Portland State
UNIVERSITY

EREBUS LABS SENSOR

DESIGN SPECIFICATION

SCOTT LAWSON

BRYAN BUTTON

CHRIS CLARY

MAX COPE

Version 1.6

6/4/2014

VERSION HISTORY

Version #	Implemented By	Revision Date	Reason
1.6	Scott Lawson Max Cope	6/4/2014	Updated Software/Firmware details Added Layouts and Schematics Added Sensor and power supply details
1.5	Scott Lawson	3/31/2014	Added interface mode flowchart Added error messages
1.4	Scott Lawson	3/30/2014	Updated 3.1 IRQ information Updated 3.2 Interface Mode details Adjusted page numbering to start on Table of Contents
1.3	Scott Lawson	3/3/2014	Added 3.2.3 Virtual COM Port Added 3.2.4 Interface Mode Updated 3.1.5 with VBUS details
1.2	Scott Lawson	2/1/2014	Fixed header typos Added Engineering Requirements to Introduction
1.1	Scott Lawson	1/30/2014	Changed data sample format Changed Appendix A name to “Glossary” from “Terminology”
1.0	Scott Lawson	1/28/2014	Initial Release Converted from Software Plan V1.0

TABLE OF CONTENTS

Introduction

Purpose of The Document

This document describes the implementation of both the hardware and software components of the Erebus Labs STEM Sensor. It is intended to be an in-depth technical description of the sensor's software and firmware for those interested in developing custom sensors or modifying the operation of the system.

Overview

Objective Statement

Encourage an interest in STEM in K-12 students by delivering a working prototype of an affordable, simple and flexible device to collect environmental data.

Theory of Operation

The Erebus Labs STEM Sensor system is an open-source electronic device for collecting environmental data over a period of time and presenting it for analysis. The system is comprised of the following components:

Base Unit

The central device that manages power, communication, and data storage, and has one or more sensors attached to it.

Sensor

The individual data collection devices such as VOC detectors and thermometers that are attached to the base unit.

User Interface

The program that that is run on a laptop or desktop computer that allows the user to analyze the data collected.

The base unit is designed to have one sensor attached to it and passively collect data without being attached to a computer system. The data collection site is chosen by the user. The user interface is a simple GUI for displaying collected data and exporting the data to a text file for analysis with a third-party program.

Engineering Requirements

See proposal for marketing requirements.

Marketing Requirements	Engineering Requirements	Justification
1, 2, 3, 4	All sensors must use the same interface to connect to the base unit	Minimizes cost and complexity for users while increasing versatility
4	The user interface must provide a method for the user to access the raw data collected	Allows advanced users to perform their own data analysis
7	A publicly-accessible repository must be used for code and documentation hosting	Encourages exploration and experimentation by students
2, 7	If third-party software is used, it must be open-source	Encourages exploration and experimentation by students, minimizes cost
5, 12	The base unit with sensors attached must operate when exposed to temperatures between -10°C and +70°C	Temperature range required for outdoor operation
2, 3	If the system is does not use a rechargeable power source, it must not use proprietary battery types	Using widely available batteries minimizes cost
2	BOM for base unit should not exceed $20.00 each	Necessary for adoption by K-12 classrooms with limited budgets
2	BOM for sensors should not exceed $5.00 each	Necessary for adoption by K-12 classrooms with limited budgets
3, 4, 9	The base unit should identify the sensor(s) attached and configure itself appropriately	Simplifies operation for younger users
1, 4, 6	The system should be able to collect data points at rates between 1 Hz and 1 per day	Accommodates a wide variety of data collection applications
4, 10	The system should be able to coordinate data collection between 6 base units simultaneously	Accommodates a wide variety of data collection applications
5, 12	The base units and sensors should be operational after a 1.5m drop-test	The system needs to survive daily use by K-12 students

5, 12	The base unit with sensors attached should operate when exposed to temperatures between -20°C and +80°C	Temperature range suggested for outdoor operation
3, 8	The base unit should be able to collect data points for 90 days without user interaction	Simplifies operation for all users
11	A wireless data dump interface should be utilized by the base unit	Provides a convenient method for users to retrieve data
11	If a wireless data dump interface is utilized by the base unit, it should not require the user to be closer to the base unit than 3 meters	Provides a convenient method for users to retrieve data
5, 12	The base and sensors may be constructed with a water-resistant case	The system needs to survive daily use by K-12 students
2, 4, 14	The base unit may contain multiple attachment points to enable multiple sensors to be used simultaneously	Enhances versatility for advanced data collection
3, 13	The base unit may use sockets and connectors to attach the controller, power, and communications devices to the PCB	Further modularity provides hardware interactivity and learning opportunities for younger users

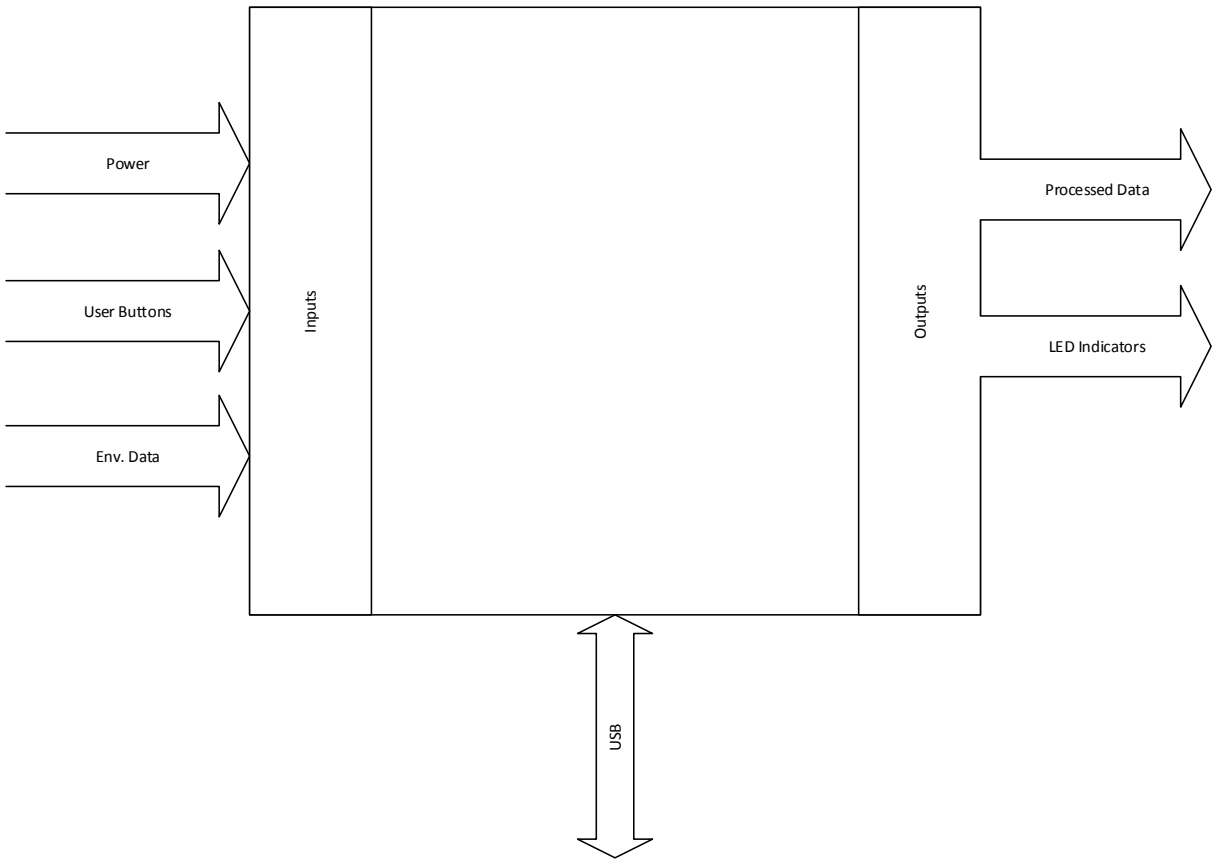
Hardware Plan

Overview

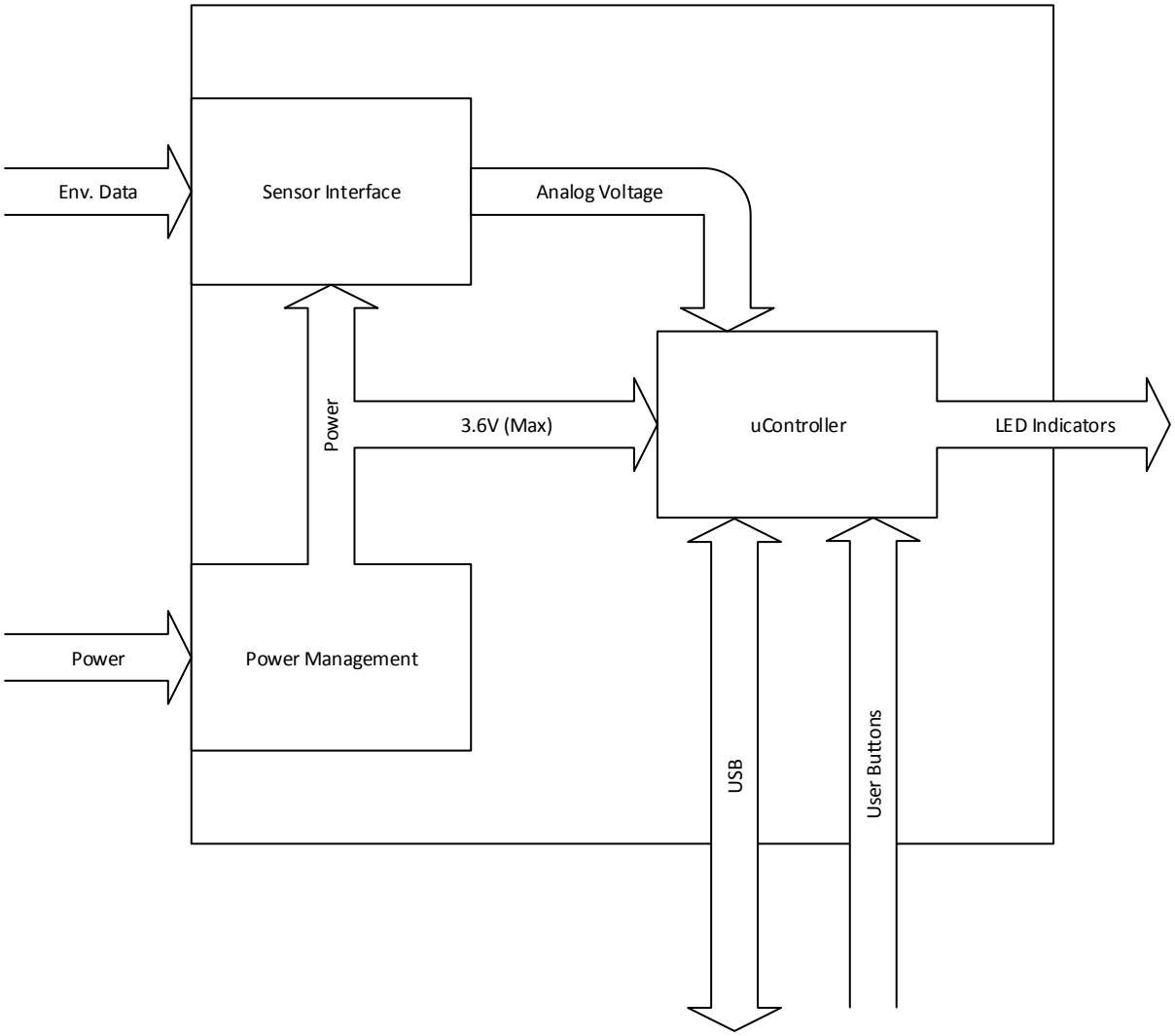
The base unit is comprised of a Cypress PSoC3 microcontroller, two voltage regulators, a sensor interface and a USB port.

