Low-Power and High Precision Sensing Circuit for a Three-Channel Electrochemical Sensor

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ABSTRACT

A discrete, compact, low-power sensor readout circuit that can simultaneously handle two current measurements, and one voltage measurement. This work provides a compact, low-power sensor architecture, with the intent for the serial readout to be replaced with a low-power radio frequency transmitter for continuous monitoring. The proposed circuit is highly precise with an average current draw of 21 micro amps for a sampling frequency of once per minute. The target application is livestock health monitoring, which would be done by placing the sensor and circuit inside of a cow's rumen to monitor changes in pH, lactate, and VFA levels to catch metabolic disease early.

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GENERAL AUDIENCE ABSTRACT

A circuit for reading a sensor with a long battery life. It is small so that it can fit in a cow's stomach to determine if it has a disease in its stomach. This diagnosis can be used to adjust its diet.

Acknowledgments

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Contents

List of Figures

List of Tables

List of Abbreviations

ADC - Analog to Digital Converter

DAC - Digital to Analog Converter

MCU - Micro-controller

MUX - Multiplexer. Allows a single output to switch between multiple inputs. If it's an analog multiplexer, signals can travel in both directions.

PCB - Printed Circuit Board

PSK - Phase-Shift Keying

RF - Radio Frequency

SNR - Signal to Noise Ratio

UART - Universal Asynchronous Receiver/Transmitter. A serial data communication protocol.

VFA - Volatile Fatty Acids

Chapter 1

Overview

1.1 Motivation

The motivation for this work is to create a potentiostat for an ingestible sensor to measure pH, lactate, and VFA levels in a cow's stomach. The data will be used to detect disease through continuous monitoring of the cow's digestive system, enabling very quick diagnosis of disease. Commercial potentiostats can be used for a wide range of input currents, however a wider sensing range results in higher power dissipation and larger size. By tailoring a circuit to a sensor, we are able to keep power dissipation and size low, offering long battery life in a compact space for a specific application.

Rumen acidosis is a problem in cows affecting their yield, caused by a dietary imbalance [1]. Currently there are no systems available for continuous monitoring for this metabolic disease. There is a need for a low-power, compact sensor readout circuit that could detect if a cow had rumen acidosis, then its diet can be adjusted leading to higher yields of milk in the case of dairy cows. This feedback loop is pictured in Figure 1.1.

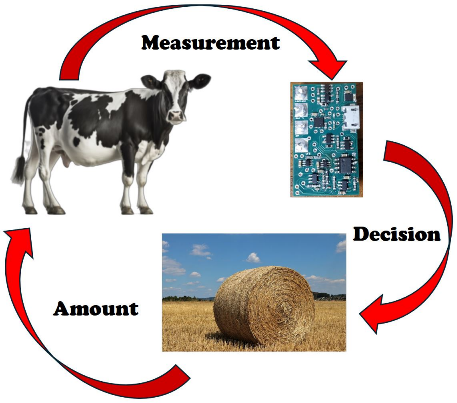

Figure 1.1: Sensor provides data to determine whether or not to adjust the cow's diet.

1.2 Proposed Circuit

The proposed circuit focuses on low power consumption and high precision, using a single power supply. A high level diagram is provided in Figure 1.2. At the heart of the circuit is the Microcontroller (MCU). It has a 10-bit Analog to Digital Converter (ADC) that is used to digitize the signals from the current and voltage sensors. The MCU takes the digitized data and sends it using the UART (Universal Asynchronous Receiver/Transmitter) protocol, which gets converted to the USB (Universal Serial Bus) protocol, so that it can be displayed in a terminal on a PC.

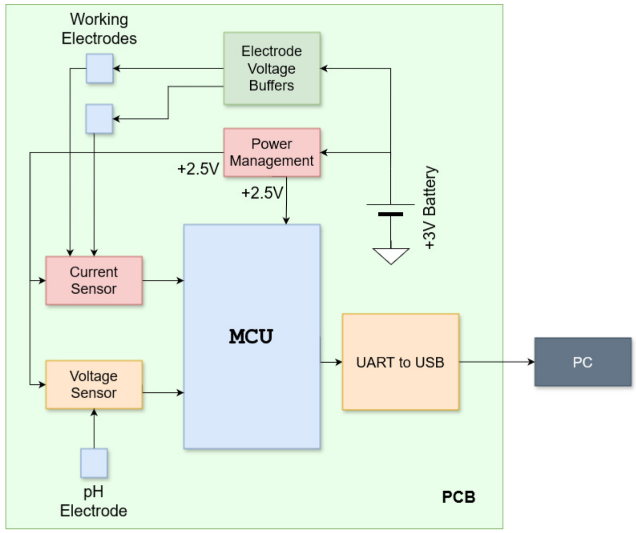

Figure 1.2: Block Diagram

The sampling frequency is correlated to the power consumption. If the sampling frequency decreases, then power consumption decreases as well. This is because the MCU and the sensors turn off when they are not in use, this is described in detail in Chapter 2.3. The battery life for the circuit must be at least six months, the battery life calculation is in Chapter 3.2.

1.3 Low Power Transmission

The low power transmission design is from Dr. Pour's paper [2] where the phase of a ring oscillator is changed by sinking current at its output. By changing the amount of current sunk, the phase shift can be tuned. This can be used to implement phase-shift-keying (PSK) to modulate the signal.

This requires a synchronization circuit to ensure that the control signal is applied at the same point of the waveform to generate a uniform phase shift. The synchronization circuit will also require a delay element to tune the amount of phase shift from each control pulse as discussed in Chapter 2.2.2.

Chapter 2

Circuit

The design of the circuit is explained here. It is split into three different parts. The 'Electrochemical Sensors' section covers the circuit that takes the sensor inputs and processes them before they are input into the ADC of the MCU. The 'Microcontroller and UART/RF Readout' section describes the code on the MCU to get the data ready for transmission, as well as the periferal hardware needed. The 'Power Management' section talks about how the supply voltage is managed so that the MCU can save power when not in use.

2.1 Electrochemical Sensors

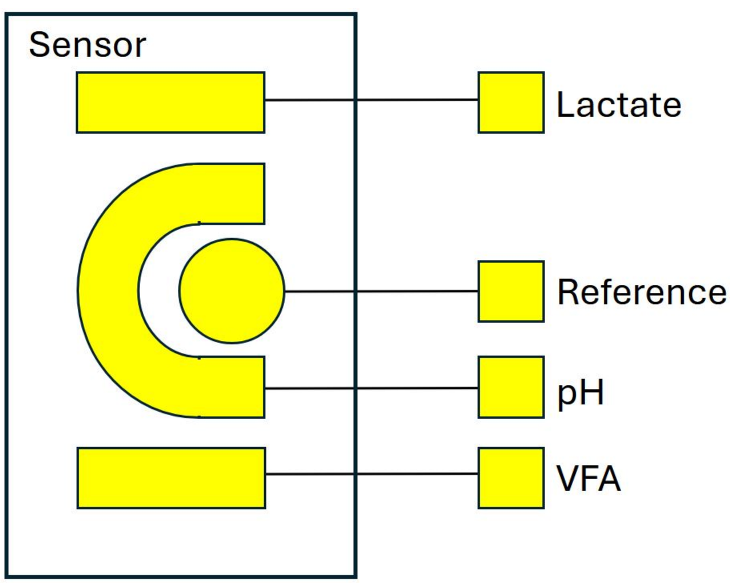

Figure 2.1: Electrochemical Sensor Diagram.

The sensor that is being sensed has four electrodes as pictured in Figure 2.1. One of those electrodes is used as a reference, the other three are used to measure pH, lactate, and VFA levels. The pH is sensed by measuring the voltage between its electrode and the reference. The Lactate and VFA measurements are both current measurements. To measure current, a voltage is applied to the electrode, and the current from the working to the reference electrode is measured.

