CryoSkills Sensor Kit

# System-level schematic

Solar Panel

Regulator

Battery

QWIIC (I2C) Sensors

Analogue Temp. Sensor

Micro-controller

(i.e. Feather M0 Adalogger)

SD Card

Wireless

Modem

Antenna

Weatherproof housing

Solar Regulator

Realtime clock

# Subsystems

## Power (Battery & Solar)

The power supply for the sensor kit is composed of a 12V lead-acid battery and a 12V 5W solar panel, connected to the battery through a EP Solar 5a charge controller.

|  |  |
| --- | --- |
| Item | URL |
| 12V 1.2Ahr lead-acid battery | <https://uk.rs-online.com/web/p/lead-acid-batteries/1501558?gb=s> |
| 12V 5W solar panel | <https://www.sunstore.co.uk/product/12v-5w-monocrystalline-solar-panel/> |
| EP Solar 5a Charge Controller | <https://www.sunstore.co.uk/product/ep-solar-5a-charge-controller-with-usb-output/> |

Table 1 - Power system components

The solar charge controller has a maximum rated battery current of 5A and maximum PV (panel) input of 30V. The mounting hole sizes are M4.5 (assumption of mm) and terminal sizes are 2.5mm2 which require wire diameter of less than 1.784mm (AWG of 14 or greater). The charger user manual recommends that cables should satisfy 3.5A/mm2 current density – AWG 14 can therefore accommodate 5.25A.

The battery terminals are tabs with width 4.75mm and length 6.35mm, hence a 5mm spade connector with AWG 14-16 crimp terminal is sufficient.

Finding it hard to find appropriate 4.75mm tabs in red/blue or red/black with matched 2.5mm2 CSA – go with blue which has 2.5mm2 max CSA.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Details | Supplier | Order Code |
| Red 16AWG Cable | 100m | Farnell / SW | [1204343](https://uk.farnell.com/lapp-kabel/4520041/wire-h07v-k-red-1-5mm-100m/dp/1204343) |
| Black 16AWG Cable | 100m | Farnell / SW | [1204340](https://uk.farnell.com/lapp-kabel/4520011/wire-100m-1-5mm2-copper-black/dp/1204340) |
| Red Crimp Terminal | 4.8mm(W), 12A, 16-14AWG | Farnell / SW | [3384774](https://uk.farnell.com/pro-power/stfdd1-187-8/female-push-on-red-12a-4-8-x-0/dp/3384774) |
| Blue Crimp Terminal | 4.8mm(W), 16A, 16-14AWG | Farnell / SW | [3384777](https://uk.farnell.com/pro-power/stfdd2-187-8/female-push-on-blue-16a-4-8-x/dp/3384777) |
| Red Ferrule | 16 AWG 10mm | Farnell / SW | [3383565](https://uk.farnell.com/pro-power/pet1515/german-single-ferrule-1-50mm-red/dp/3383565) |
| Black Ferrule | 16 AWG 10mm | Farnell / SW | [4161844](https://uk.farnell.com/pro-power/pp01538/french-single-ferrule-1-50mm-black/dp/4161844) |
| Fuse Holder | 16 AWG, Red, 5x15mm Fuse, | RS Pro / SW | [849-5594](https://uk.rs-online.com/web/p/fuse-holders/8495594) |
| 1A Fuse | 5x15mm | - | - |

Alternatively, consider using automotive blade style fuse holder & fuse – need to check options. Ideally should satisfy current rating <5A and AWG 16 gauge cable.

These place a requirement on the screw terminals used on the sensor kit PCB – they must be able to accept 1.5mm2 CSA ferrules.

### Battery Capacity

The battery capacity is calculated for an on period of 2s and a sleep period of 58s, resulting in a total measurement interval of 60s. For a 24 hour period, this would yield 1440 measurements.