Block Diagrams

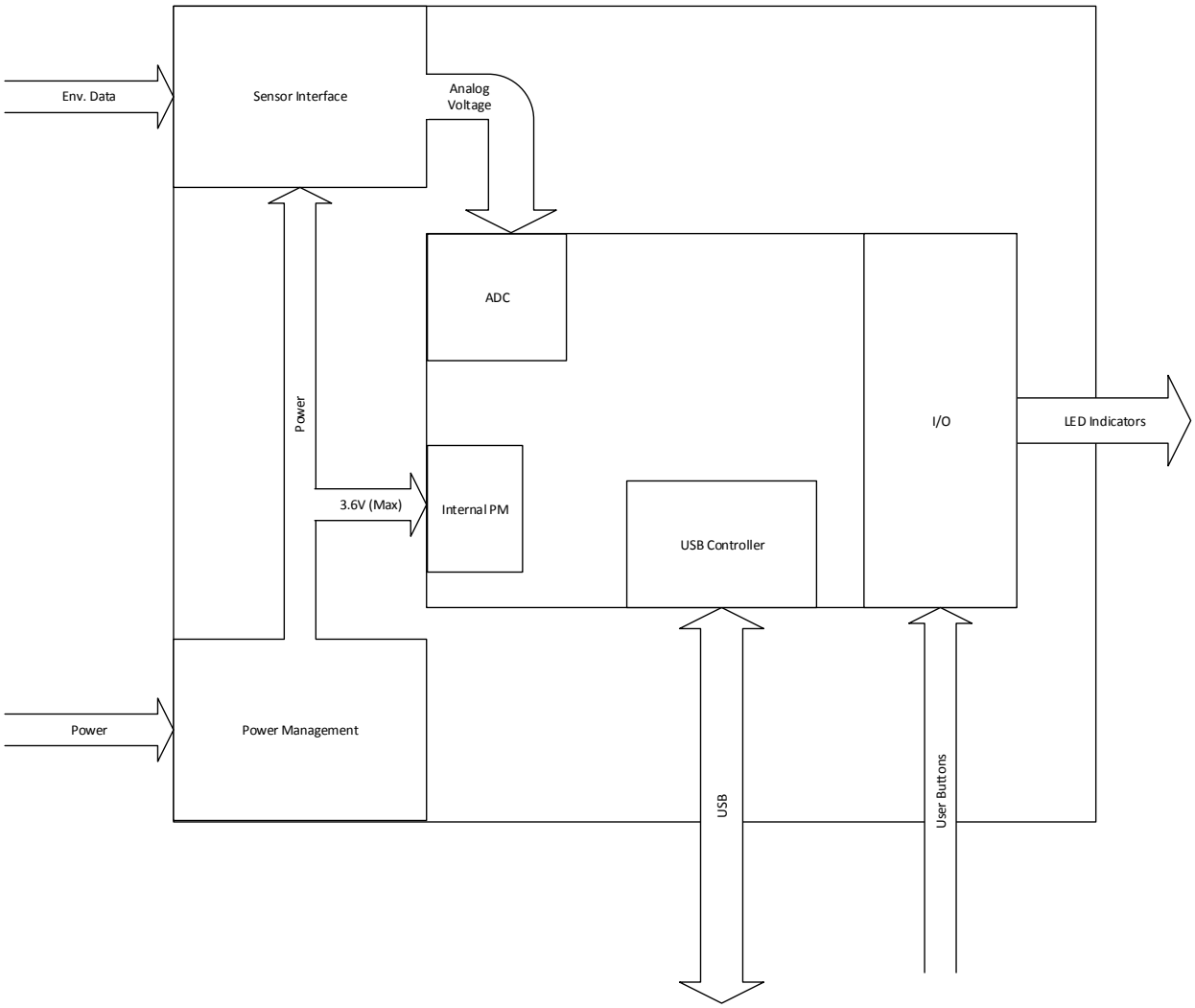
Base Unit Level 0 Block Diagram



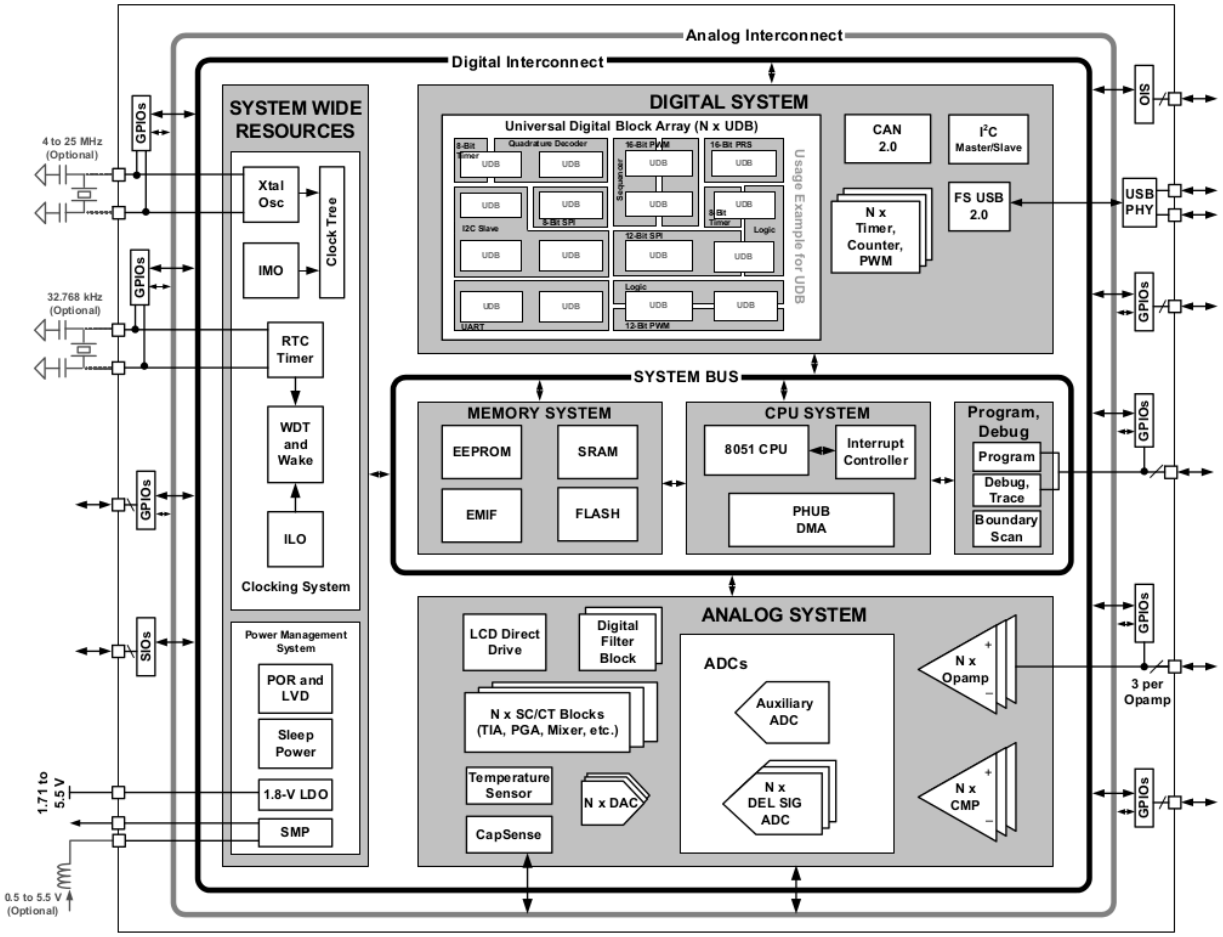
Base Unit Level 1 Block Diagram



Base Unit Level 2 Block Diagram



PSoC3 Block Diagram



Implementation

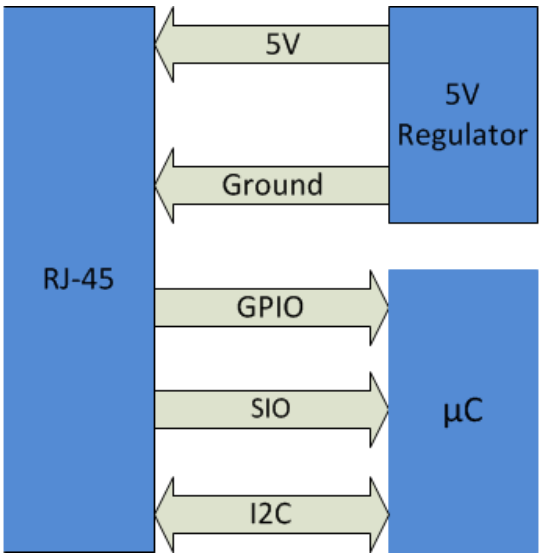
Microcontroller

The PSoC3 microcontroller from Cypress Semiconductor was selected because of its balance between flexibility and cost. It contains several embedded programmable logic blocks that can be used to implement a Full-Speed USB controller and real-time clock. Additionally, the programmable blocks also provide an interface for utilizing the chip's on-board Flash memory in place of an external EEPROM chip. Therefore, the PSoC3 provides a one-chip solution.

