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

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ABSTRACT

Soil microbial fuel cells are a promising source of energy for outdoor sensor networks. These biological systems are sensitive to environmental conditions, therefore more data is needed on their behavior "in the wild" to enable the creation of an energy system capable of being widely deployed. Prior work on early characterization of microbial fuel cells relied on extremely accurate, but expensive, logging hardware. To scale up the number of deployment sites, we present custom logging hardware, specially designed to accurately monitor the behavior of microbial fuel cells at low cost. This paper describes the design and evaluation of the board, which is open source and freely available on GitHub.

CCS CONCEPTS

• **Hardware → Printed circuit boards**; **Sensor applications and deployments**; *Sensor devices and platforms*; *Energy generation and storage.*

KEYWORDS

Microbial fuel cell, Power monitoring, Sensor networks, Power harvesting

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1 INTRODUCTION

As the demand for renewable energy grows, research into novel power sources becomes more valuable. Microbial fuel cells (MFCs) convert chemical energy into electrical energy by harnessing the electrons offloaded by exoelectrogenic microbes as they oxidize organic matter. These exoelectrogenic microbes are common in soil, wetlands, and wastewater. Prior research on wastewater MFCs have demonstrated their value as a potential sources of clean and renewable energy for low-power applications such as wastewater treatment and powering small sensors [1]. Unlike solar power, MFCs can work without light and unlike chemical fuel cells, MFCs do not become depleted over time. In soil MFCs, the natural processes in the soil continuously replenish the nutrient supply that the microbes consume to produce power. In testing of soil MFCs there is no evidence that they harm the surrounding environment. More concrete testing has shown wastewater MFCs can contribute to wastewater treatment[23].

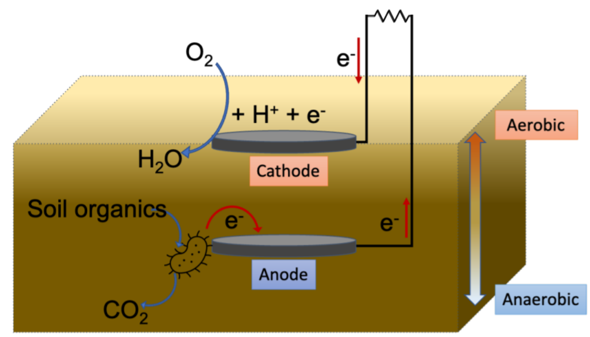

Figure 1: System diagram of a soil-based MFC. Microbes colonize the carbon anode to form a biofilm and donate electrons to cause a potential difference.

Despite their promise as a ubiquitous power source for outdoor sensor networks, we need more insight into how Soil MFCs respond to different environmental conditions. Soil MFCs are highly reactive to their environment due to being biochemical systems. MFCs can exhibit large swings in power output due to conditions such as the type of soil, weather, and human-driven interventions like irrigation or soil amendments. Therefore more data needs to be collected to build an understanding on how MFCs react to environmental conditions.

Early work in deploying and monitoring soil-based MFCs [10, 17, 18] relies on data loggers that, while very accurate, are prohibitively expensive when purchased as a commercial product. To make larger-scale deployments more feasible, we developed a lower cost alternative optimized specifically for MFC monitoring. Our custom

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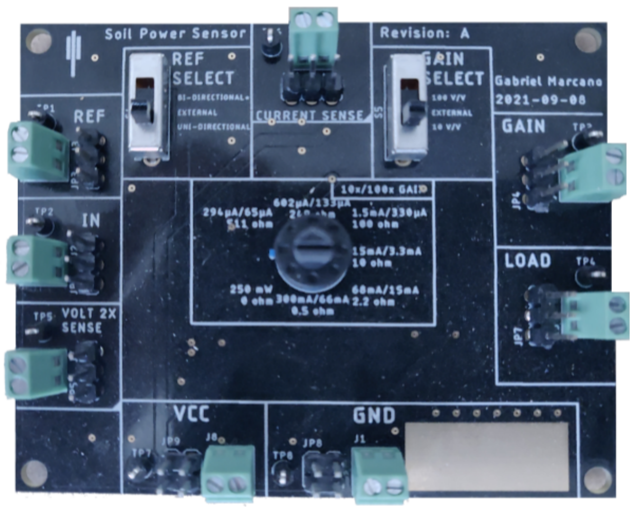


Figure 2: Our soil power sensor board has adjustable gain settings, directionality, and resistance to be able to detect a wide range of low voltage inputs. The board design files are freely available on GitHub [16].

soil power sensor board (Figure 2) was designed to monitor the low voltage and current levels typical of soil MFCs. The cost of each board was $53.71, compared to $1, 500 for the commercially available Rocketlogger. The remainder of this paper details the design of the soil power sensing board, and evaluates its performance against existing data acquisition systems.

