

## 22. Current & Heart Rate Sensors

### Introduction:

The Raspberry Pi-Pico has four 12-bit analog inputs - three of which are connected to the I/O pins on the Pi-Pico Breadboard Kit. With these A/D inputs, you can directly read sensors whose output is voltage. With some circuitry, you can also measure sensors whose output is a resistance or a current.

This lecture looks at a scattering of different types of sensors with analog outputs and ways to interface them to a Pi-Pico board.

### Current Sensing Resistors

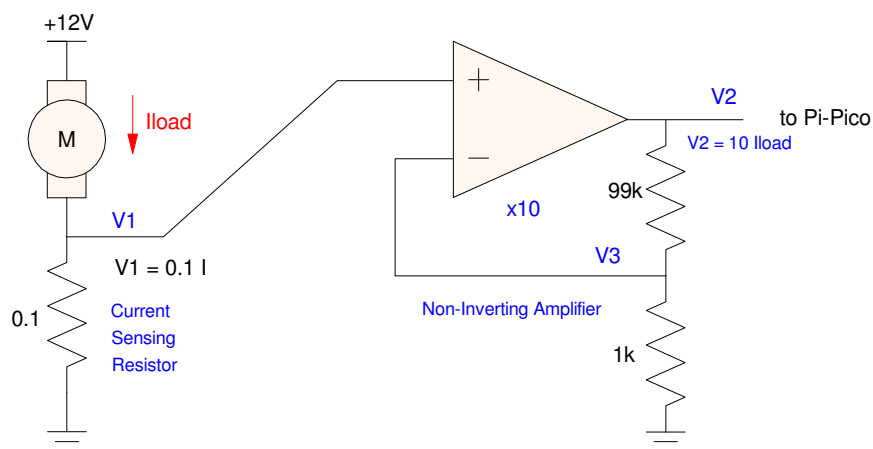
Sometimes, you want to measure current. Current tells you the energy left in a battery rated in mAh. Current tells you the brightness of an LED. Current tells you the torque of a DC motor. One problem with current, however, is all a microcontroller like a Pi-Pico can measure is voltage and time. The trick then is how to convert current to one of these parameters.

One method is to convert current to voltage using a resistor ( $V = IR$ ). One principle of sensors, however, is you don't want the sensor to change what you're trying to measure. To avoid this, a small resistance (1 Ohm or 0.1 Ohm) can be used for R. In order to convert the resulting voltage to a larger voltage relative to ground, a differential amplifier can be used.

For example, let's measure the current going to or from a load. If you place a 0.1 Ohm resistor between the load's ground and earth ground, the resulting voltage is proportional to current as

$$V_1 = 0.1 I_{load}$$

A non-inverting amplifier can then bring this to a range a Pi-Pico can read (0V - 3.3V).



A current-sensing resistor converts current to voltage - which can then be amplified

With this circuit, the output can be computed as follows. Since this is an op-amp with negative feedback:

$$V_1 = V_3$$

By voltage division:

$$V_3 = \left( \frac{1k}{1k+99k} \right) V_2$$

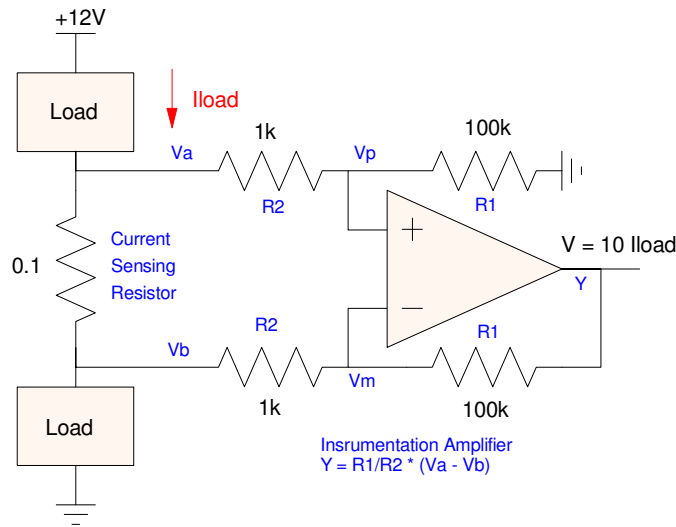
resulting in

$$V_2 = \left( \frac{1k+99k}{1k} \right) V_1$$

$$V_2 = 100 \cdot (0.1 \cdot I_{load})$$

$$V_2 = 10 \cdot I_{load}$$

Instead of placing the current-sensing resistor between ground and the load, it could also be placed anywhere in the circuit. In this case, the amplifier needs to amplify the voltage across the resistor rather than voltage to ground. A differential amplifier is useful in this case:



If the current-sensing resistor is placed elsewhere in the circuit, an instrumentation amplifier can connect the differential voltage to an output

For this circuit, the equations are:

$$V_p = V_m \quad \text{negative feedback forces the inputs to be the same}$$

$$\left( \frac{V_p - V_a}{R_2} \right) + \left( \frac{V_p}{100k} \right) = 0 \quad \text{voltage node equation at } V_p$$

$$\left( \frac{V_m - V_b}{R_2} \right) + \left( \frac{V_m - Y}{R_1} \right) = 0 \quad \text{voltage node equation at } V_m$$