Manufacturer	Cypress Semiconductor
Family	PSoC3
Model Number	CY8C3246PVI-147
Architecture	8-bit 8051
Clock Speed	50MHz
Operating Voltage	1.71V – 5.5V
Current Draw	0.8mA@3MHz, 1.2mA@6MHz, 6.6mA@48MHz
ADC	12-bit Delta-Sigma
Program Memory	64KB Flash
EEPROM	1KB
UDBs	24
Package	48-pin SSOP

Sensor Design

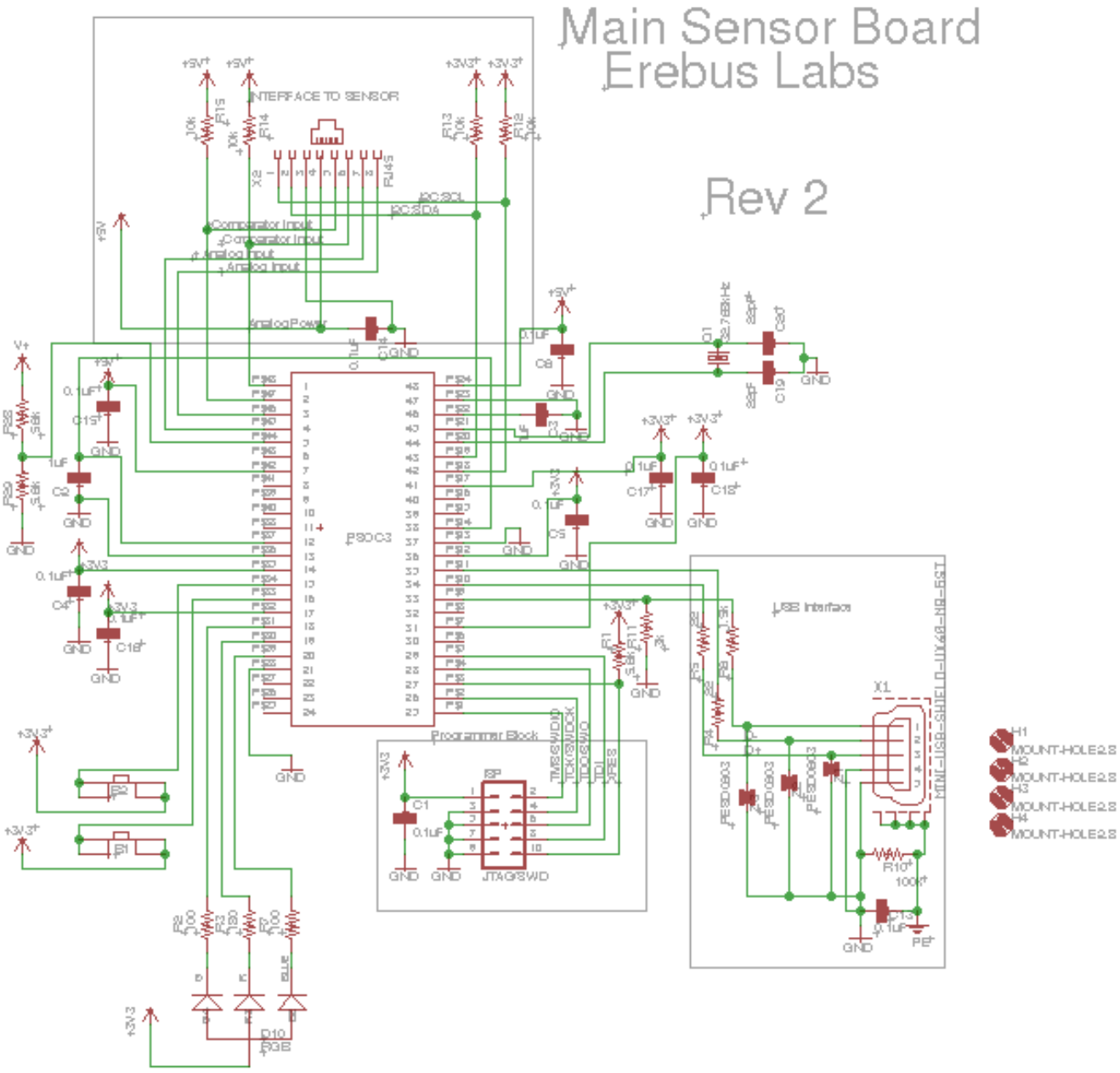
The base unit comes with two sensors. The first is a light sensor to provide high controllability during testing. The second is a Figaro T2600 low oxygen sensor to provide results in gas detection. The two stock sensors were chosen for high reliability and proof of concept. The sensor interface has up to six available outputs to the base these include: two outputs that go the microcontroller's comparator, two outputs that go to the microcontroller's ADC, and two outputs that go to the microcontroller's I2C input. This flexibility provides the user the ability to use a variety of sensors requiring only software changes. The sensor modules are connected to the base unit via a standard CAT5 cable plugged into RJ-45 jacks on both the base unit and sensor modules.



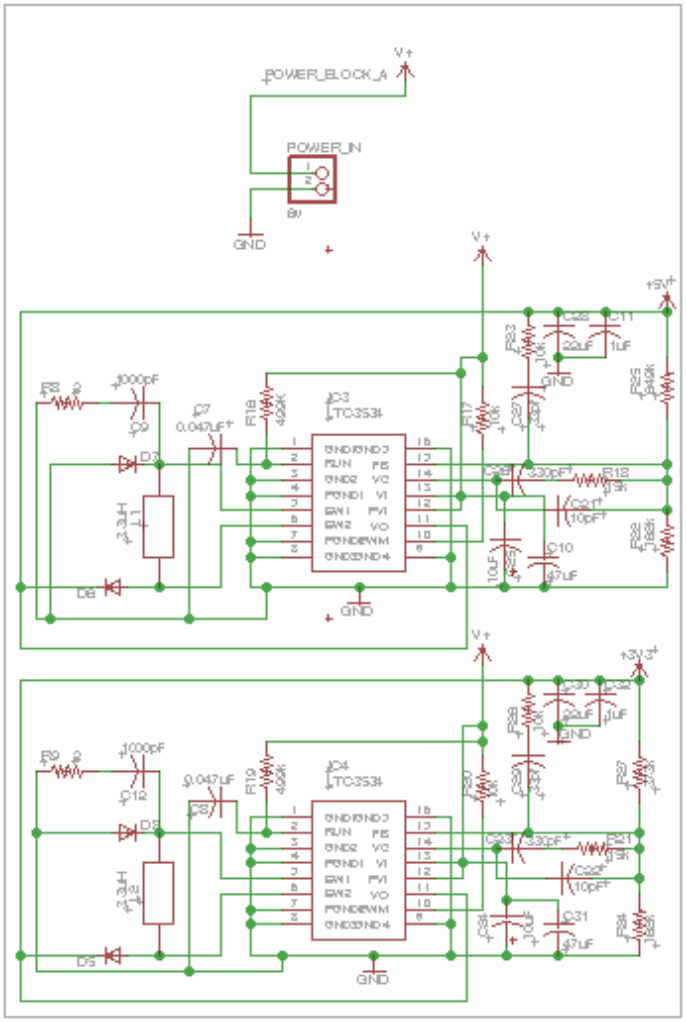
Power Supply

The Base is designed to run on four AA batteries. To do this the most efficiently, Linear Technologies' LTC3435 buck-boost regulators are used. Using these regulator allow the maximum use of the batteries by operating in all three regions: over voltage, at regulated voltage, and under voltage. There are two supplies, 3.3V (for digital needs) and 5V (for analog needs), that consume power with 90% efficiency.

