Lab Report 5

Prepared by: Heidi Eren

Date: 12/14/2025

Executive summary:

Describe what you are trying to accomplish/demonstrate. What is the purpose of this test? (**5 pts)**
The purpose of this experiment is to apply design-of-experiments principles to early-stage prototyping by developing and executing signal-processing-based test plans for a physiological color sensor. The color sensor is intended to be implemented in a ketone test strip device to automatically and accurately measure ketone levels from a urine sample color strip. The sensor measures the amount of light present within different wavelengths to detect the shade of color on the test strip, which corresponds to a specific level on a ketone concentration chart. By creating a calibration curve and computing the 10-point and 50-point moving averages, the color sensor readings stabilize within 10-20 seconds to precisely distinguish the manufacture-defined ketone levels based on the color of the ketone test strip, achieving the required accuracy sufficient for reliable classification. By computing the derivative of the sensor signal, abrupt changes in the readings can be used to flag faulty measurements due to poor lighting, improper sensor proximity, or noise, ultimately improving the reliability of ketone detection for the screening of diabetic ketoacidosis.

Procedure:

1. Describe the clinical purpose of your medical device. What condition will it treat? How will it treat it? What is the intended effect? (**5 pts)**

   The ketone test strip device is intended to non-invasively help people monitor their blood glucose levels for diabetes (DKA) by detecting ketone levels in urine sample color strips. Current test strips can be compared to a scale on a chart, but distinguishing between levels often becomes difficult when the color is faint or blurred between two levels. Having to resort to a color chart also makes it challenging for those who have color blindness. Hence, this color matching process can be automated with the device, which will precisely measure ketone levels from a urine sample. This will then indicate to the patient whether their ketone levels are high (meaning their body is burning fat for energy instead of glucose), and whether to seek a healthcare professional immediately as high ketone levels can lead to diabetic ketoacidosis, a life-threatening condition that can cause fatal complications such as brain swelling and kidney damage. The medical device simply provides information on the patient's ketone levels in their urine, indicating a critical sign of diabetic ketoacidosis, but not a diagnosis.

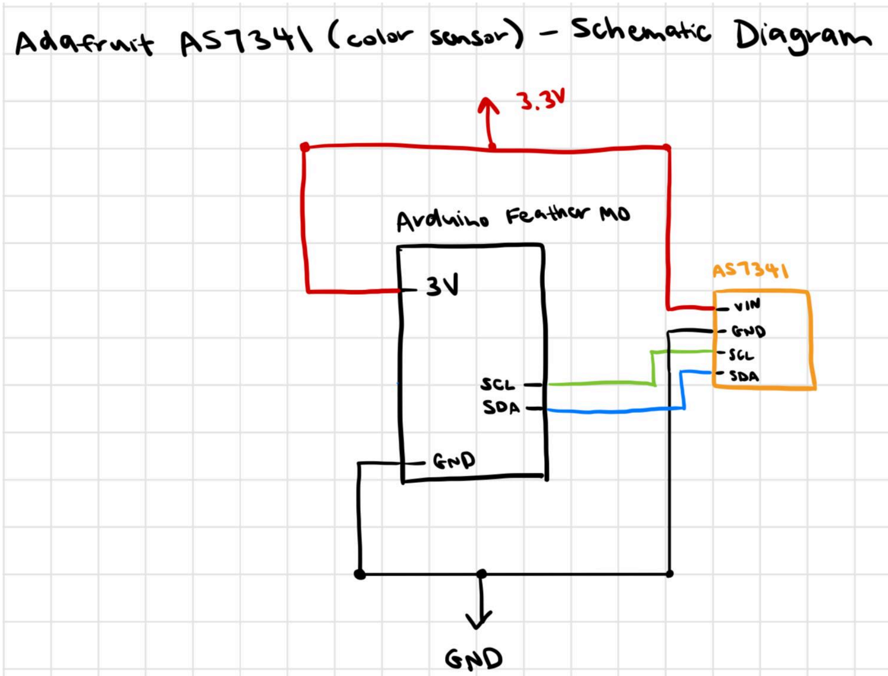
2. Describe the purpose of the sensor within the device. How will this sensor affect device performance? (**5 pts)**