2 BACKGROUND

2.1 Microbial Fuel Cells

Microorganisms derive energy for metabolism and growth by catalyzing redox reactions. This involves the transfer of electrons between a donor and an acceptor. Microorganisms harvest energy for growth and maintenance from organic matter in the soil, which acts as the electron donor. Among these microorganisms, exoelectrogenic bacterial species transport the electrons generated from soil organic matter oxidation out of their cell membrane, using external chemicals such as soil iron oxides as a solid state electron acceptor. By replacing the external electron acceptor with an anode and allowing the electrons to flow to a cathode (where a terminal electron acceptor such as oxygen is present), a soil microbial fuel cell can be constructed (see Figure 1). These bacteria are naturally occurring and found in almost every type of soil [14]. Thus, given time and organic matter, exoelectrogenic microbes grow to form a bio-film on the anode, leading to small but steady power production on the order of 1 μW to 200 μW. While wastewater and sediment MFCs have a strong body of existing research [6, 22, 23], soil MFCs have seen comparatively less investigation, especially outside the lab and targeting real world applications.

MFC power production is affected by soil properties, environmental conditions, and microbial communities. Different types of soil result in a wide range of power generating abilities [3]. To better characterize soil based MFCs, they should be monitored for periods of weeks to months, across a wide range of environments and conditions.

2.2 Power sensing

Commercial available data acquisition systems tend to be specialty test equipment, which can cost thousands of dollars. Even lower-cost systems, such as the RocketLogger [21], cost approximately 1, 500$ for one unit[1] that can be used to measure two cells. The Rocketlogger has a minimum sampling rate of 1 kSPS, which is unnecessarily high for MFCs. MFCs power output changes on timescales of days. The high sampling rate is excessive for monitoring. Reducing the sampling rate requires less specialized hardware reducing cost and decreases power consumption.

There exists three other options that are worth mentioning, the Shepherd[5], Current Ranger[4], and uCurrent[2]. The Current Ranger and uCurrent are similar enough that only CurrentRanger was investigated as it was more applicable to our problem.

While the Shepherd is accurate enough for monitoring MFCs, it was designed as a testbed for IoT devices. One of the main features of the Shepherd is allowing for simulation of energy output from energy harvesters. This is not much use for characterizing MFCs as power output is only being recorded. The Shepherd is not commercially available, thus requiring component sourcing and assembly. For this reason, a validation of the Shepherd was not preformed alongside the soil power sensor and Rocketlogger.

The CurrentRanger was only designed to measure low current. To characterize MFCs power is desired requiring both voltage and current measurements. Either modifications to the board or a separate device is required to get the voltage output. Thus the CurrentRanger is not an all-in-one solution to monitoring MFCs.

To address these challenges, we designed a custom PCB for low-frequency micropower sensing. Compared to the currently used Rocketlogger, our Soil Power (SPS) board consumes 5 times less power, and is an order of magnitude lower in cost.

3 SYSTEM DESIGN

Our soil power sensor board drew inspiration from version 4 of the CurrentSense board by Lab11 [13]. Specifically, we used similar routing and placement of headers and switches as the CurrentSense board. However, we added voltage sensing to our board allowing us to simultaneously measure voltage and current, and thus digitally calculate the power flowing through the sensor board. The hardware design files for our board are available on GitHub [16].

The soil power sensor board measures the voltage and current of the attached source, and presents the measurements as voltage readings that an analog to digital converter (ADC) can interpret to then combine into a power reading. In this paper, we use a Teensy 3.6. The Teensy was chosen over other microcontrollers because of its ease of use and availability. Using the Teensyduino framework allowed us to leverage the simplicity of coding using Arduino. Another lower power microcontroller could easily be substituted for the Teensy. The sensor board consists of two primary off-the-shelf

[1] The RocketLogger design is open-source, which makes it possible to fabricate your own unit at a lower cost. The cost was quoted for a fully assembled and calibrated rocketlogger.