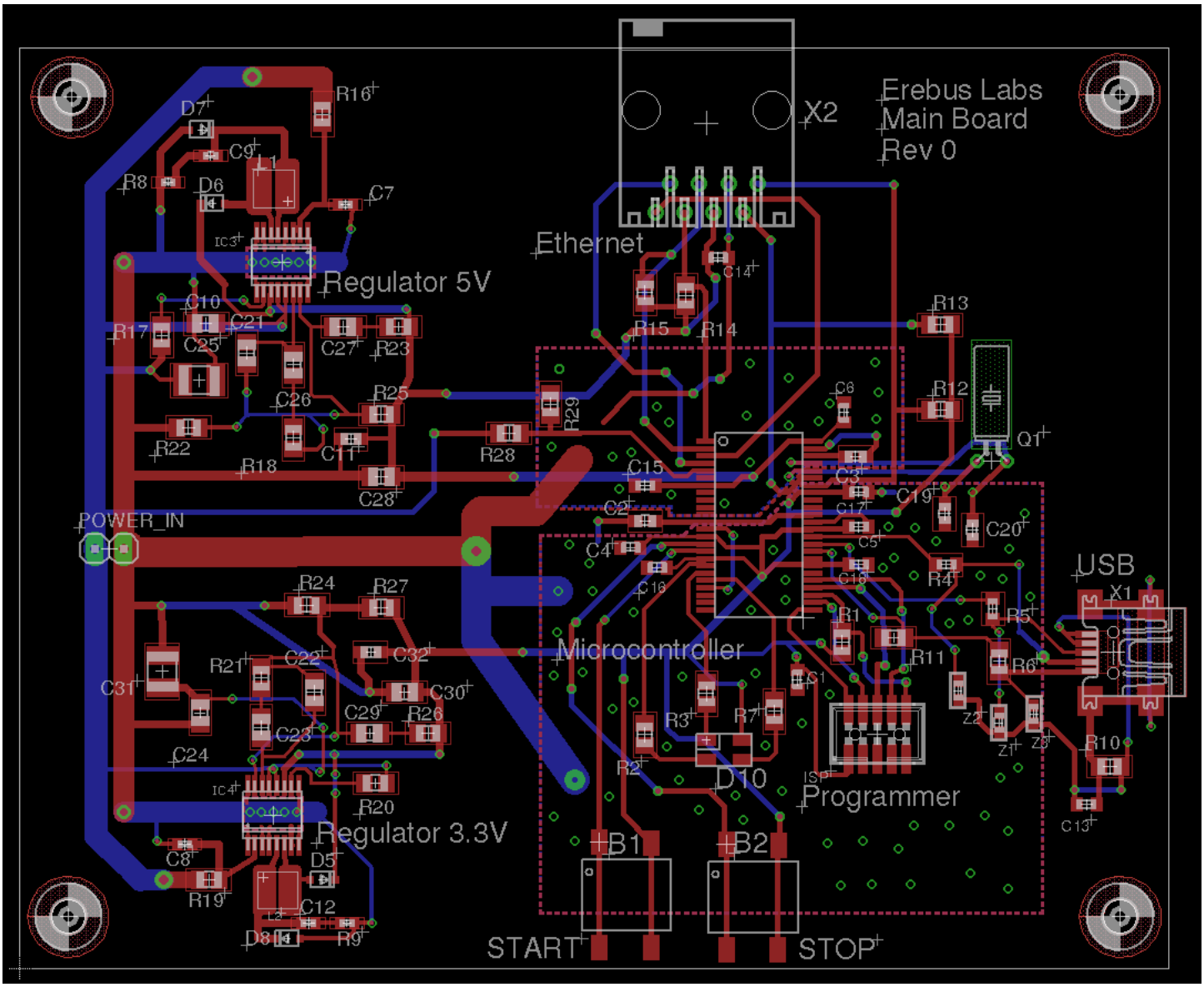
Base Unit Microcontroller Schematic



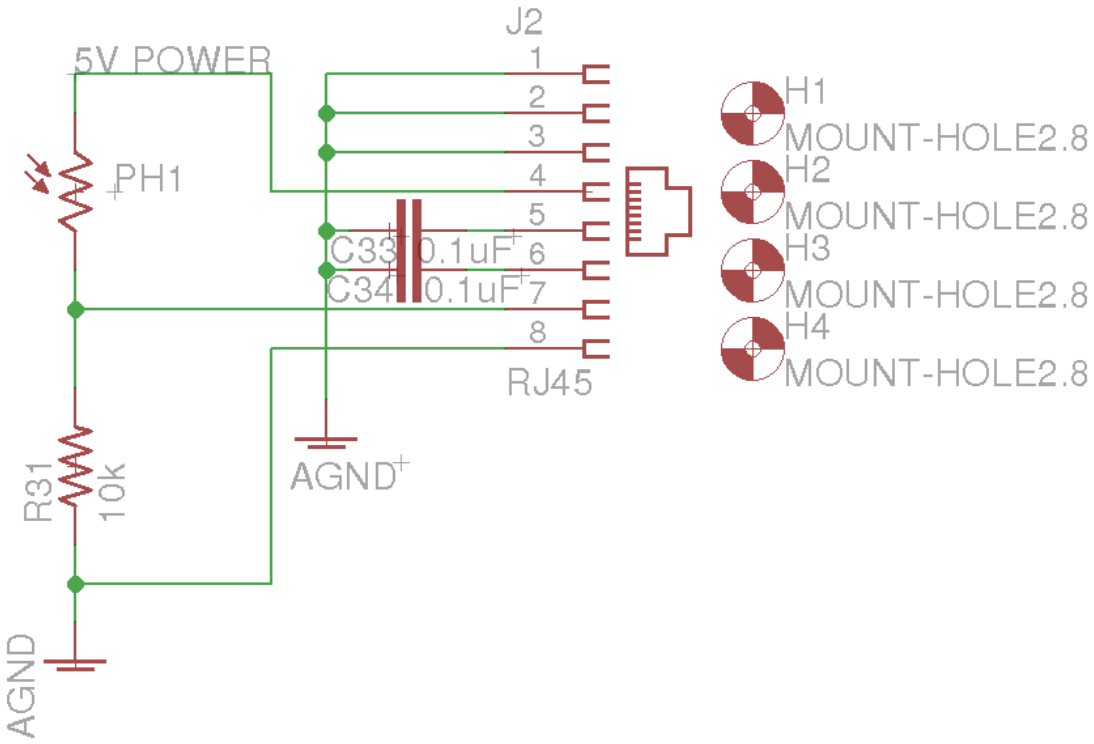
Base Unit Power System Schematic



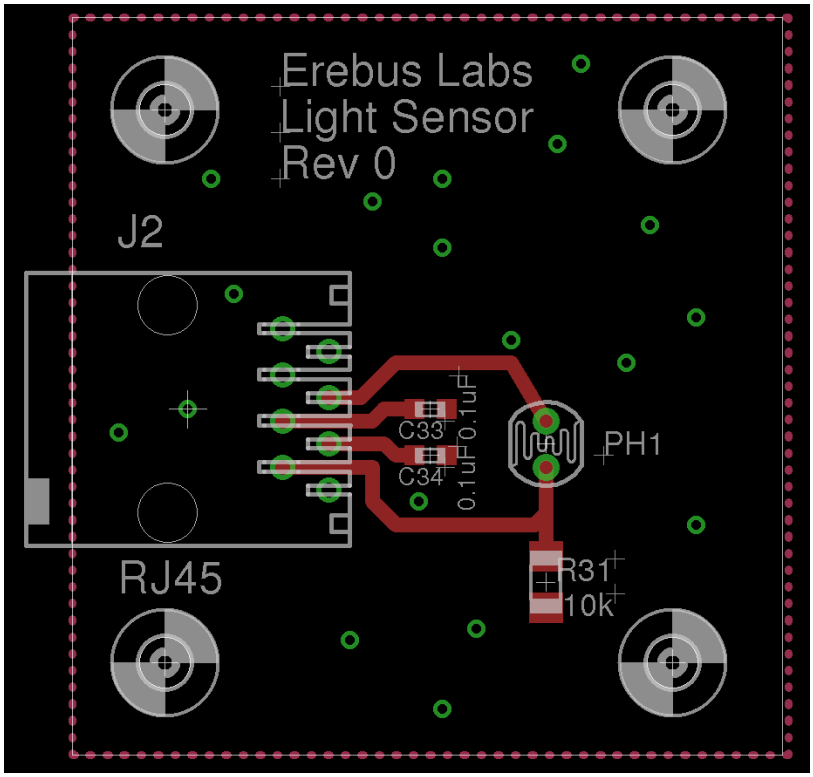
Base Unit Layout



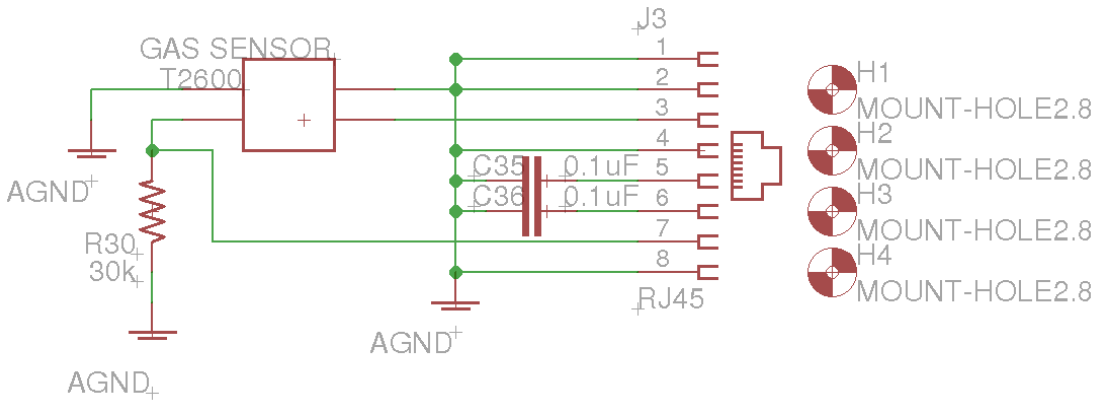
Light Sensor Schematic



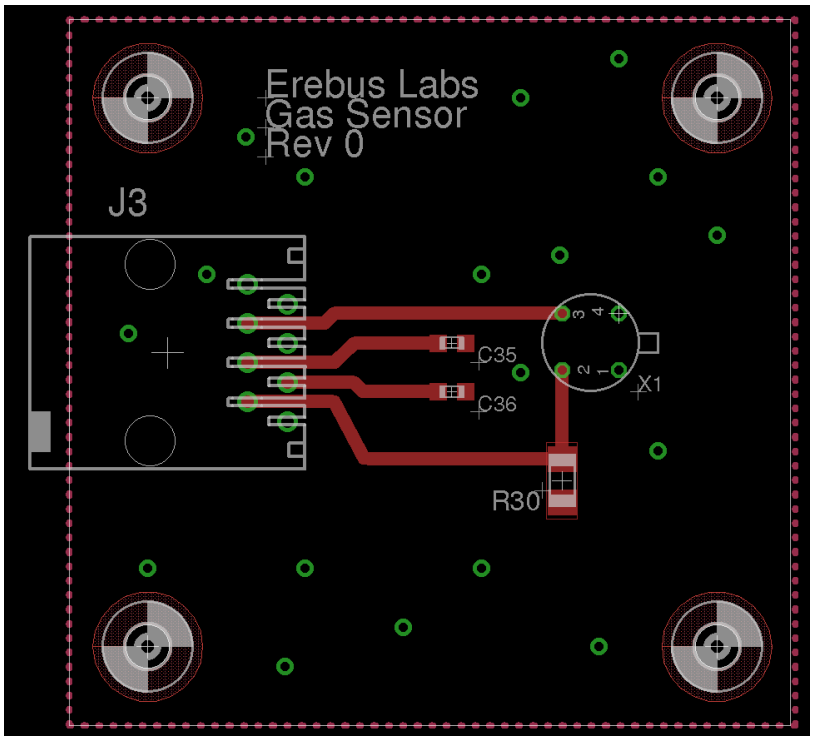
Light Sensor Layout



Gas Sensor Schematic



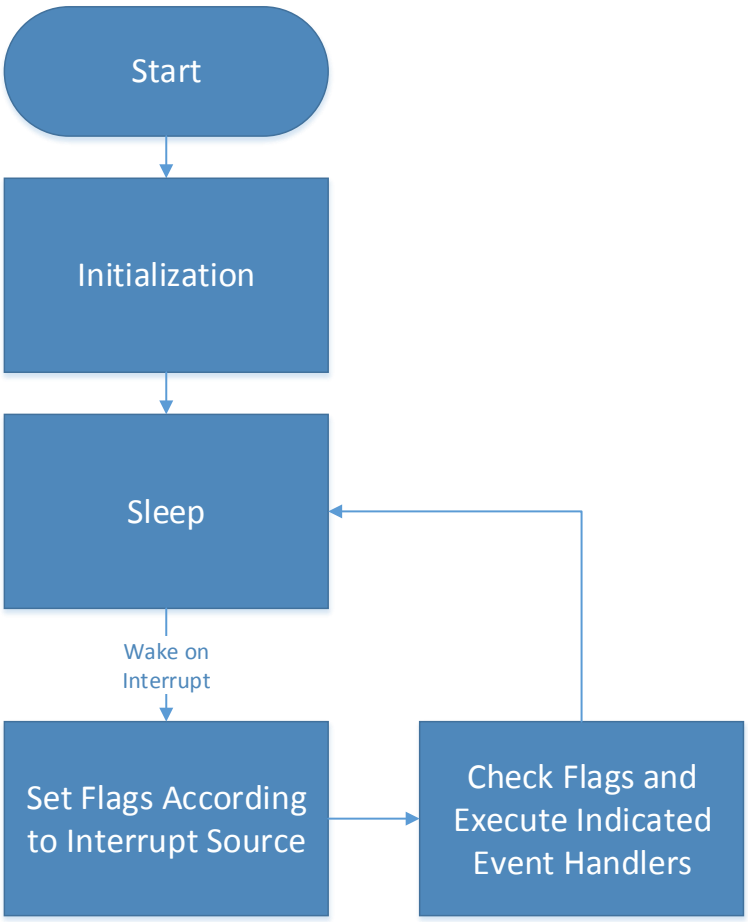
Gas sensor Layout



Firmware Plan

Firmware Overview

The Erebus Labs STEM Sensors device firmware is written in standard C compliant with ISO/IEC 9899:2011 and developed in Cypress' PSoC Creator 3.0. Upon reset, the controller operates as follows:



The STEM Sensor's main() function is responsible for putting the chip to sleep, restoring clock state on wakeup, and checking for flags that may have been set by an interrupt routine. Depending on flags set, the chip may either go back to sleep or call appropriate event handlers according to the flags.

Initialization Tasks

1. The following initialization tasks are performed upon reset:
2. Retrieve data sample pointers from Flash
3. Start Components:
   EEPROM, Real-Time Clock, PWM Controller, ADC, Analog Multiplexer
4. Retrieve and apply sampling parameters from EEPROM
5. Enable VBus_IRQ, ModifyCollection_IRQ, and global interrupts
6. Enable sample initiation

Interrupt Service Routines

Event flags are set by the following interrupt service routines:

Name	Trigger	Action
