Convex Optimization: Optimizing Resistor Value for Analog Sensing

whitloca

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1 Abstract

Analog sensing development leaves a lot of room for improvement when it comes to errors brought on by component values. Algorithms made to optimize specific parts within the sensor goes a long way towards making the sensor more accurate with little time investment in trial and error testing. Algorithms such as the one developed here are utilized in this way to create more accurate output data given a set of parameters the end user can set. This also helps developers create a sensor that is well adjusted for the end users case without having to revisit the hardware at a later date.

2 Introduction

The field of environmental sensing is ever expanding with new sensors and technology constantly being developed. Hydrology thins the scope of environmental sensing down to water related measurements including temperature, turbidity, and salinity to name a few points of measurement. One way to measure the salinity of a sample of water is to do an electrical conductivity test on it, measuring how resistive the water is. This data can provide information on the salinity of the water as well as how much pollution or nutrition is present in the water. This is a good metric on environmental health in many ways. For example rain water is extremely fresh, i.e. has a very low salinity, so if the electrical conductivity is high it is pulling pollution from the air into the environment or is carrying other pollutants/nutrients. Same analysis can apply to river water to calculate the flux of pollution or nutrients between the riverbed and river itself.

There are many commercial sensors with the specific purpose of measuring the electrical conductivity of water for environmental sensing. These often very bulky and aren't easy to transport to remote locations, often only being used for in lab testing. Having sensors that can be deployed in remote locations to continuously test water electrical conductivity is a great help towards researching the environmental health of these locations. Sensors that do this job are few and far between with the ones existing being costly. The OPEnS lab at Oregon State University under the Biological and Ecological Engineering department works to meet these sensing demands with open source technology, focusing on ease of use, low cost, accurate sensing tools.

The project RainSavor is being developed at the OPEnS lab to meet the demands of the Oregon State University forestry professor Catalina Segura to test the electrical conductivity of rain water in forests for months at a time. The goal of the project is to have a sensor that can be deployed at any location and sense samples of rain water as different rain events occur, logging the temperature, humidity, and electrical conductivity of the rain water as the storm occurs. The scope of this paper is on the electrical conductivity sensing technology as this has no small form factor out of the box solution and was developed as an in house analog sensor.

3 Electrical Conductivity, Measuring Data, Analog Sensor Technology

Sensing electrical conductivity has many challenges regarding the physical properties of water and the signals required for the measurement. The sensor circuit used here is a two pin probe method with an oscillating signal (avoiding electrolysis of the water) to get the conductivity measurement. The circuit schematic is shown here alongside the physical implementation.

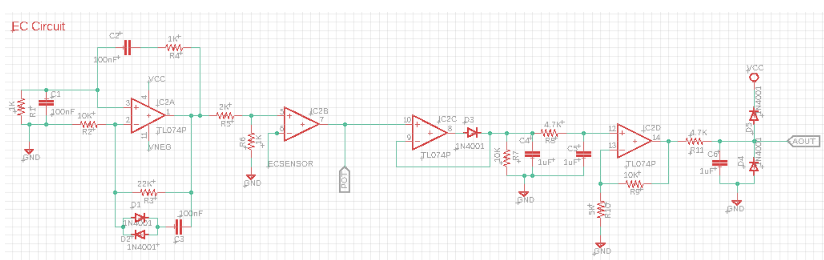

Figure 1: Electrical Conductivity Sensor Schematic

The ranges that this circuit measures widely depending on the value the variable resistor/potentiometer is set to and allows for a wide range of tuning for the user. The resistor used for extremely fresh water (0-100 uS/cm) will be much larger than the resistor used for less fresh or brackish water (0-1413 uS/cm). Many users operate in ranges even higher than slight brackish nearing salt water environments which are extremely conductive in comparison.

3.1 Circuit Limitations, Why Optimize?

The analog voltage created by the sensor is digitized using an ADS1115 analog to digital converter. This converter has 16 available bits for the conversion.

Figure 2: Circuit Box with Sensor Equipment

This resolution is appropriate for the readings when the range is set correctly but loses a lot of data if the range isn't correct, for example if the circuit is tuned to a 0-1413 uS/cm range but is operating in the 0-100 uS/cm most of the data is limited to a portion of the available bits. This limitation, alongside the need to sense in multiple types of environments, makes it difficult to know a good resistor value without extensive testing.

More so, many end users don't have electronics experience and aren't able to reprogram or swap out this resistor. The solution that I am bringing forward to solve this efficiently is to create an algorithm that can optimize this resistor value depending on the users electrical conductivity range allowing us to pick a good value immediately. This solves many debugging issues down the road and if a new value is needed the data gathered by the user can be used alongside this optimization algorithm will pick a new one for installation.