The values that the sensor produces are at very low frequencies and can be treated as DC, which means a low cutoff frequency for sensing amplifiers is practical to reduce 60Hz noise. When sensing DC values two sources of inaccuracy are the offset voltage of the op-amp, and pink noise (1/f noise). Both of these issues are addressed by selecting a zero-drift op-amp that is chopper stabilized. That means the op-amp's offset voltage will be very small and will drift very little over time, allowing for accurate sensing over time. Chopper stabilized op-amps are also highly resistant to pink noise. The zero-drift, chopper-stabilized op-amp chosen for the sensors is the MCP6V11.

Any DC offset that both the sensor and circuit have will be removed when the sensor is calibrated, but it is important that these values are stable over time or the readings will become inaccurate over time.

2.1.1 Amperometric Sensor

The amperometric sensors are sensing lactate and VFA current. These currents are in the range of 1μA to 500μA for this sensor. In order to sense current, a popular method is to use a transimpedance amplifier [3], however due to the current direction of the current sensed, this would produce a negative voltage at the output of the amplifier, and this work does not include a negative voltage source. For that reason, a sense resistor is used between

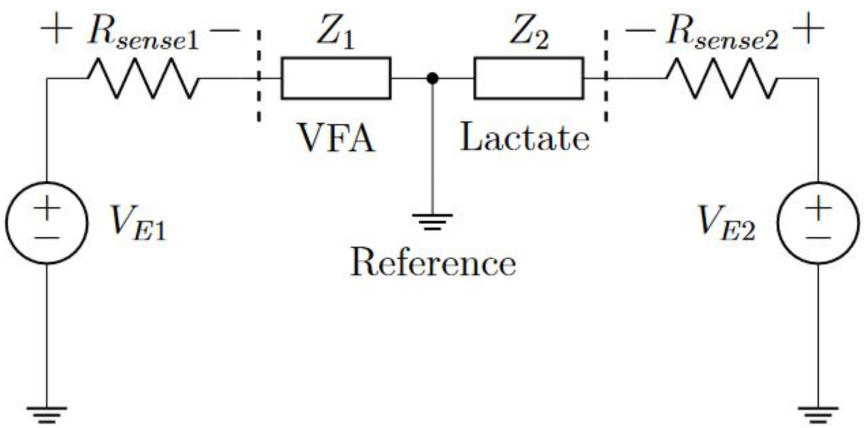

Figure 2.2: High-Side Current Sensing with Two Electrodes

Component	**Value**
R_1	390Ω
R_2	130kΩ
R_3	390Ω
R_4	130kΩ
R_5	15kΩ
R_6	100kΩ
C_1	$0.1\mu F$
C_2	$0.1\mu F$

Table 2.1: Component values in Figure 2.3

the working electrode and the applied voltage, this is commonly known as high-side current sensing [4]. A diagram is shown in Figure 2.2. Note that low-side current sensing only requires one sense resistor at the reference that is 'shared' by both electrodes. The drawback of low-side current sensing is that the current measurements must be taken one at a time since there is no way to determine what portion of the resulting current is from each electrode. Since it takes about one minute before the current measurements will stabilize, the MCU will be running or sleeping for two minutes.

If high-side sensing is used, the voltage can be constantly applied to the working electrodes,

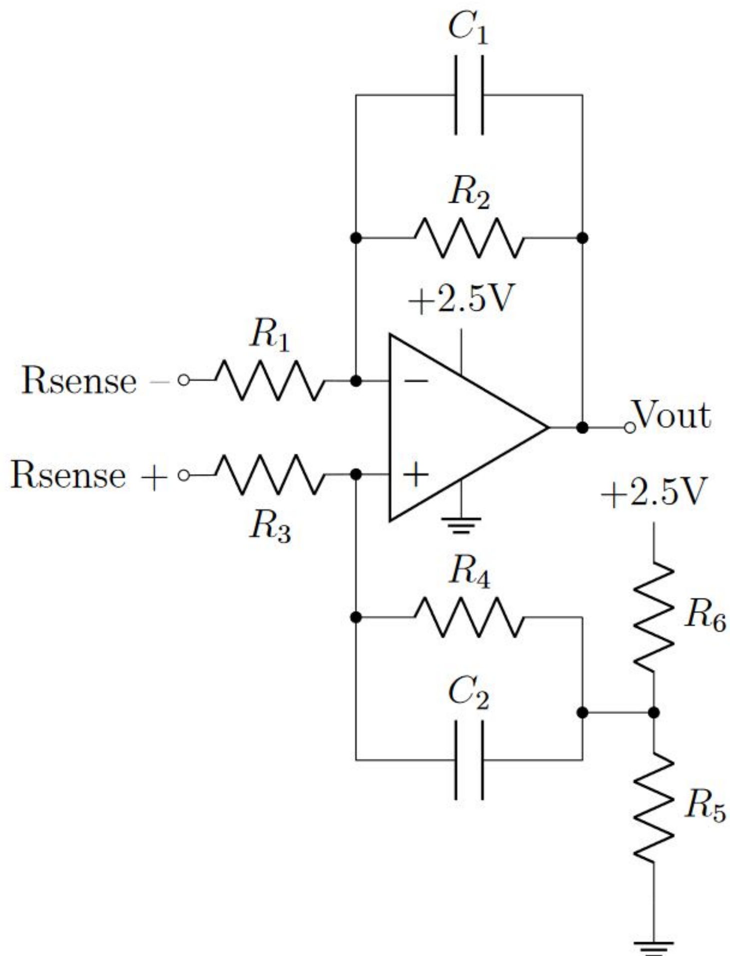

Figure 2.3: Current Sensing Circuit

so there is no wait time since the current has already stabilized allowing the MCU to take samples more frequently, and spend more time turned off. The on time of the MCU is determined by the time it takes for the capacitors in the amplifier to charge up to their steady-state value, which is about one second for each measurement. The drawback of high-side sensing is that voltage will be applied to the working electrodes constantly, draining power. High-side sensing only requires the MCU to be on or sleeping for two seconds, while low-side sensing requires the MCU to be on for two minutes. As long as the power consumed by constantly applying voltage to the electrodes is lower than the power consumed from being on for two minutes, power is being saved. The amount of power saved this way decreases as sampling frequency decreases since the circuit will be off for longer, while the circuit on time is staying the same.

To keep the size of the PCB low, only one amplifier is used for both current measurements, which is possible since they have the same current range. This requires the use of two analog MUXs to switch between the sense resistor being used. The schematic of the current sensor is shown in Figure 2.3. The MUXs determine which sense resistor terminals, as seen in Figure 2.2, are used.

The sense resistor itself is a source of significant error at higher currents. A large sense resistor allows the amplifier to have a lower gain, at a price of a larger voltage drop for higher currents and higher power dissipation. At the high end of the sensing range of 0.5mA, this 10Ω resistor will drop 5mV. If the voltage applied to the sense resistor is 100mV, then the working electrode will only see 95mV, a maximum of 5% error. As the voltage applied increases, this error decreases. The voltages applied can be anywhere from 0.1V to 1V depending on the resistor divider before the buffers. High accuracy is most important for currents under 20μA, and error is not significant for these low currents.