components: a MAX40204 current-sense amplifier, and an OPA820 high-speed operational amplifier configured in 2× gain mode to buffer the voltage of the input. We used the MAX40204 primarily for its ability to sense currents even when its sense pins are both near 0 V. The MAX40204 supports selecting bi-directional or uni-directional sensing, and two gain settings, 10 V/V and 100 V/V that are all user configurable. The configurations would allow the board to be adapted to MFCs that produce different power outputs. Limited changes to the configuration need to be made after configuration, thus not requiring a more complicated auto-ranging feature. We selected the OPA820 for its low power requirements and stability at low voltage gains. Since soil microbial fuel cells have maximum observed voltages of approximately 0.7 V [18], we configure the OPA820 in 2× gain mode, to extend the range of voltages that microcontrollers may be able to detect with their built-in ADCs.

To provide more flexibility when sensing currents, we added a rotary switch with seven resistors (one of which is a 0 Ω resistor for calibration) connected to the sense pins of the MAX40204. All of the resistors had 1% tolerances to reduce the error between the ideal and measured values. The resistor selection was based on the maximum supported voltage across the sense resistor, allow measurement of several different current ranges. We used the following equation to find the appropriate value for R_s:

$$R_s = \frac{V_s}{I_s} \tag{1}$$

Where R_s is the sense resistor, V_s is the maximum sense voltage across the resistor (depends on the MAX40204 gain mode and supply voltage), and I_s is the maximum current we want to measure with this resistor. As an example of the selection process, at an input supply voltage of 3.3 V the maximum sense resistor voltage is 150 mV at 10× gain, and 33 mV at 100× gain. A maximum power output of 200 µW from a single microbial fuel cell, at a cell voltage of 700 mV this indicates a current of almost 300 µA. So, at 100× gain, we calculate the following:

$$R_s = \frac{0.033\,\text{V}}{0.0003\,\text{A}} \tag{2}$$

$$R_s = 110\,\Omega \tag{3}$$

So a sense resistor of approximately 110 Ω is required to sense a maximum current of 300 µA at 100× gain. If we require similar performance with 10× gain, the resistor value must be approximately 500 Ω. We followed a similar process for selecting and computing the maximum currents that can be sensed by a given resistor, and for convenience we print these values on the PCB silkscreen.

We expose the functionality of the MAX40204 through switches on the power sensor board. These allow for selecting the gain and the direction of the current sensing.

The recommended setting for soil microbial fuel cells with a 3.3 V input source is 10× gain with the MAX40204 configured for unidirectional sensing. This configuration will work with the widest set of sense resistors that can still operate in the MFC power output range.

The sense resistance depends on the current state of the MFC, but will likely be 100 Ω or greater.

The current sense signal is a voltage that can be converted to the sensed current through the following equations:

$$I = \frac{V_{iout}}{GR} \quad \text{for unidirectional} \tag{4}$$

$$I = \frac{V_{iout} - V_{ref}}{GR} \quad \text{for bi-directional} \tag{5}$$

Where, I is the current sensed in amps, V_{iout} is the current signal output in volts, G is the gain, R is the sense resistor value in ohms, and V_{ref} is the reference voltage used for bi-directional sensing mode in volts (typically it is half the supply voltage). The voltage signal can be converted to a voltage as follows:

$$V = \frac{V_{out}}{2} \tag{6}$$

Where V is the voltage sensed in volts, and V_{out} is the voltage signal output in volts.

4 EVALUATION

4.1 Setup and Filtering

The soil power sensor was designed with a variable resistor R_{sense}, allowing for adjustments of the range and accuracy of measurable current output. The voltage output is not affected as by R_{sense} as it has a constant gain of of 2 V/V. To handle the input of 0.7 V and 330 µA, we powered the SPS with a 3.3 V and set to the following configuration: R_{sense} = 249 Ω, uni-directional, 10 V/V Gain. We connected a 2.2 kΩ resistor between LOAD and GND, as used when incubating the MFCs and for previous power measurements [10, 18]. This yields a theoretical measurement range for current and voltage of 0 µA to 602 µA and 0 V to 1.65 V respectively. As found during the calibration of the SPS, the limitation of the output swing voltage on the OPA820 chip limits the output voltage from the SPS to ∼2.4 V, resulting in a realized measurable voltage range of 0 V to 1.2 V. This is still beyond the max observed voltage of 0.7 V. The current sensing chip does not have this limitation and the full range can be measured.