With some algebra, the result is

$$Y = \left( \frac{R_1}{R_2} \right) (V_a - V_b)$$

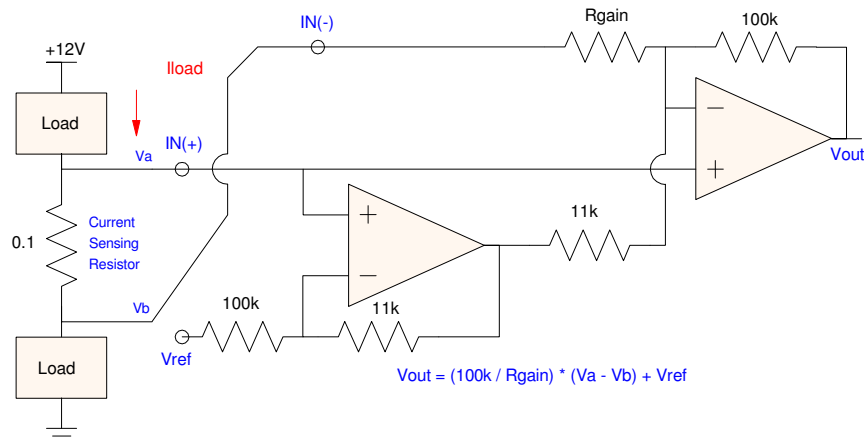
In both of these circuits, if the load current is always positive, the output voltage will also be positive. In this case, a single power supply (such as +3.3V) will suffice. If the current can be positive or negative, however, these circuits will need a +/- power supply for the op-amp.

If the load current can be positive or negative and you still want to use a single power supply, an instrumentation amplifier with a DC offset can be used, such as an AMP04 op-amp. You can also build

this with discrete op-amps as shown in the following figure. With this circuit, the gain is set by Rgain. The output voltage will be offset by Vref.

$$Gain = \left( \frac{100k\Omega}{R_{gain}} \right)$$

$$V_{out} = Gain \cdot (V_a - V_b) + V_{ref}$$

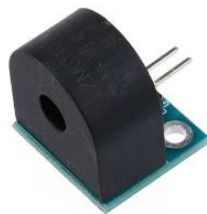


Instrumentation Amplifier with a DC offset (AMP04)

With this circuit, both positive and negative currents can be accommodated with a single +3.3V power supply by offsetting the output by 1.65V (Vref = 1.65V).

### Current Sensing Transformers

A second way to measure current is with a current-sensing transformer. Note that this only works for AC signals, however (transformers don't work at DC).



5Pcs ZMCT103C 5A AC Current Sensor Module Single Phase Micro Current Transformer Module 5A Range AC Active Precision Output 3000V for Arduino

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**About this item**

- Onboard precision miniature current transformer
- Onboard sampling resistance
- The module can measure AC current within 5A, corresponding to analog output 5A/5mA
- The output signal is an AC voltage signal
- PCB sub-size: 18.3(mm)x17(mm)

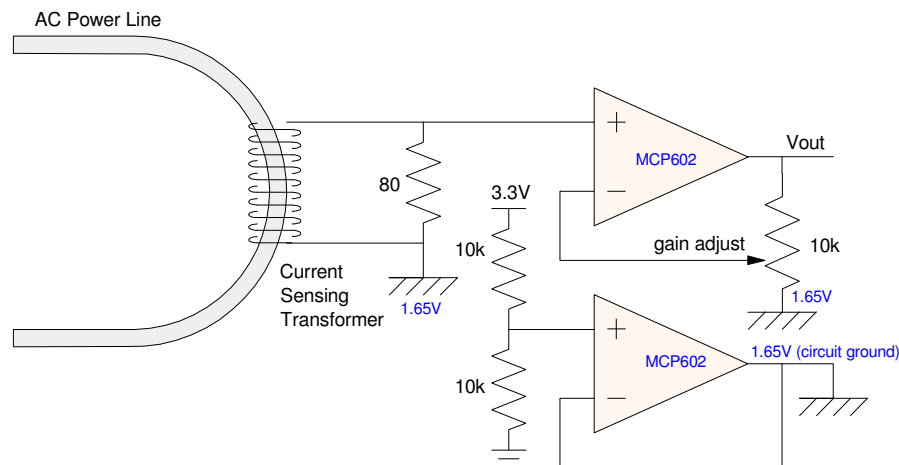
Current Sensing Transformer: The AC cord goes through the center of the transformer

Current sensing transformers are useful when

- You want to measure an AC current,
- Inserting a current-sensing resistor is not practical, or
- Inserting a current-sensor is not safe (due to the large voltages involved)

With a current-sensing transformer, you simply run one of the wires through the central hole of the sensor. The sensor then acts as an N:1 step-down transformer, converting the voltage to a safe level. Add a small resistor as a load and you can measure current as well.

Note that the output will be an AC voltage. This can be amplified and offset to produce 0V - 3.3V signals, centered at 1.65V (midrange)



A current sensing transformer outputs a voltage proportional to the AC current  
A non-inverting op-amp amplifies this signal relative to 1.65V (circuit ground)

Using this circuit along with the code on Bison Academy (kind of long to post here),

- A reading can be taken which is displayed on the TFT graphics display
- If the gain needs adjusting, adjust the potentiometer and collect another set of data by pressing button GP14
- Once you have a decent set of data, save the data to a file by pressing GP15

In this program, 1000 data points are collected for each run. Ideally, if you want to collect data over three cycles, you need a sampling rate of 20kHz

$$f = \left(60 \frac{\text{cycles}}{\text{sec}}\right) \left(\frac{1}{3 \text{ cycles}}\right) (1000 \text{ samples}) = 20,000 \frac{\text{samples}}{\text{sec}}$$

