Hardware to enable large-scale deployment and observation of soil microbial fuel cells

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jLab in Smart Sensing. *PI:* Colleen Josephson (cjosephson@ucsc.edu)

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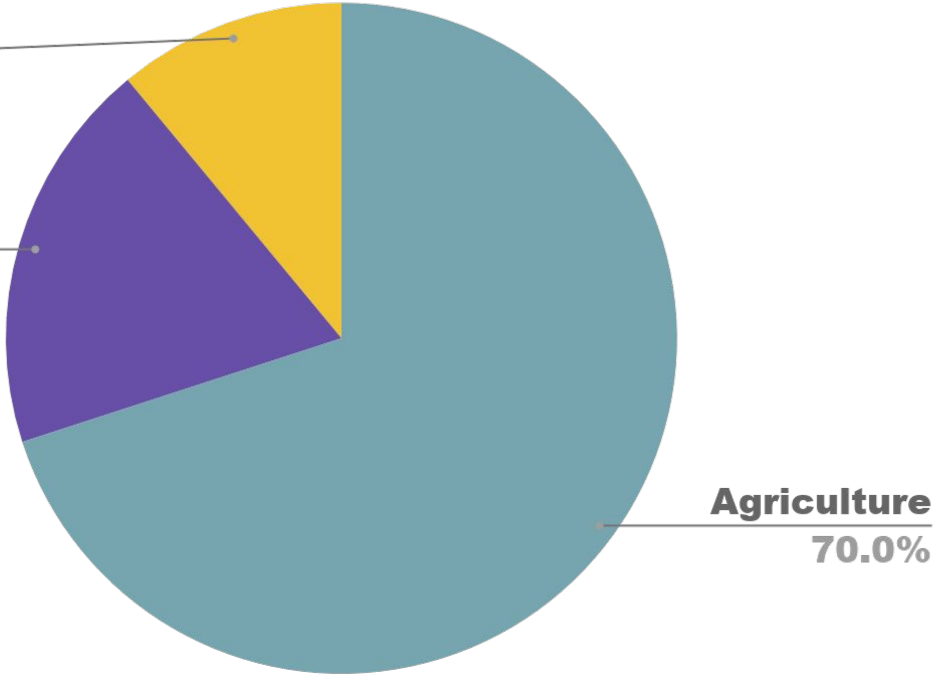
The impacts of climate change…

From drought.ca.gov and grist.org

Sensor networks: a tool against climate change

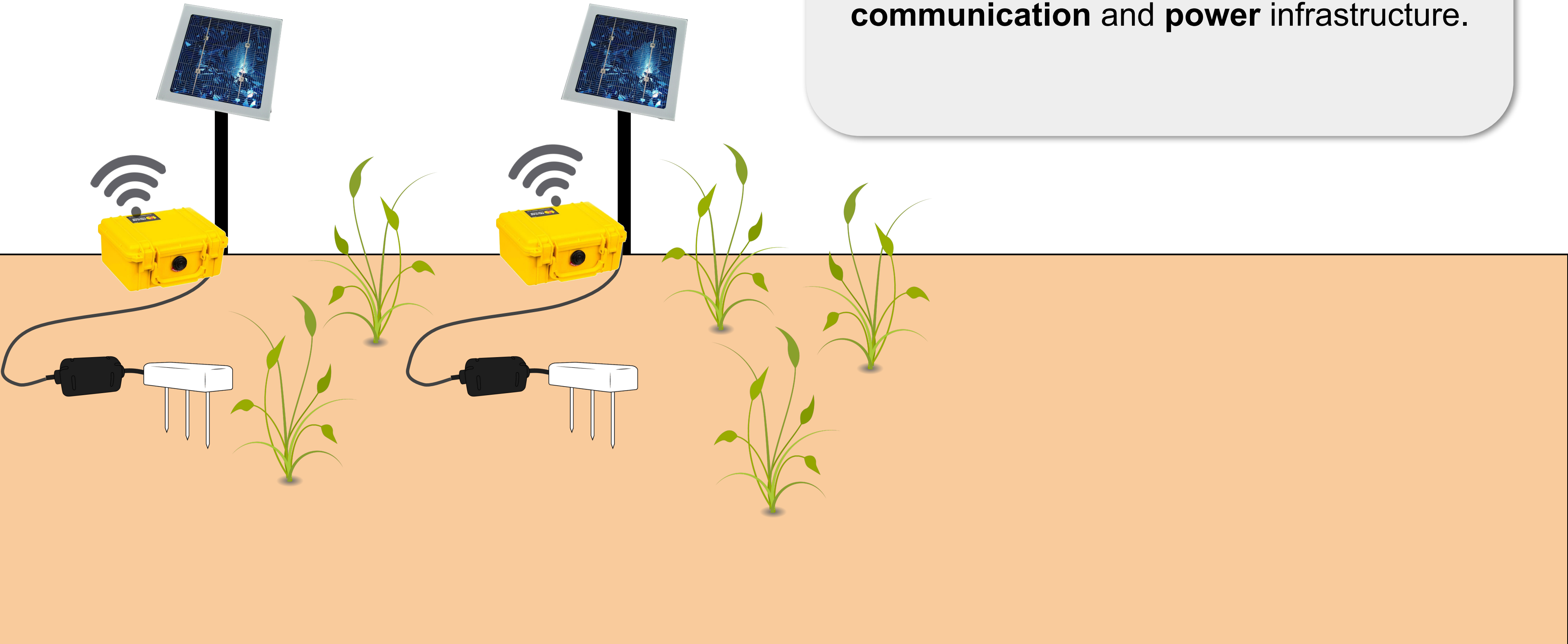
20-50% water savings
via soil moisture sensors