The average current consumed is calculated as

Hence for the values given in Table 2, the average current is 4.76mA at 3V3 and 6mA at 12V (solar charger). Hence the power consumed is 15.7mW (load) and 72mW (self consumption) or a total of 87.7mW. Over a period of 24hours, this requires 2.1Wh of energy. Assuming the battery is derated by 50% due to cold weather, the actual energy requirement is 4.2Wh, which at 12V equates to a battery capacity of 0.35Ah. A 12V 1.2Ah battery specified should be sufficient to run the sensor for the 24-hour period.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Sleep Current (mA)  @ 3V3 Vcc | Peak Current (mA)  @ 3V3 Vcc | Time-enabled per cycle (s) |
| Adafruit Feather M0 | 2 | 20 | 2 |
| Wireless module | 0.001 (sleep mode) | 120 | 1 |
| I2C atmospheric sensor | 0.0000002 | 0.000714 | 1 |
| PT1000 temp. sensor | 0.000002 | 0.210 | 1 |
| DSB1820 temp.sensor | 0.00000075 | 1.5 | 1 |
| I2C light sensor | 0.000005 | 0.220 | 1 |
| Charge controller | <6 (@12V) | <6 @(12V) | Always-on |
|  | ~8 | ~150 |  |

Table 2 - Current consumption based on subsystems

### Solar Charge Controller

Wiring of the solar charge controller is given by the (terrible [user manual](https://www.sunstore.co.uk/wp-content/uploads/2017/02/LS-EU%20Manual.pdf) supplied) diagram in Figure 1.

A diagram of a solar charger

Description automatically generated

Figure 1 - EP Solar 5a Charge Controller wiring diagram

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### INA3221 Power Meter

The Texas Instrument [INA3221](https://www.ti.com/product/INA3221) integrates a high-side ADC which can be used as a power meter. To integrate with the sensor kit, using the three available channels we can assess power from the solar panel, battery power (charge or discharge) and the power draw of the load.

**Note:** The rated open circuit voltage of the panel is 21.9V so this is within the maximum input voltage however it is perhaps prudent to add some voltage protection at the panel input in-case an alternative panel is used?

Appropriate current sense resistors need to be selected for each of the channels. The shunt voltage limits for the INA3221 are ±163.8mV and the maximum input voltage at any port is 26V.

We assume the peak current into the sensor kit will be on the order of 0.2A (rounded up from 0.15A peak consumption during radio transmission). With a 0.2 Ohm resistor, this equates to a shunt potential difference of 40mV (30mV) which uses approximately 10% of the full-scale voltage range.

The maximum charge current for the RS Pro lead-acid battery is listed as 0.36A, hence with the same 0.2 Ohm resistor as above, we yield a potential difference of 72 mV.

This appears to be a reasonable value to use across the application – the everythingpi.co.uk evaluation board uses 0.1 Ohm, which I assume is to accommodate for slightly higher average load currents.

A provisional wiring diagram for integrating the INA3221 power meter into the sensor kit is shown in Figure 2. This results in a total of 6x screw terminals being present on the sensor kit board, one each for the solar panel and battery and then an additional to wire the load to the solar controller. An external 6-way connector (i.e. 2x 5-way Wago?) is also necessary to provide a common ground for the panel, battery, charge controller and load.

HellermanTyton 8-way splice for 1mm2 to 2.5mm2 common splice (RS Stock No. 124-2530).

A diagram of a solar charge controller

Description automatically generated

Figure 2 - Wiring diagram for sensor kit using INA3221 power meter with solar panel, 12V battery and solar charge controller. (Note add connector indication to diagram…)

### Linear (LDO) vs Buck Voltage Regulator

If there is a sufficient pin-for-pin replacement (3-pin 100mil, Vin-GND-Vout) for the Multicomp Pro drop-in MP-K78L03-500R3 DC/DC regulator then participants can have the choice/compare the performance of linear vs. buck boost regulated instrument using data from the INA3221. The higher efficiency DC/DC converter should draw less current from the 12V supply and hence less power.

### Mechanical Considerations (Panel)

Mounting for solar panel up to M7.5 screws through back of panel separated by 128mm height and 156mm width.

## Microcontroller and Datalogger

An Adafruit Feather M0 Adalogger has been selected as the microcontroller for the sensor kit because of the integrated MicroSD slot and compatibility with existing code. It is based on the Amtel SAMD21G18 ARM Cortex M0 processor.

