µPINPOINT: AN INEXPENSIVE DATA LOGGER FOR SCIENTIFIC EXPERIMENTATION AND EDUCATION

BY

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µPINPoint: An Inexpensive Data Logger for Scientific Experimentation and Education

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Abstract

Traditionally, scientific data collection in schools has been a tedious process involving hand-written measurements. More recently, electronic equipment has been introduced, but there often is not enough of it for all students to participant.

In this thesis, an inexpensive data logging device, the µPINPoint, is developed and evaluated. The µPINPoint has on-board sensors to measure ambient temperature, pressure, and light, as well as linear acceleration in three dimensions. Altitude and acceleration magnitude are automatically derived from these sensor readings by the µPINPoint. All of these measurements are written to a CSV file at a user-configured sample rate. To retrieve the data from the µPINPoint, the device is simply plugged into a USB port, where it is mounted as a disk drive. The CSV file is then copied to the user's computer.

The purpose of the device is to act as a catalyst to scientific exploration and collaboration both inside and outside of the classroom. It gives students the ability to have hands-on personal experiences collecting data. Collaborative data collection with input from many students can lead to better understanding and classroom discussion, as shown in previous work.

The device facilitates simple cross-platform data collection and complements iSENSE, the web-based collaborative visualization tool developed by the Engaging Computing Group at UMass Lowell and Machine Science Inc. This enables instructors and students to focus on the concepts under study rather than the process of getting the recorded data onto their computers for analysis.

Two workshops were conducted with educators to gain insight into the value added by such a device. Feedback about this prototype device was collected using questionnaires administered at the conclusion of each workshop. This feedback was analyzed and used to make improvements to the device. The thesis also includes an analysis of the commercial potential of the µPINPoint.

Acknowledgments

The work presented in this thesis was only possible because of the helpful feedback provided by members of the Engaging Computing Group in the Department of Computer Science at UMass Lowell. None of the work presented here would have been possible without the years of prior work and research. The iSENSE team in particular provided the foundation on which this work was based.

I give my sincere thanks to Dr. Fred Martin for his constructive criticism and guidance in this work. He was patient and open-minded, and helped me develop the concept of the µPINPoint from simply an idea into a prototype and potential product, fulfilling the requirements of the Entrepreneurship Option in Computer Science MS. I would also like to thank Dr. Martin for his unique understanding of requirements for this work, and helping to keep me focused.

I thank Dr. Steven Tello for his guidance and excellent knowledge of product development, innovation, and marketing.

I extend my thanks to Ivan Rudnicki of Machine Science for his feedback and criticism of the µPINPoint device and his general suggestions.

I give special thanks to the developers of the previous PINPoint data logger, especially James Dalphond and Michael McGuiness, as this device formed the basis for the development of the µPINPoint data logger. Much was learned from this past work and an examination of the use of this device by students.

Several members of the iSENSE team also provided support for the workshops held to evaluate the µPINPoint device and I extend my thanks to these individuals. These individuals include Edward Tonelli, Don Rhine, Dr. Michelle Scribner-MacLean, Alan Rosenthal, Erin Graceffa, and Katelyn Carcia.

My most sincere thanks go to my wife, Heather, for her constant and continued support. She has always been the first person I test new ideas on has helped me extensively with editing of this document. She has been understanding and helpful in the entire process of the development of the work presented here.

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Chapter 1

Introduction

The development of the µPINPoint data logger described here is the result of many months of effort, both in understanding and formulating the requirements for such a device and in the actual process of engineering design and evaluation. Several goals and features were explored and ultimately abandoned after careful consideration and discussion, leading to the problem statement and key features defined below.

It is important to understand some of the history of this work, in particular the iSENSE web-system, of which an overview is given below.

1.1 The iSENSE Web-System

The iSENSE web-system is a National Science Foundation-funded project to create a collaborative data visualization system for science education. The work presented here was funded under the larger umbrella of the iSENSE project. The project is described as follows on the iSENSE web site,

> The Internet System for Networked Sensor Experimentation (iSENSE) is designed to let users engage in collaborative scientific inquiry. The iSENSE site offers a shared repository of user-contributed data-collection activities, such as engineering projects, environmental studies, classroom science experiments, and surveys, together with the data produced by those

> activities. The system enables users to contribute their own activities, upload data, and configure and save dynamic data visualizations.
>
> In middle school and high school instruction, iSENSE helps make science more accessible, collaborative, visual, and fun. Teachers can use iSENSE to identify, refine, and share best practices. Students can use iSENSE to examine data contributed by their peers, participate in collaborative data-collection activities, and investigate science questions that they find personally meaningful.

The µPINPoint data logger described in this thesis complements the iSENSE web-system by providing a tool with which users of the iSENSE web-system collect data. Although the µPINPoint is not restricted to use with the iSENSE web-system and functions as a standalone data logger, it was developed for use with iSENSE specifically.

1.2 Motivation

Numerous studies have shown that there is a strong correlation between the resources available to students and the learning which takes place (Hedges and Laine, 1996). This is the ultimate motivation behind this work: to provide a powerful but inexpensive resource to students which aids in the learning process.

Following from this, the work presented here was motivated by the past success of the iSENSE web-system as a resource and learning tool for science education. By leveraging this system, which past work has shown to aid in learning through collaborative data visualization (Dalphond, 2010), the µPINPoint ultimately increases the resources available to students. Rather than recording data manually when performing experiments, which can be time consuming and tedious, students can use the µPINPoint data logger to collect data.

1.3 Problem Statement

The problem addressed by the work presented here was to develop a data logging device primarily for science education with the following key features:

- Simple to use
- Inexpensive
- Small enough to be attached to larger objects or placed inside of them
- No host system software installation required
- Provides enough sensors to be useful for science education

1.4 Initial Design Decisions

In an initial attempt to create a device which provided the above mentioned features, several important design decisions were made. First and foremost was the decision to create a device which was essentially modeled after a standard USB flash drive. The belief was that this would be small enough to attach to objects and would also provide a familiar reference point to users. Also, by operating in the same way as a USB flash drive when plugged into a USB port of a computer, the software interface learning curve would be minimal.

With the goal of minimizing component cost for the µPINPoint, the most inexpensive microcontroller (MCU) with the required features was chosen for the design. The initial choice was ultimately too limited in program memory capacity and led to a change in this central component between the first and second µPINPoint prototypes. This will be discussed later in more detail.

To balance manufacturing cost and usefulness, it was decided that the µPINPoint data logger should record the following:

- Acceleration in all three dimensions

- Acceleration vector magnitude (computed from dimensional components)
- Ambient temperature
- Barometric pressure
- Altitude (computed from temperature and pressure, dependent on current weather conditions)
- Ambient light intensity

To provide easy access to the data collected by the µPINPoint all data would be written to a standard .CSV ASCII text file, an example of which is shown in Appendix C. Sample rates would be configurable by the user, but would default to 32 Hz. Date and time as well as elapsed time would also be recorded for each measurement taken.

It should also be mentioned that the minimum physical size of the µPINPoint was limited by the choice of a AAA battery for the power supply. Discussions during the initial concept phase suggested four possibilities for powering the device: a non-rechargeable lithium coin cell battery, a rechargeable lithium coin cell battery, a AAA battery, and a super capacitor. If either a rechargeable coin cell battery or a super capacitor were used, the idea was to recharge the device simply by plugging it into a computer. These two options were ruled out fairly quickly due to the extra circuitry required and ultimately the increased manufacturing cost. Between the two remaining choices, the non-rechargeable coin cell option was attractive because of the small size compared to a standard AAA battery. Conversely, using an AAA battery had the advantage of making battery replacement inexpensive and easier for the user. For these reasons, a AAA battery was chosen to power the µPINPoint.

Chapter 2

Background

Several devices have been developed by various groups which attempt to fill the same need as the µPINPoint. Unfortunately, none of these offerings fulfill the requirements met by the novel µPINPoint data logger. We will review some of the more competitive commercial and academic offerings, but first a description of the previous PINPoint data logger will be given.

2.1 Past Work

The µPINPoint data logger concept ultimately grew out of the desire for an improved version of the previous PINPoint data logger. This device, which also went through multiple revisions, had one major drawback—it required special software to be installed on a user's computer to download data off of it. The creation of a new data logger which did not require software installation stemmed from this single drawback of the previous PINPoint data logger.

Original PINPoint data logger

The previous generation device, the PINPoint data logger, is shown in Figure 2-1. It was a much larger device and incorporated the same sensors, as well as some additional sensors, as the µPINPoint data logger described in this thesis. The PINPoint data logger was the inspiration for many of the key features of µPINPoint data logger.

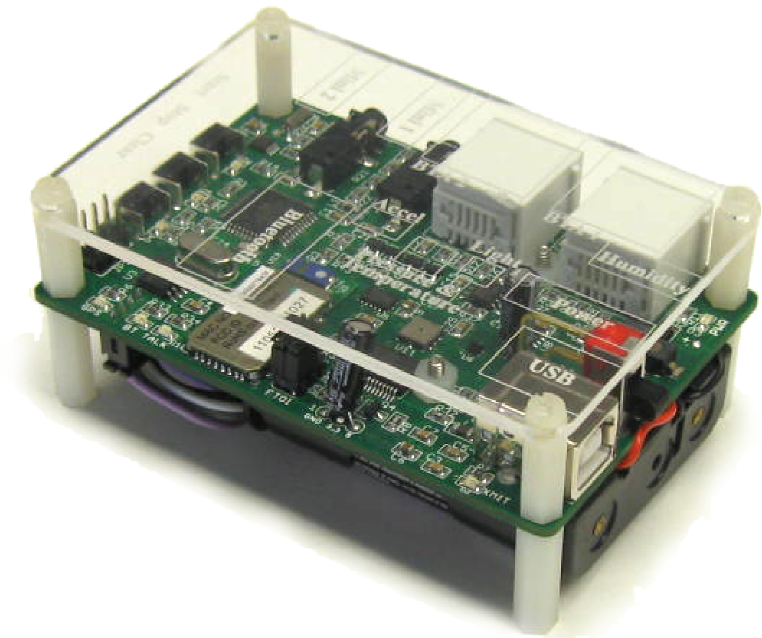

Figure 2-1: Previous PINPoint data logger.

The PINPoint data logger included on-board sensors for the following parameters: temperature, pressure, humidity, 3-axis acceleration, and light intensity. The PINPoint also included an on-board GPS module to record the geographic location of logged data (assuming a GPS signal was available). In addition, the PINPoint data logger included four jacks for external sensors, two compatible with Vernier Software & Technology Inc. brand sensor probes, and two for custom sensor probes.

For power, the PINPoint data logger used three AA batteries, which contributed to the total weight of 145 g.

To facilitate the fast development of the first µPINPoint prototype the exact same sensors for acceleration, pressure, temperature and light were incorporated into its design. This allowed the firmware code that communicated with these sensors on the previous PINPoint to be used as a starting point for this part of the firmware for the µPINPoint prototypes.

Figure 2-2: Vernier LabQuest 2 data logger.

2.2 Competing Designs

There are several data loggers available which are targeted at the educational market. As of this writing, none exist which are as inexpensive as the µPINPoint and as simple to use without the need for custom software installation. We will only discuss a few key products here.

Vernier LabQuest 2

The LabQuest 2 from Vernier Software & Technology Inc., shown in Figure 2-2, is a feature-rich data logger with several internal sensors as well as jacks for external sensors also available from Vernier. This device provide many features available on tablets and smart phones, such as wireless internet connectivity and a touch screen interface. Because of these many features, they are also large and heavy when compared to the µPINPoint, with the LabQuest 2 measuring 8.8 cm x 15.4 cm x 2.5 cm and weighing 250 g. The LabQuest 2 is marketed for classroom use and retails at $329, as of this writing.

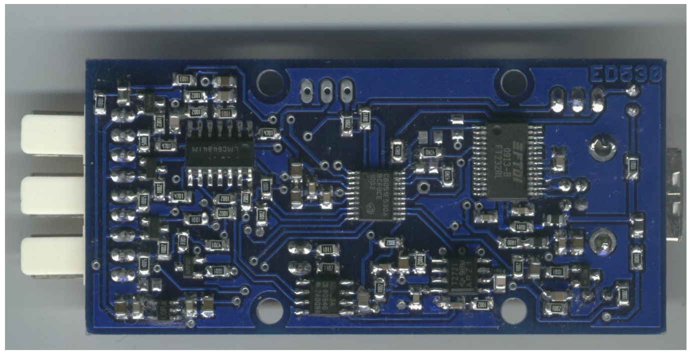

Figure 2-3: eDAQ530 data logger.