As with all electrical components, ambient noise can come from various sources. Part of the evaluation process was to filter out the noise from the soil power sensor and create a consistent method for calibrating the noise. Two passive low-pass filters were placed between V_{iout} and V_{out} outputs and the analog input pins to the Teensy. Each low-pass filter had a 4 kHz cutoff frequency as recommended by the OPA820 datasheet [7].

4.2 Analog to Digital Conversion

As the soil power sensor only handles analog signals, an analog to digital converter (ADC) is required convert the analog signal to a digital signal that can be recorded. Regardless of noise in the analog voltage signals, the ADC must support a minimum resolution of 0.1 µA for the current channel and 1 mV for the voltage channel for voltage measurements to accurately reproduce the original signal. If R_{sense} is not chosen carefully then either the voltage or current outputs reach the supply rail, clipping the measurements.

The required number of bits was calculated with the following equation for voltage and current respectively

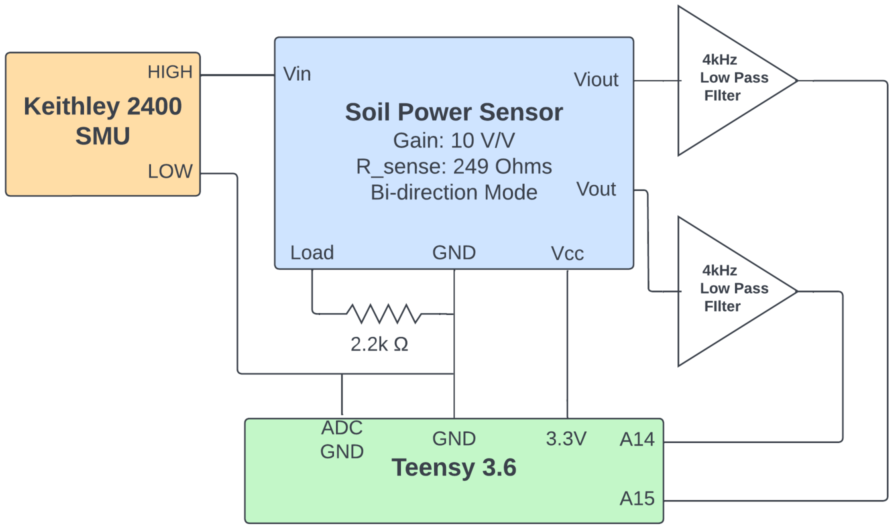


Figure 3: Block Diagram of Testing Configuration of the Soil Power Sensor Board

$$n_v = \log_2\left(\frac{V_{ref}}{2V_{out}}\right) \quad (7)$$

$$n_i = \log_2\left(\frac{V_{ref}}{IGR}\right) \quad (8)$$

In order to obtain a high enough resolution such that no information is lost in the conversion process, the voltage and current channels require 14.01 bits and 13.694 bits, respectively. Thus, the Teensy 3.6 development board was chosen for its 16-bit ADC and integration with the Arduino framework. Only 13-bits were used to hopefully reduce the noise in the ADC measurements. Firmware was developed to read two analog pins, take the average over n number of samples, and output the values over serial. For the entirety of the testing n was set to 100, which results in a 100 point moving average filter. In addition to the moving average filter implemented in software, the internal ADC is already configured to take the average of four samples. The number of averaged samples effects the effective number of bits (ENOB) and the sampling rate of the ADC. As stated earlier, the soil power sensor board was configured in uni-directional current sensing mode. Limitations of the Teensy determined this configuration, as its ADC had a input voltage range of 0 V to 3.3 V, and therefore would not be able to measure the negative voltage values.

Now that the number of ADC bits is known, the theoretical precision can be calculated. This is dependent on the minimum measurable voltage V_{min} from the ADC given by the following

$$V_{min} = \frac{V_{ref}}{2^n} \quad (9)$$

where V_{ref} is the reference voltage and n is the number of ADC bits, in the case of the Teensy, 3.3 V and 13 bits respectively. The equation is only measuring pure voltage, so both Equation 4 and Equation 6, need to be taken into account to get the minimum measurable voltage, thus substituting Equations 9 for V_{out} and V_{iout} in these equations results in the following