Interrupts are not used since they took too long. Instead, the A/D is called as fast as possible, along with a `sleep_us()` statement to trim the sampling rate. The resulting main loop's data collection code is then:

```

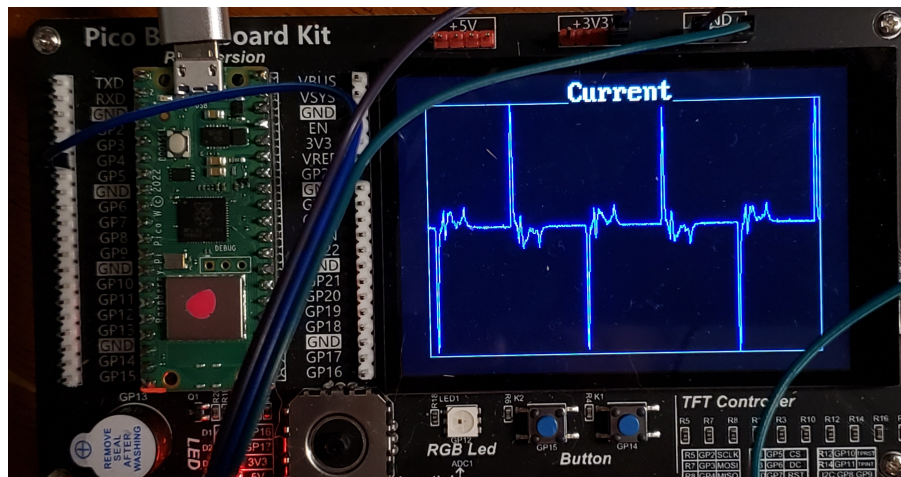
AAA4V
raw = [0]*1000
Volts = [0]*1000
kV = 3.3 / 65535

while(1):
    for i in range(0:1000):
        raw[i] = a2d2.read_u16()
        sleep_us(10)

    for i in range(0:1000):
        Volts[i] = raw[i] * kV

```

Data Collection section of the main routine.  
The A/D is read at 20kHz (ideally)



Output of the program Current\_Reading.py. The gain of the amplifier is adjusted until the peaks are reasonably large without clipping.

Once the data has been saved to the Pi-Pico, it can then be copied to Matlab (or your favorite program) for displaying, including in a report, etc.

Just for fun, the current draw for five different types of light bulbs were recorded:

- 58W Incandescent light bulb
- 61W Halogen light bulb,
- 20W LED, and
- 21W CFL light bulb

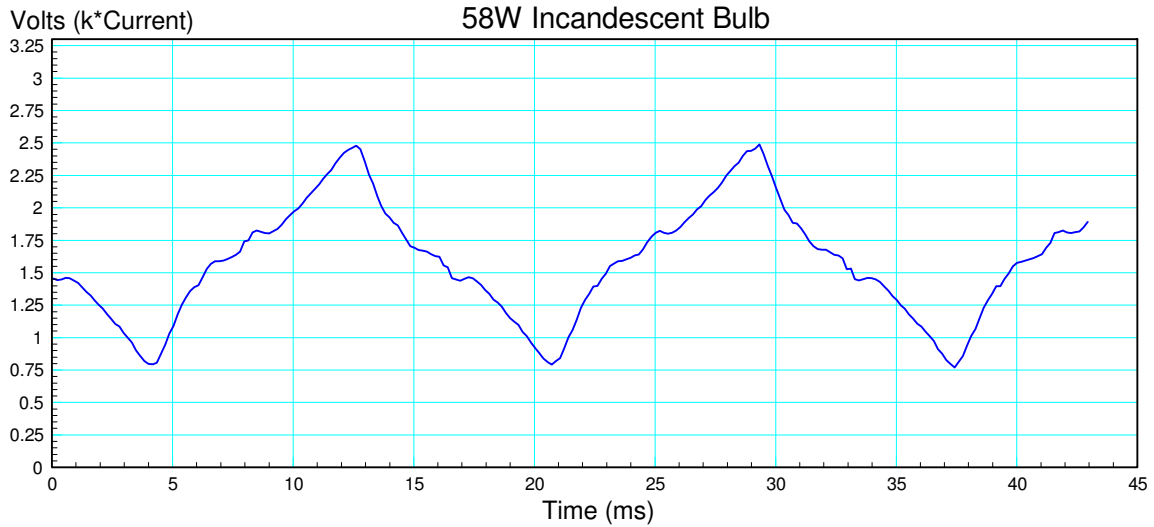
(Power as measured by a Bluetti EB3A battery)

In the following figures, the voltage as read by the Pi-Pico is displayed

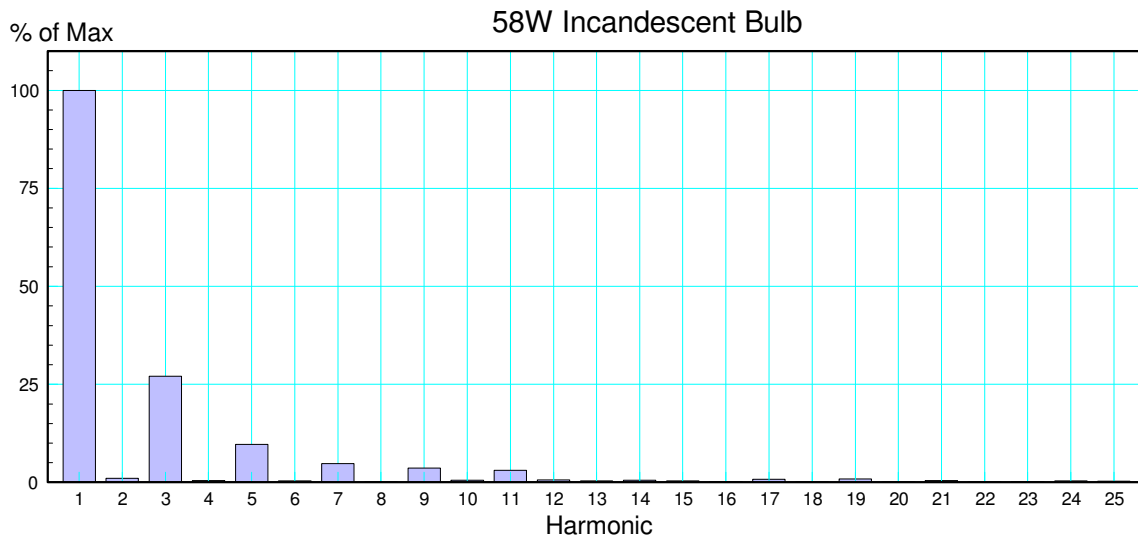
- Voltages clip at 0V and 3.3V
- Midband (1.65V) corresponds to 0mA
- Current is proportional to the voltage deviation from midband (1.65V)