This device actually fills a different need than the µPINPoint data logger, but it is discussed here because before the goals for the µPINPoint were fully defined development of a comparable device was considered (a prototype was even designed.) The previous PINPoint data logger was more comparable to the LabQuest 2 device (although with fewer features) than the µPINPoint described in this work. It was decided that rather than attempt to compete with a mature commercial product, which would be difficult, it would be better to fill an unmet market need.

eDAQ530

The eDAQ530, shown in Figure 2-3, attempts to fill the same need as the µPINPoint data logger. It was designed for educational use, like the µPINPoint, and was small and light weight (Kopasz et al., 2011). It has basically the same short-coming as all of the other competing devices: the requirement for software installation on a host computer. It provides a USB interface, but users must either use the provided software or write their own software using a provided Application Program Interface (API) library. At the time of this writing a retail price for the eDAQ530 was not available.

DrDAQ

The DrDAQ, shown in Figure 2-4, is a small data logger designed for educational and hobbyist use. It includes on-board sensors for temperature, pressure and light intensity as well as providing six inputs for external sensors. Data collected with the DrDAQ is retrieved over a USB connection, but requires custom software to be

Figure 2-4: DrDAQ data logger.

installed on the user's computer (Butlin, 2001). It weighs about 60 g and is sold for $163 retail. This data logger has many features, but like other products does not offer the simplicity for the end user that the µPINPoint data logger does.

Chapter 3

Methodology

A method for producing and refining a device which fulfills the initial goals described above was formulated for this work. The process pursued was a traditional product design approach, where an initial prototype was produced based on expected needs and usage, and the prototype was evaluated with what was essentially a focus group (in this work, we also refer to this as a workshop.) Using feedback from the focus group, a second prototype was produced that incorporated changes based on that feedback.

The purpose of a focus group is described by Krueger and Casey (2009, Chapter 1) as such:

> The purpose of conducting a focus group is to listen and gather information. It is a way to better understand how people feel of think about an issue, product or service. Focus groups are used to gather opinions. Participants are selected because they have certain characteristics in common that relate to the topic of the focus group. The researcher creates a permissive environment in the focus group that encourages participants to share perceptions and points of view without pressuring participants to vote or reach consensus.

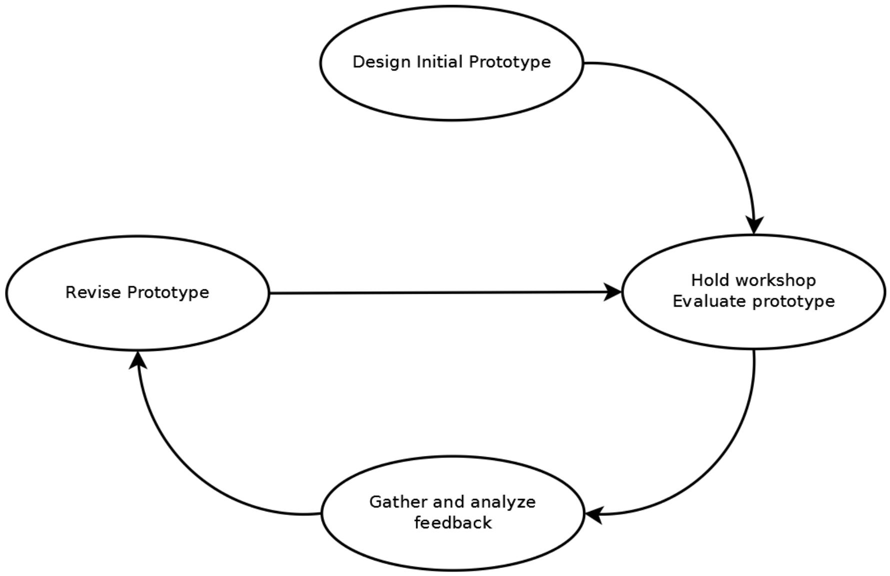

Figure 3-1: General product design strategy.

3.1 Design Cycle

A visual representation of the product design cycle followed for this work is shown in Figure 3-1. This type of product design cycle is commonly incorporated with focus group market research (McDaniel and Gates, 2010). The scope of this work restricted the process to two prototype iterations, but one more prototype, as a candidate for a final product would likely be worthwhile.

3.2 Use Case

Following from the initially formulated requirements for the device, the use case diagram, shown in Figure 3-2, represents visually how a user would interact with the µPINPoint to collect data. The emphasis is on simplicity, as this is one of the major factors that differentiates the µPINPoint data logger from other inexpensive data loggers for educational use, such as the DrDAQ.

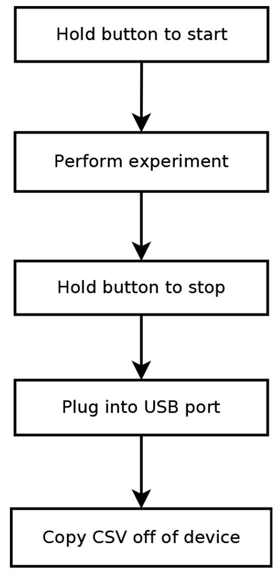

Figure 3-2: Use case diagram.

3.3 First Educator Workshop

After designing and assembling the first µPINPoint prototype based on the defined requirements, an educator workshop was held on August 16th from 9:00 AM to 1:00 PM to give middle school and high school teachers an opportunity to test the device and provide feedback. Ten units were hand assembled and provided to participants working in groups of two. This was a fairly open-ended workshop and the goal was to allow educators to have a "hands on" experience with the µPINPoint and generate useful feedback and criticism.

In addition to providing a chance for educators to work with the first µPINPoint prototype this workshop also provided an introduction to the iSENSE web-system as a whole. It was meant to highlight how the µPINPoint could be used as a simple way to collect data that could then be visualized using the iSENSE web-system. The work described here was primarily concerned with feedback about the first µPINPoint prototype.

Participants were asked several days prior to attending the workshop, via email communication, to begin thinking about experiments that they could conduct using a small data logger like the µPINPoint. They were also instructed to bring any equipment that they were interested in attaching the µPINPoint to. During the introduction at the beginning of the workshop the µPINPoint was described and and overview of its sensors and operation was provided, as well as a live example of collecting data and uploading it to the iSENSE web-system for visualization.

Several interesting experiments using the µPINPoint were proposed by participants and many of them tested on the day of the workshop. The data collected during these experiments was used to lead an interactive discussion for the last thirty minutes of the workshop. Participants were asked to voluntarily come up in front of the group, talk about their experiment and display their data using the iSENSE web-system. Several interesting experiments were conducted by participants using the µPINPoint:

- Acceleration and periodicity of a swinging pendulum

  The µPINPoint was attached to the end of a pendulum, data recording was started, and the pendulum was lifted and released. The pendulum was allowed to swing until it came to a stop. When visualizing the collected data, the periodicity of the pendulum was clearly visible in the acceleration readings. In addition to the acceleration data, the change in light intensity also indicated the period when the pendulum was setup to swing near a light source (such that it was exposed to more light during part of the arc.)

- Car rolling down a ramp

  The µPINPoint was placed on a cart (the type typically used for high-school physics experiments) and released from the top of a ramp, allowing it increase in velocity as it rolled down the ramp. The expectation was that the cart's acceleration could be examined, but this was actually a misconception and led to some debate during the workshop. The source of debate was the fact that the accelerometer on the µPINPoint actually will measure the acceleration due to gravity (9.81 m/s^2) even when no motion is present. This is an important fact to understand—one that came up often during workshop discussions about the data collected by the µPINPoint.

- Altitude and acceleration of a model rocket

  The μPINPoint was placed in the nose cone of a model rocket which was then launched. The acceleration and altitude data clearly showed the time when the rocket engine was burning, when the engine had quit and the device was in free fall, and when the parachute had opened. What was surprising to many participants was that the μPINPoint measured an acceleration of close to zero while in free fall. The expectation of many was that the acceleration due to gravity would still be measured, but this is not the case. When an object is in free fall it experiences weightlessness, such that the lack of contact forces opposing gravity results in no measurement by the accelerometer.

- Impact acceleration on different locations when walking / jumping

  This was a novel experiment and involved a few participants attaching the μPINPoint to three different locations on their body and stepping off a sidewalk ledge (12 cm to 20 cm high.) The μPINPoint was attached to the top of the foot, then the hip, and finally the neck. Examining the acceleration data, it was clear that a much greater acceleration (from impact) was experienced by the foot than by the hip and the neck. This experiment was an example of how the μPINPoint could be used to examine body mechanics.

- Altitude change between floors of a building

  Simply carrying the μPINPoint from floor to floor in a typical multi-story building showed a change in altitude. Since time is included in the recorded data, it was also possible to find vertical velocity by the slope of the line when the data are visualized.

Before leaving, participants were asked to fill out a one-page qualitative survey indicating their opinions about the first μPINPoint prototype. The questions as they appeared on the questionnaire are shown in Table 3.1. The actual instrument used can be seen in Appendix A-1.

Was the device easy to use? Are there any improvements that you could think of?
Do you prefer long-term battery life or small size (coin cell)?
Would you more likely use this device for class room experiments (short-term) or long-term environmental data collection?
What else would you like the device to measure (if anything)?
How much would you pay for a device such as this?
Other comments:

Table 3.1: First educator workshop questions.

The survey responses as well as verbal feedback during the actual workshop session were used to revise the first µPINPoint prototype and produce the second µPINPoint prototype, which was provided to participants of the second educator workshop, discussed below.

3.4 Second Educator Workshop

After completing revisions to the first µPINPoint prototype based on feedback from the first educator workshop a second educator workshop was held on November 3rd, 2012 from 9:00 AM to 3:00 PM. The goal of this second workshop was to have users evaluate the second µPINPoint prototype and provide useful feedback regarding the improvements over the first µPINPoint prototype. Workshop registration was open to teachers or all grades, but it was expected that primarily high school or middle school math and science teachers would attend. Close to 50 individuals registered for the workshop, with about 35 individuals actually attending and providing feedback.

In preparation for the second workshop, 100 units of the second µPINPoint prototype were ordered from the low-cost manufacturing firm Schotry (see Appendix B). The per unit cost for manufacturing was $36.89, including shipping costs.

In contrast with the first educator workshop, three handouts describing different experiments which could be performed using the µPINPoint data logger were provided to participants at the second educator workshop. Ideas from the first educator workshop influenced these choices for experiments for the second workshop. The goal was to provide a starting point for participants to evaluate the second µPINPoint prototype and give examples of experiments which could be performed by students with the µPINPoint in a classroom situtation.

The three handouts described these three data collection experiments: acceleration and altitude change in an elevator, acceleration of a pendulum, and the temperature in a solar oven. These three handouts can be seen in Appendix A-2, Appendix A-3, and Appendix A-4, respectively. In addition to these three handouts, a single page "quick-start" guide was provided to participants about how to use the µPINPoint data logger. This handout is shown in Appendix A-5.

Data collected from all three experiments were generally clear, and visualizations using the iSENSE web-system were highly descriptive of the physical situations. Unfortunately, the acceleration in an elevator experiment did not provide meaningful acceleration data, likely due to low acceleration in the elevator in which the workshop was held. During the day of the workshop this was noted, and many participants chose to simply walk up and down the stairs in the building and visualize the change in altitude. In addition to the experiments described in the handouts, simply throwing the µPINPoint in the air while it was recording resulted in interesting acceleration data which clearly showed the period in which it was in free-fall. Like the model rocket experiment of the first workshop, the lack of measurable acceleration during free-fall was surprising to many participants.

The change in altitude measured by the second µPINPoint prototype, as visualized using the iSENSE web-system, is shown in Figure 3-3. The workshop was held on the third floor of a six story building and this data shows that the participant first walked down two floors to the first floor, then all the way up to the sixth floor, and finally returned to the third floor. The y-axis on the graph, showing the altitude, is in meters and the x-axis is time in seconds. The floors in the building are separated by roughly 3.5 m and this is clearly visible on the graph.