$$V_{min} = \frac{V_{ref}}{2(2^n)} \quad (10)$$

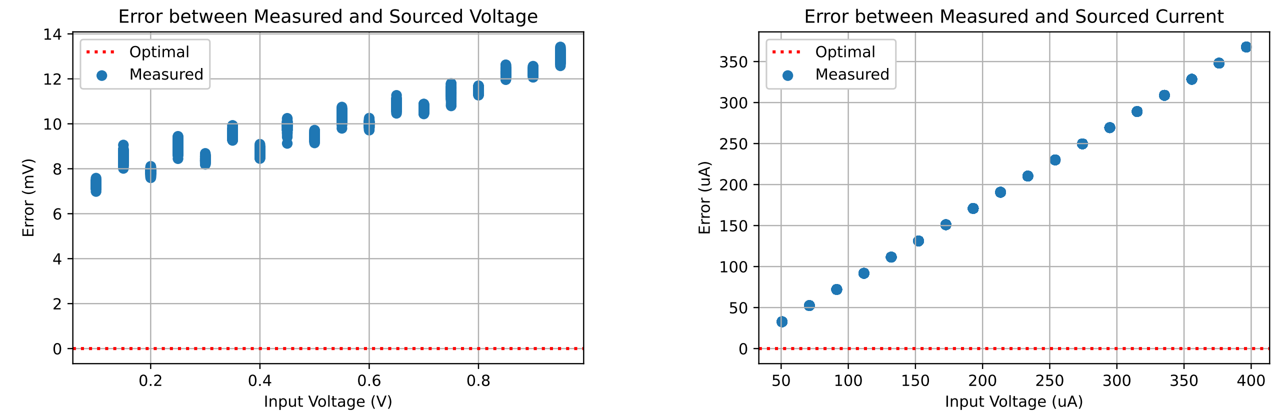
$$I_{min} = \frac{V_{ref}}{GR(2^n)} \quad (11)$$

Solving these equations, the accuracy for the voltage and current channels was obtained: $V_{min} = 201.4\,\mu V$ and $I_{min} = 161.78\,nA$. Using the maximum measurable values discussed in Section 4.1, the dynamic range for the voltage and current channels wsa found to be 75.5 dB and 71.4 dB respectively. These values are compared to RocketLogger performance in Table 1. After finding the accuracy and selected components, the circuit was calibrated before finding the measurement precision.

4.3 Calibration

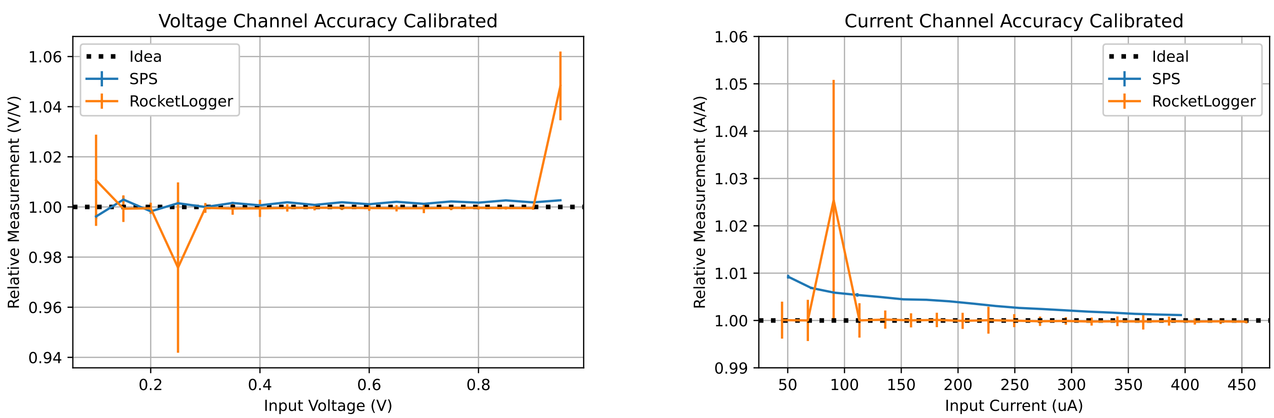
Before evaluating the board, they were first calibrated to account for component tolerances. A Keithley 2400 Source Measurement Unit (SMU) was used as a voltage source and to measure the voltage/current on the board. The SMU was configured for 2-wire sensing and connected to V_{in} and GND on the soil power sensor. Measurements taken from the SMU were considered ideal as the device has a voltage measurement accuracy of 0.012 % + 300 µV and current measurement accuracy of 0.027 % + 60 nA, which is a far greater then the desired accuracy for the board.