Logic levels are at 3V3.

### Power Considerations

The sensor kit board has its own 3V3 regulator from the battery supply, hence the Adalogger can be powered directly from the output of the system regulator rather than its on-board 3V3 LDO ([SPX3819-3.3](https://assets.maxlinear.com/web/documents/spx3819.pdf)). This requires that the internal Adalogger 3V3 regulator is disabled by tying **EN** to GND and ensuring the **3V** pin is connected to the output of the system regulator.

If it was desirable to use the USB to power the sensor kit (i.e. during development or testing) then a header can be fitted to connect the USB bus voltage from the Adalogger board to the sensor kit input.

**Note:** **Either** care must be taken to ensure that the battery isn’t connected at the same time as the USB power is enabled, or a physical switch is implemented on the board to ensure that this can’t take place.

For now, the second option is implemented with a slide switch to alternate between battery or USB power, using an [RS Pro 734-7334](https://uk.rs-online.com/web/p/slide-switches/7347334) SPDT On-Off-On switch.

### Pinout Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Pin No. | Pin Name | Group | Description | Used in design |
| 1 | NRESET | Misc | Resets on logic low (i.e. tie to GND) |  |
| 2 | 3V3 | Power |  |  |
| 3 | AREF | Analog |  |  |
| 4 | GND | Power |  |  |
| 5 | A0 / DAC | GPIO/Analog |  |  |
| 6 | A1 | GPIO/Analog |  |  |
| 7 | A2 | GPIO/Analog |  |  |
| 8 | A3 | GPIO/Analog |  |  |
| 9 | A4 | GPIO/Analog |  |  |
| 10 | A5 | GPIO/Analog |  |  |
| 11 | D24 / SCK | SPI |  |  |
| 12 | D23 / MOSI | SPI |  |  |
| 13 | D22 / MISO | SPI |  |  |
| 14 | D0 / UART RX | UART |  |  |
| 15 | D1 / UART TX | UART |  |  |
| 16 | GND | Power |  |  |
| 17 | D20 / SDA | I2C |  |  |
| 18 | D21 / SCL | I2C |  |  |
| 19 | D5 | GPIO |  |  |
| 20 | D6 | GPIO |  |  |
| 21 | D9 | GPIO | Also analog input A7, connected to a votage divider for the LiPo battery – avoid use. |  |
| 22 | D10 | GPIO |  |  |
| 23 | D11 | GPIO |  |  |
| 24 | D12 | GPIO |  |  |
| 25 | D13 | GPIO |  |  |
| 26 | USB | Power | Output from USB 3V3 pin |  |
| 27 | EN | Power | Used to disable internal 3V3 regulator. |  |
| 28 | VBAT | Power |  |  |

### I2C Address Table

To avoid clashes of I2C addresses, Table 3 lists the address for devices being considered or actively used in the sensor kit design.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Part No. | Description | Address | Programmable | Used in design |
| [INA3221](https://www.ti.com/lit/ds/symlink/ina3221.pdf?ts=1704862707360) | Power Meter | 0x40-0x43 | Yes (A0 pin) | Yes |
| [PCF48574](https://www.ti.com/lit/ds/symlink/pcf8574.pdf?ts=1704953203134) | 8-bit I/O expander | 0x40-0x4E | Yes (A0-2 pins) | No |
| [BH1750](https://thepihut.com/products/adafruit-bh1750-light-sensor-stemma-qt-qwiic) | I2C Light Sensor | 0x23 or 0x5C | Yes (ADDR pin) | ??? |
| [LTR-329](https://thepihut.com/products/adafruit-ltr-329-light-sensor-stemma-qt-qwiic) | I2C Light Sensor | 0x29H | No | ??? |
| [BME280](https://www.sparkfun.com/products/15440) | I2C Atmos Sensor | 0x76-0x77 | Yes (SDO pin) | ??? |
| [SparkFun Qwiic Soil](https://www.sparkfun.com/products/17731#reviews) | Soil Moiture Sensor | 0x28 | No | ??? |

Table 3 - I2C address table for devices used in the CryoSkills sensor kit

## Digital Temperature Sensor

The DS18B20 digital temperature sensor is available in a waterproof wired version which make it suitable for the sensor-kit application.