This optimization algorithm can be formed as a euclidean distance optimizer with the graphed data from the run time experiments done with the sensor itself. Figure 3 shows example data from a test ran with the sensor that will later be optimized with the algorithm.

The 16 bit ADC limits the data output between 2600-13600 (partly with DC bias in the circuit itself). There are a few variable to control and constrain here. The first is the 'average' output for a given EC. Often times some headroom is wanted in case spikes in salinity occur, so tuning the wanted EC to a value such as 10000 is a common occurrence. Allowing this to be flexible per sensor setup will be useful. Additionally this headroom amount can fluctuate depending on the resistor. Allowing the user to add how much it can vary around this electrical conductivity is extremely helpful. The goal of the algorithm will be to take tuning data at a given EC that is un-tuned, provide the algorithm with

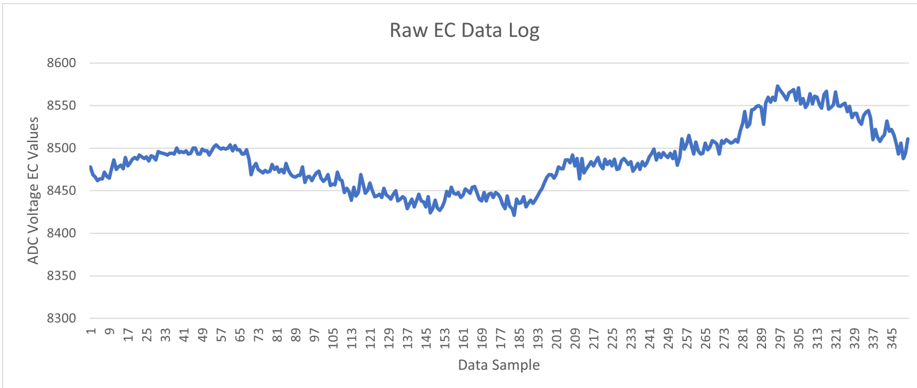

Figure 3: Example Data from Lab Testing (100 uS/cm)

the EC measured, the tuning value between 2600-13600 (generally 10000), and the percent error or 'leniency' around this point of measurement.

4 Formulating Optimization Problem

There are a few steps towards creating the optimization algorithm, the first is finding a way to estimate the resistor value for a given data reading at a specific EC. This will allow the resistor to be altered in software allowing the output to be optimized, the resistor can be physically changed later.

Some of the derivation of this equation will be quickly brushed by as it is a conversion of example data and tuning data run through some algebraic equations to find lines of best fit. The important graph to show for this calculation is how some of the electrical conductivity solutions reacts to different potentiometer values. An important note, the potentiometer used is an I2C device that can take values up to 128, where this value is divided by 128 and multiplied by 100k Ohms to get the resistor value.

The tuning graph in figure 4 shows the results of the variable resistor increases in increments of 10 for each solution. The higher the solution faster the quicker the output saturates at the maximum, in other words as the resistor increases in value the output saturates quicker. Higher ECs require much lower resistances. The data in this graph is used to find a variable slope equation for a best fit curve for the tuning of a given sensor setup.

Using the equations provided by the datasheet for the potentiometer (AD5246) and the best fit equations found in excel, the equation for the raw value given the EC and the used resistor is as follows.

$$RawData = 4.3 * (EC)^{0.5743} * \frac{Resistor * 128}{100000} + 2538 \tag{1}$$

This is a decent model for the raw data as well, and is a good estimator for the

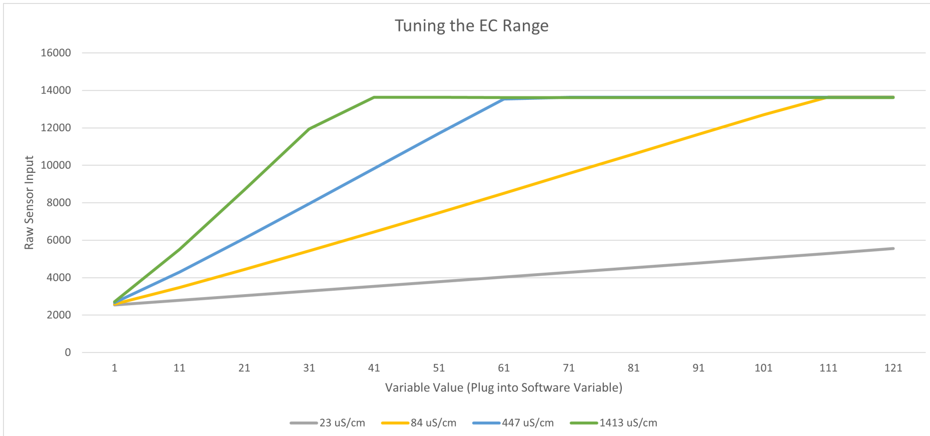

Figure 4: Tuning Data

fixed output data. Some conversions will be off depending on the multiplier as it may vary slightly on conductivity beyond what this equation can model. This equation will be used in conjunction with the optimized values to reconstruct the data based on the new model.