Since the ADC has a range from 0V to 2.048V, and the input signal to the amplifier with a 10Ω resistor is 10μV to 5mV differential, the amplifier is designed to have a gain of about 330V/V, with the resistor values chosen, the pass-band gain is 333V/V using equation 2.1. This is confirmed by simulation as seen in Figure 2.4 where the gain is 50.46dB which is a gain of 333V/V.

$$Av_{diff} = \frac{R_f}{R_{in}} = \frac{130k\Omega}{390\Omega} = 333V/V \tag{2.1}$$

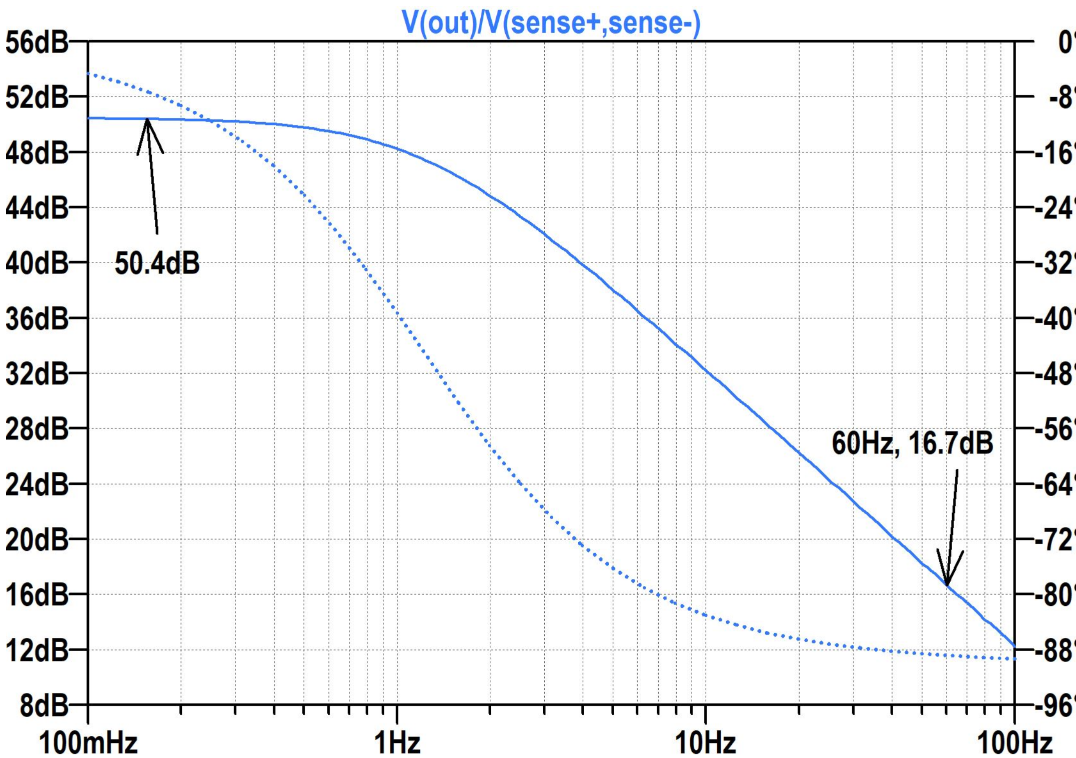

Figure 2.4: Current Sensor Frequency Response

With inputs of 1μA to 500μA, the output voltage has a resolution of 0.616μA. This is found by looking at Figure 2.5, the input range of the ADC is 0 to 1023 since it is a 10-bit ADC, and the output of the circuit goes from 402.7mV to 2.0276V when a current signal from 0A to 500uA through the sense resistor is applied. Due to the capacitors across the feedback resistors, there is a breakpoint around 1Hz which causes the signal to be attenuated by 35dB when it reaches 60Hz noise.

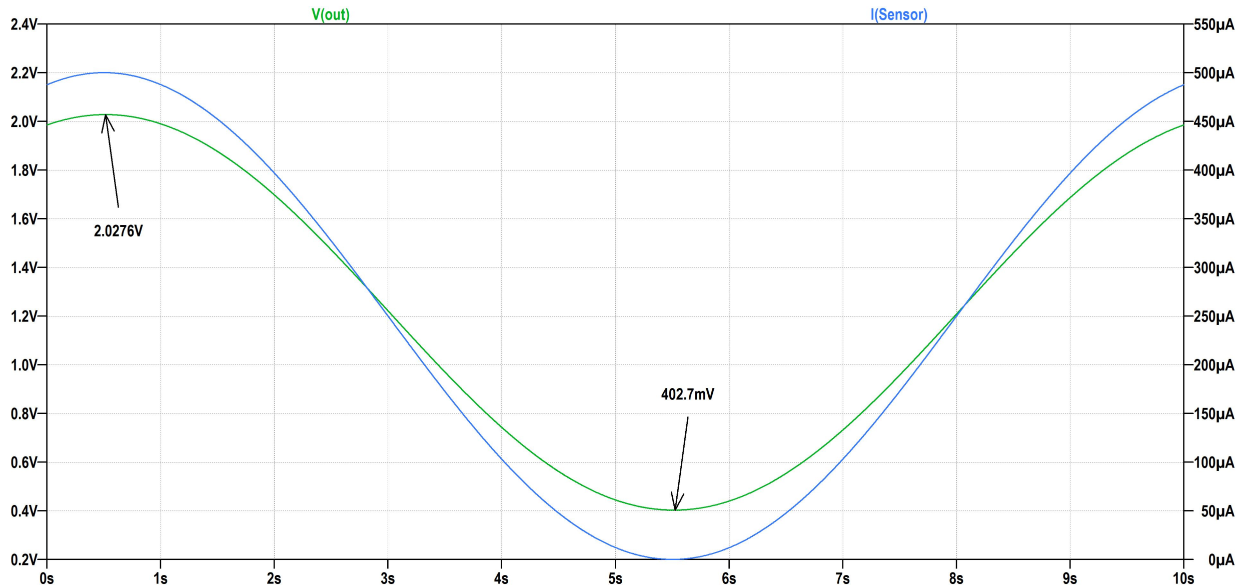

Figure 2.5: Current Sensor Transient Simulation

2.1.2 Potentiometric Sensor

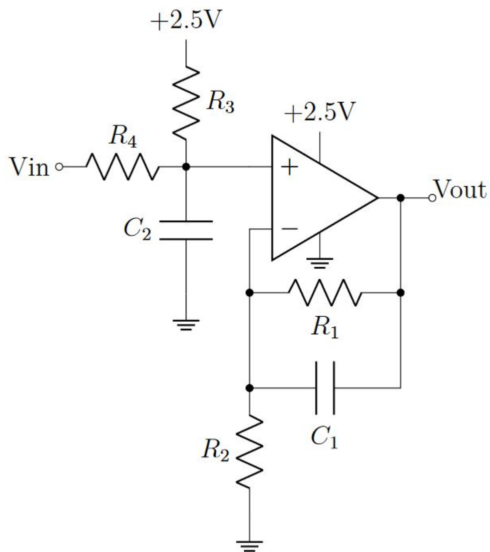

Figure 2.6: Voltage Sensing Circuit

Component	**Value**
R_1	127kΩ
R_2	100kΩ
R_3	402kΩ
R_4	100kΩ
$C1$	$0.1\mu F$
$C2$	$1\mu F$

Table 2.2: Component values in Figure 2.6

There is a fatal flaw with this amplifier since the output impedance of a pH electrode is very large and not negligible. This causes the output to be saturated at the positive voltage supply when used reading a real pH electrode. See Chapter 4 for some potential solutions. If the current amplifier is to be used, the pH electrode voltage needs to be buffered which would require a negative voltage supply due to the range of the input signal as described in the next paragraph.

The voltage between the pH electrode and the reference electrode can fall within the range of -0.5V and +0.5V, specified by the team making the four electrode sensor. The voltage sensor is realized by using a summing, non-inverting op-amp amplifier 2.6. It is a summing amplifier to add a DC offset to the input since decoupling capacitors cannot be used in the signal path in this case due to the signal being very low frequency. There is also a capacitor that provides 60Hz noise a path to ground while still preserving the input signal amplitude. A single power supply is used, so DC the offset is necessary to shift the input signal within the power supplies of 0V and 2.5V. This offset will attenuate the input signal at the positive input to the op-amp, but this attenuation is accounted for by increasing the gain of the amplifier.