The acceleration magnitude of a swinging pendulum measured by the second µPINPoint prototype, as visualized using the iSENSE web-system, is shown in Figure 3-4. The y-axis is in m/s^2 and shows acceleration vector magnitude and the x-axis is time in seconds. This data shows that the acceleration due to gravity is initially

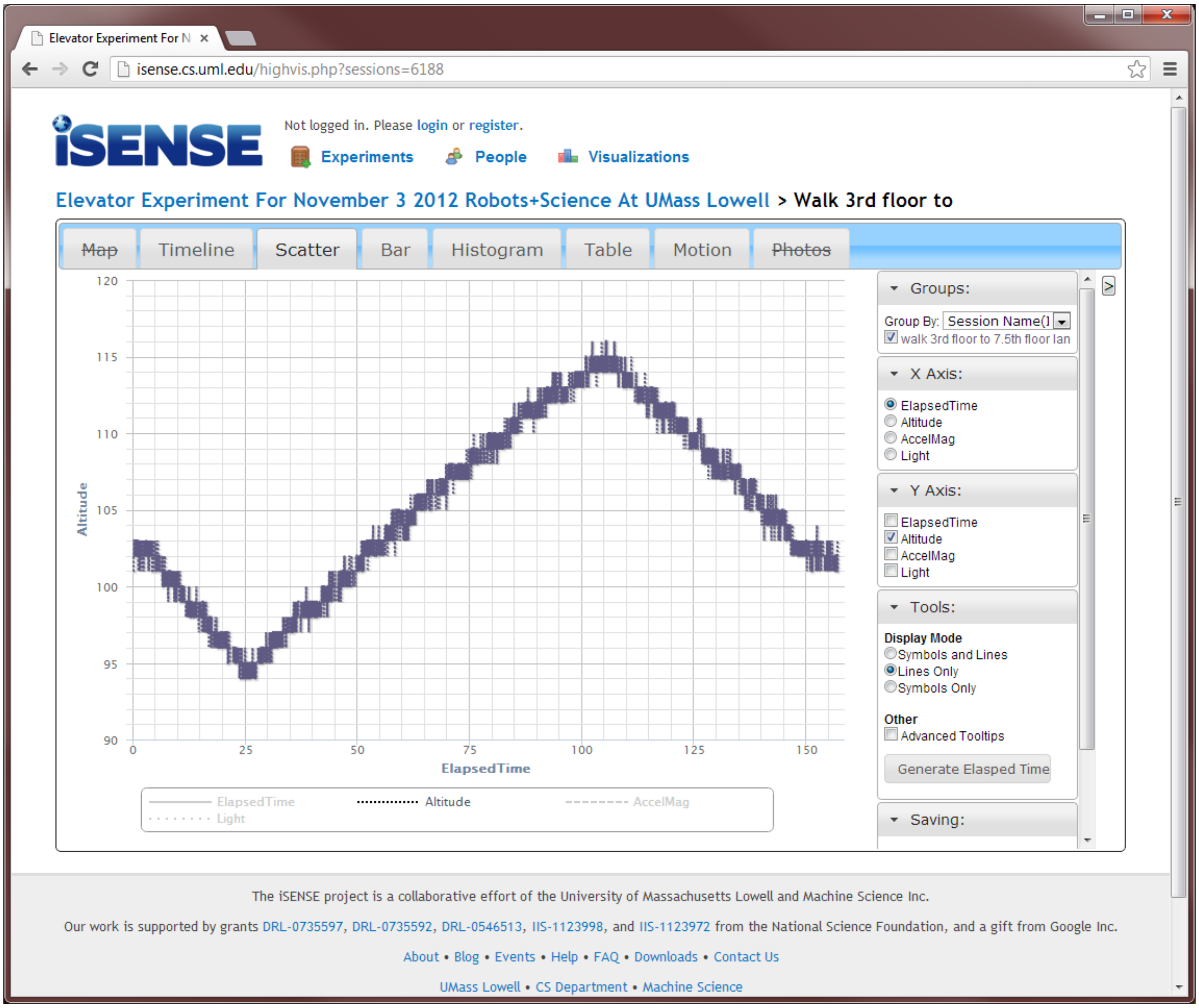

Figure 3-3: iSENSE web site displaying altitude data collected by the µPINPoint when walking up and down a flight of stairs.

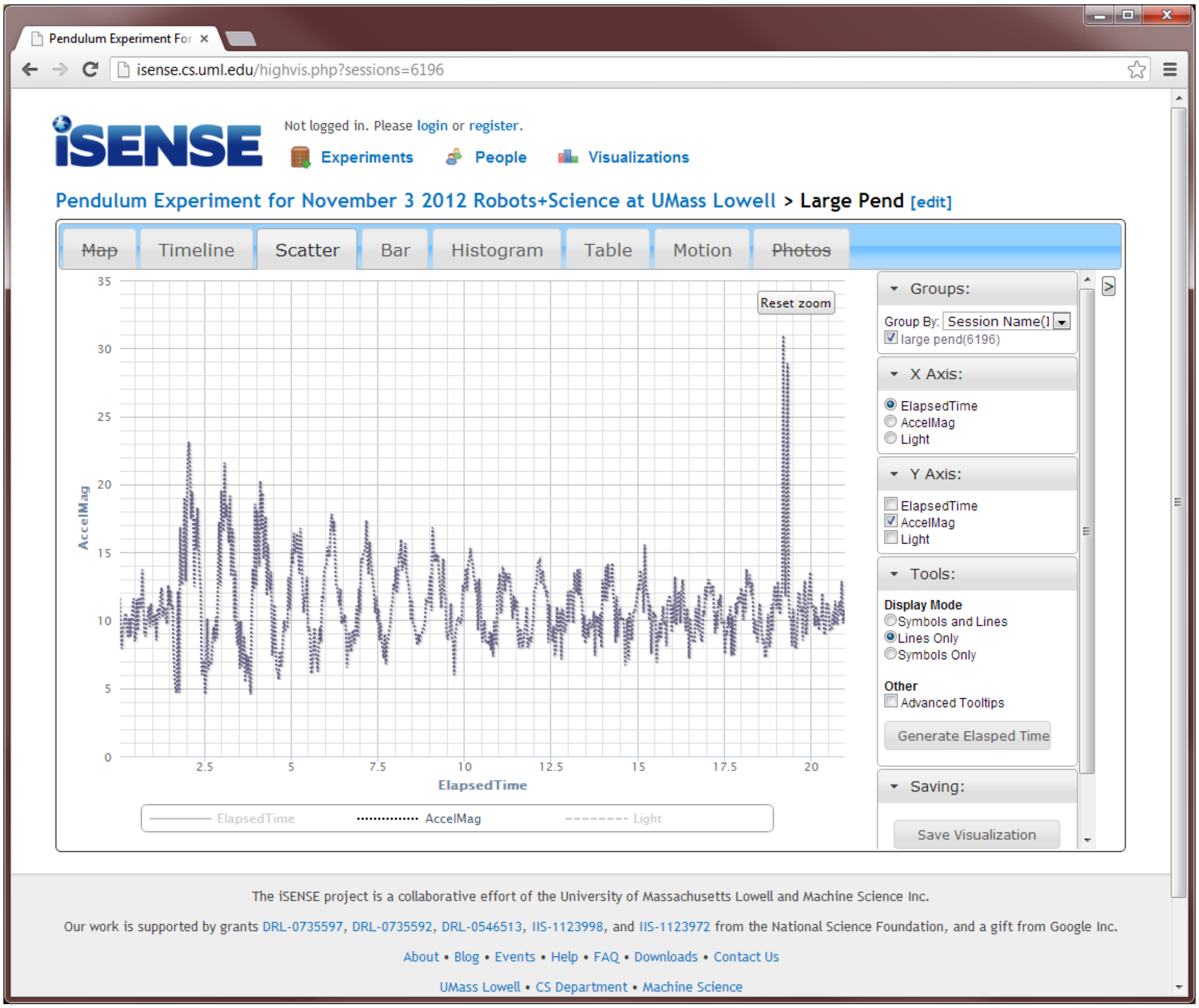

Figure 3-4: iSENSE web site displaying acceleration magnitude data collected by the μPINPoint attached to a pendulum.

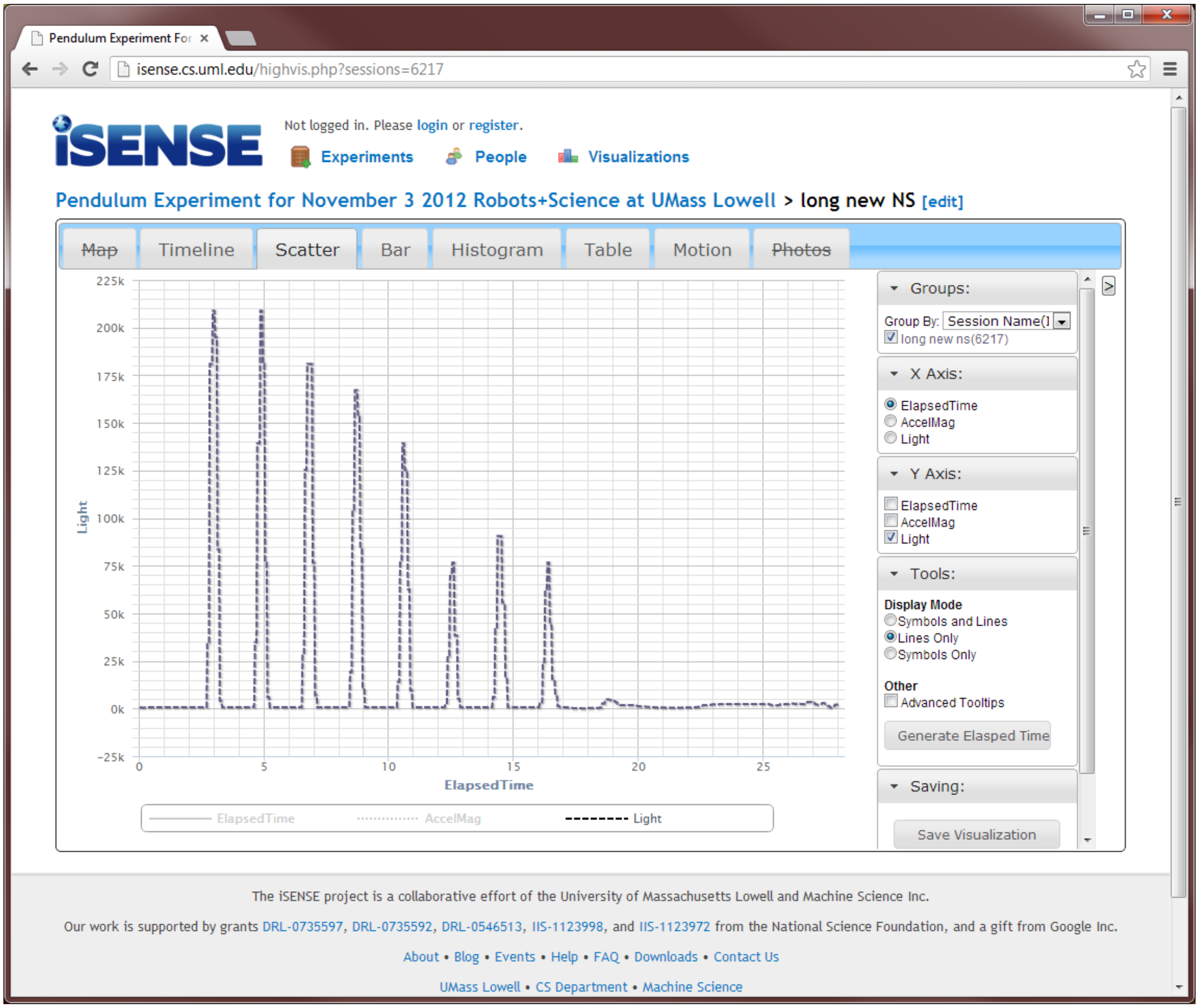

Figure 3-5: iSENSE web site displaying light intensity data collected by the µPINPoint attached to a pendulum.

measured to be close to 10 m/s^2, which can be seen at the beginning of the graph before the oscillations begin. When the pendulum is released, the oscillations on the graph begin due to the vector sum of the acceleration due to gravity and the centrifugal force experienced by the µPINPoint. The periodicity of the of the pendulum and the decaying amplitude with time are clearly visible. The large acceleration seen at the end of the graph was when the pendulum was stopped by the participant.