Now with the base problem constructed, and a euclidean objective function can be formed, the optimization algorithm can be constructed. I will be utilizing CVX in Matlab to optimize the variables according to the constraints.

To begin the optimization problem I abstract the original resistor to a vector that can be optimized. The optimized resistor will then be a vector of many resistor values after the algorithm completes. All values will be close but this allows flexibility in checking the data on the minimum, maximum, or average resistor value for greater control. Additionally the raw input data is reconstructed into a diagonal matrix. Using Matlab syntax where applicable.

$$ResistorVector = \frac{(RawData) * 100000}{4.3(EC)^{0.5743*128}} - 2538 \tag{2}$$

$$RawDataMatrix = diagonal(RawData) \tag{3}$$

The last two inputs are the error allowed (leniency) and the tuning values. This tuning value is what the EC is being mapped to, i.e. 100 uS/cm as measured by the sensor will equal the tuning value (10000). The leniency is then the area above and below this value that the data can reside in. The leniency will be included in the objective function to optimize, allowing the user to input a large leniency and the algorithm to find the smallest amount of error per resistor.

With the graph it is simple to view this problem as a euclidean optimizer, allowing the objective function to be the sum of two, two norm equations. One of these two norms is the euclidean distance between the data and resistor variable and the tuning value. The second is a two norm on the leniency value.

$$minimize||RawDataMatrix * Resistor - tuning||_2^2 + ||leniency||_2^2 \quad (4)$$

The objective function now must be subject to the needed constraints. The first of these constraints is an equality constraint of the components in the first two norm, where the difference between the components is equal to zero.

$$RawDataMatrix * Resistor - tuning == 0 \quad (5)$$

The next three constraints map the leniency optimizer with the resistors and tuning value.

$$AverageResistor*MaxRawDataValue <= tuning+leniencyAverageResistor*MinRawDataValue >= tuni \quad (6)$$

This forms the entire optimization problem for the EC resistor fixing algorithm.

5 Optimization Goals and Results

The optimizer equation formed in the previous selection is implemented utilizing CVX in matlab. The following figure is the algorithm operating on the raw data.

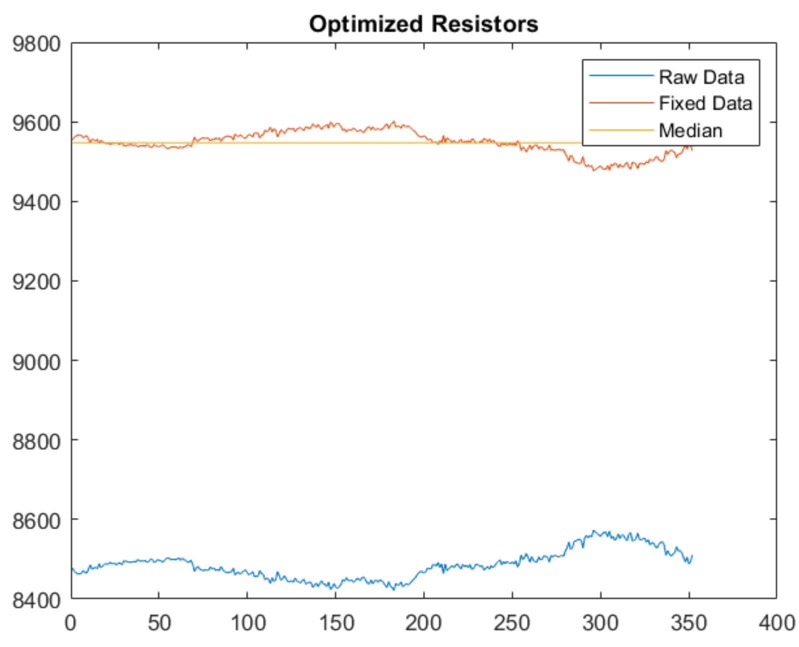

Figure 5: Data Tuning Range 1 (9500)