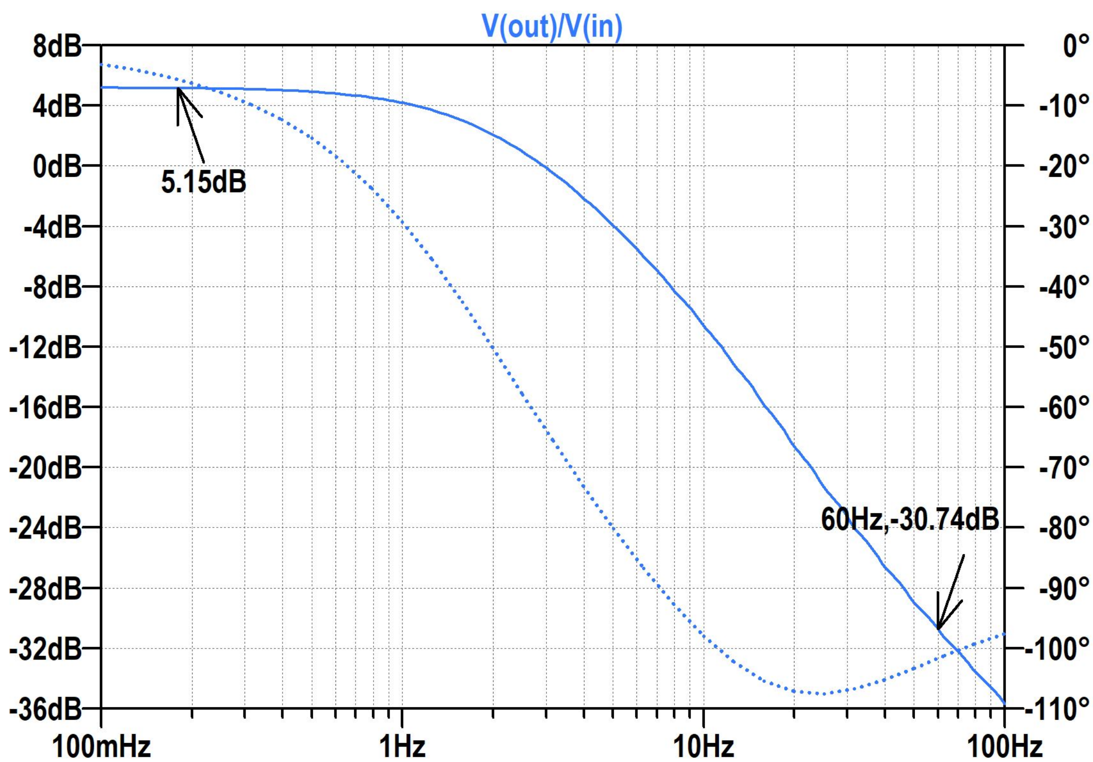

Figure 2.7: Voltage Sensor Frequency Response

The gain of the circuit does not need to be very high since the input signal is from -0.5V to 0.5V, a peak to peak value of 1V. To utilize the entire ADC, a gain around two is needed.

The gain is 5.2dB as seen in Figure 2.7, which is equal to 1.8V/V. The gain is not quite two because there is a negative headroom limit due to using a single power supply. The 60Hz noise is attenuated by 35dB as seen in Figure 2.7 as well. Most of this attenuation comes from the 1uF capacitor in the input low pass filter, about 6dB comes from the capacitor in the feedback loop since that capacitor can only reduce the noise by the gain of the amplifier. This is because when the capacitor impedance reduces, the amplifier looks like a buffer to 60Hz noise.

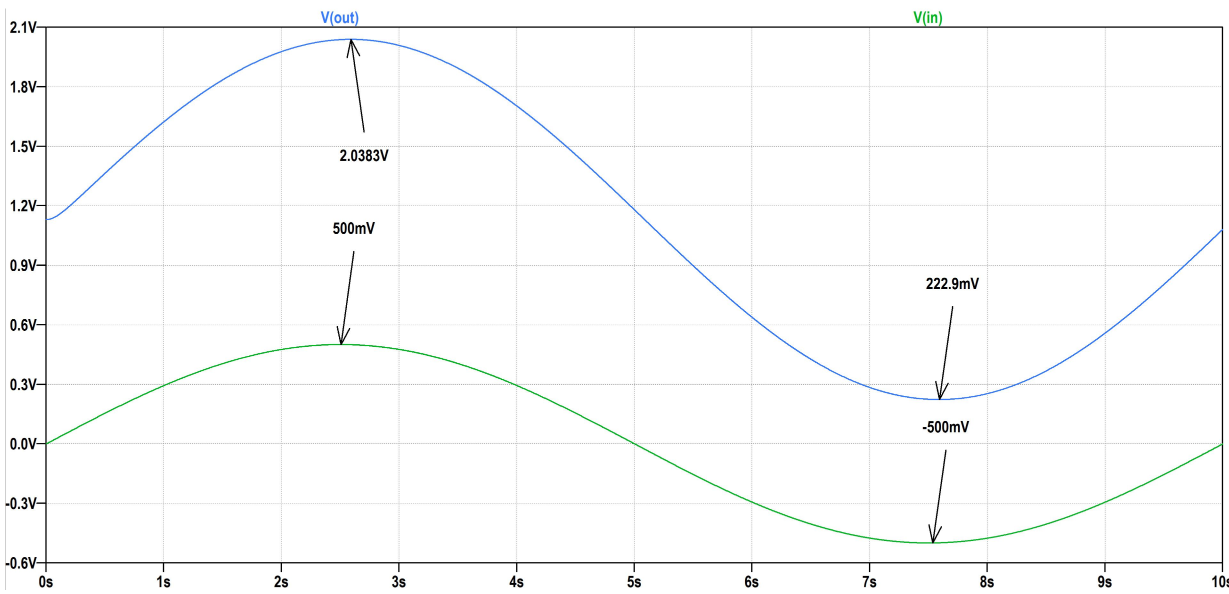

Figure 2.8: Voltage Sensor Transient Simulation

As seen in Figure 2.8, the output signal goes from 222.9mV to 2.0383V. Since the input signal is from -0.5V to 0.5V, the resolution of the amplifier is 1.103mV with a 10-bit ADC.

2.1.3 Working Electrode Voltage Buffers

To create a constant voltage reference for the working electrodes for Lactate and VFA for current sensing, two resistor dividers are used to choose a specific voltage between 0.1V and

1V. These resistor dividers have an output impedance equal to the two resistors in parallel, and that output impedance will create a loading effect with the working electrode impedance if it is too high, causing the applied voltage to be lower than expected. Since the voltage divider resistors must be large (in the Mega Ohms) to decrease the amount of current drawn to the order of micro-amps, the output resistance of the dividers will be large and the loading effect will decrease the applied voltage. This means a voltage buffer is needed, so an op-amp is used after the resistor dividers to buffer their output before applying those to the working electrode through the sense resistor, in Figure 2.2 the outputs of the buffers are the voltage sources.

Because the resistor divider is dividing the voltage of the battery so that the voltage is applied even while the sensor is off, there is error for the applied voltage over the lifetime of the sensor due to the battery voltage dropping. The battery voltage starts at 3V, and overtime once it drops to 2.5V, the applied voltage will be 17% lower than intended. Once the voltage drops to 1.8V, the applied voltage will be 40% lower than intended. This will cause error in the produced current since the peak for the current found using amperometry will be at a specific voltage level.

The fix for this is to add a DC-DC converter to apply a stable voltage reference over the lifetime of the sensor for the voltage dividers, so that even as the battery life changes, the voltage across the dividers will not change. This comes at the cost of some power dissipation, about 200nA of quiescent supply current for a DC-DC converter from the MYRLP-F-RD Series. This extra DC-DC converter will consume 864μAh over a six month period. This is less than 0.5% of the battery capacity and is an acceptable cost for accuracy over the battery life.