A datasheet describing the wired version is provided here: <https://docs.rs-online.com/8ff0/A700000007238410.pdf>.

It exposes a 1-wire digital interface which can be implemented with any of digital output pins of the Adafruit Feather M0 microcontroller. The DS18B20 requires three electrical connections listed in Table 4.

|  |  |  |
| --- | --- | --- |
| Wire Identifier | Description | Connected to |
| Red | VCC (3V3-5V) | VCC\_3V3 |
| Black | GND | GND |
| Yellow | Data | Adalogger D5 |

Table 4 - DS18B20 pinout

**Note:** A pull-up resistor of 4.7kOhm is required between the VCC and DATA pins.

### Mechanical Considerations

A three-way screw terminal block can be used to connect the sensor to the board, allowing easy installation through a cable gland in the sensor kit housing – no information provided on gauge of internal conductors (approximate diameter is 1mm).

The stainless-steel sensor tube is 6mm (diameter) by 35mm (length). The cable connecting the sensor to the cable is 4mm diameter.

A candidate cable gland is therefore [RS Pro 822-9571](https://uk.rs-online.com/web/p/cable-glands/8229571), rated to IP68 for cables between 3.5mm to 6mm.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Details | Supplier | Order Code |
| DS18B20 | 3-wire digital temperature sensor | RS Components / SW | 2049893 |
| 4.7k Ohm resistor | Pull-up resistor | Farnell / SW | 2329947 |
| 3-way screw terminal |  |  |  |
| Cable gland | Suitable for 4mm diameter cable | RS Components / SW | 822-9571 |

## Analog Temperature Sensor (PT1000)

Cost of the RTD (resistive temperature detector) device is a main factor in the selection of the analog temperature sensor, owing to the increased cost of 3-wire and 4-wire variants.

The [RS Pro 896-8399](https://uk.rs-online.com/web/p/rtd-sensors/8968399) PT1000 RTD is a Class A two-wire RTD. A useful guide on RTD measurement circuits is provided by Texas Instruments in [Application Note “A Basic Guide to RTD Measurements”](https://www.ti.com/lit/an/sbaa275a/sbaa275a.pdf).

Takeaways from the TI application note are:

* Use first-order common-mode filters at the input to ADCs to reduce common-mode noise.
* Ratiometric measurements - where the same current source is used for the RTD and the reference – remove error from current-source noise, drift and temperature effects.
* For any two-wire device, the lead resistance will affect the measurement accuracy – although at 1.5m this is likely to be minimal for a PT1000 device. It may be possible to calibrate out the effect of lead resistance.
* Keep layout in mind to ensure low-impedance current source/sink paths.

### PT1000 Characteristics

The resistance of a PT1000 sensor is given by

where the constants , , and are given by

Figure 3 - Nominal PT1000 resistance vs. temperature over values relevant to the CryoSkills sensor kit.

Figure 3 shows the nominal resistance for a PT1000 sensor over a temperature range of -30C to 110C which equates to a range of 882.22 to 1422.93 Ohms.

Three possible designs for the analog temperature sensing circuit are described below:

1. Turn-key solution – a Texas Instruments DAC/iDAC is used to provide a constant current source and integrated 16-bit DAC, which communicates with the Adafruit Feather M0 Adalogger over a SPI, UART or I2C interface.
2. Minimal additional peripherals – an external current source is configured to provide the reference current for the RTD but the internal ADC to the SAMD21 is used to perform the resistance calculation.
3. No additional peripherals – making use of the integrated DAC and ADC on the Atmel SAMD21 to provide a constant current source and ratiometric measurement of the RTD resistance. Requires only precision resistors to act as references.

### Turn -Key Solution

The Texas Instruments [ADS1120](https://www.ti.com/lit/ds/symlink/ads1120.pdf?ts=1704969991225) integrates a 4-channel 16-bit ADC with a maximum sampling rate of 2-kSPS with an integrated programmable gain amplifier, voltage reference and external reference input.