The change in light intensity of a pendulum swinging back and forth in front of light source as measured by the second µPINPoint prototype and visualized using the iSENSE web-system is shown in Figure 3-5. The periodicity is also visible here, and

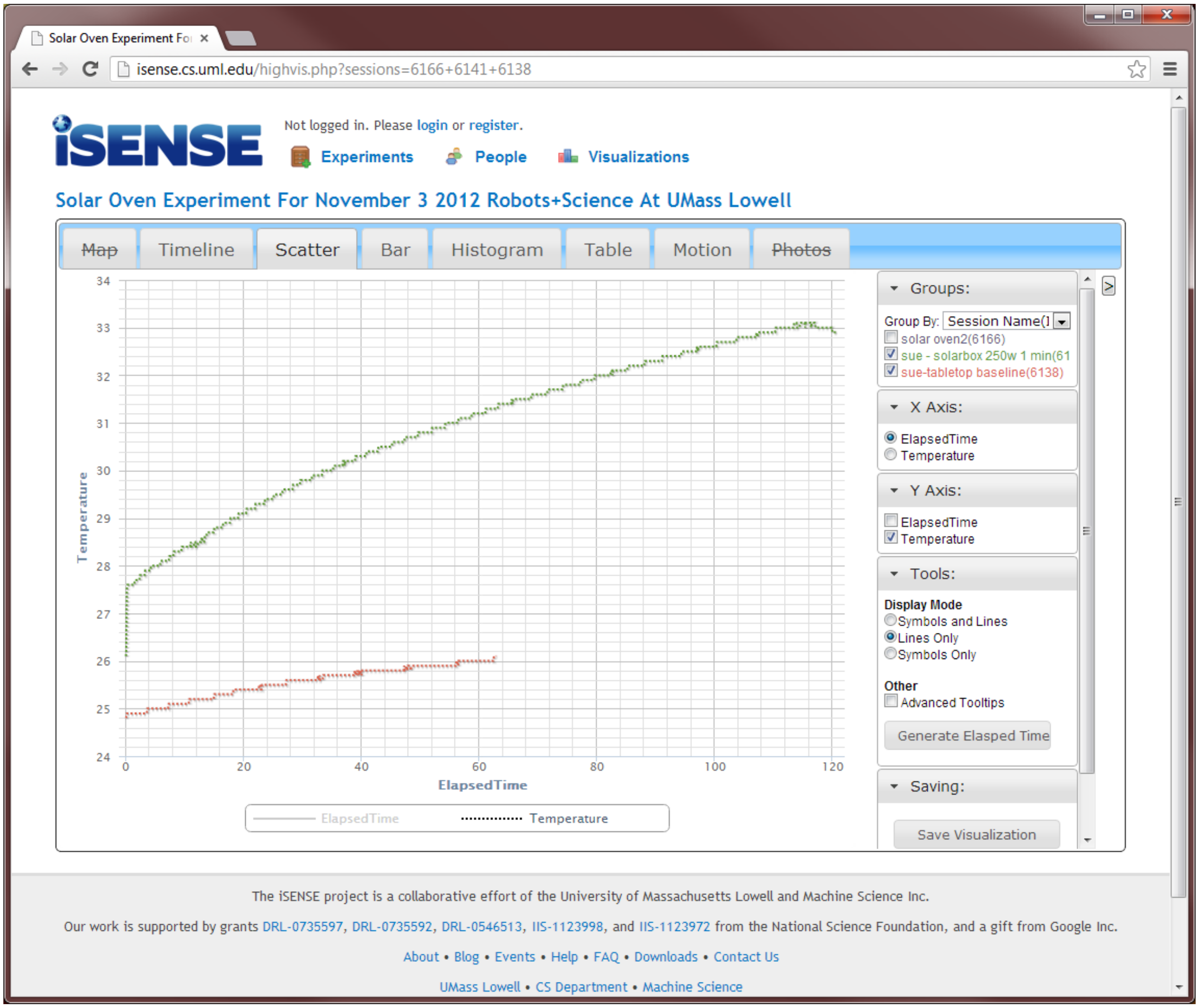

Figure 3-6: iSENSE web site displaying temperature data collected by the μPINPoint placed in a solar oven vs. placed outside of the solar oven.

also the amplitude to some extent. The y-axis is light intensity in lux and the x-axis is time in seconds.

Figure 3-6 shows data collected by a participant who constructed a simple solar oven and measured the change in temperature inside the solar oven using the μPINPoint data logger when a light source was turned on verses the same light source turned on above the μPINPoint data logger not in the solar oven. The temperature on the y-axis is in Celsius and the x-axis is time in seconds. From this experiment, it is clear that the solar oven had an effect on the temperature.

Figure 3-7 shows a visualization of the acceleration magnitude data collected when

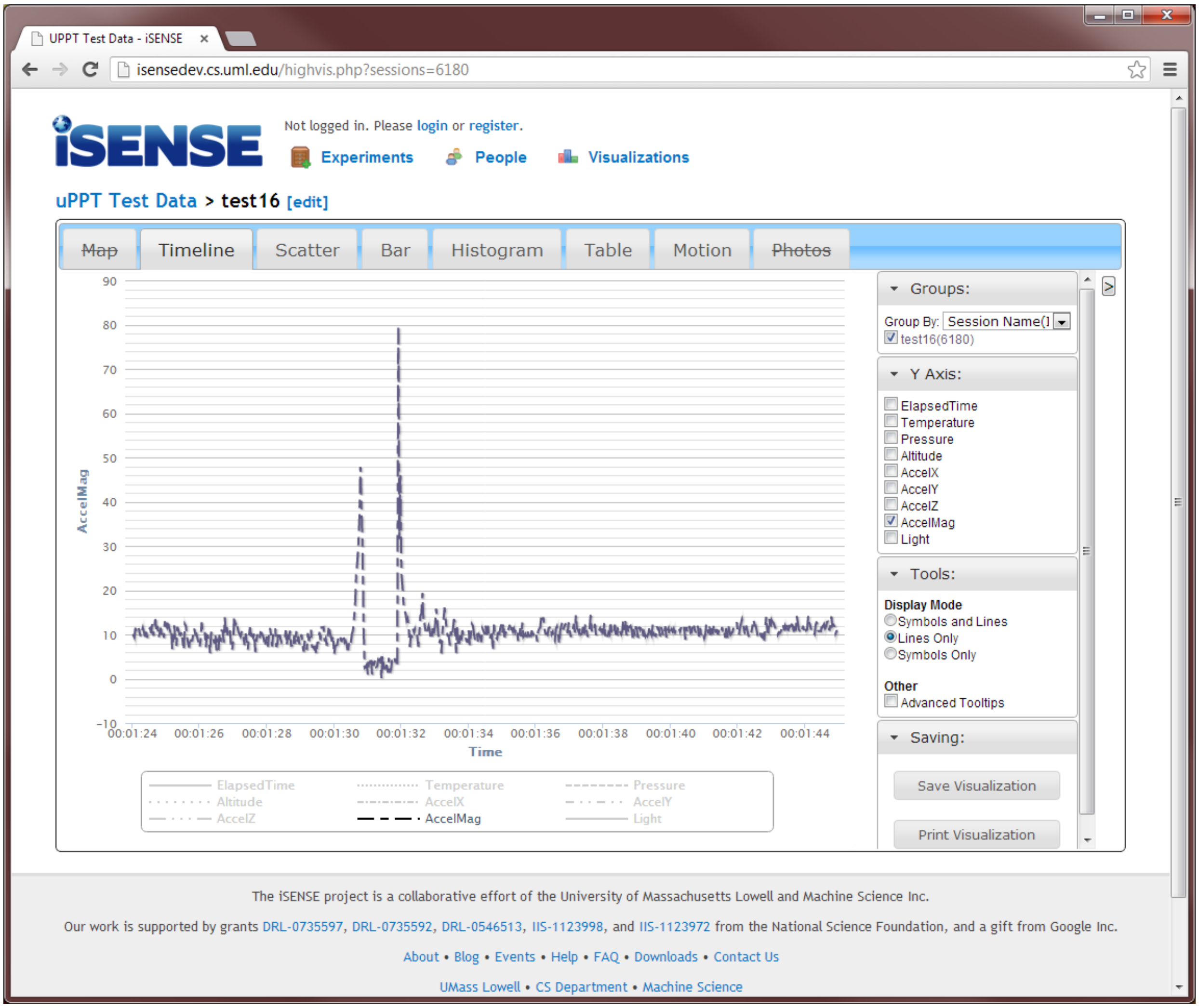

Figure 3-7: iSENSE web site displaying acceleration magnitude in free fall data collected by the μPINPoint.

the µPINPoint data logger was thrown in the air and caught. The y-axis is in m/s^2 and shows acceleration vector magnitude and the x-axis is time in seconds. The flat parts on the graph show the acceleration due to gravity. The initial large acceleration measured is when the device was first accelerated upwards. The flat line close to zero in between the two large acceleration measurements was when the device was in free-fall (immediately after being released—even when traveling upwards). The second large acceleration measured was when the device was caught.

Chapter 4

Engineering Design

In this chapter, an overview of the engineering design of both the first µPINPoint prototype and the second µPINPoint prototype is given. More attention is given to the second µPINPoint prototype including a functional description of the different sub-sections of the design. The full system may be broken down into several logical blocks, and these are described here. Each block serves a unique function and is somewhat independent of the full system.

The engineering design of the first and second µPINPoint prototypes entailed a significant effort. Much attention was given to creating a device that was inexpensive to manufacture and as simple as possible to use while still providing the desired features. Computer Aided Design (CAD) software was utilized to create a schematic of the system and a printed circuit board (PCB) design. A two-layer PCB was hand-routed using the CAD software EAGLE to exert maximum control over the process.

Both prototypes were the same small size and weight, measuring only 7.2 cm x 2.0 cm x 1.6 cm without a plastic case, and 8.3 cm x 2.4 cm x 1.7 cm with a minimal plastic case, and weighing only 24 g. (Compare this to the competing designs discussed previously, weighing between 60 g and 250 g.)

The engineering design process was undertaken as outlined by Pahl et al. (2007, Chapter 4), but on a smaller scale due to an individual rather than a team effort. These steps of engineering design are:

- Planning and Task Clarification
- Conceptual Design
- Embodiment Design
- Detail Design

The first two items were covered in previous chapters. The embodiment design step is not extensively discussed here, but entailed an initial layout of the device, size and weight considerations, and preliminary component choices. The detail design is what we will focus on in this chapter.

4.1 First Prototype

The first µPINPoint prototype was the result of the initial design decisions made to provide the features defined in the problem statement. This prototype was successfully in the sense that it did meet the requirements initially laid out. As with any prototype, some issues were discovered and this led to changes incorporated into the second µPINPoint prototype, described later.

System Schematic

The full system schematic of the first µPINPoint prototype, as shown in Figure 4-1, consisted of six logical blocks: the microcontroller (MCU) and support circuitry, the power supply, the SD card interface, and the three sensor blocks. Each of the individual blocks will not be specifically discussed here, as there is enough similarity to the second prototype to delay explanation until that section. The key difference from the (later) second prototype was the use of a lower-end MCU, a Microchip PIC24FJ64GB002 (Microchip Technology Inc., 2010), and a simpler power supply circuit which did not include automatic switchover to USB power when plugged into a computer. These features were improved in the second prototype.

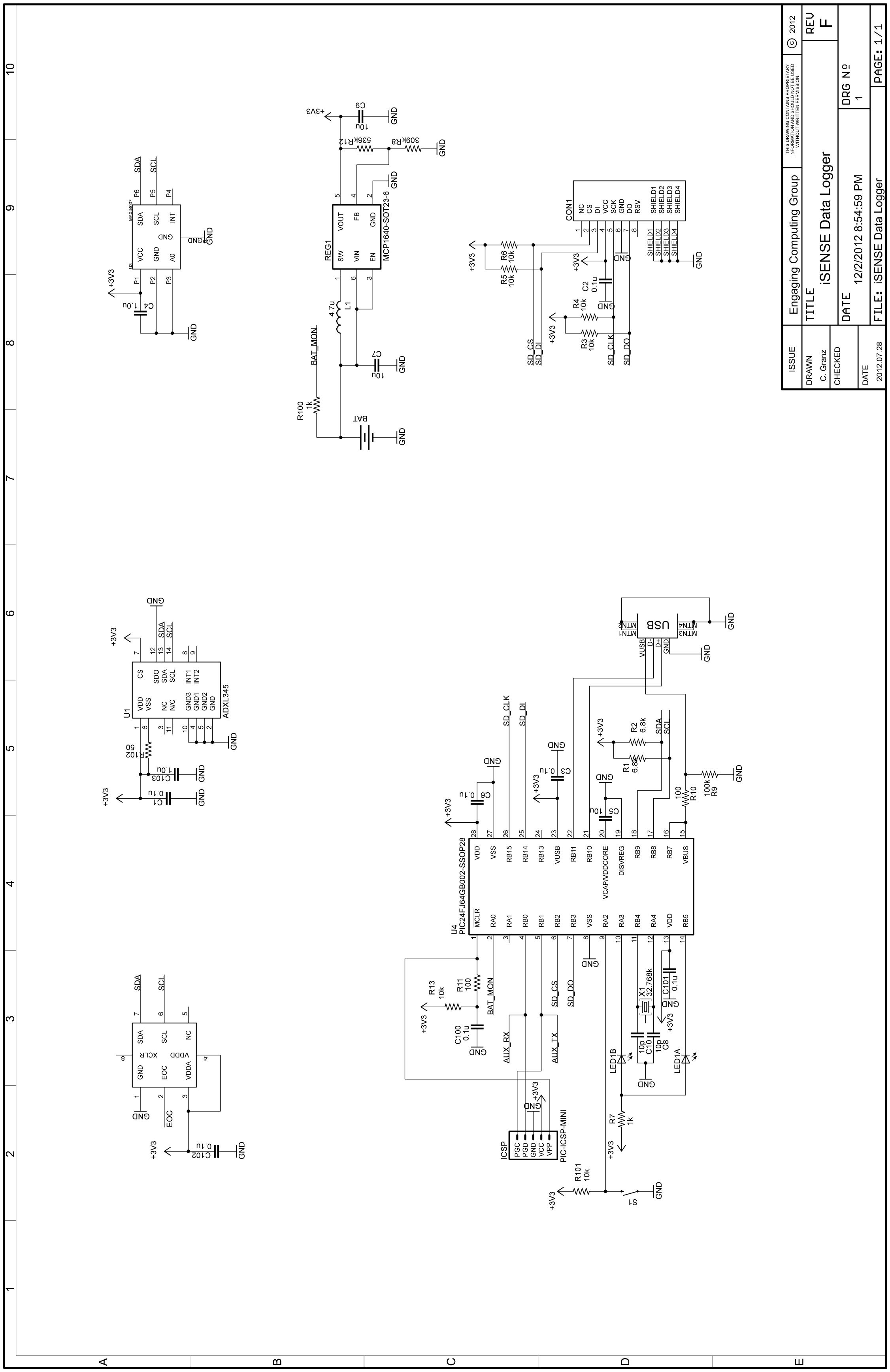

Figure 4-1: First µPINPoint prototype system schematic.