2.2 Microcontroller and UART/RF Readout

The MCU reads the sensors and controls the readout. For the PCB in the results section, this is a UART readout, with the plan to later be changed into a low power RF readout. In the case of the UART readout, the MCU has a way to encode UART signals onto a pin. For the low power RF readout, some control signals are necessary to change the phase of the oscillator. The following section will cover how the RF readout works, then the digital circuit for PSK synchronization, and then how the UART readout works.

2.2.1 RF Readout

Once the data is sampled by the ADC, the data needs to be processed so that it can be sent by the RF circuit. To modulate the data into the RF signal, 16-PSK is used, so four bits will be sent at a time. The data to be sent must be split into groups of four bits, then from those values the number of control pulses that need to be applied to change the phase the right amount can be calculated. With four bits the values sent can range from 0 to 15. For this architecture, the phase can only travel in one direction around the unit circle. So to send a 2 then a 1, 15 pulses must be applied. The phase can only travel in one direction because the phase shift is constant for each control signal, as the control signal is only one bit. For this to work, the control signal must be applied at the same point of the waveform consistently, and this means that the control pulses must be synchronized to the waveform [2]. This synchronization is discussed in Chapter 2.2.2.

$$steps = (current - last) + 16((current - last) < 0) \tag{2.2}$$

The idea is to change the phase of the oscillator by sinking current, and the oscillator chosen is a ring oscillator since it consumes low amount of power [2]. If the data can be encoded into pulses, and those pulses are synchronized to control a switch to sink current, then the signal can be transmitted. The main problem is how to determine how long to sink the current for to get the desired phase shift to implement 16-PSK. The phase shift needed for the least significant bit is 22.5 degrees. For this reason there is a potentiometer used to calibrate the width of the applied pulse, which then calibrates the phase shift of each pulse. This will be discussed in more detail in Chapter 2.2.2.

To convert the data into pulses, the data is first packed into groups of four bytes, which gives a number from 0 to 15, being the location on the unit circle that the phase should be for successful transmission. Then the number of steps to get from the last point to the current point is computed using Equation 2.2. This is done for all points. Now all that is left is to send sequences of control pulses in clusters equal to the steps needed to get from point to point around the unit circle. These control signals are applied to the switch that sinks the current.

The code for the functions to implement this functionality in C for a PIC16 MCU is shown below in Figure 2.9. The add_byte function can be used to build an array of 4 bit numbers from 8 bit numbers so that they correspond to positions on the unit circle. Then the num_to_phase function takes that array of 4 bit numbers and updates the 'result' array with the number of pulses to apply to get from the current position on the unit circle to the next position, implementing Equation 2.2.

```
void num_to_phase (uint8_t arr[], int size, int8_t *result) {

    int curr;
    int last = 0;

    for (int i = 0; i < size; i++) {
        curr = arr[i];
        result[i] = curr - last;
        last = curr;
        if (result[i] < 0)
            result[i] += 16;
    }

}

void add_byte (uint8_t byte, uint8_t index, uint8_t *result) {

    result[index] = (byte >> 4) & 0x0F;
    result[index + 1] = byte & 0x0F;

}
```

Figure 2.9: Data to Pulses Functions.

2.2.2 Digital Circuit for PSK Pulses

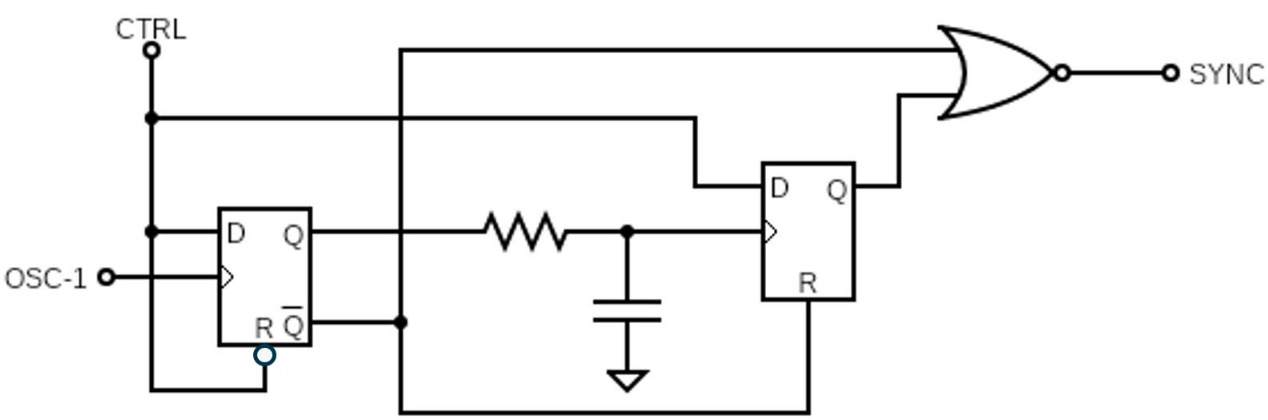

Figure 2.10: Digital Control Synchronization Diagram

As mentioned in Section 2.2.1, the applied pulse width must be calibrated to calibrate the phase of the output, and the pulse must be applied at the same point of the oscillator waveform to get a uniform phase shift. The circuit to achieve this is seen in Figure 2.10 [2]. This circuit is a modified version of the circuit found in the paper written by F. L. Pour [2]. The circuit takes an un-synchronized control signal and when the OSC-1 input goes HIGH while the control signal is applied, the SYNC control signal output is pulled HIGH. Then after some delay, the next flip-flop is clocked and the SYNC output is pulled LOW, completing the pulse generation. This delay is implemented through a potentiometer and a capacitor forming an RC delay. The potentiometer is included so that the phase can be calibrated. The width of the pulse is the RC delay plus the propagation delay of the DFF.

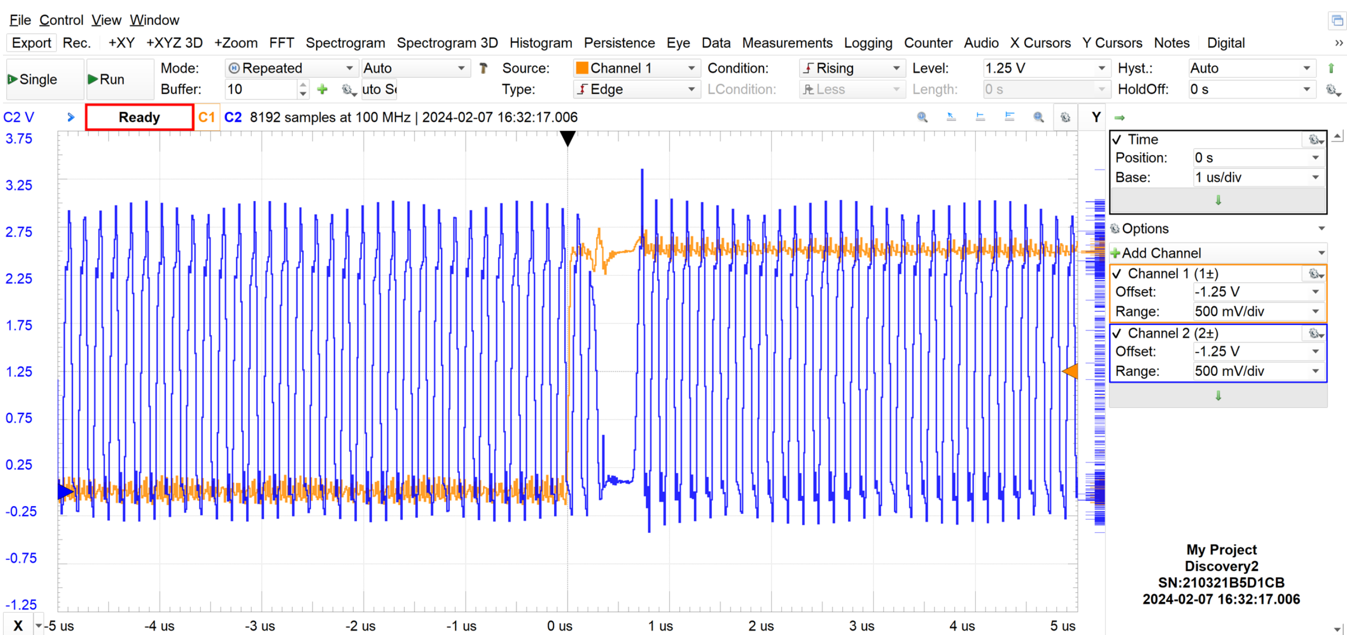

Figure 2.11: RF Output with Control signals from 14-Pin MCU (LF15323)