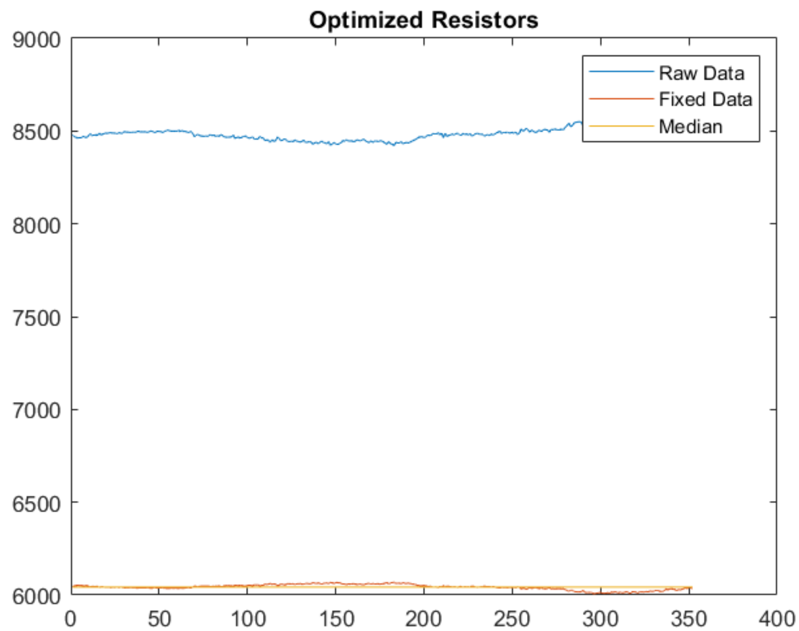

Figure 6: Data Tuning Range 2 (6100)

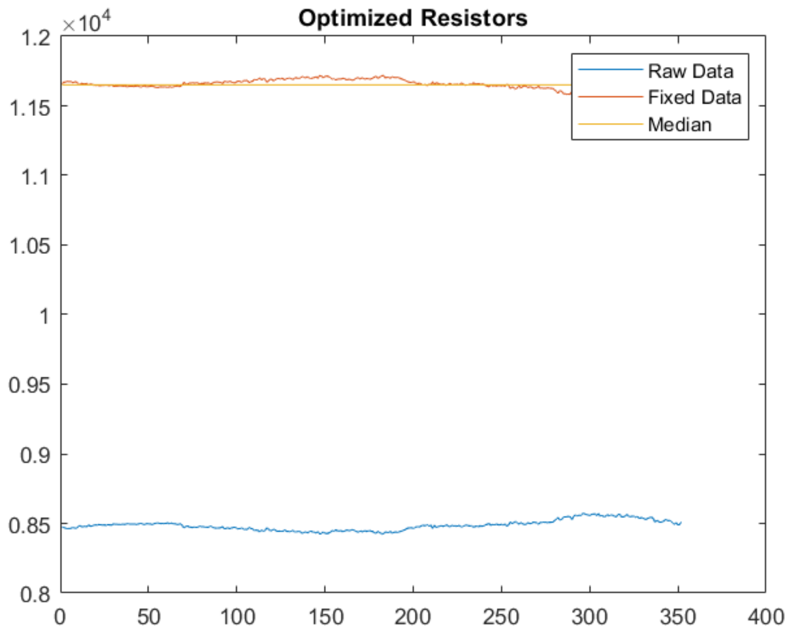

Figure 7: Data Tuning Range 3 (11800)

Each instance of the setting of the variables alters the resistor value from the optimized values. Each of the figures shown above are a different tuning value and leniency to optimize the resistor values to. Each one accurately constrains the analog sensor values around the decided region.

6 Conclusion

An optimization algorithm can be utilized to decide the discrete resistor value in a specific spot in the designed circuit. This is easy to do with this algorithm by feeding it data from a generically chosen resistor, fixing the value with a multiplier and providing multiple, more efficient options. This algorithm could be abstracted to optimize for other variables within the equation as long as others are fixed.

It is important to note that some errors in the level from optimizer come from errors in the algebra when creating the base equation. Due to the nature of temperature effects for different EC levels some small errors are creating. This can be fixed with a more accurate model at this stage.

7 References

[1] Boyd, Stephen P. Convex Optimization / Stephen Boyd Lieven Vandenberghe p. cm. Includes bibliographical references and index. ISBN 0 521 83378 7 1. Mathematical optimization. 2. Convex functions. I. Vandenberghe, Lieven. II. Title. QA402.5.B69 2004 519.6–dc22 2003063284 ISBN 978-0-521-83378-3 hardback

[2] Data Sheet AD5246 Rev. C Information furnished by Analog Devices is believed to be accurate and reliable. However, no responsibility is assumed by Analog Devices for its use, nor for any infringements of patents or other rights of third parties that may result from its use.

[3] What Is Electrical Conductivity? - Know Conductivity Of Water and Saltwater, Specific Conductance and FAQs. https://byjus.com/physics/conductivity-of-water/. BYJUS. December 11, 2021. April 28, 2021