A diagram of a machine

Description automatically generated

Figure 4 - 2-wire RTD measurement with Texas Instruments ADS1120 (Texas Instruments Incorporated © 2017)

Three interface options are available (SPI/I2C/UART) and there is a currently un-used SPI peripheral on the Adafruit Feather M0 Adalogger.

The voltage reference is limited to be within a range of 075V to AVDD (3.3V), with a nominal value of 2.5V. It is recommended to keep the excitation current below 1mA, hence for an excitation current of 500uA and a reference resistor of 1.8kOhm, the reference voltage is 0.9V which is within the valid operating range.

**Note:** Need to check that this value is within the compliance range for the IDAC and the input range for the PGA.

#### Common-mode and differential filters for ADC inputs

A Texas Instruments application note on design of the common-mode and differential input filters for the ADC is given in <https://www.ti.com/lit/an/sbaa201a/sbaa201a.pdf?ts=1704987999288>.

To choose appropriate values for the ADC input filter, a sampling rate is also required. Assuming that some averaging is completed on the microcontroller, then a sample rate of 20 SPS is sufficient for 10 noise free 16-bit samples within an operating window of 0.5s. Designing for a cutoff frequency of approximately 20 Hz therefore gives:

To compensate the two common mode filters are each input, we require:

Hence, the differential input resistances become

Hence given that is 1.8 times the ‘mode’ (most common that might be encountered) resistance then we require that

So that we have all the resistances defined by the ‘mode’ RTD resistance and a single variable . That then leaves choosing the values of each capacitor to give the 20 Hz cutoff frequency.

Starting with the differential cutoff frequency for the RTD input,

[INCOMPLETE]

#### Component list for turn-key solution

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Details | Supplier | Order Code |
| RS PRO PT1000 RTD | 2 wire, 1.5m length | RS Components / SW | 896-8399 |
| ADS1120 | 16-bit ADC/iDAC | Texas Instruments | [ADS1120IPW](https://www.ti.com/product/ADS1120) |
| 0603 1.8k resistor | Low temp. coefficient | Farnell / SW | [2991923](https://uk.farnell.com/neohm-te-connectivity/8-1614881-8/res-1k8-0-1-0-063w-0603-pel-c/dp/2991923?st=precision%20resistor) |
| [additional required for filtering] |  |  |  |

### External Current Source Solution

Configures a LM334 as a constant current source, requiring 2x resistors for current setting and diode for temperature compensation.

Requires 1x additional precision/low temperature coefficient resistors to provide the reference voltage to implement a ratiometric temperature measurement.

A diagram of a circuit

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Table 5 - External current source PT1000 circuit

#### Calculation of R1, R2 and RREF

R1 and R2 need to be chosen to set the value of the constant current source. This material is referenced from the LM334 datasheet documentation/analog\_temperature/DATASHEET\_LM334.pdf – page 8. The value of RREF must then also be selected to satisfy the voltage reference requirements of the ADC.

where is the reference voltage of the LM334 and is the diode forward voltage. No data or simulation model for the 1N457 diode forward voltage temperature coefficient is available. An alternative model 1N4149 is selected and the simulation model from Onsemi used to assess the theoretical temperature coefficient.

The materials used to derive the simulated temperature coefficient can be found in design/analog\_temeprature/lm344/. The simulated temperature coefficient is which is smaller than the value of used in the LM334 datasheet example.

A graph of a temperature

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Table 6 – Simulated temperature coefficient for 1N4149 diode

To account for the change in the voltage reference and diode forward voltage with temperature, it is necessary to solve

Therefore the ratio of R2 to R1 can be found as

Continuing to follow the example laid out in the LM334 datasheet

Hence to set a current of 0.5mA requires R1 is 312 Ohm and hence R2 is 2496 Ohm. Selecting E24 series values for these as 330 Ohm and 2400 Ohm, the actual current set is given as 498uA.