In addition to displaying the current, also display the spectral content (a.k.a. Fourier transform) of the current. Incandescent light bulbs are essentially resistors: the filament gets hot and emits light as a

radiating black body. Most of the radiant energy is in the form of heat (infra-red radiation) - but around 2% gets converted to light.



The frequency content (from Matlab) is:



Frequency content of the current draw

Comments:

- Ideally, the current should be a 60Hz sine wave. It's more of a triangle wave.
- This shows up in the harmonics: the current contains primarily a 60Hz terms, but odd harmonics are present.
- The harmonics are small enough they don't pose a huge problem for the utility.

You can also compute the frequency content in Python as follows:

The sine and cosine terms of the Fourier transform are:

$$f(t) = \sum (a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t))$$

where

$$\omega_0 = \frac{2\pi}{T}$$

and T is the period of the sine wave. The terms {an, bn} can be computed as

$$a_n = \frac{2}{T} \int x(t) \cdot \cos(n\omega_0 t)$$

$$b_n = \frac{2}{T} \int x(t) \cdot \sin(n\omega_0 t)$$

The period of the waveform doesn't affect the Fourier coefficients. So, arbitrarily, set the period to N seconds (where N is the number of data points in one cycle).

In Python, assuming the data is read into an array X[]

```
N = len(X)
dt = 1/N
w0 = 2*pi/N
c = [0] * 25
for n in range(1,25):
    a = b = 0
    for i in range(0,N):
        a += X[i] * cos(n*i*w0) * dt
        b += X[i] * sin(n*i*w0) * dt
    c[n] = (a**2 + b**2) ** 0.5
```

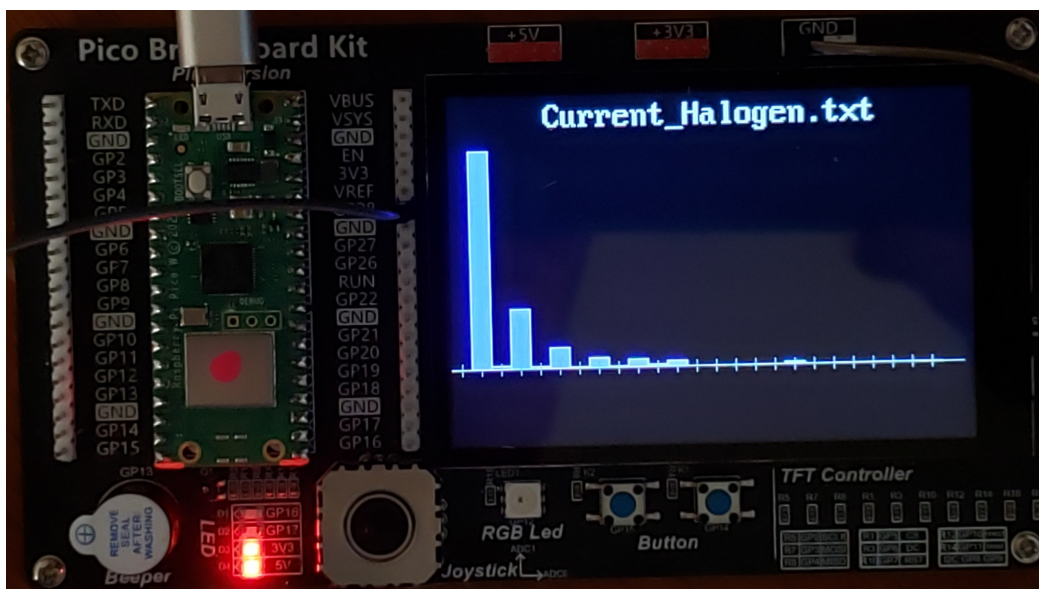
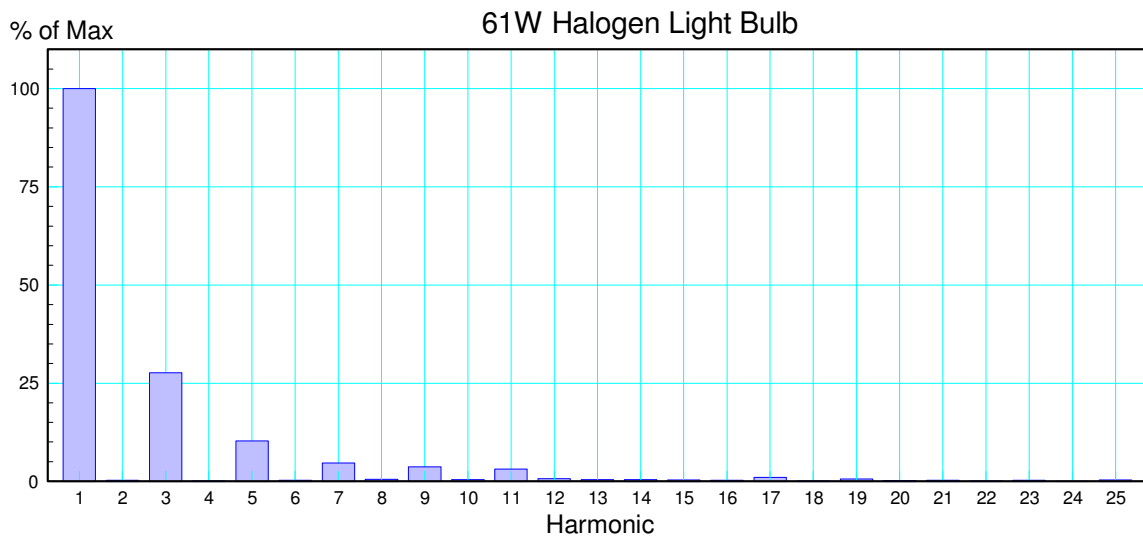
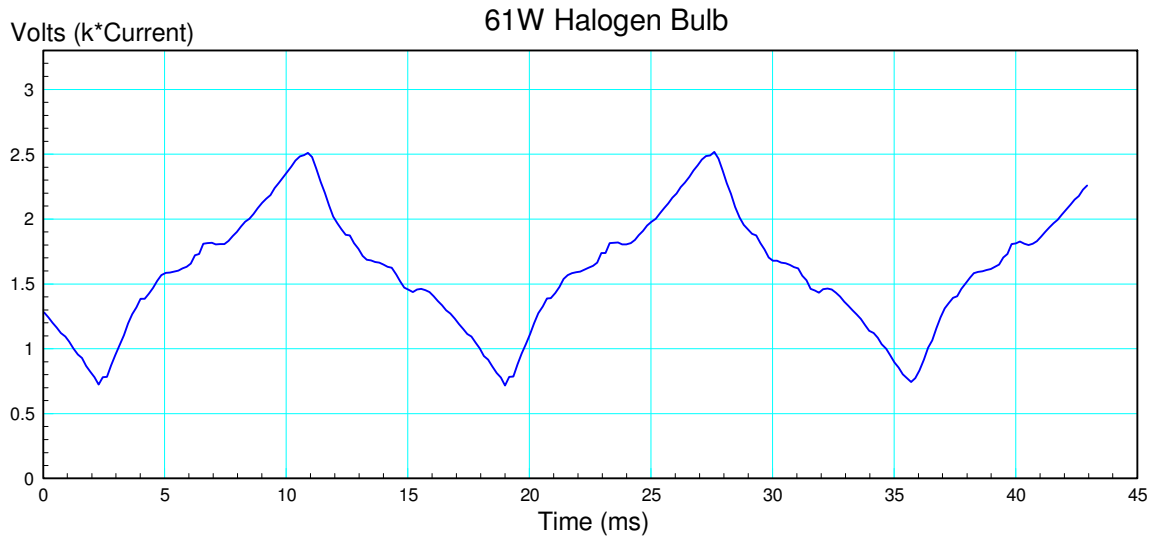