…but <10% of US farms use them!

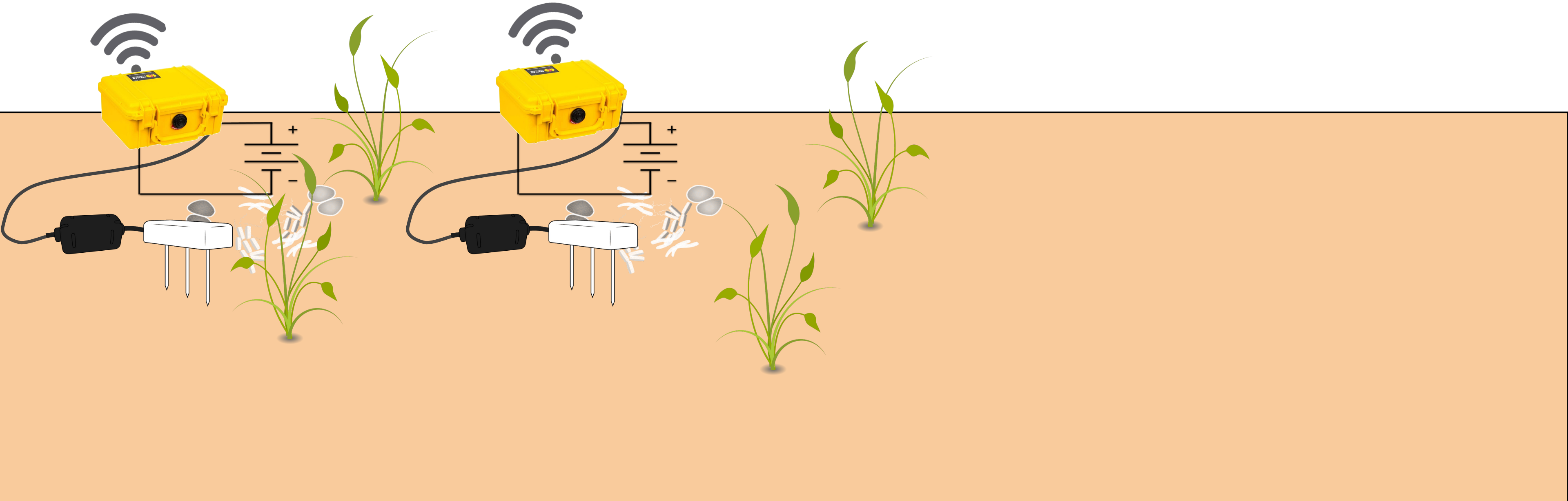


[1] United States Environmental Protection Agency. 2013. WaterSense Notice of Intent (NOI) to Develop a Draft Specification for Soil Moisture-Based Control Technologies.
[2] Datta, S.; Taghvaeian, S.; Ochsner, T.E.; Moriasi, D.; Gowda, P.; Steiner, J.L. Performance Assessment of Five Different Soil Moisture Sensors under Irrigated Field Conditions in Oklahoma. Sensors 2018, 18, 3786.
[3] Martin, E.C.; Pegelow, E.J.; Stedman, S. Comparison of Irrigation Scheduling Methods in Cotton Production; College of Agriculture, University of Arizona: Tucson, AZ, USA, 1995.
[4] D.K.; Hanks, J.E.; Pringle, H.L., III. Comparison of Irrigation Scheduling Methods in the Humid Mid-South. Irrigation Association. 2009.
[5] Sui, R. Irrigation Scheduling Using Soil Moisture Sensors. J. Agric. Sci. 2017, 10, 1.
[6] Kebede, H.; Fisher, D.K.; Sui, R.; Reddy, K.N. Irrigation Methods and Scheduling in the Delta Region of Mississippi: Current Status and Strategies to Improve Irrigation Efficiency. Am. J. Plant Sci. 2014, 5, 50005. [