To set RREF with a current of 498uA, we must satisfy that the external voltage reference to the SAMD21G18 microcontroller is within the range of 1.0V to VDDANA-0.6V (1.0V to 2.7V). To exceed the minimum voltage reference by 10% (i.e. VREF of 1.1V) then RREF must be greater than 2200 Ohm. For a 1% precision 2.2k Ohm resistor, we therefore have reference voltage range of 1.08V to 1.11V which is acceptable.

Considering the resistance range of the PT1000 sensor (882 to 1422 Ohms), the output voltage range is 0.439V to 0.708V.

Increasing the reference voltage to 1.5V would allow the use of the 2x gain stage in the SAMD21 ADC which improves the dynamic range of the sensor.

An increased reference voltage of 1.5V would be achievable with a 3kOhm resistor. The total maximum voltage across the sensor chain would be approximately 2.2V.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Details | Supplier | Order Code |
| RS PRO PT1000 RTD | 2 wire, 1.5m length | RS Components / SW | 896-8399 |
| LM334 | Constant current source | Farnell / SW | SC18674 |
| 1N4149 | Diode | Farnell / SW | 1651147 |
| 330 Ohm | R1 | Farnell / SW | 9343032 |
| 2400 Ohm | R2 | Farnell / SW | 9342907 |
| 2200 Ohm | RREF (1) | Farnell / SW | 9342834 |
| 3000 Ohm | RREF (2) | Farnell / SW | 9342990 |

Table 7 - Component list for constant-current source analog temperature sensor

A candidate cable gland is therefore [RS Pro 822-9571](https://uk.rs-online.com/web/p/cable-glands/8229571), rated to IP68 for cables between 3.5mm to 6mm.

### Adalogger-only Solution

Needs 2x precision resistors (and maybe some filtering?) [to be completed].

**Note:** Check cable diameter of PT1000 RTD and add correct cable gland size to order

## I2C Peripheral Sensors

For each peripheral sensor type we need to consider:

* weatherproofing options and how these will affect sensor function
* calibration methods and tools required

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Part No. | Description | Address | Programmable | Used in design |
| [BH1750](https://thepihut.com/products/adafruit-bh1750-light-sensor-stemma-qt-qwiic) | I2C Light Sensor | 0x23 or 0x5C | Yes (ADDR pin) | ??? |
| [LTR-329](https://thepihut.com/products/adafruit-ltr-329-light-sensor-stemma-qt-qwiic) | I2C Light Sensor | 0x29H | No | ??? |
| [BME280](https://www.sparkfun.com/products/15440) | I2C Atmos Sensor | 0x76-0x77 | Yes (SDO pin) | ??? |
| [SparkFun Qwiic Soil](https://www.sparkfun.com/products/17731#reviews) | Soil Moiture Sensor | 0x28 | No | ??? |

Table 8 - Summary of I2C peripheral sensors

### BH1750 – I2C Light Sensor

[section]

### LTR-329 – I2C Light Sensor

[section]

### BME280 – I2C Atmospheric Sensor

[section]

### SparkFun Qwiic Soil Moiture Sensor

[section]

## Wireless Modem

Existing libraries available for the [Adafruit RFM96W LoRa module](https://uk.rs-online.com/web/p/communication-wireless-development-tools/1245502?gb=s) at 433 MHz from AirSpacey ([RadioHead](https://www.airspayce.com/mikem/arduino/RadioHead/)).

If using plug & play module with 2.54mm headers, then no need for controlled impedance traces in PCB layout.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Details | Supplier | Order Code |
| Adafruit RFM96W | LoRa 433MHz transceiver | RS Components / SW | 1245502 |
| ANT-4WHIP3H-SMA | 433 MHz quarter-wave whip antenna | Farnell / SW | 2305892 |
| CON-SMA-EDGE-S | SMA connector (PCB mount, 1.7mm) | Farnell / SW | 3498459 |
| LRPS RG174 150MM | SMA bulkhead jack to SMA plug cable assembly (150mm) | Farnell / SW | 2096227 |

## Weatherproof Housing

[Section]

## Installation and Mounting

[Section]

# Firmware

[Section]