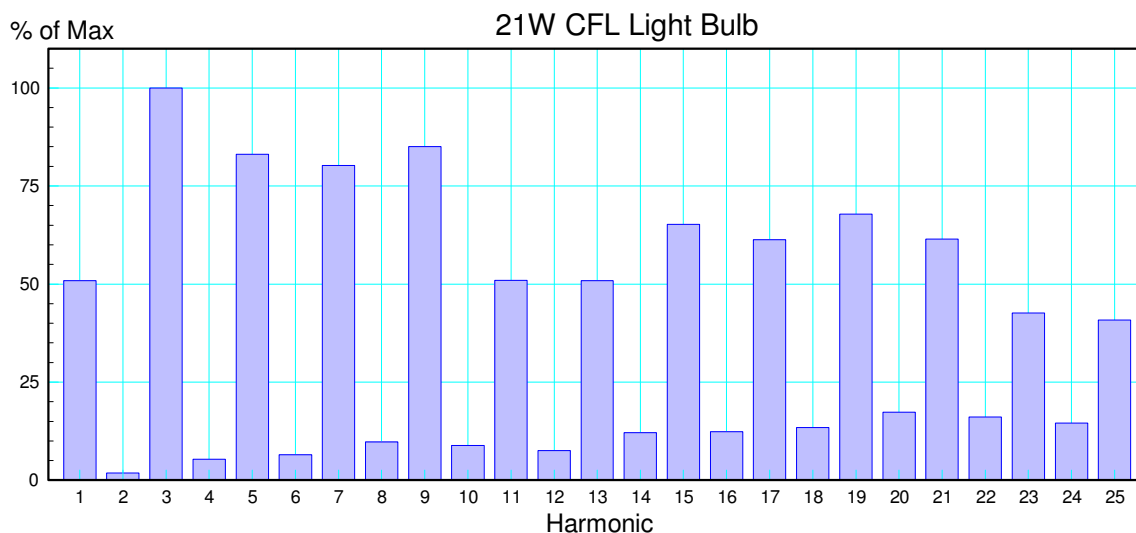
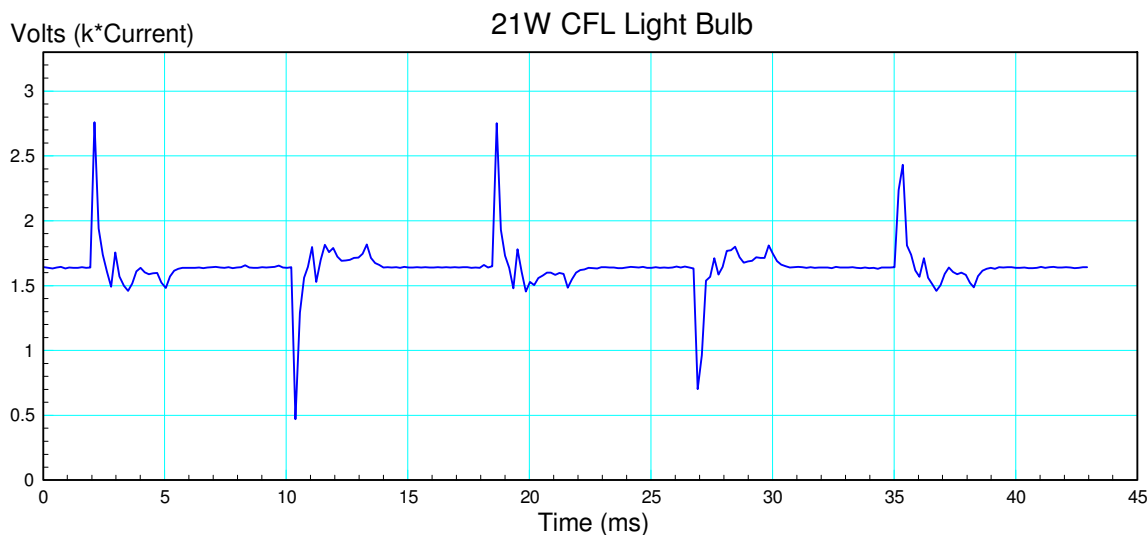
Figure - TFT display showing harmonic content