   The Adafruit AS7341 color sensor is intended to accurately distinguish the ketone levels based on the color of the ketone test strip. The sensor uses a multi-channel spectrometer to detect the amount of light present within different wavelengths. The sensor will detect the shade of color from the test strip, which can then be corresponded to the ketone levels chart to determine the concentration of ketone present in the urine. The sensor can easily affect the device performance because of noise, distance, and intensity of the test strip. Firstly, the sensor requires the test strip to have sufficient light but complete coverage (on the surface of the sensor) in order to detect the appropriate color. The sensor itself does not have high precision and requires a controlled light source and field of view. The sensor also requires enough proximity to the test strip in order to reliably detect the amount of light present. If the field of view is obstructed, the test strip is too far away, or the test strip is not directly covering the sensor, noise (background/ambient lights) can be detected which disturbs the readings and skews its ability to correctly classify the ketone concentration, ultimately hindering the performance of the device.

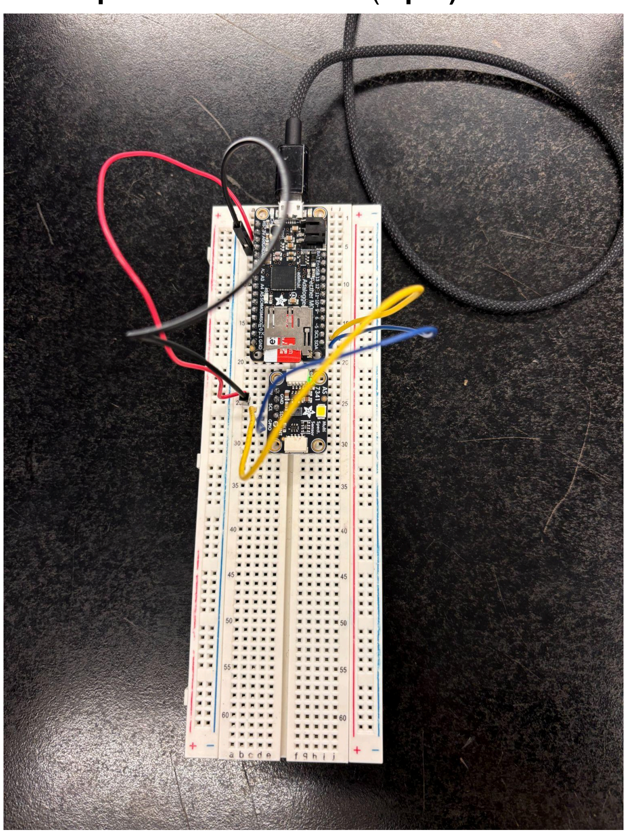
   Output channel: RGB
   Output type: Digital (16-bit)
   Tolerance: +/- 10 ADU per channel

3. Using your sensor, build a circuit which will measure your target signal. Consider the level of accuracy that might be required.

4. **Sketch a circuit diagram of the circuit (5 pts):**



5. **Take a photo of the circuit (3 pts):**



6. In the Arduino IDE, calculate the relevant output from the sensor. Include any relevant calculations that were used to reach your final code. (**You will upload your final code to Canvas**). **(5 pts for data acquisition)**

7. Create a test plan for your circuit/sensor that includes:
    a. A "confirmatory" test with a known input to confirm your circuit is working properly **(4 pts)**

The confirmatory test will ensure that there is a difference between lighter colors from darker ones in the detected light intensity of the sensor. The test will use diluted shades of the same color (e.g. green) by testing varying dye to water ratios (1:1, 1:3, 1:5). The same light color channel (e.g. green, 480 nm) will be compared. Darker shades, or higher dye to water ratios, should detect lower light intensities for the violet light channel. Lighter shades, or lower dye to water ratios, should detect higher light intensities. See the below graph, which visually demonstrates a stark contrast between one shade of green to the other with 1-2 seconds in between. Moving from left to right, the shade of green becomes darker. Hence, this verifies that the circuit is working properly with the color sensor detecting a change in color shade appropriately.