[7] Zotarelli, L.; Scholberg, J.M.; Dukes, M.D.; Muñoz-Carpena, R.; Icerman, J. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil Agric. Water Manag. 2009, 96, 23–34.
[8] Aaron Hrozencik. 2019. Irrigation & Water Use. United States Department of Agriculture Economic Research Service (2019).

The two primary challenges of outdoor sensor networks are the lack of reliable **communication** and **power** infrastructure.

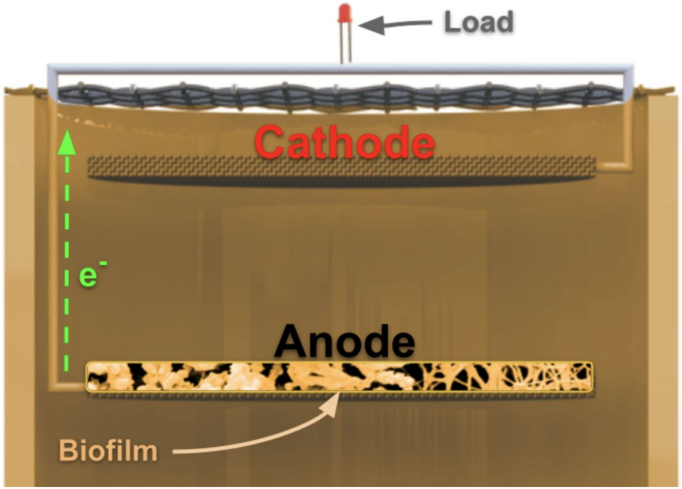


Could we harvest power from the ground itself?



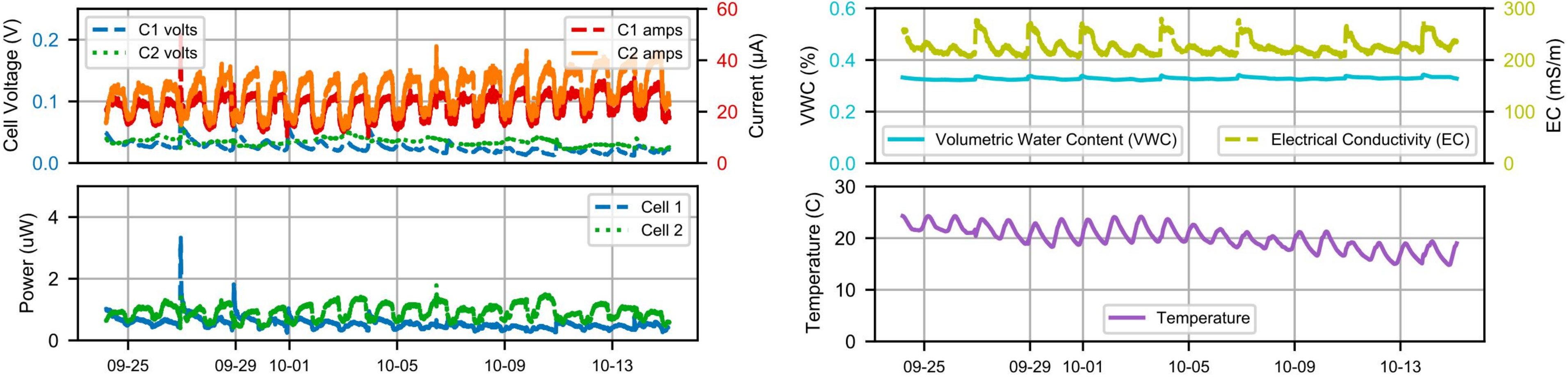
Microbial fuel cells (MFCs)

- Naturally occuring *exoelectrogenic microbes*, produce spare electrons during their natural respiration process
- Microbes colonize an electron acceptor (anode) in the soil to form a biofilm
- Anaerobic anode + aerobic cathode + load = potential difference (fuel cell!)
- Well-known to civil and environmental engineers, but new to the EE and sensing communities
- Our work focuses on **soil-based** MFCs



Soil-based MFC. Microbes colonize the carbon anode to form a biofilm and donate electrons to cause a potential difference.

