thompson
  “Advanced Arduino Sound Synthesis"
  Make Vol. 35