    b. A plan for processing the signal using at least three separate techniques discussed previously in class (with explanation for why these techniques were chosen and what the expected output is) **(21 points, 7 each)**

Calibration curve
The calibration curve technique will compare six known color shades (standard ketone concentrations) with what is detected with the color sensor. The detected readings for the violet light frequency channel at 415 nm will be measured (see shades below) and plotted against the standard ketone concentrations. The (nonlinear) line of best fit in exponential regression will map the raw sensor readings to known ketone concentration values, which ensures that when converting the 16-bit ADU readings to ketone concentrations, it computes the actual concentration. Hence, the calibration curve is a crucial signal processing technique to convert the raw ADU readings into ketone concentrations for proper classification. This can then help determine the thresholds for where sensor readings would fall into the distinct ketone levels for the ketone device.

The exact shade of ketone levels below were used for this test.

Standard ketone levels color chart

TRUEplus® ketone test strips for diabetics - 50-count. TD Health Store. https://www.tdhealthstore.com/products/trueplus-ketone-test-strips-50ct.

By measuring what the color sensor detects at each standard ketone shade, a graph can be plotted where the concentration of the standards are on the x-axis and the corresponding color sensor values are on the y-axis. This technique can validate the precision and reliability of the Adafruit AS7341 color sensor by evaluating the detected light channel values with standard values. The equation of the calibration curve can be used to reliably transform the raw sensor readings into a quantitative measurement for the concentration of ketone with a tolerance of within 0.5% mg/dL. Within more reliable classifications of levels, the sensor would measure color values with reasonable accuracy. Given the sensor's highly sensitive nature, the calibration curve normalizes and scales the raw output of the sensor with the line of best fit equation.

For the test plan, the calibration curve will be produced by creating a Powerpoint slidedeck with each ketone level color matched to the background color on a slide. Then, resting on a whiteboard eraser for uniform distance, the laptop screen on full brightness will display the Powerpoint slide for each shade. The color sensor readings will be recorded after stabilization for about 5-10 seconds. The values will then be recorded in an Excel spreadsheet and graphed with an exponential regression line of best fit.

Moving average

Simple moving average helps smooth out the data by averaging the detected light channel values over a specific period of time. By taking the average, the variability from noise in the sensor can be minimized. Background light or ambient light can easily be detected, disrupting the measurement of the light intensity from the test strip. The amount of light on the test strip can also affect the detected light intensity, which can be adjusted by distance. If not enough light is on the test strip, the sensor may not detect any color even when there is a color on it. Hence, the average across 10 data points or 50 data points is one way in which the detected light intensity values can be smoothed, producing a more accurate reading. The expected output is that when the color channel values are detected, there would be fewer jumps and smaller variability between measurements. A value closer to the color sensor's true detection would be outputted for the desired color channel (violet).

For the test plan, the Arduino code will be changed to include the moving average component for the 1-point (no moving average), 10-point, and 50-point moving average calculations. The same ketone color shades will be displayed for the color sensor to read. The minimum, maximum, and variance for each shade will be measured and recorded in a table. The moving averages should show that by taking the average of a greater number of points, the readings become more consistent. To ensure that the previous shade does not affect the moving average of the next shade, the sensor was normalized with a black screen displayed to restart each reading to 0.

Derivative

The derivative represents the rate of change of a signal. With the color sensor, taking the derivative of the detected light intensity signal can amplify noise. This can help flag the color sensor when the test strip is out of range or has insufficient light. Similar to event detection, computing the derivative would detect abnormalities in the light intensities output. Using thresholding and identifying the frequency of peaks or troughs over time, the first derivative of the light intensity measurements can detect these changes and notify the patient to adjust the placement of the test strip on the color sensor. The expected output would be a print statement in the serial monitor that flags this change immediately to the user. In the medical device, this would be in the form of a flashing light or text box on the screen of the device. That way, the patient will know whether the test strip needs to be closer or farther away from the sensor for an accurate and reliable reading.