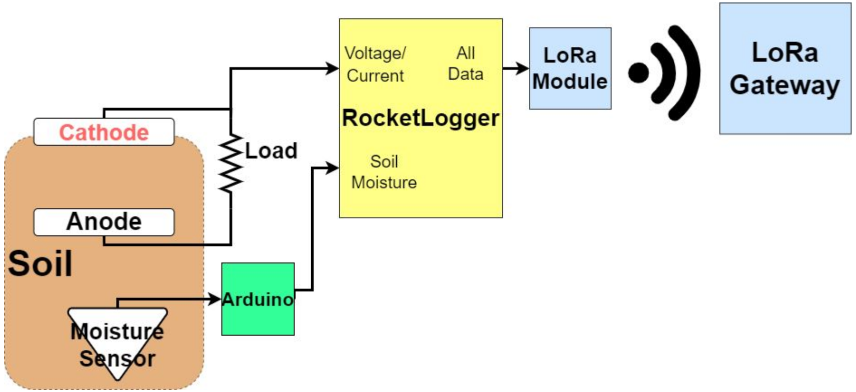
MFCs are hard to model

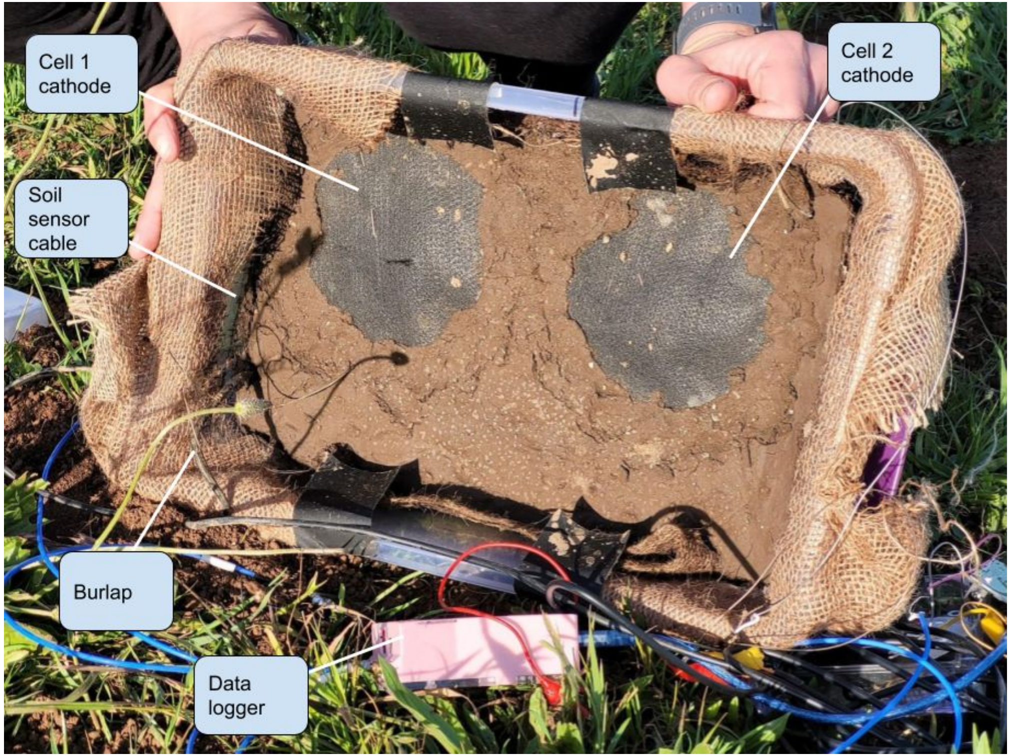


[1] *Early Characterization of Microbial Fuel Cells,* IEEE ISCAS '22. G. Marcano, C. Josephson, P. Pannuto
[2] *The Future of Clean Computing May Be Dirty*. C. Josephson, W. Shuai, G. Marcano, P. Pannuto, J. Hester, and G. Wells. ACM GetMobile September 2022.. 26, 3 (2022).