Using the Arduino framework, measurement firmware was written for the Teensy to allow for measuring of current, voltage, and temperature over serial. The Arduino framework configures the ADC to continuously sample at 64 kSPS where reading over serial provides the most recently measured value. Similarly software was written for a host computer to read the measurements from the



(a) Voltage **(b) Current**

Figure 4: Error for uncalibrated measurements calculated as the difference between observed and measured values. The deviation between the ideal and measured values appeared to be linear, suggesting a linear regression model to calibrate.



(a) Voltage Channel **(b) Current Channel**

Figure 5: DC channel accuracy 24 hours after calibration. The error bars are $\pm 1\sigma$ intervals. A coefficient of determination (r^2) value of > 0.99 for both current and voltage channels supports the assumption that the correlation was linear. For the soil power sensors had a sample size of $n = 10$ at each voltage step, while the Rocketlogger had a sample size of $n = 538$.

Teesny over serial and control the current/voltage provided to the board from the SMU.. The resulting measurements were recorded in csv format. All the sources and data collected are open source[8]. The process was repeated at different ambient temperatures to alllow for calibration of thermal drift.

The integral nonlinearity of both the current and voltage channels are shown in Figure 4. The current and voltage channels on the SPS were calibrated independently using linear regression with ADC current/voltage readings as inputs and sourced current/voltage as outputs in terms of µA/V. The regression was preformed using sklearn's `LinearRegression`[20].

4.4 Evaluation Data Collection

The evaluation data was collected using the same configuration for the calibration data discussed in Section 4.3. The evaluation measurements were taken 24 hours after the initial calibration. The mean average error (MAE) was computed across the entire range of voltage measurements to get the min, mean, and max values in Table 1. Plots of the accuracy for both our soil power sensor and a Rocketlogger are shown in Figure 5. Measurements were collected with a single linear sweep from voltages 0.1 V to 0.95 V with a step of 0.05 V. We noted large jumps in the Rocketlogger error for particular values, despite repeated measurements over a 24h period. We found that our soil power sensing board can measure voltage with an average accuracy of 0.61 % + 201.4 µV and current with an average accuracy of 1.01 % + 161.78 nA. This comparable

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 ± 0.01%
Current Accuracy	0.11%	0.37% + 161.78 nA	1.01%	2.19% + 4 nA[6]	381nA ± 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

to the Rocketlogger, which we measured to have average accuracy of 0.26 % + 13 µV and 2.19 % + 4 nA in the ranges of interest. This is significantly higher than the values stated in the datasheet (0.02 % and 0.03 %, respectively), largely due to spikes in error observed for particular source values.

4.5 Power Consumption

The power consumption for the soil power sensing system (soil power sensor board plus Teensy) and RocketLogger were measured with a AT35 USB Tester connected to a USB 3.0 port on a laptop. The RocketLogger was configured to match the logging capabilities of the SPS with channels `V1`, `I1L` enabled. Measurements were taken during idle and while logging. The RocketLogger was configured via the web interface to sample at a rate of $1kSPS$ to a binary file. The power consumption for the SPS while idle was taken while waiting for a serial command. The measurements are shown in Table 1.

5 DISCUSSION AND CONCLUSION

The soil power sensor board is that is a straightforward, standalone board that can be used with any system that has an ADC allowing for more flexibility in the system design. In the case of the evaluation, the ADC on the Teensy 3.6 was used to read the voltage levels. With the Teensy being Arduino compatible, there is already a large variety of expansion boards and modules to fit future system requirements such as remote logging.

We have established that our soil power sensing board is can measure power with an minimum accuracy of 1.62 % + 32.5828 pW in the ranges of 0 µW to 722.4 µW. Even at a fraction of the cost of current commercially available systems, it performs well. This will enable inexpensive deployment and monitoring of MFCs in a broad range of environments. As of now deployments are limited to only measuring the power output. The deployed MFCs are not being used to power sensors. In the design, low power operation was emphasised to allow for long term remote deploys powered by conventional batteries.

During testing of the soil power sensor board we overlooked that the resistance of the current sensor may not be negligible, and may need to be taken into account when connecting it in series with other equipment.

Finally, this board does not compute power on its own; an external device is required to digitally measure current/voltage and compute the power. In the evaluation of the board, a Teensy 3.6 was used to read the current and voltage.

In the future we propose a revision of the board to integrate a low-power MCU such as the MSP430 series and low-power communications such as LoRa, NB-IoT [15] or RF backscatter [9, 11, 19] along with a dedicated ADC to allow for bi-directional current/voltage sensing. The bi-directional mode can be used to facilitate investigating the adverse *voltage reversal* phenomenon in MFCs [12].

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