For the test plan, the Arduino code will be changed to compute the derivative of the color sensor readings. The sensor reading will then be compared to the threshold value of what the general range of ketone readings should be. The derivative will be compared to the threshold value of how significant of a jump there is in the readings. The number of times the detected readings exceed these threshold values will be counted, and after three consecutive readings, the Serial monitor will print a “WARNING: Test strip out of range" to flag the user.

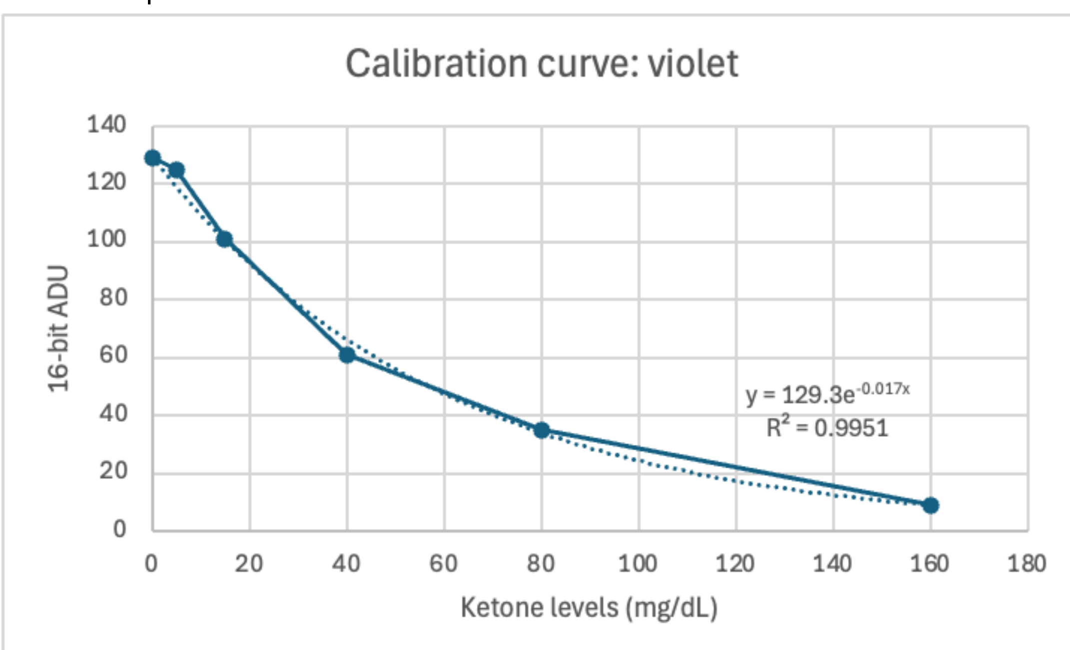
Citations:

1. Industries A. Adafruit AS7341 10-channel light / color sensor breakout. adafruit industries blog RSS. Accessed December 9, 2025. https://www.adafruit.com/product/4698?srsltid=AfmBOopyoT71TB6DVd2IxLMZ77uWALfliNck21jMEUGfHisasD77B9P4.
2. Adafruit AS7341 10-channel light / color sensor breakout. Accessed December 10, 2025. https://cdn-learn.adafruit.com/downloads/pdf/adafruit-as7341-10-channel-light-color-sensor-breakout.pdf.
3. Datasheet DS000504 AS7341 11-channel multi-spectral digital sensor. Accessed December 10, 2025. https://cdn.sparkfun.com/assets/0/8/e/2/3/AS7341_DS000504_3-00.pdf.