Next, the current draw of a 61W halogen light bulb is measured. Halogen light bulbs are a little more efficient than LED lights (around 6% vs. 2%) - and are also essentially resistive in nature.



Next, try a 21W CFL light bulb. CFL lights were popular since the 1990s and are around 26% efficient. From the current draw, however, it is clear that these are *not* resistive in nature. The spikes indicate an AC to DC rectifier is being used (see lecture #8 for ECE 320 Electronics). These spikes also produce a large amount of odd harmonics.

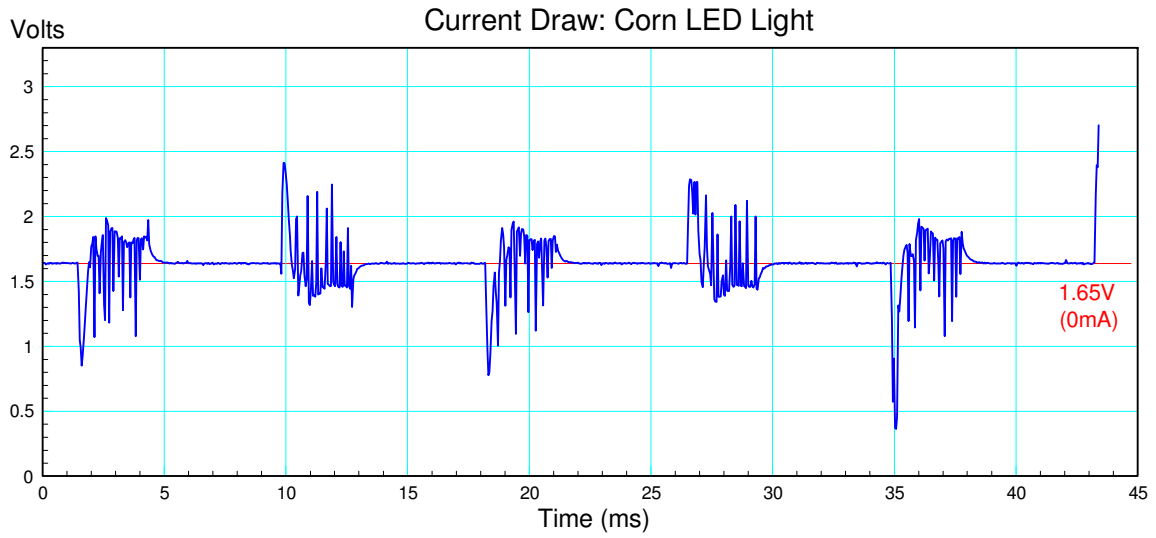




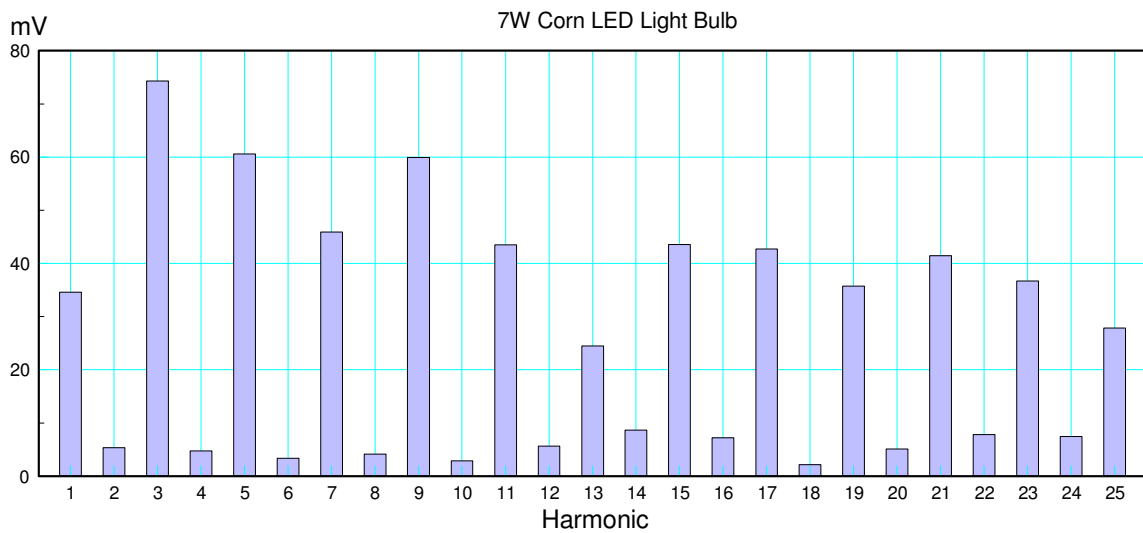
Finally, try a 20W LED light bulb with 37% efficiency. Again, the current shows this is a nonlinear device - with spikes indicating that an AC to DC full-wave rectifier is being used. This too produces a large amount of odd harmonics.