VBus_IRQ	Logic High voltage on VBUS pin	Activate USB Component, eumerate device on host, receive and store user settings, dump data samples to host, restores entry state on exit
ModifyCollection_IRQ	Either start or stop collection button press	Examine PICU to identify interrupt source, enable or disable sampling accordingly
RTC_EverySecondHandler	RTC Every Second Periodic Interrupt	If sample unit is seconds and sampling enabled, increment counter; if counter == sample interval, take sample. Increment low battery blink counter; if battery power is low and blink count == blink interval, blink low battery LED indicator
RTC_EveryMinuteHandler	RTC Every Minute Periodic Interrupt	If sample unit is minutes and sampling enabled, increment counter; if counter == sample interval, take sample. Increment battery check count; if battery check count == battery check interval, check battery level
RTC_EveryHourHandler	RTC Every Hour Periodic Interrupt	If sample unit is hours and sampling enabled, increment counter; if counter == sample interval, take sample.
RTC_EveryDayHandler	RTC Every Day Periodic Interrupt	If sample unit is days and sampling enabled, increment counter; if counter == sample interval, take sample.

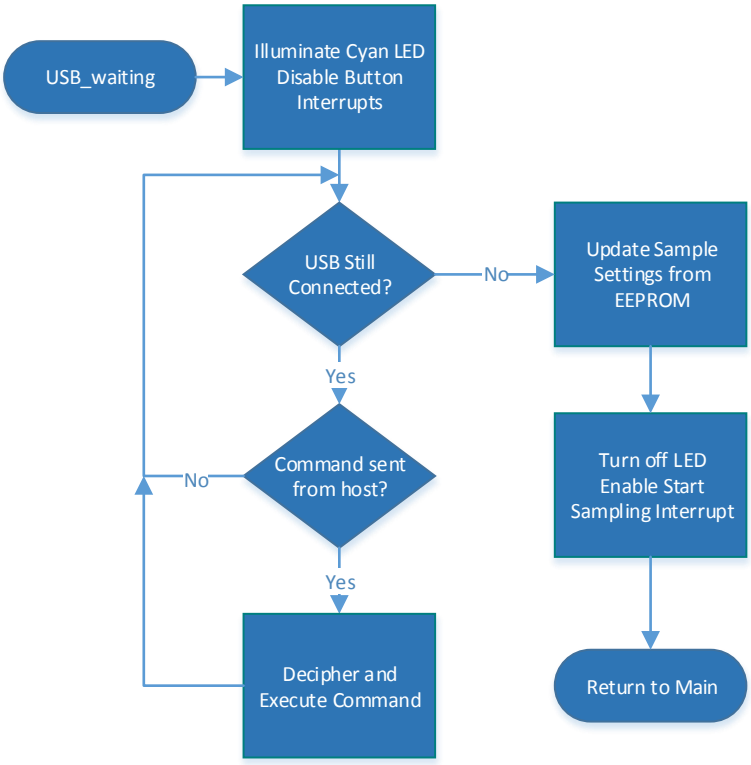
Note: RTC interrupt routines can be found in Generated_Source/PSoC3/RTC/RTC_Int.c. They all share one interrupt vector titled RTC_isr in Erebus_Sensor.cydwr -> Interrupts.

Event Handlers

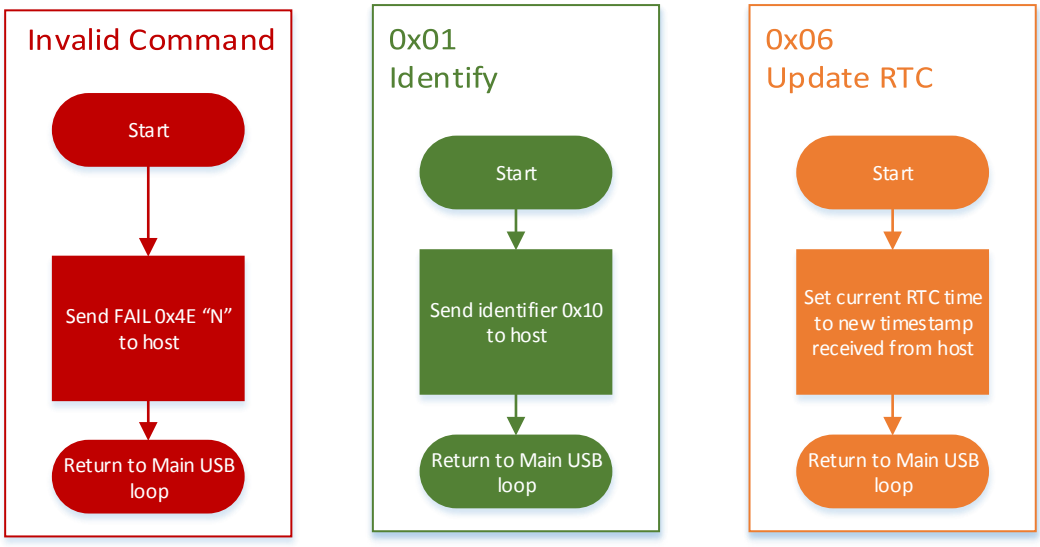
The following events are to be handled by function calls from main by the procedures described in these flowcharts.