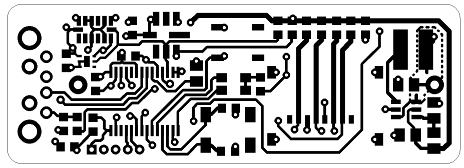

Figure 4-2: First µPINPoint prototype PCB artwork top layer (actual size).

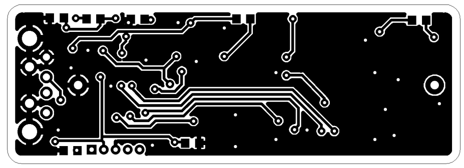

Figure 4-3: First µPINPoint prototype PCB artwork bottom layer (actual size).

One of the major disadvantages of the PIC24FJ64GB002 in this application was the amount of program flash memory available—only 64 kBytes. This became an issue as features were added to the device firmware during development. The USB interface code as well as the FAT32 file system code consumed an especially large amount of program flash memory.

A second shortcoming of the first µPINPoint prototype that was identified was the power supply circuit. This circuit provided 3.3 V for the system by boosting the 1.5 V from a AAA battery. Although the first µPINPoint prototype did detect when it was attached to a USB port of a computer, it did not utilize the 5 V available from the USB port to power the device. This confused users as to why the device did not work when plugged into a USB port without a battery installed.

Printed Circuit Board

The first µPINPoint prototype was built on a 2-sided PCB of which the CAD layout of the top and bottom sides of PCB are shown in Figure 4-2 and Figure 4-3, respectively. These figures show the actual size of the PCB.

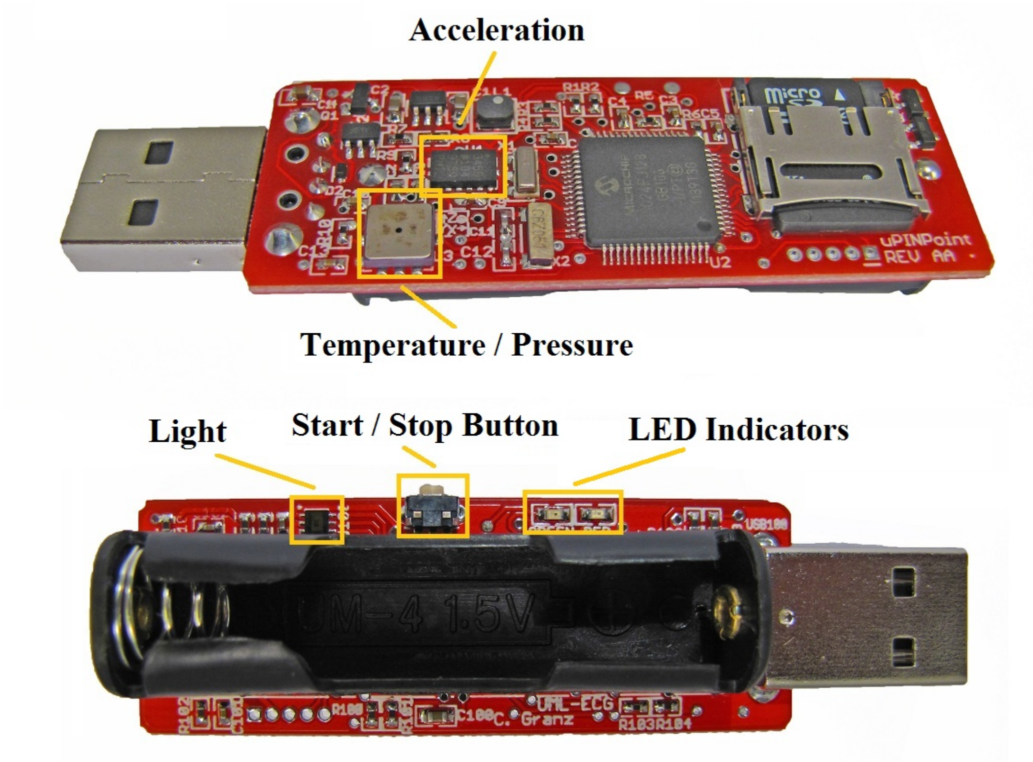

Figure 4-4: Second µPINPoint prototype.

4.2 Second Prototype

The second prototype was created by building on the design of the first prototype and making the appropriate changes based on what was learned during the August 16th educator workshop. Both the top and bottom of the actual finished second prototype are shown in Figure 4-4 with key components identified. The most significant change from the first prototype was the selection of an improved MCU for the device which provides for future expansion through firmware improvements.

System Schematic

The full system schematic of the second µPINPoint prototype, as shown in Figure 4-5, consists of six logical blocks, as the first prototype did. The major changes from the first prototype are the addition of an automatic change-over to USB power when the device is plugged into a USB port and the improved MCU, a Microchip PIC24FJ128GB106.

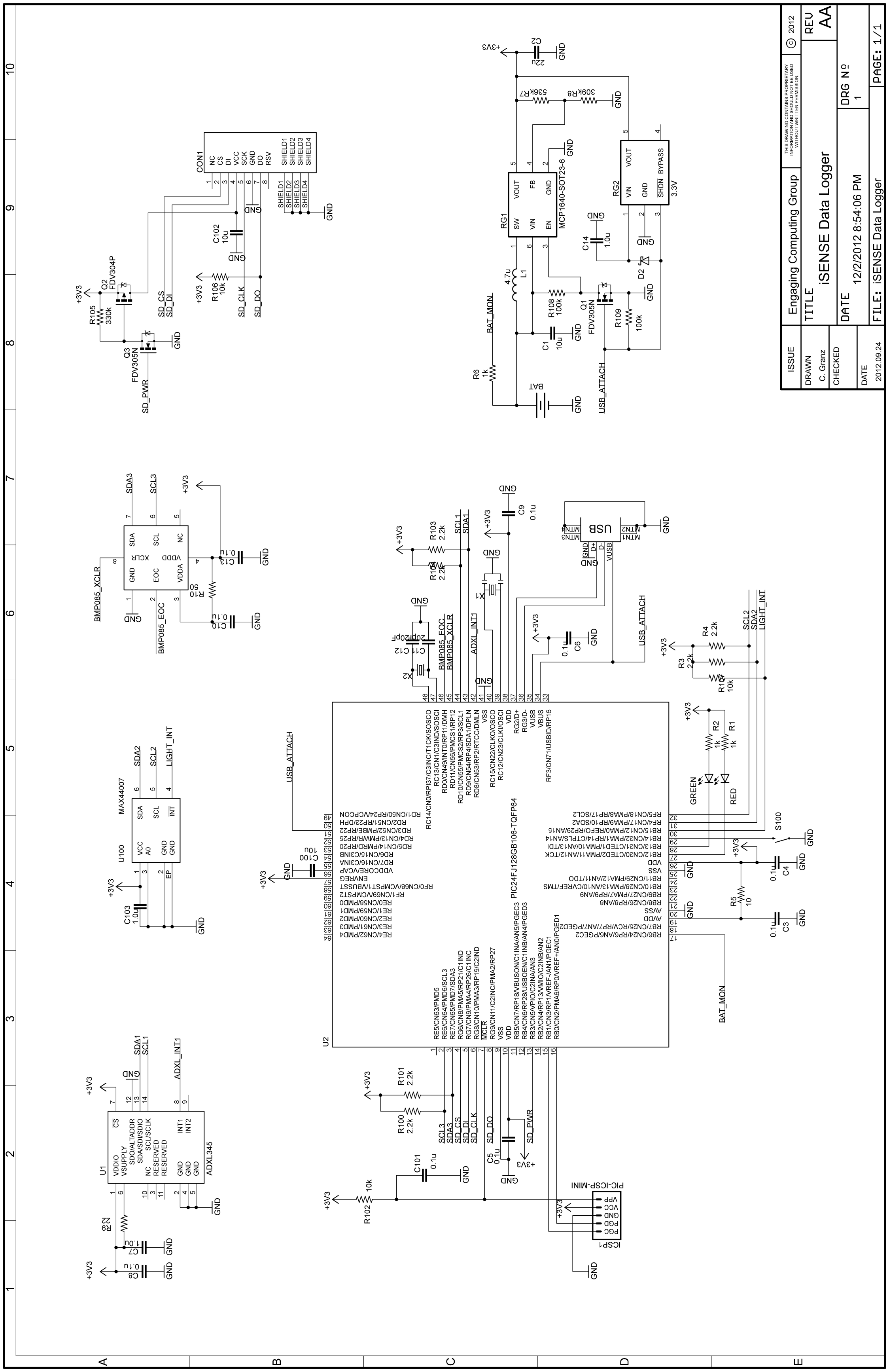

Figure 4-5: Second µPINPoint prototype system schematic.

MCU & Support Circuitry

The MCU chosen for the second µPINPoint prototype was functionally similar and related to the MCU used for the first µPINPoint prototype and included the following key features (Microchip Technology Inc., 2009),

- 16-Bit RISC architecture
- 128 kBytes of Program Flash Memory
- 16 kBytes of Data SRAM
- 32 MHz system clock
- Hardware USB 2.0 module
- On-chip real-time clock / calender (RTCC)
- Ultra low-power sleep mode with RTCC continued operation
- Excellent software support, including free C compiler and USB library

The MCU and surrounding support circuitry are shown in Figure 4-6. Starting at the left of this schematic block and working counterclockwise, the different connections will now be described.

Resistors R100 and R101 serve as pull-ups on the I^2C bus lines SCL3 and SDA3. The barometric pressure and temperature sensor is connected to this bus, as described in a later section. Moving counterclockwise, the group of four connections labeled SD_CS, SD_DI, SD_CLK, and SD_DO form the SPI link to the SD card. The connection labeled SD_PWR is used to enable and disable power to the SD card, as described later. The capacitor C5 functions as a high-frequency bypass path on the power supply pins to reduce noise, as is common practice. The block labeled ICSP1 is actually not a real component on the PCB, but is simply a small through-hole connection that allows a programmer device to be connected to perform In Circuit Serial Programming of the MCU. Resistor R102 serves as a pull-up on the pin labeled MCLR, which simply

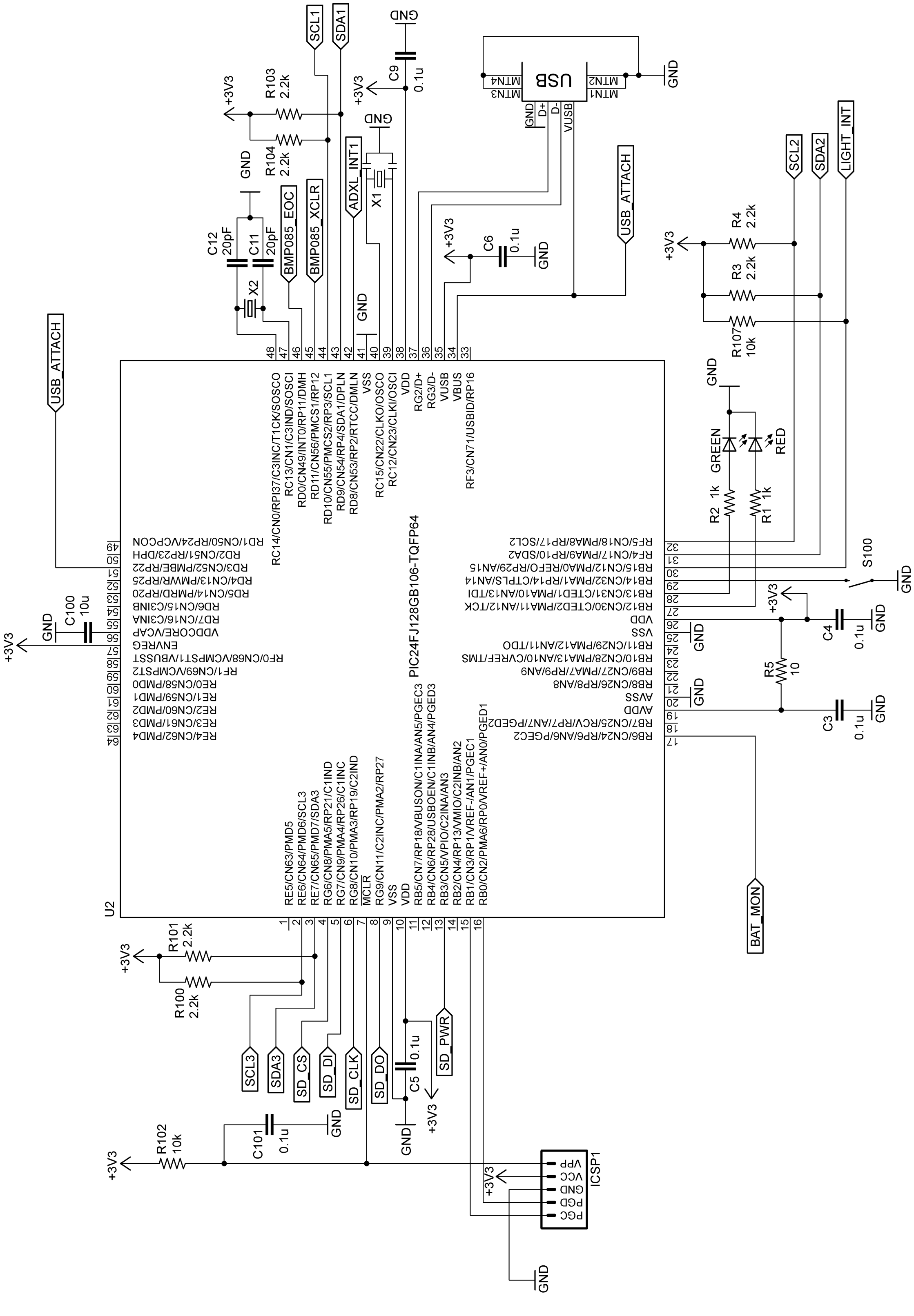

Figure 4-6: MCU & support circuitry schematic.

stands for "memory clear," and is used for resetting the MCU (a feature not used on the µPINPoint) and during programming of the internal flash on the IC.