Shown above in Figure 2.11, the orange signal is the control signal, and blue is the output from the ring oscillator. This waveform shows that the circuit is working, because the control signal goes HIGH, current is sunk, and then after some RC delay, the oscillator begins running again, at some shifted phase. The exact phase can be calibrated by calibrating the potentiometer. Figure 2.11 was done with the MCU providing the control signal, as well as using digital logic implemented with the MCU. The RC delay was implemented outside of the MCU, using pins on the MCU to access the digital hardware. Configurable Logic Cells (CLC) are provided on the MCU used and can be used to implement various digital hardware blocks. These are used to implement the flip flops and NOR gate.

The propagation delay of the flip flops are not negligible compared to the period of the oscillator, however this is not an issue since they are constant. The delay of the NOR gate is an issue, it determines the minimum pulse width, which is the delay for the RC delay. If the delay is too short, then the hold time of the NOR gate will be violated, and a HIGH signal will not appear at the SYNC output.

Looking at Figure 2.10, the second DFF is reset by the complementary output of the first DFF. If this reset was not added, the circuit would only be able to produce one pulse, as the second DFF would be stuck HIGH since it will never receive a postive edge clock signal unless CTRL is HIGH. For the second DFF to be set to LOW, it must be clocked while CTRL is LOW, but that is not possible, so it must be reset. It should be reset when the CTRL signal is brought LOW, which is about when the first DFF becomes LOW, or the first DFF complement becomes HIGH.

The first DFF is reset by the complement of the CTRL signal because it is necessary in case of noise on the RC delay. Since the delay element for the second DFF clock is RC, some noise could cause a false postive edge clock signal while the capacitor is discharging, which would cause the output DFF to become LOW, if that happens before the first DFF output becomes LOW, then SYNC will stay HIGH and it will be stuck there because the clock of the first DFF is the oscillator and that oscillator will be stuck LOW (Not oscillating). The fix is to reset the first DFF with the complement of CTRL so that when the RC delay begins to discharge when CTRL becomes LOW, the second DFF reset will be stuck HIGH so a false positive edge clock will be reset causing the output of the second DFF to be stuck LOW. This way the inputs to the NOR gate will be 1 and 0 so the output will be a 0.

2.2.3 UART Readout

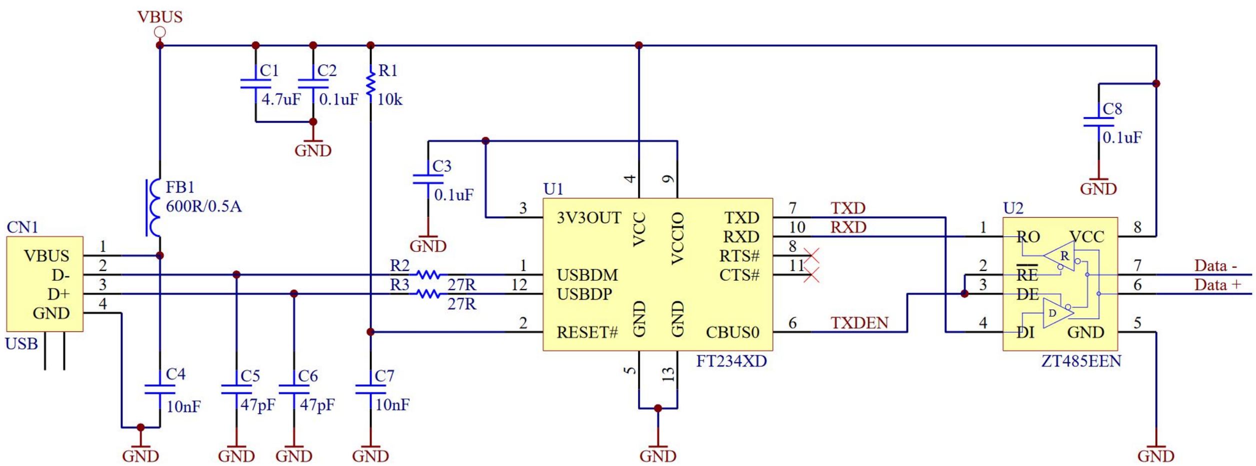

Figure 2.12: UART to USB Diagram

Instead of using the RF readout, UART readout was used to verify that the system works since the RF part has not yet been implemented. Both readouts should transmit the same data, and this UART readout will be replaced by an RF readout in the future.

The UART to USB chip used is the FT234XD-R [5]. This was chosen because it is the most basic chip in its family of chips, sufficient for only transmitting UART signals via USB from the MCU to a personal computer. The schematic followed is from the datasheet [5] and is shown in Figure 2.12. Some modifications were made, the reset pin was connected to the 3V3OUT pin, only the RX pin was used since the MCU only needs to send data, not receive, the CBUS0 pin is disconnected, and the CTS pin is pulled LOW meaning that data is always 'Clear to Send'.

The MCU can encode data in a UART format character by character, so a function is implemented to take a string and loop through it to send the data via UART to the UART to USB chip. This chip then converts the UART data to USB protocol, and sends that data to a personal computer where it can be displayed on a terminal. This only requires two signals from the MCU, one signal is the UART data, and the other signal is ground. The supply voltage for this chip is +5V via USB.

2.3 Power Management

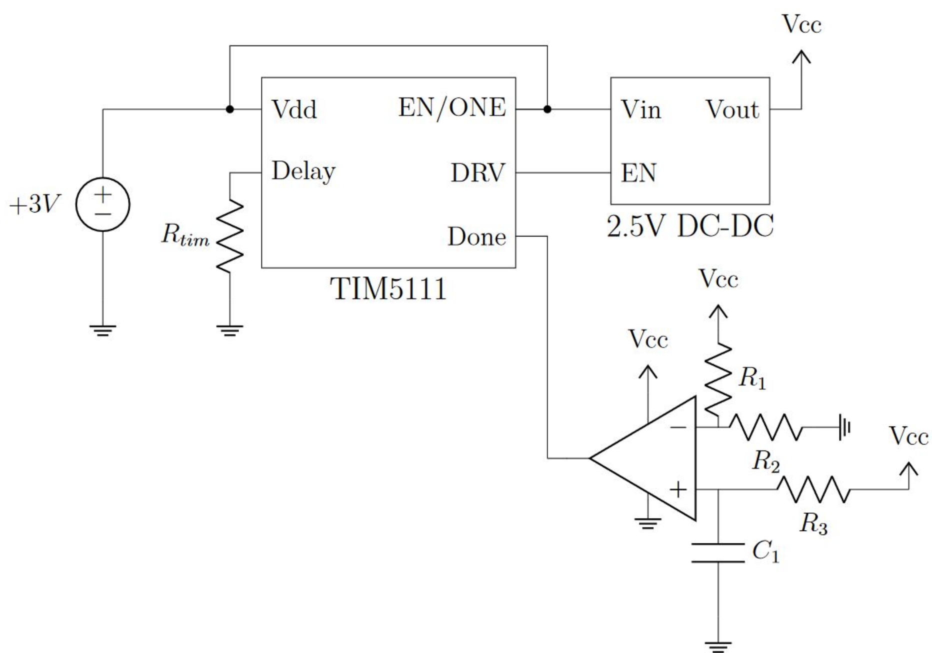

Figure 2.13: Power Management Diagram

To keep power consumption low over time, the circuit goes into a sleep mode where the power supply for the MCU and sensors is turned off completely. This is implemented with a timer, a DC-DC converter, and a delay element. The timer used is the TPL5111 [6] and the schematic is shown in Figure 2.13. The timer works by setting the period with a resistor