The harmonics can cause problems for a utility. If just a few CFL or LED lights are being used, the inductance on the power grid is able to handle the current spikes from these devices. Essentially, the inductors act as batteries, providing short bursts of energy stored in their magnetic fields. If a large number of CFLs and LEDs are used on a power grid, however, the harmonics can cause problems and reduce the overall efficiency of the power grid. (The power grid was designed for 60Hz.)

This creates an open problem in electrical and computer engineering. The higher efficiency of LED lights is a good thing. The spikes in the current draw is a bad thing. How do you make an LED light which has high efficiency and low cost but has a sinusoidal current draw? So far, that problem hasn't been solved. Whoever does so will be worth billions.



Measured current draw from a 20W corn cob LED light



Frequency content of the current draw

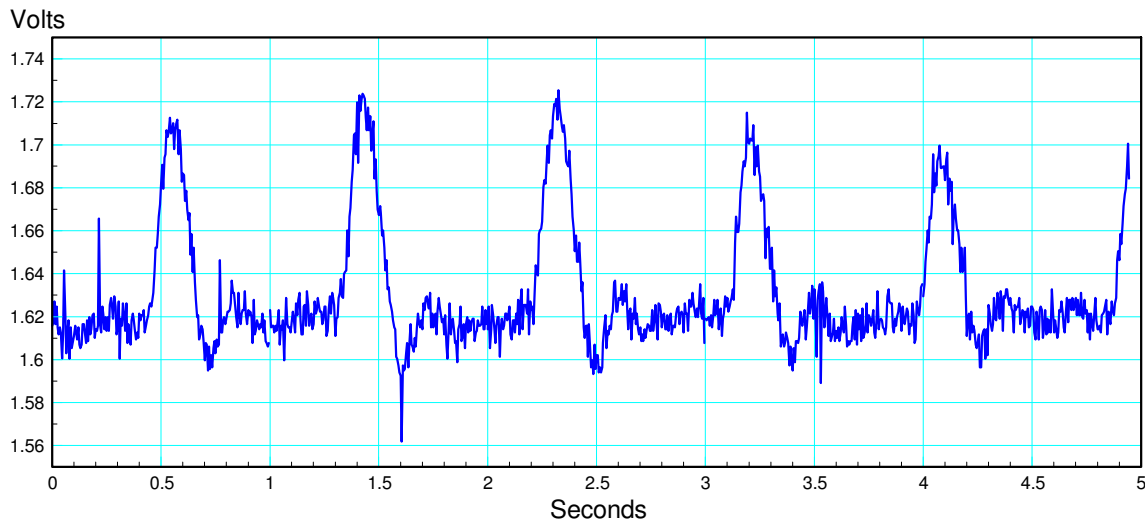
## Heart Rate Sensor



Next, let's look at measuring your heart beat using a heart rate sensor from Amazon. This sensor measures the reflectivity of your skin to green light. The idea is:

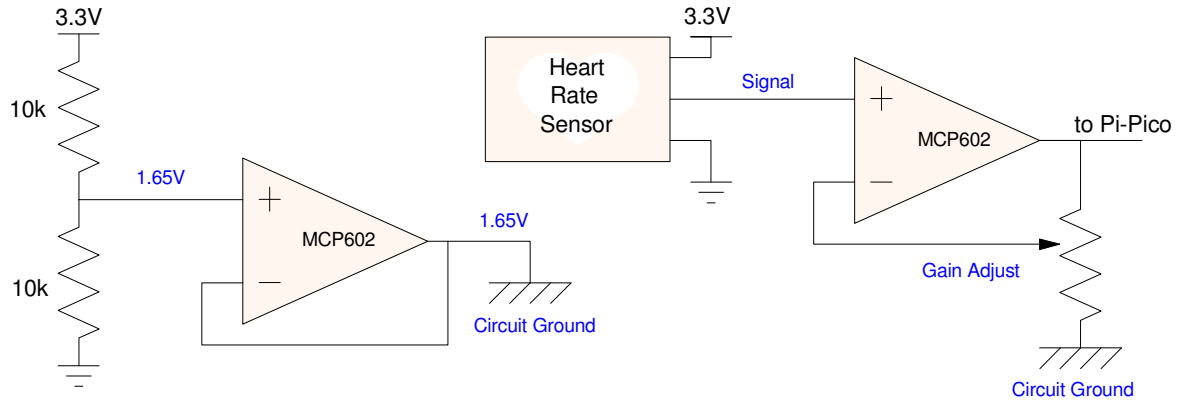
- Oxygenated blood has a different absorption of green light than deoxygenated blood
- Each heartbeat, fresh oxygenated blood goes through your fingers
- By measuring the change in reflectance of green light, the heart rate can be measured

If you place your finger on the sensor and look at the signal line, what you see is a small signal about 40mVpp, centered at midband (1.65V).