Continuing counterclockwise around the schematic block, BAT_MON is connected to the AAA battery through a resistor and allows the software to use the on-chip Analog-to-Digital Converter (ADC) to read the battery voltage. This allows the device firmware to terminate data collection when the battery is low and to notify the user. Capacitors C3 and C4 provide the usual high frequency bypass function and are placed physically close to the IC on the PCB. The resistor R5 and C3 form a low-pass filter for the analog power supply pin AVDD. The resistors R1 and R2 and the associated Light Emitting Diodes (LEDs) provide indication to the user of the current device state. The single button, S100, provides the only user interface. The connections labeled SCL2, SDA2, and LIGHT_INT and the associated pull-up resistors R4, R3, and R107 are the I^2C bus lines uses to communicate with the ambient light sensor described later.

On the right side of the schematic block are the connections for the on-chip USB module, as well as both the main oscillator crystal, X1, which is a 4 MHz crystal. The MCU has an internal Phase Locked Loop (PLL) module which multiples this frequency to generate the system clock of 32 MHz. The second crystal, X2, is a 32.762 kHz crystal, which is used as the clock source for the on-chip real-time clock and calendar. The connection labeled USB_ATTACH is used to switch the power supply from the battery to the 5 V on the USB connection. The connections labeled ADXL_INT1 and BMP085_EOC are inputs to the MCU from the accelerometer and barometric pressure and temperature sensor, respectively, and provide notifications to the MCU when new data are available from these sensors. BMP085_XCLR is an output from the MCU which allows the barometric pressure and temperature sensor to be reset if needed. The connections labeled SCL1 and SDA1 are the I^2C bus lines for communication with the accelerometer.

Pins 49 through 64 are essentially unused, except for a bypass capacitor, C100, needed for the internal on-chip voltage regulator, a connection on ENVREG (Pin 57) to 3.3 V to enable the IC, and the connection labeled USB_ATTACH. USB_ATTACH

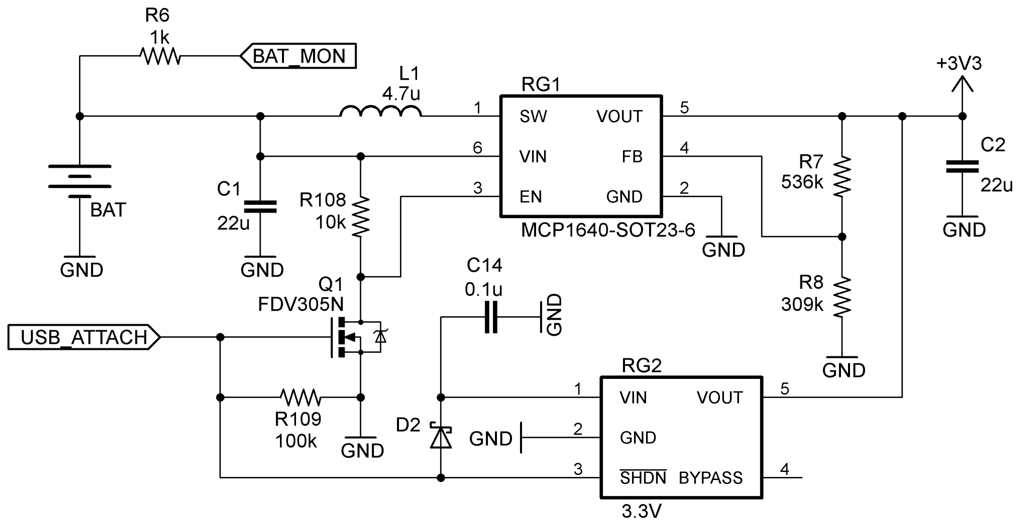

Figure 4-7: Power supply schematic.

is used to notify the firmware that the device is connected to a USB port of a computer, and this must be connected to a pin of the MCU which is 5 V tolerant (since the system voltage is 3.3 V).

Power Supply

The µPINPoint power supply schematic block, shown in Figure 4-7, serves the function of providing a well-regulated 3.3 V to the rest of the system during all operating conditions, including when the device is connected to a USB port of a computer and when it is not. The power supply may be decomposed into two sections, each based around the ICs labeled RG1 and RG2, respectively.

To provide 3.3 V to the system from the single 1.5 V AAA battery a boost regulator is used. The boost regulator consists of components RG1, L1, R7, R8, and C2. The controller is RG1 and operates at a fixed frequency of 500 kHz during normal operation using Pulse Width Modulation (PWM) to control the voltage across C2. During sleep mode this controller automatically switches to Pulse Frequency Modulation (PFM) operation, which reduces idle current consumption to a minimum (typically less than 10 µA.) A comprehensive description of boost regulator operation is beyond the scope of this document, but essentially the controller switches a path to ground which allows current to flow through inductor L1, allowing a magnetic field to build up around L1. The controller then switches off the path to ground and connects the inductor to the output of the regulator where C2 is connected. The inductor L1 tries to maintain the same current flowing through it as the magnetic field collapses by essentially developing a voltage across it. This voltage is added to the battery voltage, thus producing a higher voltage than available from the battery directly. The time that the path to ground is connected is precisely controlled by RG1 based on a measurement of the output voltage taken from the voltage divider formed by R7 and R8.

The other half of the power supply consists of a simple linear regulator, RG2, and a few surrounding components to enable and disable the appropriate regulator depending on if the device is plugged into a USB port or not. The label USB_ATTACH is connected to 5 V when the device is connected to a USB port on a computer and pulled to ground by R109 when the device is not connected to a USB port. The MOSFET Q1 serves to disable the boost regulator when the device is plugged in by pulling the EN input of RG1 low. The diode D2 allows current to flow from the 5 V USB_ATTACH line to the input of the linear regulator RG2. The SHDN pin of RG2 is also pulled high when the device is plugged into a USB port, enabling the linear regulator. The diode is necessary here because RG2 contains an intrinsic internal diode from VOUT to VIN which would allow the output from the boost regulator to pass back through and bring the USB_ATTACH line high, thereby disabling itself in the process.

The boost regulator, RG1, was chosen for its excellent low-voltage and low-power characteristics and efficiency up to 96%, as well as low cost and small size. While still providing a well-regulated output this component draws only 19 µA of quiescent current (Microchip Technology Inc., 2011).

The low-drop out linear regulator, RG2, was chosen primarily for its low cost and small size. It will provide up to 100 mA at 3.3 V from the 5 V available when the µPINPoint is connected to a USB port, while only consuming 50 µA of supply current (Microchip Technology Inc., 2007).

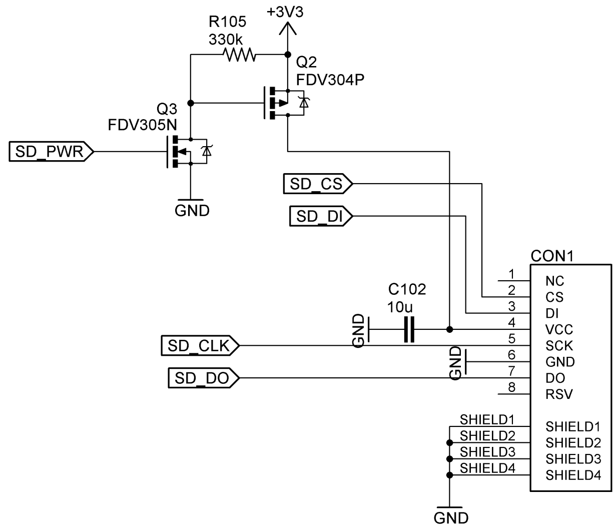

Figure 4-8: SD card schematic.

SD Card

The SD card schematic block is quite simple, and is shown in Figure 4-8. Essentially there are direct connections from the pins of the SD card to the relevant pins of the MCU. The SD card is accessed via the SPI protocol, which is a standardized and simple synchronous serial protocol. To facilitate ultra-low shutdown power consumption by the µPINPoint, a simple power control circuit consisting of the two MOSFETs Q2 and Q3 and the resistor R105 is included in this block. The MOSFET Q2 is a P-channel type and is turned off when its gate voltage is high, with respect to its source, and on when its gate voltage is low, with respect to its source. The MOSFET Q3 is a N-channel type and is off when its gate voltage is low, with respect to its source, and on when its gate voltage is high, with respect to its source. The resistor R105 serves to pull the gate of Q2 high when Q3 is off, also assuring that Q2 is turned off. When SD_PWR is brought high by the MCU Q3 turns on pulling the gate of Q2 low and also turning it on, allowing current to flow to the SD card.

The external power control circuit is vitally important for low power consumption because there is no standard current consumption specification for SD cards across different manufacturers. Even when not being accessed, it was found that some SD

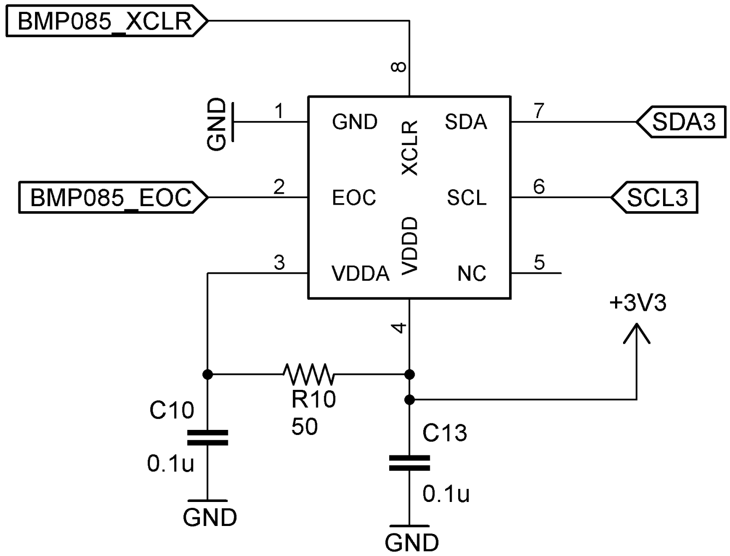

Figure 4-9: Pressure/temperature sensor schematic.

cards draw an unacceptable amount of current which would cause the battery to go dead in a short amount of time even when the device was not being used.

Pressure/Temperature Sensor

The barometric pressure and temperature sensor schematic block, shown in Figure 4-9, includes only the actual sensor IC and power connections. This sensor requires two power connections, one for the internal digital logic, labeled VDDD, and one for the analog circuitry, labeled VDDA. This are both connected to 3.3 V with a high-frequency bypass capacitor close to each pin (C13 and C10, respectively.) The resistor R10 combined with the capacitor C10 form a simple low-pass filter to reduce noise on the analog power connection. The interface to the sensor is the industry standard I^2C protocol, indicated by the pins labeled SDA and SCL. Two other connections to the MCU are made, labeled BMP085_XCLR and BMP085_EOC. The XCLR pin of the sensor allows the MCU to reset the device to a known state. The EOC pin, which is an abbreviation for "end-of-conversion," provides a notification to the MCU when an operation requested has been completed. This sensor is slow compared to other components, so the idea is that the MCU instructs it to take a pressure or temperature

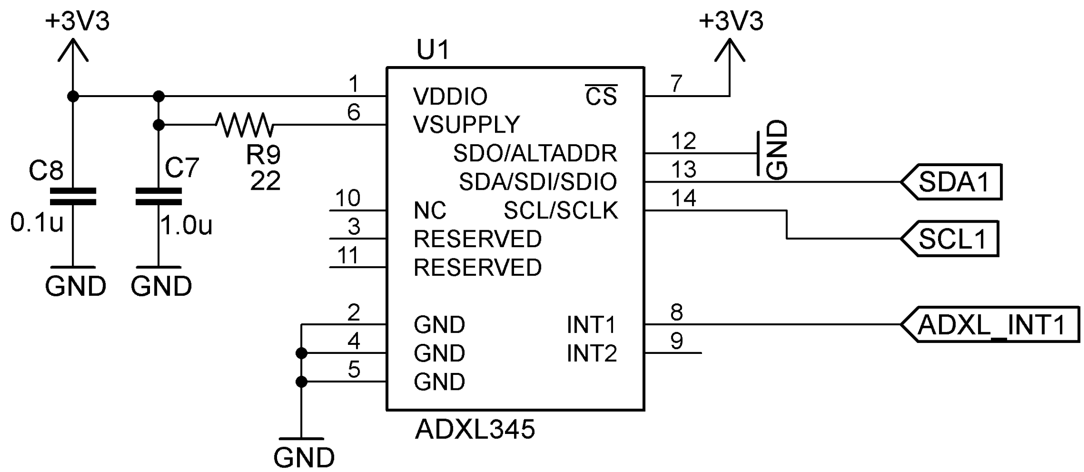

Figure 4-10: 3-Axis accelerometer schematic.

reading and than performs some other work and later reads the result when the sensor brings EOC high.