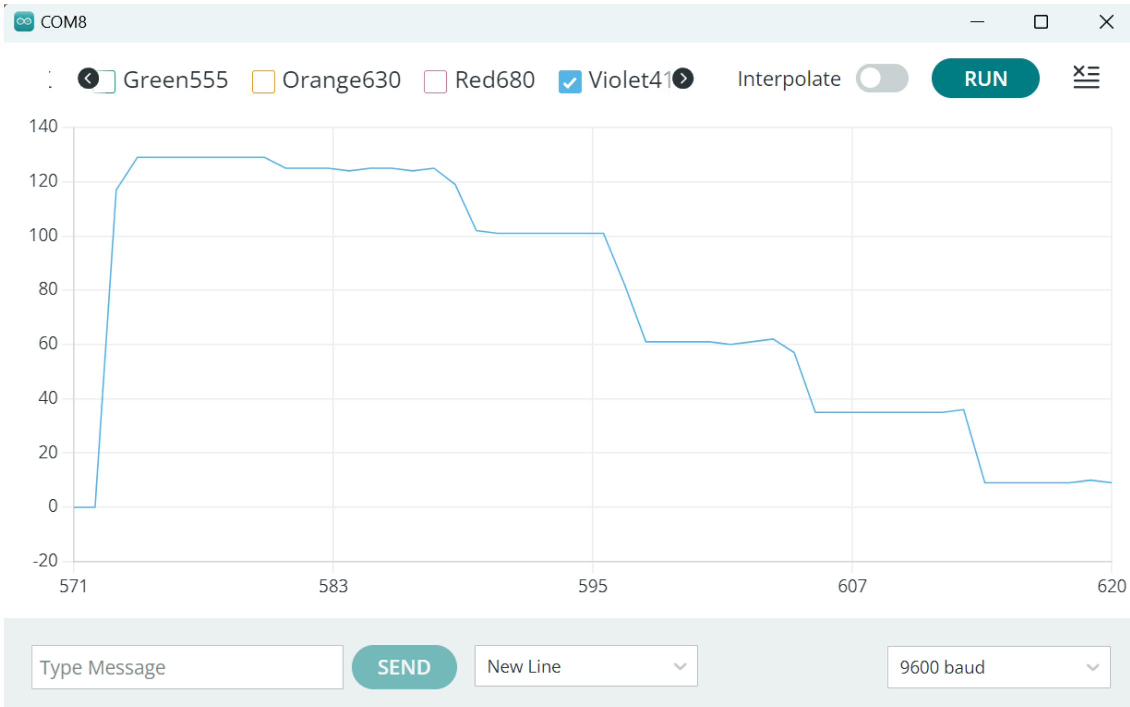
8. In the Arduino IDE, implement any signal processing described above. (**You will upload your final code to Canvas**). **(15 points, 5 each)**

9. Report your results for your test plans developed in 7 (a,b,c). Results should be presented in a way such that they are comprehensible and easy to read. **(10 pts)**