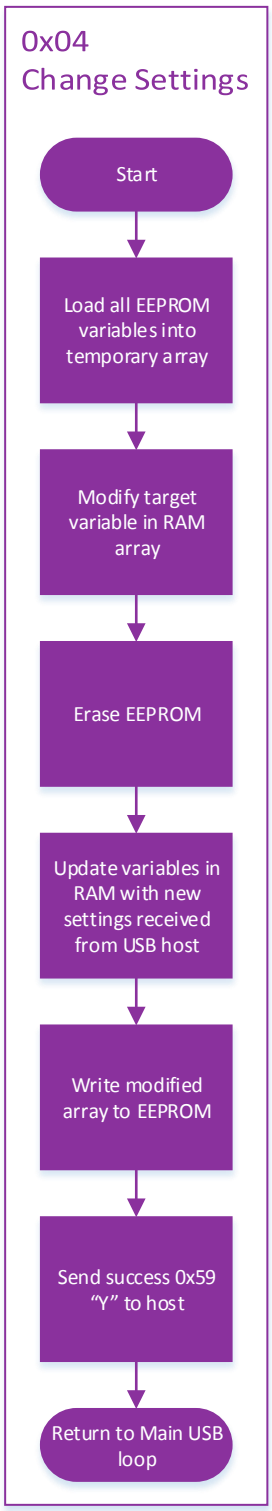
USB Waiting

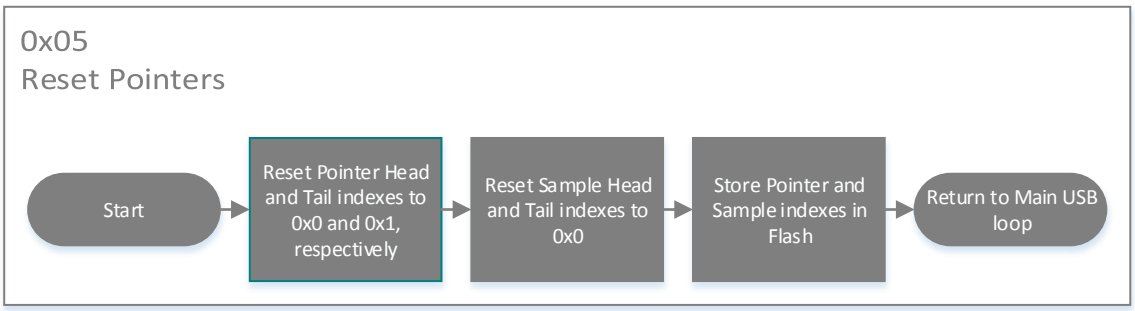
The USB_waiting flag indicates that the device's USB port has been attached to a host. The various commands that may be sent by the host are handled according to the USB Command Handling flowcharts below.

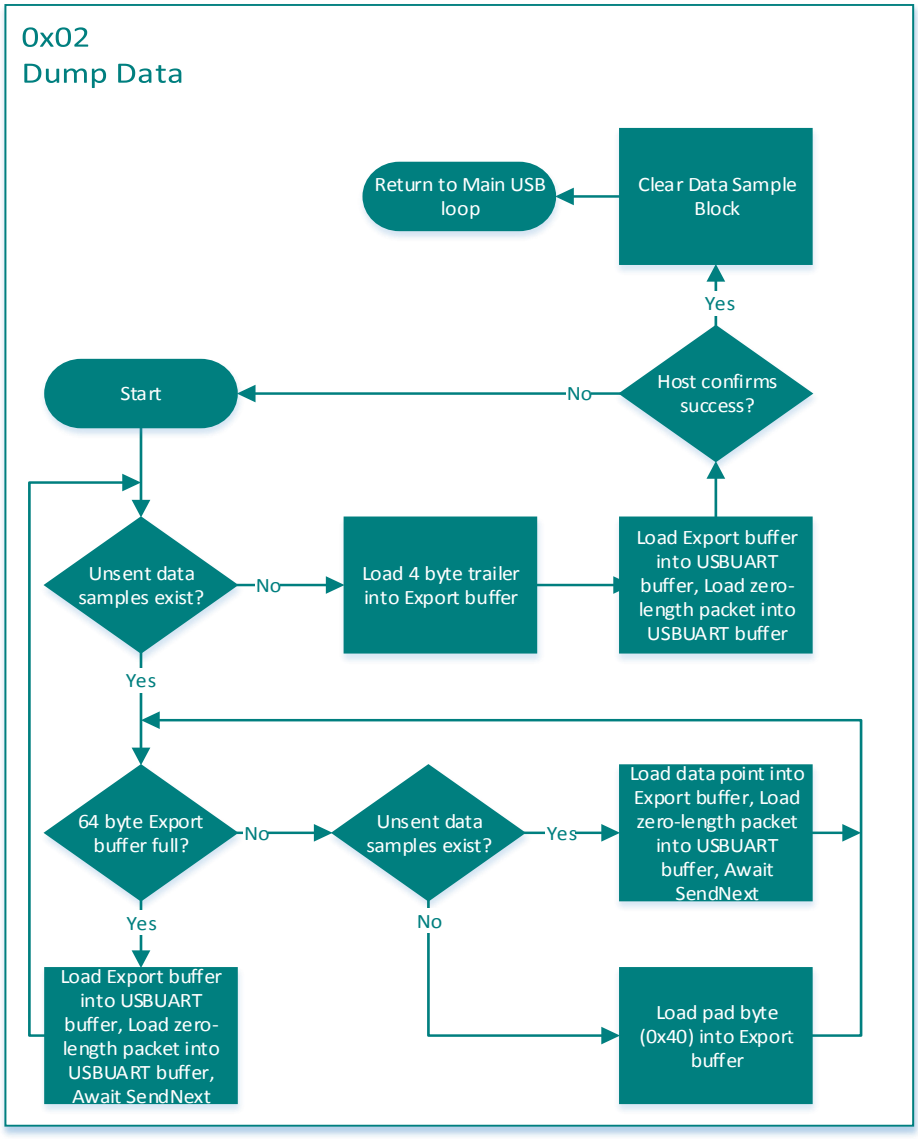


USB Command Handling



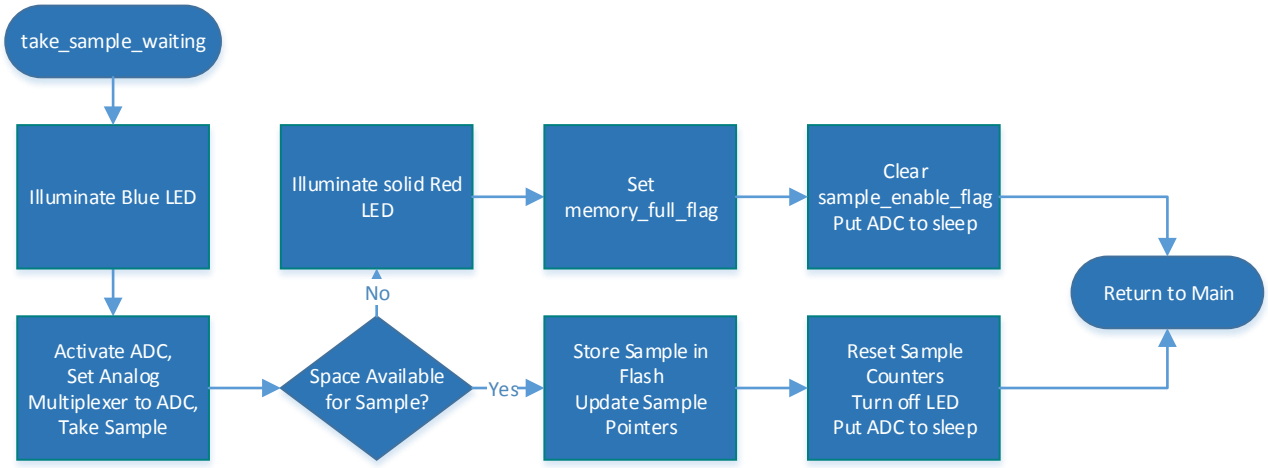

0x04
Change Settings
Start
Load all EEPROM variables into temporary array
Modify target variable in RAM array
Erase EEPROM
Update variables in RAM with new settings received from USB host
Write modified array to EEPROM
Send success 0x59 "Y" to host
Return to Main USB loop


0x05
Reset Pointers
Start
Reset Pointer Head and Tail indexes to 0x0 and 0x1, respectively
Reset Sample Head and Tail indexes to 0x0
Store Pointer and Sample indexes in Flash
Return to Main USB loop


0x02
Dump Data
Return to Main USB loop
Clear Data Sample Block
Yes
Start
No
Host confirms success?
Unsent data samples exist?
No
Load 4 byte trailer into Export buffer
Load Export buffer into USBUART buffer, Load zero-length packet into USBUART buffer
Yes
64 byte Export buffer full?
No
Unsent data samples exist?
Yes
Load data point into Export buffer, Load zero-length packet into USBUART buffer, Await SendNext
Yes
No
Load Export buffer into USBUART buffer, Load zero-length packet into USBUART buffer, Await SendNext
Load pad byte (0x40) into Export buffer

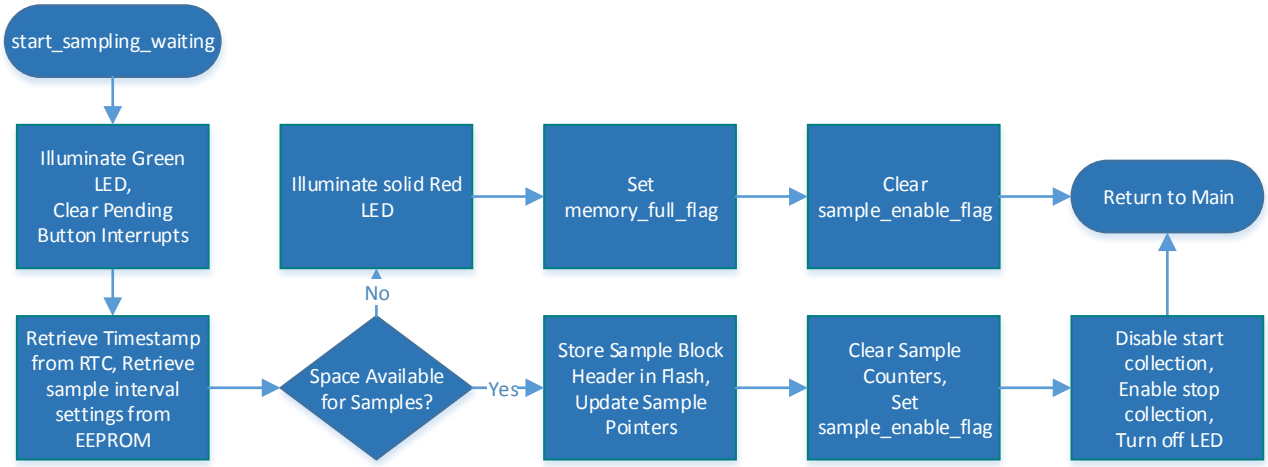
Take Sample Waiting

The take_sample_waiting flag indicates that the sample interval has been reached according to the Real-Time clock and a sample must be taken.