Goal: gathering data on MFCs across the globe

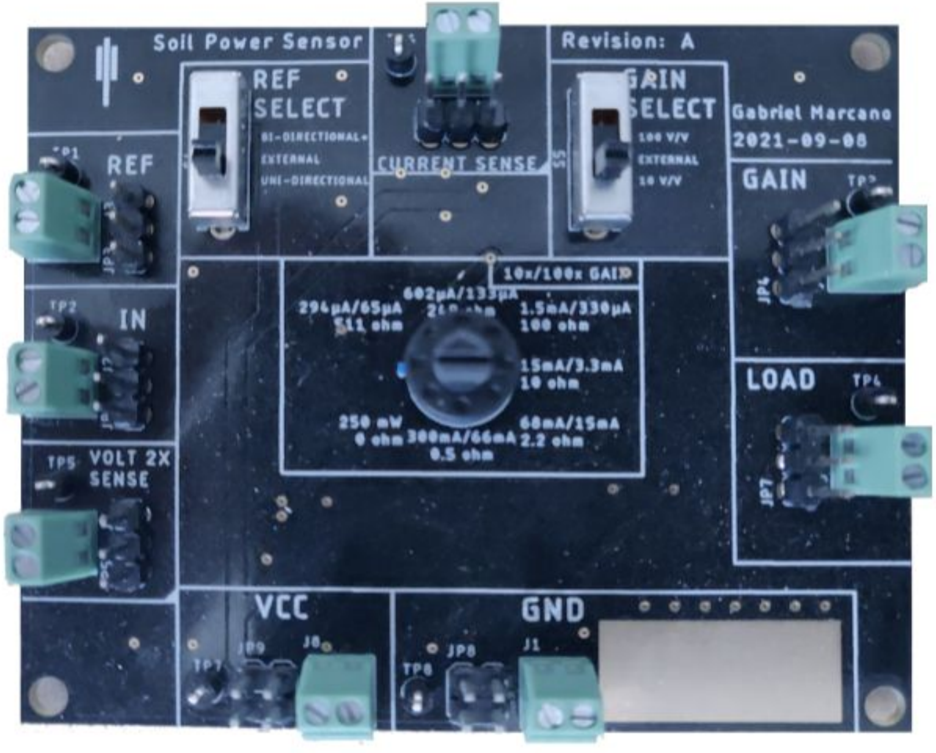
- Wanted: an international network of MFCs deployed with soil sensors and power monitoring
- Data streamed to central data repo
- Most expensive part of deployments is the RocketLogger used to monitor power… $1500+ USD per unit