Calibration curve plot

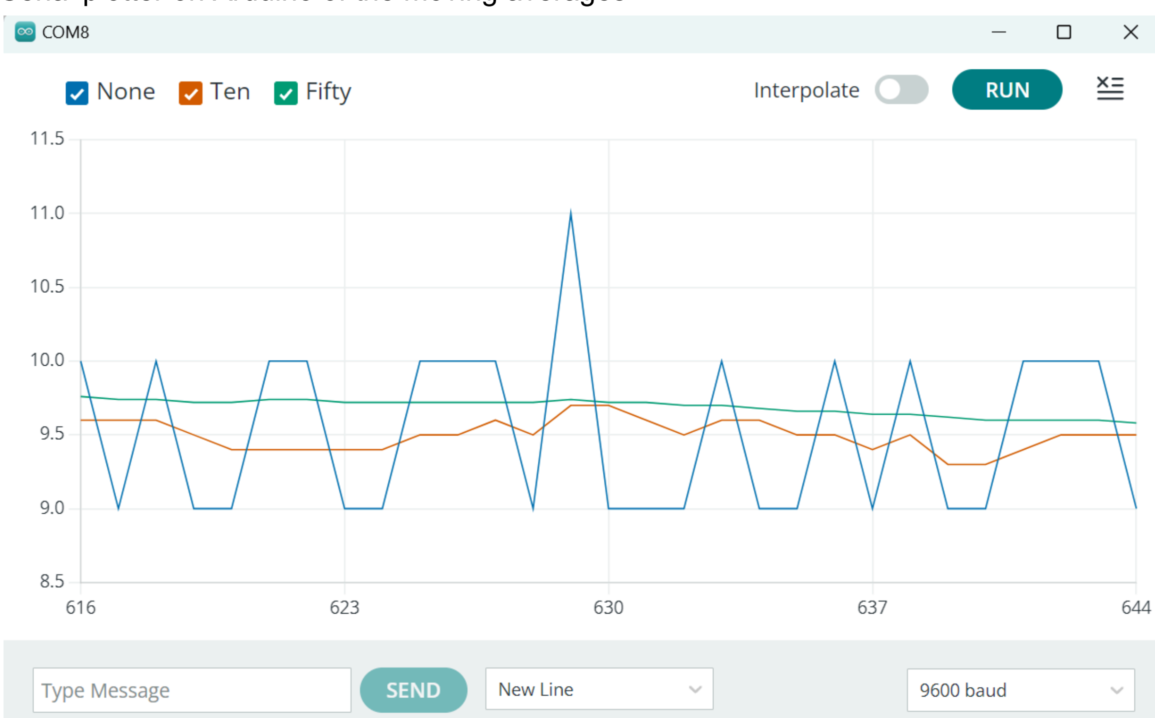


Serial plotter on Arduino of the calibration curve



This was a demonstration of how the color sensor is detecting each shade correctly. The sharp drop in the measurements represent the change in ketone color shade. From left to right, the ketone levels increase (shade becomes darker).

Serial plotter on Arduino of the moving averages



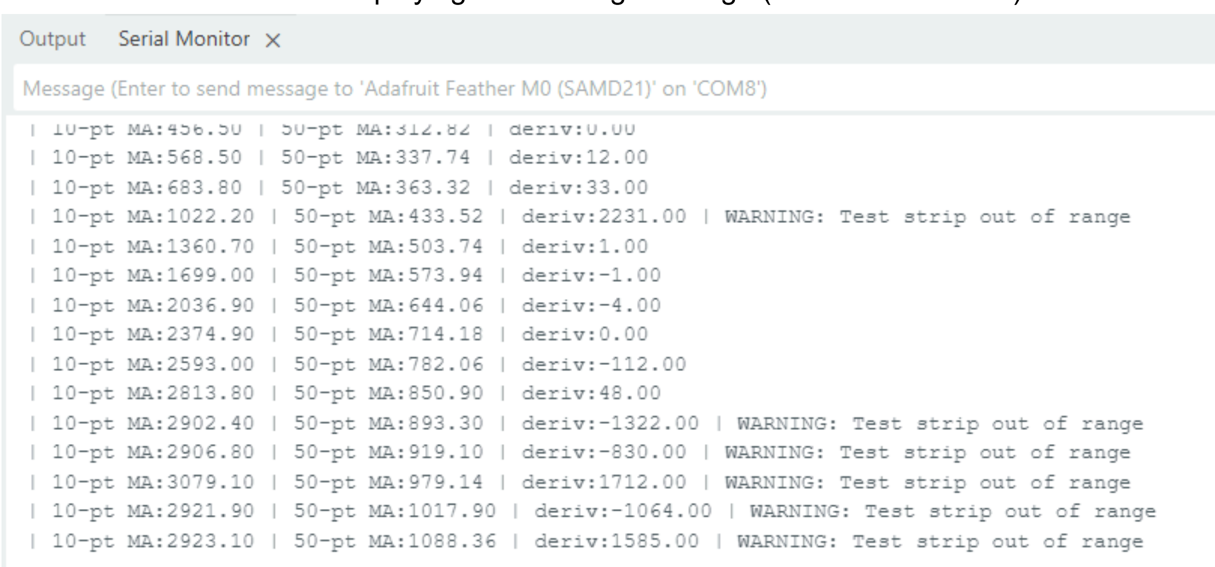
This demonstrates how the moving averages “smooth” the sensor readings from noise.