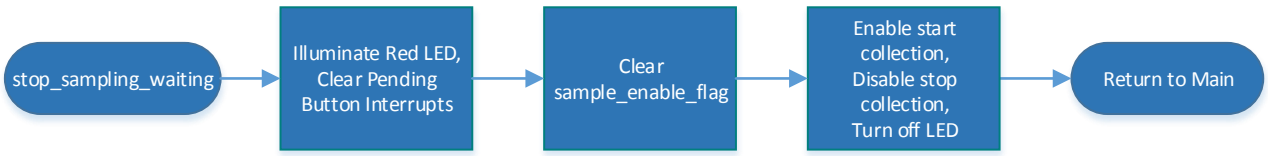
Start Sampling Waiting

The start_sampling_waiting flag indicates that the user has pressed the “Start Sampling” button.



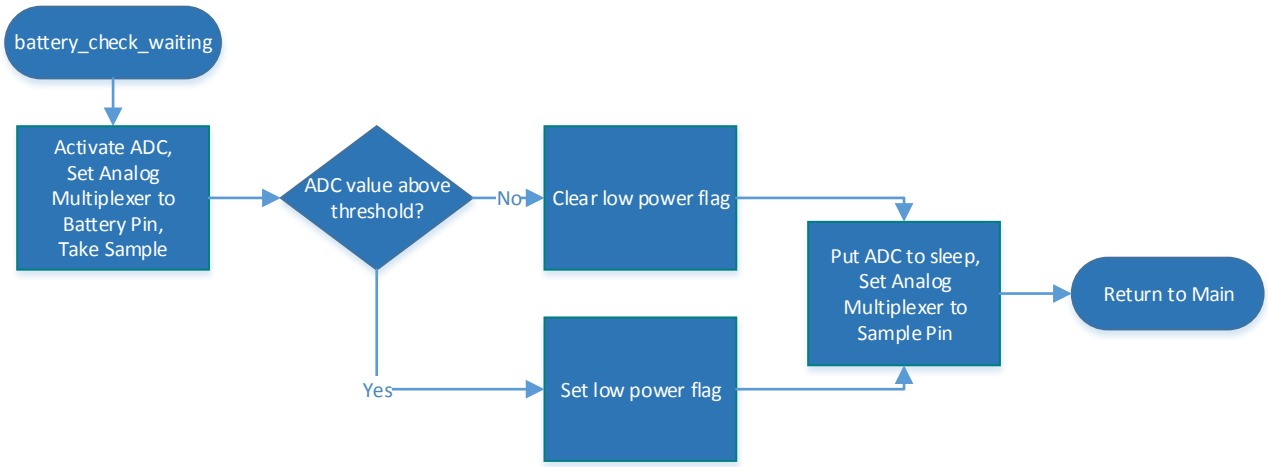
Stop Sample Waiting

The stop_samping_waiting flag indicates that the user has pressed the “Stop Sampling” button.



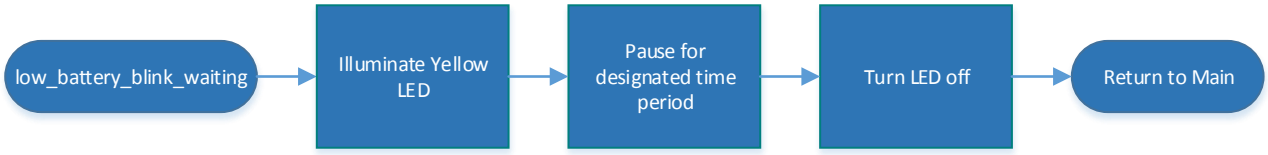
Check Battery Waiting

The check_battery_waiting flag indicates that it is time to check the battery level.



Low Battery Blink Waiting

The low_battery_blink_waiting flag indicates that as of the last battery sample, the voltage level of the battery is below the threshold, so the LED must be used to alert the user.



Sample Blocks

Data samples are stored in Flash memory along with program code by utilizing the EEPROM emulator component available for the PSoC3. Each section of data samples begins with a 16-byte header (HE). The header contains information about the sensor used, the sample period, the sample interval, and a date/time stamp from when data collection was started. There are also four reserved bytes at the end of the header to force the header to be 16-byte aligned.

A new sample block is initiated every time the user presses the Start Sampling button if the sensor is not currently collection samples.

The header has the following format:

Bits	Number of Bytes	Description
HE[127:112]	2	Unsigned integer containing sample block start signature 0x200
HE[111:96]	2	Unsigned integer indicating sample start year
HE[95:88]	1	Unsigned integer indicating sensor used 0 = Light Sensor 1 = Low Oxygen Sensor 2 = Custom Sensor

HE[87:80]	1	Unsigned integer indicating sample unit: must be in the range [0:3] 0 = Seconds 1 = Minutes 2 = Hours 3 = Days
HE[79:72]	1	Unsigned integer indicating sample interval
HE[71:64]	1	Unsigned integer indicating sample start second
HE[63:56]	1	Unsigned integer indicating sample start minute
HE[55:48]	1	Unsigned integer indicating sample start hour of day
HE[47:40]	1	Unsigned integer indicating sample start day of month
HE[39:32]	1	Unsigned integer indicating sample start month: must be in the range [1:12] 1 = January 2 = February 3 = March Etc.
HE[31:0]	1	Reserved: write as 0x00000000

Data Samples

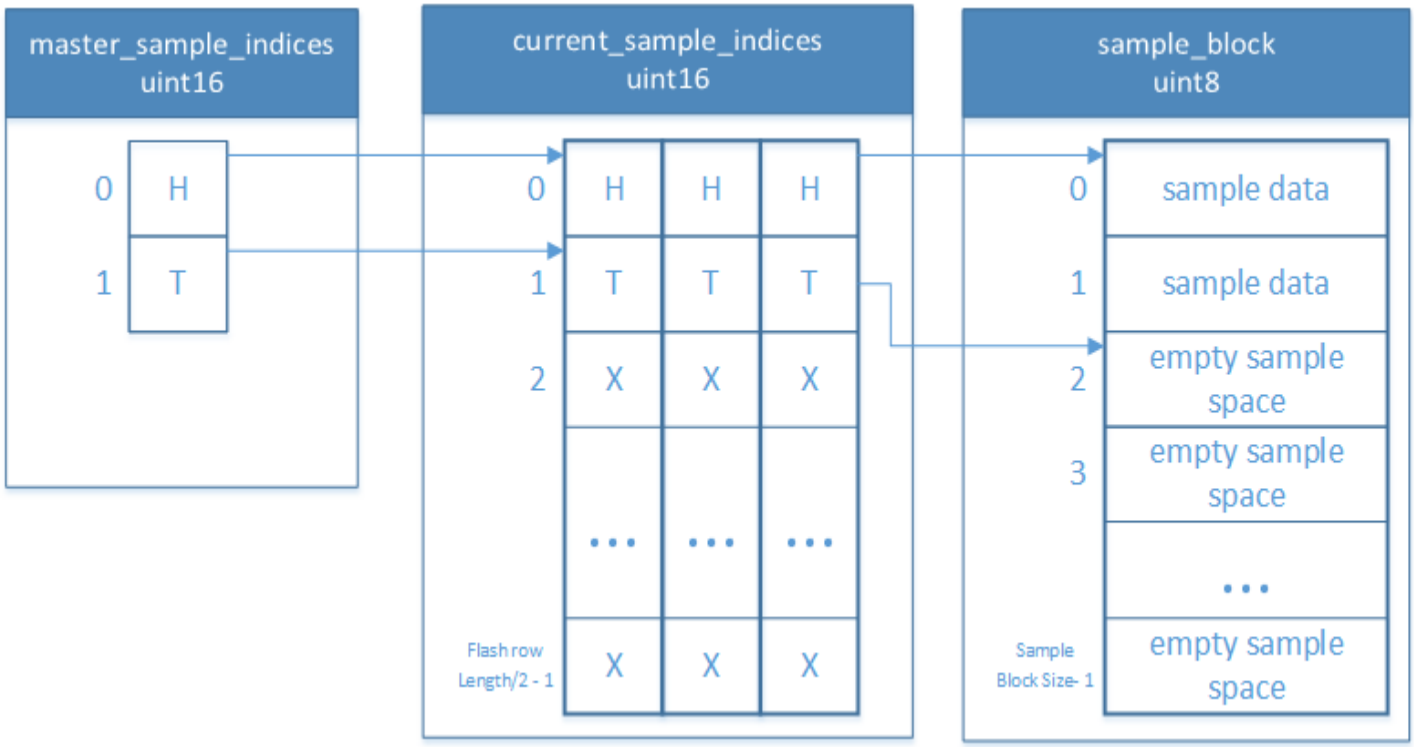
The data samples themselves are recorded in a 2-byte bit-field (DA) comprised of the 12-bit ADC output and a 4-bit reserved field:

Bits	Description
DA[15:12]	Reserved: write as 0x0
DA[11:0]	Unsigned raw ADC output

During sampling, the Reserved field of the sample should be written as 0x0. The data dump routine in the USB Handler uses these bits to communicate information to the host during dumping, such as End of Data or No Data Present.

Wear Levelling

The use of the Emulated EEPROM component allowed us to realize the goal of minimizing the number of chips required on the main board, but it created certain challenges as well. The most significant challenge was the need for wear-levelling. Although the Flash memory in the PSoC3 is guaranteed for up to 100,000 write cycles, we wanted the base unit to be as durable as possible. To achieve greater product longevity, a wear-levelling scheme was implemented. The wear-levelling method employed is shown by the following diagram:



Both the master_sample_indices and current_sample_indices arrays are stored in flash so that stored data and array indices are retained in the event of power failure. The arrays perform the following roles:

sample_block

The sample_block array is an array of uint8's (unsigned chars) and stores sample data and sample block headers. This array is only written to when beginning sampling (to store the block header) and when taking a sample. It behaves like a circular buffer, with the current head and tail indices stored in the current_sample_indices array.

current_sample_indices

The current_sample_indices array contains the indices of the sample_block array that correspond to the current block's head and tail. As samples are taken and collection periods are started and stopped, the tail pointer is incremented through the sample_block array. Head does not move until the existing data is successfully exported to a host computer. When a data dump is successfully completed, the head index is set equal to the current tail index, effectively clearing existing data without subjecting the Flash memory to unnecessary erase cycles.