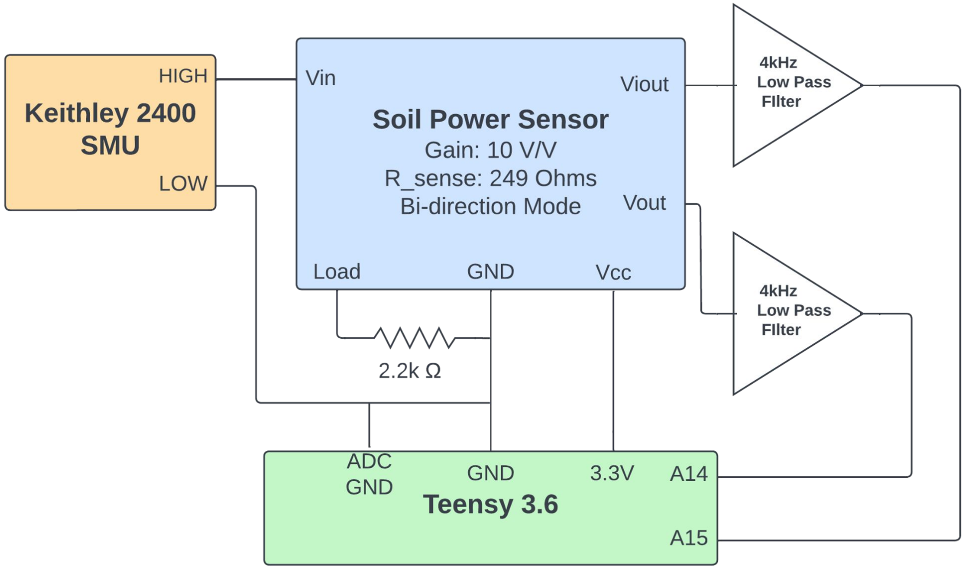


Designing a soil power sensor board

- A variable resistor *Rsense* allows for adjusting the range/accuracy of current measurements
- We also used a MAX40204 current-sense amplifier, and an OPA820 high-speed OpAmp
- MAX40204 chosen because it can sense currents even when sense pins are both near 0 V
- OPA820 configured in 2x gain mode to buffer the voltage of the input
- $53.71/unit for a parts, fabrication and assembly of a 50 unit run



Evaluations



Block diagram of the testing configuration for our board. A Keithley 2400 Source Measurement Unit (SMU) was used as a voltage source and to measure the voltage/current on the board. The SMU was configured for 2-wire sensing and connected to *Vin* and *GND* on the board

- Core question–will our lower-cost system still perform to our needs?
- **Filtering:** to filter out the noise from the soil power sensor, two passive low-pass filters w/ 4 kHz cutoff were placed between *Viout* and *Vout* outputs and Teensy analog input
- **Analog to Digital Conversion:** to accurately reproduce the original signal, need min resolution of 0.1 μA for current and 1 mV for the voltage. Full calculations in paper.
- **Calibration:** to account for component tolerances, the current/voltage channels were calibrated independently using linear regression with ADC I/V readings as inputs and sourced I/V as outputs in terms of μA/V

main

soil-power-sensor-calibration / calibration.ipynb

Go to file

John Madden Added options for multivariate regression

Latest commit e06757c 19 days ago History

1 contributor

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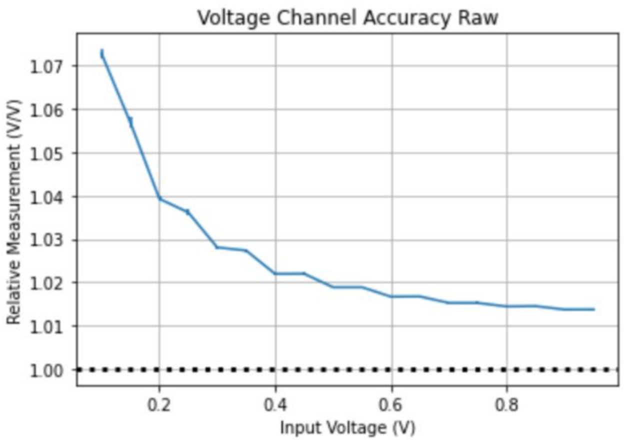
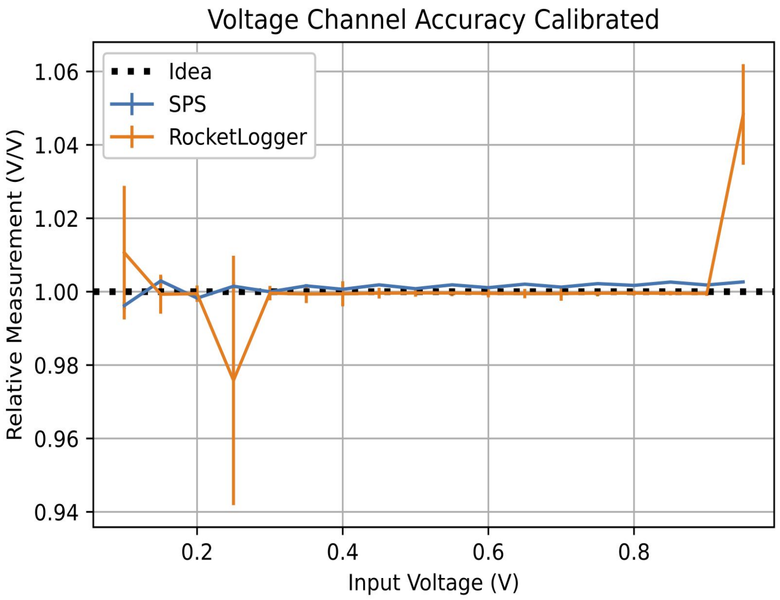
Raw Blame