Component	**Value**
R_{tim}	22kΩ
R_1	2.32MΩ
R_2	1MΩ
R_3	8.45MΩ
C_1	$0.1\mu F$

Table 2.3: Component values in Figure 2.13

value. For a 1 minute period, that value is 22kΩ. The timer pulls the DRV pin HIGH every minute, and keeps it HIGH until the DONE pin is asserted. The comparator is used with an RC delay to assert the DONE pin when 30% of the supply voltage is reached for the RC delay. The comparator is needed because it is not possible to know at what percentage the DONE pin will assert since it may vary from chip to chip. The 30% of the supply voltage being the reference voltage is arbitrary, and this value could be set higher, which would allow for smaller components in the RC delay.

Using Equation 2.3 for the RC delay, the time constant (τ) is 8.4s for a 3 second delay. Using a resistor with a 1% tolerance, and a capacitor with a 5% tolerance, the actual time constant will be within 7.6s and 9.3s. That gives a range of 2.7 to 3.3 seconds for the capacitor to charge up to the reference voltage and for the 'done' pin to be asserted. The circuit takes two seconds to sense, and needs some additional time for the UART to transmit. At 9600 baud it should transmit around 960 symbols per second, so a conservative estimate of 100ms will be assumed for the transmission time. This means the circuit needs to be on for at least 2.1 seconds which is less than the minimum on time of 2.7 seconds.

$$\%charge = (1 - e^{-t/\tau}) \tag{2.3}$$

The DONE pin can also be asserted using a pin from the MCU, which is the most space efficient, and power efficient way to do it. If there are no more output pins available for the MCU, then this is a good way to limit the amount of time that the circuit is on.

It is very important to limit the amount of time that the MCU is on because draws significantly more current than the other components.

Chapter 3

Results

3.1 PCB

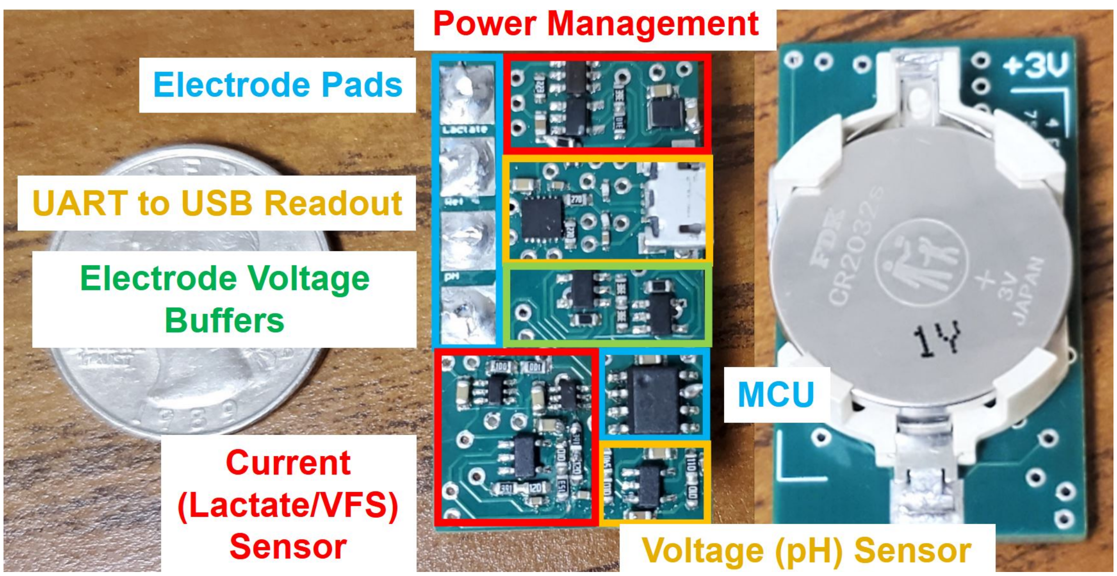

Figure 3.1: Image of final PCB.

Shown in Figure 3.1 is the PCB built. The PCB dimensions are 20.4mm x 35.6mm. The PCB has four layers. The bottom layer routes the battery terminals to vias, the second and third layers are used for the power supply and ground planes, and all four layers are used for signal routing, the ground plane layer is only used for signal routing if absolutely necessary.

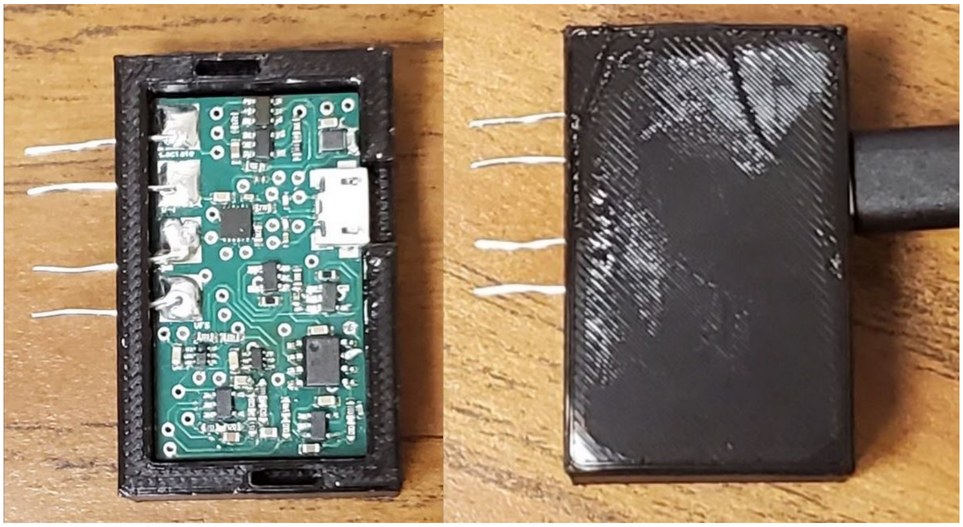

Figure 3.2: Image of PCB in a box.

Shown in Figure 3.2 is the 3D-printed case for the circuit. The box has a lid that is held onto the box by friction (Interference Fit), and there are two holes for the USB connection and the electrodes connection on the sides. The electrodes being pads is useful if an adhesive tape is used to contact the sensor. Wires should be good enough, and for future iterations these pads should be taken out of the design and replaced with small pads to help fit the additional components needed (See Chapter 4).

3.2 Measurements

The measured current draw is 0.9μA while the circuit is off, 555μA while the circuit is fully on, and 96μA while the circuit is on and the MCU is in sleep mode. The circuit is on for two seconds, sleeping for one second, and off for 57 seconds. The average current draw of the circuit is 21.0μA (63μW). The voltage of the battery is 3V, and has a capacity of 235mAh before the voltage drops from 3V to 2V. The circuit can function as long as the supply is at least 1.8V, so the system can run for over 15 months.

To verify the circuit works, a DC voltage was applied to the pH electrode and stepped from -0.5V to +0.5V. For the current sensor, different resistors were placed from the Lactate electrode to ground to set the current through the sense resistor. The R^2 values are calculated for both sensors. R is a value from 0 to 1 describing how correlated the data points are, and R^2 is the square of the correlation, a value as close to 1 as possible is desired.