There are three pairs of head and tail indices in the current_sample_indices array that are separated a number of bytes equal to the length of a Flash row - 2. This arrangement ensures that the pairs of head and tail pointer pairs are in separate rows of Flash memory. Every time the head or tail indices are modified, the new index must be updated in the current_sample_indices array. The head and tail index pointers are in separate rows so that they can have their wear levelled as well.

master_sample_indices

The head and tail indices in the master_sample_indices array contains the index of the currently used head and tail index pair in the current_sample_indices array. As data headers and samples are stored in Flash, the current tail index in the current_sample_indices array is incremented, but the master_sample_indices array is untouched. Eventually, enough data will be collected that the current tail index is wrapped around the end of the sample_block array because it is a circular buffer. When that data is dumped and setting the head index equal to the tail index requires the head to be wrapped around the end of the sample_block array, the head/tail indices in the master_sample_indices are set equal to the next pair of head/tail indices in the current_sample_indices array.

Initialization

After the base unit has been reprogrammed, the indices must be reset to their default locations before the device can be used. To accomplish this, the base unit is connected to a host system and the Reset Device command is issued from the user application. From that point on every time the device is powered up, the master and current sample indices are retrieved from Flash allowing the device to store samples properly.

Sample Exporting

When data sample blocks are exported to the host system over USB, the current block of data samples and headers are iterated over until the tail pointer matches the head pointer. If the end of the sample block is reached before a 64-byte packet can be filled, the remaining bytes are filled with the pad-byte signature (0x40) to indicate to the user application that those bytes do not contain sample data and should not be counted when calculating the total number of good bytes received.

The data export routine does no interpretation of the data it is iterating over; it simply loads bytes from the sample block into the USBUART buffer. After all data has been transferred, a four-byte trailer (TR) is sent to the host to confirm that the correct number of bytes were received. It has the following structure:

Bits	Number of Bytes	Description
TR[31:16]	2	Number of non-pad bytes transmitted
TR[15:8]	1	Pad byte: write as 0x00
TR[7:0]	1	End of data transmission marker: write as 0x80

USB Packets During Sample Export

Host commands and device replies are sent in single byte packets. Data is transmitted in 64-byte packets, the maximum size allowed by the USB specification. Between each 64-byte packet sent, the firmware waits for the

NEXT command (0x07) from the host before initiating the transmission of the next packet. This includes waiting after the last sample has been sent before sending the trailer.

IMPORANT NOTE: After each 64-byte packet, a zero length packet MUST be sent to the host to notify it that the sensor is done with that transaction and is awaiting the NEXT command. Failure to do this may cause the last 64-byte transmission to be held in a USB buffer on the host before being transferred to the Erebus Sensor application, causing both the firmware and user application to stall while waiting for data from the other.

Real-Time Clock Updates

When the current time of the RTC is to be updated, the current time stamp is expected to be received in an array of bytes (CT) of the following format:

Bits	Number of Bytes	Description
CT[55:40]	2	Unsigned integer indicating current year
CT[39:32]	1	Unsigned integer indicating current second
CT[31:24]	1	Unsigned integer indicating current minute
CT[23:16]	1	Unsigned integer indicating current hour of day
CT[15:8]	1	Unsigned integer indicating current day of month
CT[7:0]	1	Unsigned integer indicating current month: must be in the range [1:12] 1 = January 2 = February 3 = March Etc.

User Application Plan

User Interface

The host computer user interface is a simple GUI that performs two functions:

1) Provide a method for the user to change data collection settings or reset the base unit.
2) Allow the user export data from the device and present it in a text file. Python provides a platform-independent framework for a GUI and for interacting with the sensor.

The user interface is written in Python 3.2x utilizing the PySerial library for serial communications and the tkinter library for GUI rendering.

Device Interface Mode

While plugged into the computer, the sensor remains in Interface Mode. During this time, the PSoC3 continually monitors its input buffer for commands from the host computer and respond to them accordingly. The microcontroller exits interface mode when power from the USB VBUS pin is no longer detected.

All commands to the sensor from the host and replies from the sensor are one byte long, with the exception of sampled data dumps and when returning current sampling settings. All command and data packets use Big-Endian byte-ordering.

Available Commands

Command	Bit Pattern	Sensor Action
IDENTIFY	0x01	Replies with identifier
DUMP_DATA	0x02	Exports sampled data points to host
GET_SETTINGS	0x03	Retrieves current sampling settings from EEPROM and sends them to the user application
CHANGE_SETTING	0x04	Stores new sampling settings provided in EEPROM
RESET_PTRS	0x05	Resets data sample block pointers to default values
UPDATE_RTC	0x06	Updates the time and date of the Real-Time Clock with the values provided
NEXT	0x07	During sample block dump, sensor proceeds with next sample transaction – illicits a FAILURE response if sent when not transferring sample data

Incoming Messages from Sensor

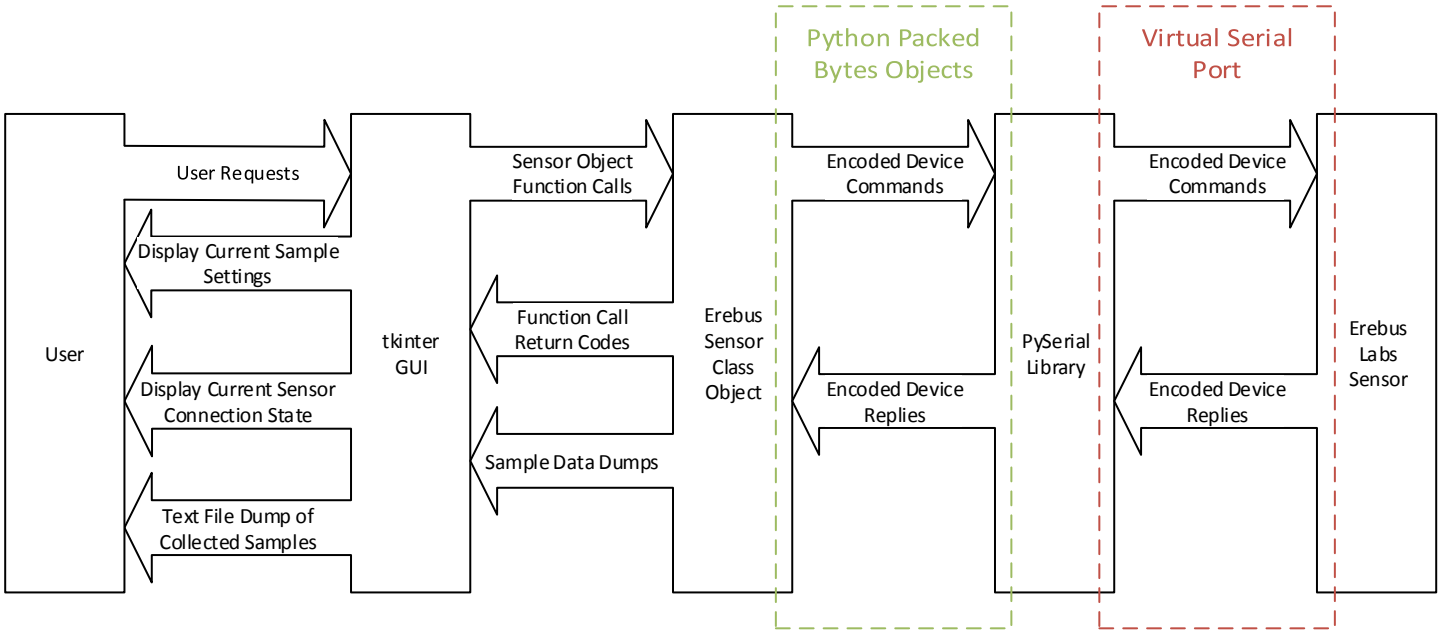
Messages	Bit Pattern	Meaning
IDENTIFIER	0x10	Differentiates Erebus Labs Sensor from other serial devices
SUCCESS	0x20	Last action was successful, ready for next command
FAILURE	0x30	Last action failed, reattempt command

Virtual COM Port

The PSoC3 microcontroller USBFS_UART component is used for communication with the host computer. The Python library PySerial is used to communicate over the serial port with the base unit. Communicating using a virtual serial port provides a cross-platform method of enumerating on and communicating with a host without the need for additional drivers.

Command Resolution

User communication with the device involves four layers as shown in the following diagram:



As the user selects menu options or enters new settings, the GUI executes callbacks into the Erebus Sensor class object which maintains a handle to the attached sensor. It is the responsibility of the Erebus Sensor object to resolve the user's commands into the appropriate bit fields and transfer them to the device through calls to the PySerial routines. The Erebus Sensor object must also interpret the device replies to notify the user whether the last command succeeded or failed.

Appendix A: Acronyms

Acronym	Meaning
ADC	Analog-to-Digital Converter
BOM	Bill of Materials
CO	Carbon Monoxide
CSV	Comma-separated-value formatted file
EEPROM	Electrically Erasable Programmable Read-Only Memory
EPL	The Portland State University Engineering and Prototyping Lab
GUI	Graphical User Interface
LED	Light Emitting Diode
I^2C	The Inter-Integrated Circuit communication protocol
ISR	Interrupt Service Routine
K-12	Kindergarten through 12^{th} grade school
LED	Light Emanating Diode
PCB	Printed Circuit Board
PICU	Port Interrupt Control Unit
PSoC	Programmable System On Chip
SI	Silicon
SPI	Serial Peripheral Interface Bus
STEM	Science, Technology, Engineering and Math
TRM	Technical Reference Manual
USB	Universal Serial Bus
USBUART	Universal Serial Bus Universal Asynchronous Receiver/Transmitter (refers to the PSoC3 USBUART component)

Appendix B: System Architecture

Base Unit

The central device that manages power, communication, and data storage, and has one or more sensors attached to it.

Sensor

The individual data collection devices such as VOC detectors and thermometers that are attached to the base unit.

User Interface

The program that is run on a laptop or desktop computer that allows the user to view and interact with the data collected.

System

The operational product comprised of base units with attached sensors and a user interface.