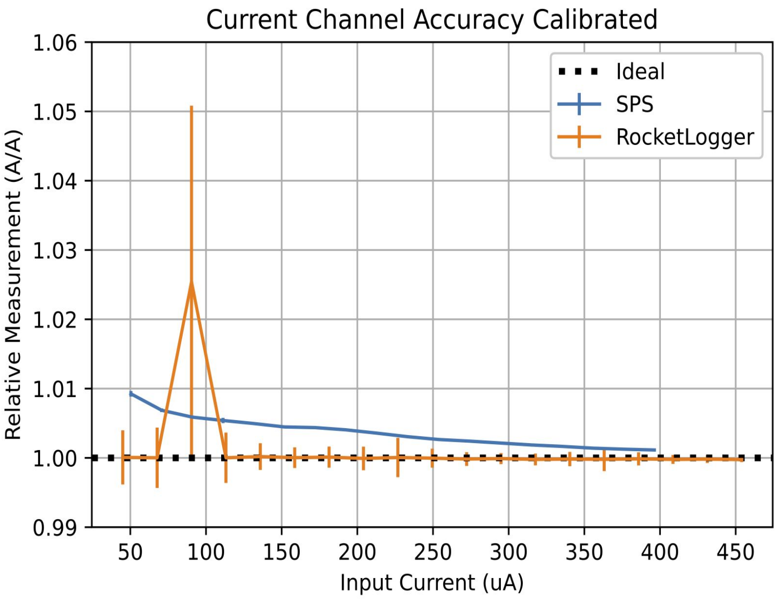
Out[7]:
```
Text(0, 0.5, 'Relative Measurement (V/V)')
```



In [8]:
```
fig, ax = plot_accuracy([
    (data["I_in"], data["I_meas"]),
])
```

Evaluations, cont'd





Key result: our board measures power with a minimum accuracy of 1.62% + 32.5828 pW in the ranges of 0 μW to 722.4 μW

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Table 1: Summary of Soil Power Sensor board performance characteristics compared to the Rocketlogger and Shepherd.

	Soil Power Sensor			Rocketlogger	Shepherd
	Min	*Avg*	*Max*		
Voltage Range (V)	0	–	1.2	±5 V[1+]	10 µV to 3 V
Current Range	0	–	602 µA	±2 mA (low current mode)[+]	0 mA to 50 mA
Voltage Accuracy	0%	0.18% + 201.4 mV	0.61%	0.26% + 13 mV[6]	$19.53uV \pm 0.01\%$
Current Accuracy	0.11%	0.37% + 161.78 nA	1.01%	2.19% + 4 nA[6]	$381nA \pm 0.07\%$
Sampling Rate (kSPS)	0	–	45	1 to 45[+]	100
Voltage Dynamic Range (dB)	–	–	75.5	–	–
Current Dynamic Range (dB)	–	–	71.4	172 [+]	–
Idle Power Consumption (W)[2]	–	~ 0.415	–	~ 2.35	1.725
Logging Power Consumption (W)[3]	–	~ 0.429	–	~ 2.35	–
Cost per unit (USD)	–	$53.71[4]	–	$1500[5]	$60.9

[1] Taken from the max output voltage from V_{2x}, opamp voltage swing is the limiting factor.

[2] Taken while waiting for serial input

[3] Taken while continuously sampling ADC via "cont" command

[4] Parts, fabrication and assembly for a run of 50 units.

[5] Commercially available for $1500, but the design is open-source. The cost of parts to make DIY Rocketloggers (excluding fabrication and assembly) is ~$350+ per unit at the time of this writing.

[+] Value taken from datasheet

Next steps

- Soil Power Sensor Board v2.0:
  - v1.0 uses external Teensy 3.6 to calculate I/V due to high-availability and high-res ADC…in v2.0, revise to integrate a lower-power MCU, e.g. MSP450 series
  - Use a dedicated ADC to allow for bi-directional current/voltage sensing
  - Integrate low-power communications such as LoRa, NB-IoT or RF backscatter
- Improved calibration processes:
  - Account for fact that resistance of the current sensor may not be negligible
  - Use temperature and humidity sensors for more robust calibrations
- **Long-term vision:** a straightforward and inexpensive MFC kit we can send to anyone, and it can stream to our database, creating an international MFC dataset
  - Real-time monitoring and visualization of MFC data over the web

In closing

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Resources:

- Lab website: `sensors.soe.ucsc.edu`
- Project repo: `github.com/jlab-sensing/soil-power-sensor-calibration`

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- Content