The current sensor has an R^2 value of 0.9995, the points used in the calculation are plotted in Figure 3.3. The error is due to the voltage drop across the sense resistor as mentioned in section 2.1.1.

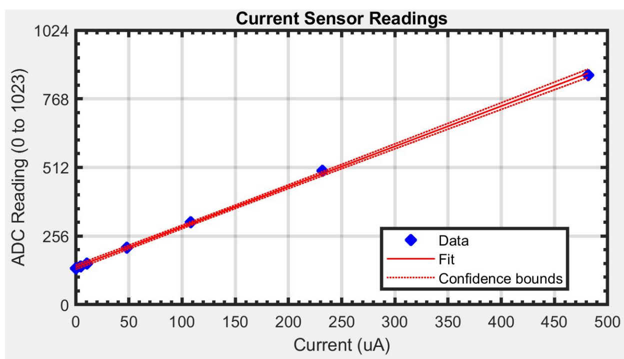

Figure 3.3: Current Sensor Measurement

The voltage sensor has an R^2 value greater than 0.9999, the points used in the calculation are plotted in Figure 3.4.

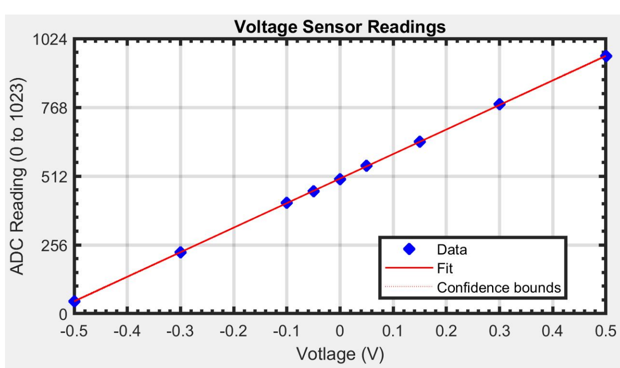

Figure 3.4: Voltage Sensor Measurement

Using the data points, the resolution of the current and voltage sensors can be calculated by taking the range of current applied, and dividing that by the number of ADC steps covered. The resolution of the voltage sensor is 1.1mV, and the resolution of the current sensor is 0.63μA.

3.3 Existing Work

	This Work	**2019** [7]	**2017** [8]	**2012** [9]
Off/Sleep Current (μA)	0.9	267	0.01	—
On Current (mA)	0.555	30	6	—
Battery Capacity (mAh)	235	850	255	1700
Battery Life (months)	15*	2	>24	∼2.5
Sampling Period (min)	1	1	60	10
Case Volume (cm^3)	20.2	35.3	28.5	102.5
pH Correlation (R^2)	>0.9999**	—	—	0.972
pH Accuracy (±pH)	—	±0.1	±0.1	—

Table 3.1: Comparison to Existing Works

**This is the correlation of the circuit, if the electrochemical sensor has a less than ideal correlation then the overall correlation will decrease. Since the correlation of the circuit is very close to one, the overall correlation is almost completely dependent on the correlation of the electrochemical sensor. *This work does not include an RF readout, while the works being compared to include an RF readout. The readout system is not included in this work's current draw. With this in mind, the analog portion is very low power, largely due to the ability to completely turn off the circuit when not in use.

The works being compared only sense pH and some also sense temperature. This work incorporates ability to sense pH, lactate, and VFA. For this reason the works being compared can fit in a smaller space easier. As seen in the results, this work occupies the smallest total volume. This is due to the small battery size, as well as a small readout size. The size should not change with good design when going from a UART readout to an RF readout as explained in Chapter 4. This work does not incorporate the volume of the sensor attached, if the sensor needs a bulky reference electrode then the total volume will increase significantly.

Compared to the other works, when an RF readout is incorporated, this work has high potential for consuming less power, as well as taking up a smaller physical volume due to the custom RF readout and low power consumption. The other works use either bulky antennas, large batteries, or separate PCBs for RF readout that contribute to the total volume.

Chapter 4

Future Work

The readout method will be changed from UART to RF [2]. A DC-DC converter should be added to eliminate the error from the output of the electrode voltage buffers due to battery voltage changes. The IO pads should be taken out to make room for both the extra DC-DC converter just mentioned and the antenna for moving from a UART to an RF readout.

When an RF readout is used, the power supply should be controlled by a switch. One switch that can be used is the TS5A1066 which has a maximum R_{on} of 12Ω. The R_{on} of the switch will have some I^2R power loss depending on the amount of power that the RF readout draws, so it helps to have a lower R_{on} value. The quiescent current it draws from the supply is not a significant amount.

The antenna will take up an area equal to two of the pads, the DC-DC converter and its capacitors will take up an area of one pad, and the IO pads can be shrunk down to the size of one IO pad. The recommended layout would be to take the top two and change those to the antenna, the third pad down would be changed into the smaller IO pads, and the bottom pad is where the DC-DC converter should go. Then the UART conversion chip with all of its extra components and the Micro-B USB port can be taken out to make room for a low-power RF readout.

The MCU will need to be changed to the 14-pin version to allow for enough pins to control the RF section, and the RC delay element will also need to be added. To make room for these components, the voltage buffers in the middle of the PCB should be replaced with their SC-70 version to free up some space. The current sense amplifier may be shifted slightly to the left as well as there is some unused space in the bottom left of the PCB.

For the pH (Voltage) sensing circuit, there is a portion that adds a DC offset. This will not work with a real pH electrode because it has an output impedance in the Mega-ohms. One solution is to buffer the input, but this adds an op-amp and requires a negative power supply. Another solution is to supply the pH electrode voltage to the positive input of the op-amp and not have any filtering or offset there, and apply a low pass after the amplifier, and an offset in the negative feedback path just like in the current sensing circuit (See Figure 4.1). This would require a negative offset which means a negative power supply is needed, but would not require another op-amp. The third solution is to implement the pH sensor with a transistor that controls current through a sense resistor, and read the voltage with an ADC. This is the method found in Zhang's paper [8]. To implement this would require the pH sensor to be designed with the circuit in mind so that the response of the pH sensor will be in the triode region of the mosfet. In their paper it drew about 880μA of current, which may be okay in short bursts. Note that for the first two solutions, a negative supply may not be required if the pH sensor's output is designed to be positive with respect to the reference electrode.

Component	**Value**
R_1	127kΩ
R_2	100kΩ
R_3	100kΩ
C_1	$0.1\mu F$
C_2	$1\mu F$

Table 4.1: Component values in Figure 4.1

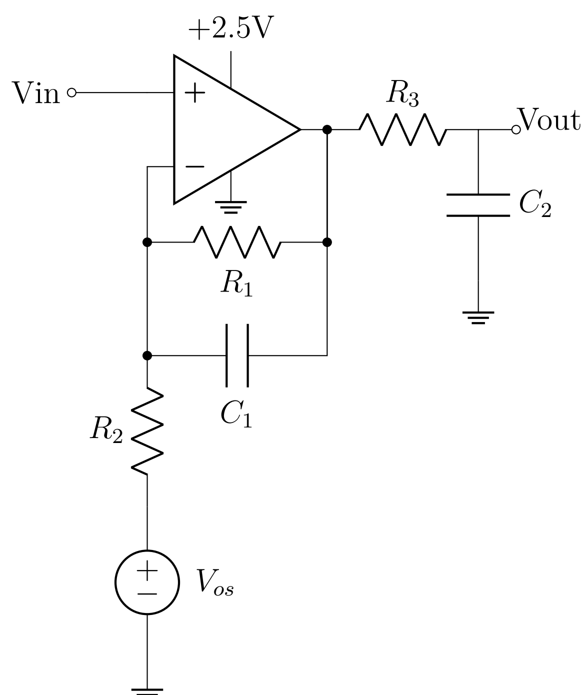

Figure 4.1: New Proposed Voltage Sensing Circuit

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