Moving averages table

Ketone level (mg/dL)	metric	No average	10-point average	50-point average
0	min	124	124.8	125.26
0	max	126	125.2	124.94
0	var	2	0.08	0.0512
5	min	124	124.8	125.14
5	max	126	125.4	125.98
5	var	2	0.18	0.3528
15	min	99	99.2	99.18
15	max	100	99.8	99.52
15	var	0.5	0.18	0.0578
40	min	57	57.6	57.9
40	max	59	58.1	57.92
40	var	2	0.125	0.0002
80	min	36	36.2	36.46
80	max	38	36.6	36.62
80	var	2	0.08	0.0128
160	min	9	9.3	9.58
160	max	11	9.7	5.76
160	var	2	0.08	7.2962

This table demonstrates how much variation there can be between each consecutive sensor reading, so taking the average can reduce the fluctuations (from external noise) that the sensor can pick up.

Serial monitor on Arduino displaying the warning message (from the derivative)



```
Output    Serial Monitor ×
Message (Enter to send message to 'Adafruit Feather M0 (SAMD21)' on 'COM8')
| 10-pt MA:456.50 | 50-pt MA:312.82 | deriv:0.00
| 10-pt MA:568.50 | 50-pt MA:337.74 | deriv:12.00
| 10-pt MA:683.80 | 50-pt MA:363.32 | deriv:33.00
| 10-pt MA:1022.20 | 50-pt MA:433.52 | deriv:2231.00 | WARNING: Test strip out of range
| 10-pt MA:1360.70 | 50-pt MA:503.74 | deriv:1.00
| 10-pt MA:1699.00 | 50-pt MA:573.94 | deriv:-1.00
| 10-pt MA:2036.90 | 50-pt MA:644.06 | deriv:-4.00
| 10-pt MA:2374.90 | 50-pt MA:714.18 | deriv:0.00
| 10-pt MA:2593.00 | 50-pt MA:782.06 | deriv:-112.00
| 10-pt MA:2813.80 | 50-pt MA:850.90 | deriv:48.00
| 10-pt MA:2902.40 | 50-pt MA:893.30 | deriv:-1322.00 | WARNING: Test strip out of range
| 10-pt MA:2906.80 | 50-pt MA:919.10 | deriv:-830.00 | WARNING: Test strip out of range
| 10-pt MA:3079.10 | 50-pt MA:979.14 | deriv:1712.00 | WARNING: Test strip out of range
| 10-pt MA:2921.90 | 50-pt MA:1017.90 | deriv:-1064.00 | WARNING: Test strip out of range
| 10-pt MA:2923.10 | 50-pt MA:1088.36 | deriv:1585.00 | WARNING: Test strip out of range
```

Because the warning message requires at least a minimum number of “out of range” readings, there was a gap in between the normal readings and the inaccurate readings containing the warning message.

Notes and recommendations:

1. Describe the interaction between a. Your chosen sensor; b. The type of data you can collect; c. the type of device the sensor can be integrated into **(5 pts)**

The color sensor measures the amount of light reflected at specific wavelengths through filtered photodiodes that convert photons to electrons. The charge accumulates and amplifies by the gain, which then converts the ADC to a 16-bit digital ADU value. This ADU value is collected to compare with the ketone concentration levels using the calibration curve, which determines what the true color of the test strip is in terms of ketone concentration. Once the color sensor identifies the color and which ketone level it falls under, the color sensor will communicate to the integrated device to output the ketone concentration category for the user to see. If the color sensor is measuring a color strip that has insufficient light or is at an out of range distance, the sensor will communicate to the device to output a warning message to notify the user to make an adjustment to the placement of the test strip.