This sensor has an excellent pressure measurement range from 30.0 kPa to 110.0 kPa (+9000 m to -500 m above sea level), operating temperature range from -40°C to +85°C, operating current of 5 µA and standby current of only 0.1 µA, respectively. In addition, the resolution of pressure measurement is 0.1 kPa and the resolution of temperature measurement is 0.1°C (Bosch Sensortec GmbH, 2009).

3-Axis Accelerometer

The 3-axis accelerometer schematic block, shown in Figure 4-10, includes only the actual sensor IC and power and data connections. Like the barometric pressure and temperature sensor, this IC requires two power connections, one for the digital circuitry and one for the internal analog circuit. The bypass capacitors C8 and C7 are located physically near the component on the PCB. The IC is configured and accessed over the industry standard I^2C protocol, noted by the connections labeled SDA1 and SCL1, indicating the data and clock lines, respectively. The connection labeled ADXL_INT1 is driven by the sensor and used to indicate to the MCU when new data are available.

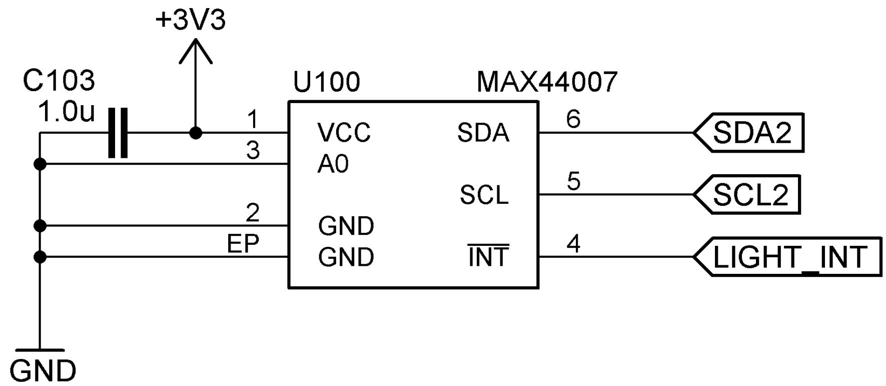

Figure 4-11: Light sensor schematic.

This accelerometer is high-performance and provides a multitude of features. Besides measuring acceleration in all three dimensions, it also has configurable measurement ranges of ± 2 g, ± 4 g, ± 8 g, and ± 16 g (where g = 9.81 m/s^2). Measurement noise increases with each higher measurement range. In addition, it draws only 23 µA in measurement mode and 0.1 µA in standby mode (Analog Devices, Inc., 2011). For both µPINPoint prototypes the range is fixed at ± 8 g, but could be made to be user configurable in future firmware versions.

Light Sensor

The ambient light sensor schematic block, shown in Figure 4-11, also includes only the actual sensor IC and power and data connections. Unlike the other on-board sensors this IC requires only a single power supply connection for both the internal analog and digital circuitry. A single high-frequency bypass capacitor, C103, is placed physically near the part on the PCB. The sensor is configured and accessed over the industry standard I^{2}C protocol, like the other on-board sensors. The connection labeled LIGHT_INT is driven by the component to indicate to the MCU when new data are available to read.

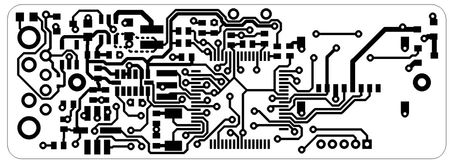

Figure 4-12: Second µPINPoint prototype PCB artwork top layer (actual size).

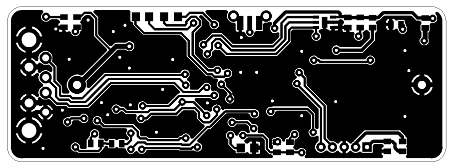

Figure 4-13: Second µPINPoint prototype PCB artwork bottom layer (actual size).

This sensor has an very wide measurement range from 0.025 lux to 104,448 lux, operating temperature range from -40 °C to +85 °C, and operating current of only 0.65 µA (Maxim Integrated Products, Inc., 2011).

Printed Circuit Board

Like the first µPINPoint prototype, the second µPINPoint prototype was also built on a 2-sided PCB to minimize manufacturing cost. The CAD layout of the top and bottom sides of PCB are shown in Figure 4-12 and Figure 4-13, respectively. This was essentially a completely new PCB layout. Several changes were incorporated based on feedback from August 16th workshop. These included moving the battery to the opposite side of the device (or, alternatively, flipping the USB connector) and relocating the start/stop button and the LED indicators to the side of the device. The battery was moved to the opposite side to faciliate plugging the device into a laptop computer. Also, because the MCU was a physically larger component from what was used on the first prototype, many of the other components had to be relocated. Despite the redesign, the physical size of the PCB was kept at exactly the same as the first µPINPoint prototype.

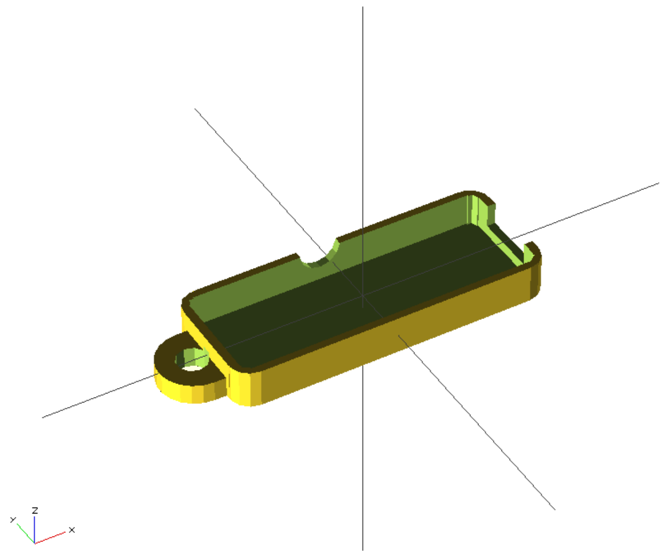

Figure 4-14: Case design - top view.

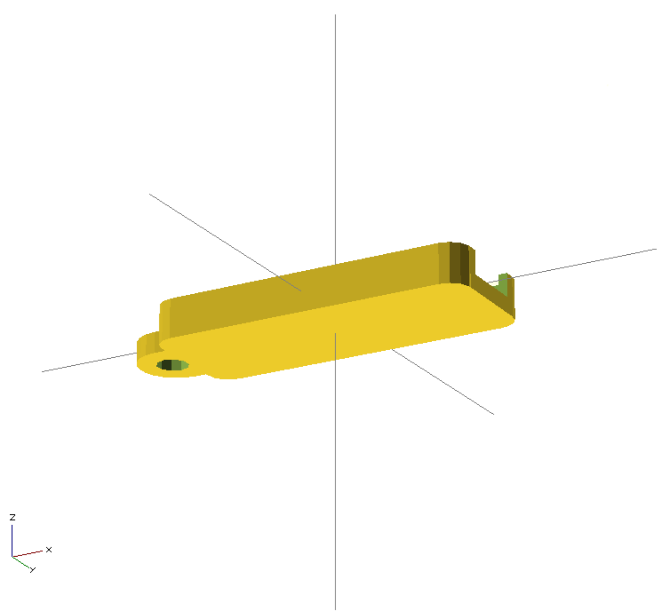

Figure 4-15: Case design - bottom view.

Rapid-prototyped ABS Case

To provide protection for the µPINPoint a case was designed using the free CAD software OpenSCAD. A rendering of the top and bottom of this design is shown in Figure 4-14 and Figure 4-15. The case was a simple design which snaps around the µPINPoint PCB and provides physical protection to the major components, as well as providing a loop for a lanyard. The case was manufactured using Additive Manufacturing ("3D Printing") on a RepRap 3D Printer in black ABS plastic. This design was intended for the prototype device only, and a suitable injection-molded case could ultimately be designed for mass production.

4.3 Firmware Design

The firmware development for the µPINPoint data logger was the most time-consuming component of the work described here. A high level flow chart of the firmware is shown in Figure 4-16. This flow chart correctly represents both the first µPINPoint prototype firmware and the second µPINPoint prototype firmware. There were differences between the two versions because of the different MCU (PIC24FJ64GB002 vs. PIC24FJ128GB1006) used as well as other small hardware changes, but the overall flow was the same.

The hardware design of the µPINPoint is such that the AAA battery is always connected and power is always available to the MCU. There is no physical switch which disconnected the battery from the system. This is important for the real-time clock to continue to run even when the device is not being used. It is vitally important that current consumption be at a minimum during the time when the device is not being used. Referring to Figure 4-16, this shutdown state is indicated by the "sleep" block. When entering this block, the firmware first shuts down all other peripherals, including all sensors and all on-chip peripherals (A/D converter, USB module, etc.) except for the real-time clock and calendar module, and then shuts its own main oscillator down. Likewise, when exiting this block, the MCU enables its main oscillator in response to an interrupt generated by the button being pressed or being plugged

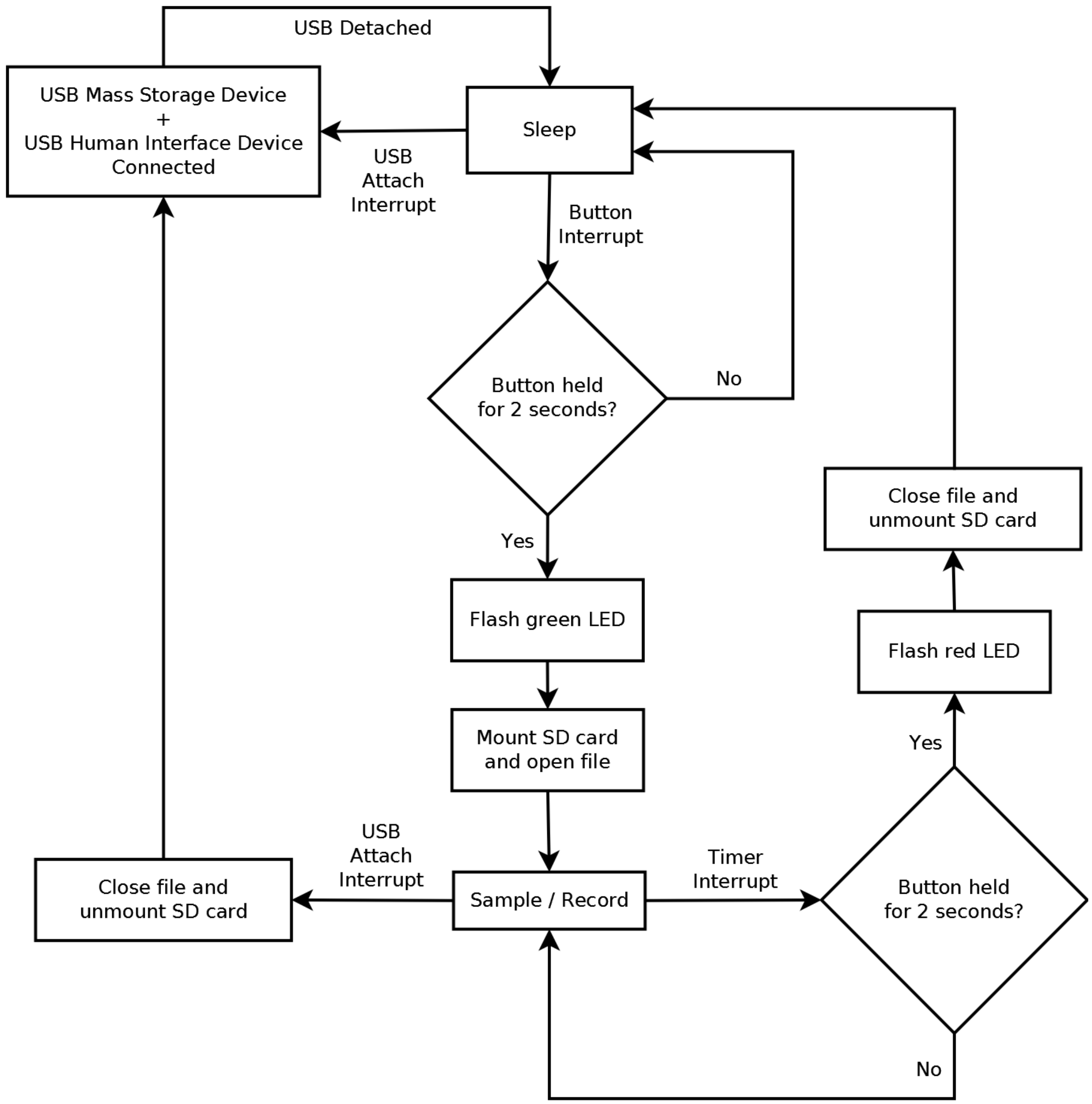

Figure 4-16: Firmware flow chart.

into a USB port. The firmware then enables all of the sensors and on-chip peripherals.