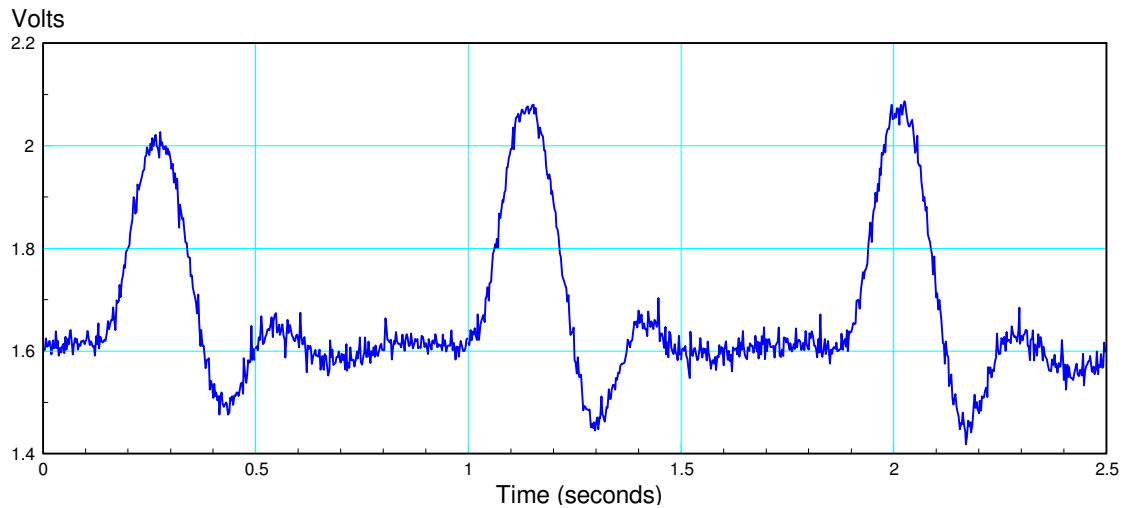
Raw signal from the heart rate sensor

To amplify the signal, a non-inverting amplifier which uses 1.65V as circuit ground can be used. The gain for the following circuit is adjustable from 1 to infinity using the potentiometer.



To get a better reading, the output of the heart rate sensor is amplified relative to 1.65V (circuit ground)

Once amplified, the analog signal can be collected with a Pi-Pico.



Amplified heart rate signal

On Bison Academy, the program *22 Heart Rate*

- Uses timer interrupts to set the sampling rate to 2.5ms
- Collects 1000 data points over a span of 2.5 seconds
- Once collected, the signal is displayed on the TFT graphics display.
- If you like the data and want to save it, press button GP15. This saves the data to a file
- If you want to try again, press button GP14. That discards the data and lets you try again.

In-between measurements, you can adjust the gain of the potentiometer until the signal is fairly large but not clipping.

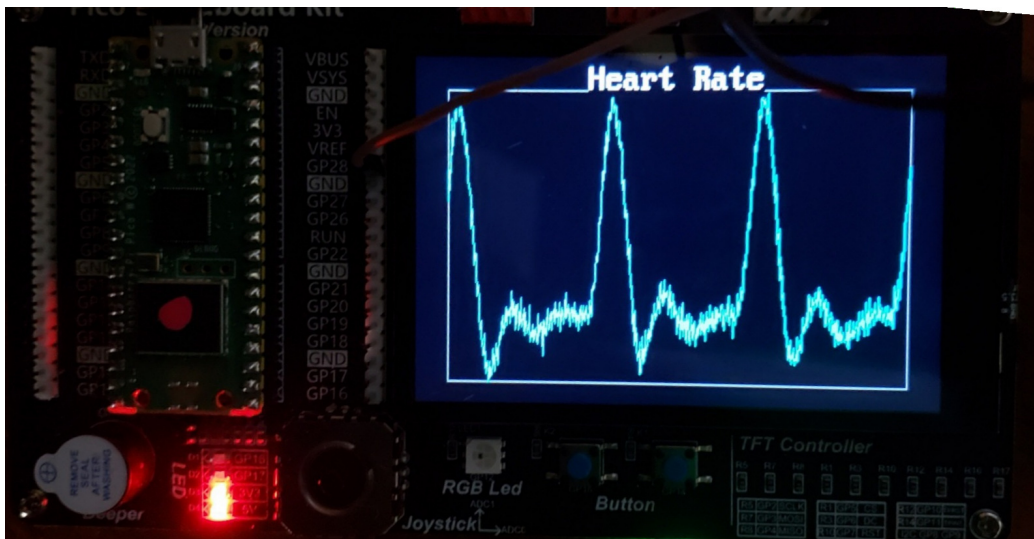


Figure - Heart Rate on TFT display

## Summary:

The Pi-Pico's 12-bit A/D allows you to measure analog signals. Couple this with a circuit to measure current or your pulse and you can record

- The current draw of different types of light bulbs
- Your pulse with a heart rate sensor,

or just about anything else.

## References

### Pi-Pico and MicroPython

- [https://github.com/geekpi/pico\\_breakboard\\_kit](https://github.com/geekpi/pico_breakboard_kit)
- [https://micropython.org/download/RPI\\_PICO/](https://micropython.org/download/RPI_PICO/)
- <https://learn.pimoroni.com/article/getting-started-with-pico>
- <https://www.w3schools.com/python/default.asp>
- <https://docs.micropython.org/en/latest/pyboard/tutorial/index.html>
- <https://docs.micropython.org/en/latest/library/index.html>
- <https://www.fredscave.com/02-about.html>

### Pi-Pico Breadboard Kit

- <https://wiki.52pi.com/index.php?title=EP-0172>

### Other

- <https://docs.sunfounder.com/projects/sensorkit-v2-pi/en/latest/>
- <https://electrocredible.com/raspberry-pi-pico-external-interrupts-button-micropython/>
- <https://peppe80.com/adding-external-modules-to-micropython-with-raspberry-pi-pico/>

- <https://randomnerdtutorials.com/projects-raspberry-pi-pico/>
- <https://randomnerdtutorials.com/projects-esp32-esp8266-micropython/>