2. How does your chosen sensor implementation impact your choice of signal processing technique? **(5 pts)**

The color sensor implementation limits the choices of signal processing techniques that can be applied because the color sensor readings do not continuously change over time, but rather, output discrete values at each time point. Once the sensor reads the light intensity on the test strip, it would marginally fluctuate (depending on noise) but mostly stay constant. There is no feedback control, autocorrelation, nor FFT for continuous signal measurements. The color sensor does not have a dominant frequency or repeating oscillatory pattern in its readings, so the signal cannot be analyzed for such periodic changes. The color sensor can only measure a slow, non-periodic color transition rather than an oscillatory signal. Hence, the signal processing techniques are restricted to calibration curve mapping, moving averages, and derivative-based event detection.

3. Is your sensor implementation up to the task that you selected? Comment on the results you collected regarding accuracy, difficulty of implementation, etc. in the context of your chosen clinical need. **(7 pts)**

The color sensor implementation is up to the task selected (reliably detect ketone concentration from color strip). When obtaining results, the color sensor was difficult to implement because controlling all other variables (distance, light source) to obtain reliable readings was challenging. Using a whiteboard eraser, we set a fixed distance for the color sensor to measure the test strip colors. Using the screen of a computer on full brightness, we ensured the test strip color covered the entire surface of the color sensor. We also ensured that the color sensor was able to stabilize its reading by showing the test strip color for 10-20 seconds prior to recording results. By controlling these confounding variables, the sensor readings were more consistent and accurate especially when taking the moving average. This was evident when the variance decreased as the number of time points in the moving average increased. For the data collection, the sensor outputs 16-bit ADU values, which cannot be directly converted to standard RGB values, so we could not validate that the readings are true to the color shade that they truly are. Although we can use the calibration curve to convert these ADU values to ketone concentrations, it does not verify that the original ADU values are accurate to the color on the test strip.

For the calibration curve, the R^2 value was 0.9951, so the conversion from 16-bit ADU sensor readings to ketone concentration is reasonably accurate. Hence, the exponential regression model is a strong fit in predicting the ketone concentration.

The serial plotter of the moving averages shows that without the moving average, the sensor readings fluctuated significantly due to noise or background light. The 10-point and 50-point moving averages smoothed out the readings so that the values were much more consistent to one another. The table also verifies that the variance was significantly lower for the 50-point moving average than without the moving average for each ketone level. Hence, without as much noise being accounted for and weighing the data, the sensor readings became more accurate overall.

The derivative calculations were also accurate as tests such as when the distance was purposefully changed or the color was completely different from the shades of ketone levels were flagged. The serial monitor immediately displayed the warning message, which verifies the reliability of this method.

In the context of a handheld ketone test strip reading device, the requirements for the sensor to be able to measure reliably and accurately means that either the device overall needs to be designed in a way to meet these requirements or the user has to make sure they follow directions. The line of best fit from the calibration curve, moving averages, and derivative calculation can all be encoded into the device with the color sensor integrated, but implementing a way to control the distance between the sensor and color strip, the background light source, and scaling the color strip so that it covers the sensor in a realistic and practical way for the device can be accounted for in the future. Although the derivative calculation flags a warning for the user to adjust the distance between the color strip and sensor, it does not give sufficient information as to how far away or how much closer they need to adjust to.

4. What are the next steps for your device development? **(5 pts)**

The next steps would be to design the device to control all the confounding variables. To make it as user-friendly as possible, we would want to ensure that all the patient needs to do is insert the test strip into the device, and the device handles everything from there in order to output the ketone concentration and category. The device would integrate the color sensor, and the device would be designed so that the distance between the color sensor and test strip is fixed, with a small LED set to a fixed brightness inside the compartment for the sensor to detect the test strip. The device would also be designed so that there is a black rectangular aperture-like tunnel so that the test strip fills the sensor's field of view while eliminating background light. With the test strip being inserted into the device, there would be no possibility of noise interfering with the ketone level readings. On the surface of the device, there would be a screen that displays the measured readings in concentration (mg/dL) and level (negative, trace, small, moderate, large). The optical housing of the device would first be tested to ensure repeatable strip placement and controlled illumination from the light bulb. The detected readings would then be validated to ensure that there is an improvement with minimal background light interfering. This would enhance the overall design of the device with integration of the color sensor by minimizing user interaction, improving the measurement consistency and repeatability.