Although not visible to the user when normally used, it should be mentioned that both prototype versions of the µPINPoint included a USB boot-loader program which occupied the first segment of program flash memory. This provided for the ability to easily upgrade the device firmware without any external hardware being necessary. To activate the boot-loader, all that was necessary was that the button be held down for approximately five seconds when the battery was inserted. If the button was released before five seconds had passed the µPINPoint would simply run the regular firmware. Assuming the button was held down long enough the red LED indicator would light to show the user that it was in boot-load mode. The µPINPoint could then be plugged into a USB port where it would be recognized by a special application that allowed a .hex file containing new firmware to be opened and uploaded to the µPINPoint. This was an important feature, especially during this product development phase, because it allowed new firmware to be put on the device quickly and easily.

All firmware was written in the C programming language and compiled using the freely available compiler C30 (lite version) from Microchip Technology Inc. In addition, all code was and will continue to be hosted on github.com, providing access for anyone who wishes to edit and compile the code themselves.

A general approach to firmware (and hardware) design as described in Stringham (2010, Chapter 2) was followed. This includes planning ahead and designing for contingencies. The inclusion of a boot-loader on the µPINPoint follows from this approach: It allows the firmware to be easily upgraded "in the field" if new firmware features and improvements are produced after the device has been delivered to customers. This said, a final production version would be released without the expectation of user firmware upgrades.

Chapter 5

Discussion

The overall development process of the µPINPoint data logger was highly successful. The feedback from the two educator workshops was overwhelmingly positive and this evidence suggests that the µPINPoint data logger is viable as a commercial product. The opinion of this author is that the simplicity and ease-of-use of the µPINPoint in comparison to other small data loggers provides a competitive advantage. The goal of the project was to create a device which was significantly different from other offerings which are targeted at classroom use, such as the Vernier LabQuest devices, and in this respect the µPINPoint data logger was successful.

In addition to the commercial potential of the µPINPoint data logger, the device facilitates data collection and collaborative visualization when combined with the iSENSE web-system.

5.1 First Educator Workshop Feedback

The feedback from the first workshop was positive about the use of the µPINPoint data logger for classroom situations. In fact, several participants inquired about purchasing the device immediately for their work. Of the qualitative feedback collected via the questionnaire shown in Appendix A-1, eight out of the 15 respondents indicated that they would prefer the battery to be on the opposite side of the device. Five suggested that the start/stop button be relocated to the side of the device. All respondents

Currently use in-class electronic instrumentation	Currently use Vernier products
11	4

Table 5.1: Second workshop survey responses regarding the current use of electronic instrumentation.

indicated that they would only like to use the device in a classroom setting and were not interested in sending the device home with students for long-term experiments. Ten of the 15 respondents claimed they would be willing to pay $50 to $100 dollars for the device, while the other five gave no indication of how much they would be willing to pay for the device.

5.2 Second Educator Workshop Feedback

The feedback from the second educator workshop was in the form of categorical responses to specific questions, rather than fill-in-the-blank qualitative responses as in the first educator workshop. The survey was administered on-line through a website and consisted of only four questions related to the µPINPoint data logger. This survey also consisted of questions related to other activities during the day of the workshop. These other questions are not discussed here. Of the roughly 50 registered participants for the workshop, 32 responses to the on-line survey were recorded.

Table 5.1 gives the number of individuals who indicated that they currently use electronic instrumentation in the classroom and also the number of individuals who use Vernier products specifically. Of the participants, 34% currently use electronic instrumentation, and of these individuals 36% use Vernier Software & Technology Inc. products. When these numbers are compared to the number of individuals who indicated that they believe electronic instrumentation is very useful in the classroom, shown in Table 5.2, it is clear that there is a market for a device such as the µPINPoint data logger. Table 5.2 indicates that 87% of respondents believed electronic instrumentation to be useful or very useful.

The third survey question, which asked about the value of inexpensive electronic instrumentation, gave essentially the same results as the second question. Of the 32

Using electronic instrumentation to collect data			
Very Useful	Useful	Somewhat useful	Not useful
21	7	2	1

Table 5.2: Second workshop survey responses regarding the value of electronic instrumentation.

Using inexpensive electronic instrumentation to collect data			
Very Useful	Useful	Somewhat useful	Not useful
23	4	4	1

Table 5.3: Second workshop survey responses regarding the value of inexpensive electronic instrumentation.

respondents, 84% indicated that they believed inexpensive electronic instrumentation to be useful or very useful. In retrospect, this question was perhaps not clear enough to differentiate it from the second question, and therefore may not have provided useful data. The original idea was to determine how important an inexpensive data logger device is to educators verses a more expensive device such as the Vernier LabQuest.

The fourth survey question asked how important participants believed it was to be able to collect real-world data with portable instrumentation. Of the 32 respondents, 87% indicated that they believed this was useful or very useful. This confirms that the small size and portability of the µPINPoint data logger is a valuable feature to educators.

5.3 Conclusions

In conclusion, a small portable device for scientific education was developed and found to be highly marketable to educators for classroom use. The design cycle followed was successful in refining the device to the point where it is essentially ready to manufacture and market. The simplicity of use of the µPINPoint data logger was the most novel feature of the device, and does not currently exist in competing commercial or academic devices. When used with the iSENSE web-system, the µPINPoint data logger provides a simple means of collaborative data visualization with the shortest possible setup time.

Having the ability to collect data during real-world situationswith portable instrumentation			
Very Useful	Useful	Somewhat useful	Not useful
25	3	2	2

Table 5.4: Second workshop survey responses regarding the value of real-world data collection with portable instrumentation.

5.4 Future Work

Future work includes some small changes to the second µPINPoint prototype based on feedback from the second educator workshop, and securing funding to manufacture the device on a larger scale or providing the design to an established company to sell.

One small issue discovered during observation of participants during the second educator workshop was the loss of current date and time information when the battery was removed, something that happened frequently during the second educator workshop. The first and second µPINPoint prototypes both used the main battery to keep the on-board clock running when the device is not being used. With this design, when the battery is removed the current date and time is then lost and must be re-set when the battery is replaced. This must be done with special software as there is no way to do this using the standard USB mass storage device drivers on a computer. The µPINPoint data logger still works normally, but the recorded dates and times on the data are not correct when this has happened. Before production and marketing, a small revision of the second µPINPoint prototype could add a tiny back-up battery to prevent the current date and time from being lost when the battery is removed.

In regards to selling the µPINPoint data logger, one option is to offer the design to a company which already markets products for educational use, such as Vernier Software & Technology Inc., or a hobbyist-oriented reseller, such as Sparkfun Electronics Inc. Another option is to seek private investment and form a start-up company to further develop and sell the µPINPoint data logger. In the immediate future, Machine Science Inc., the non-profit collaborator on the work described here, will sell the device. Appendix D shows a condensed “business scan” including a SWOT (Strength, Weakness, Opportunities, and Threats) break down of the µPINPoint data logger as the product for a small entrepreneurial start-up, as is commonly done for innovative products when evaluating their commercial potential.

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Appendix A

Workshop Handouts

Figure A-1 shows the actual survey instrument provided to participants at the close of the first educator workshop. This was completed by participants as shown here.

Paper handouts were provided for the second educator workshop held on November 3rd, 2012. These handouts gave participants three example experiments to try using the µPINPoint data logger to collect data.

iSENSE Physics Workshop
UMass Lowell
Department of Computer Science
Engaging Computing Group
August 16th, 2012

USB Drive Data Collector Survey

Name: [redacted]

School: [redacted]

Was the device easy to use? Are there any improvements that you could think of?

YES ; ON/OFF BUTTON SAME SIDE AS BATTERY

Do you prefer long-term battery life or small size (coin cell)?

SMALLER THE DEVICE, THE BETTER

Would you more likely use this device for class room experiments (short-term) or long-term environmental data collection?

BOTH – I THINK STUDENTS WILL PREFER THE VERNIER PROBES FOR EASY USE; BUT THE PINPOINT IS IDEAL FOR ATTACHING TO OBJECTS.

What else would you like the device to measure (if anything)?

ALTITUDE WITH GREATER ACCURACY

How much would you pay for a device such as this?

$75 – 100 ??

Other comments:

Figure A-1: First educator workshop survey questionnaire.

iSENSE

Acceleration and Altitude in an Elevator

Purpose

1. Personally sense the acceleration and deceleration of a normal building elevator.
2. Record the acceleration and change in pressure altitude using a µPINPoint data logger.
3. Use iSENSE to visualize the acceleration and change in pressure over time.
4. Use iSENSE to compare data sets with others and to draw conclusions.

Materials

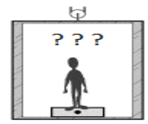
1. Elevator
2. µPINPoint data logger
3. Computer with internet access

Method

Place a µPINPoint data logger on the floor on an elevator before it has begun to move. Be sure to let others know that you are performing an experiment and to avoid stepping on the device. Carefully press and hold the button on the side of the µPINPoint data logger until it flashes green and begins recording data. Select a floor two or more floors above or below the current floor. When the elevator has come to a complete stop carefully press and hold the button on the side of the µPINPoint data logger again until the red light flashes. This concludes the collection phase of the experiment. Repeat the experiment going in the opposite direction on the elevator if desired.

Plug the µPINPoint data logger into an available USB port on the computer and copy the .csv file with the most recent date and time to a convenient location. Log into iSENSE and upload your .csv. Using the "Visualize" button, display acceleration and pressure altitude versus time. Try to identify events on the graph as compared to what you observed when riding the elevator.

Observations



1. What did you notice about the elevator and the µPINPoint data logger during the experiment? Did it feel as if there was a higher acceleration at the beginning than deceleration at the end? Did the µPINPoint data logger bounce around on the floor at all during the ride? How do you know?

   ____

   ____

iSENSE Analysis

1. Use the Scatter Plot visualization to examine your data session in iSENSE.
2. Add data contributed by other participants to your Scatter Plot.
3. Save any visualization that you find particularly interesting.

Discussion Questions

1. What do the data suggest about orientation of the µPINPoint data logger with respect to its x, y, and z axes?
2. What physical phenomena would explain the events recorded on the graph?
3. From the graphs, are you able to spot where the elevator started to move and where it stopped?
4. What questions might you specifically investigate if you were to repeat this experiment?
5. How might you use the µPINPoint data logger with your students to examine motion?

iSENSE is a collaborative project of the University of Massachusetts Lowell and Machine Science Inc.
The project is supported two grants from the National Science Foundation (IIS-1123998 and IIS-1123972).

Figure A-2: Elevator experiment handout provided to workshop participants.

iSENSE

Oscillations of a Pendulum

Purpose

1. Observe and examine the properties of motion of a swinging pendulum.
2. Record the acceleration and change in light intensity using a µPINPoint data logger as a pendulum swings near a light source.
3. Use iSENSE to visualize the acceleration and change in light intensity over time.
4. Use iSENSE to compare data sets with others and to draw conclusions.

Materials

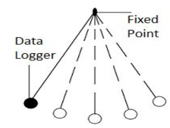
1. Pendulum apparatus
2. µPINPoint data logger
3. Computer with internet access

Method

Using a fixed pendulum arm, find a suitable attachment point or frame which allows the arm to swing unobstructed and orthogonal to a directional light source. Be sure that the attach the µPINPoint data logger such that it does not twist while swinging. The intersection of a wall and a window where the pendulum swings across dark areas is ideal. Attach a µPINPoint data logger to the end of the arm with either a rubber band or piece of string such that the light sensor (battery side) faces the directional light source. Lift the pendulum arm up to one extreme of its arc and hold. Carefully press and hold the button on the side of the µPINPoint data logger until it flashes green and begins recording data. Release the pendulum, allowing it swing back and forth for at least 30 seconds or until it stops swinging. When the pendulum has come to a complete stop, carefully press and hold the button on the side of the µPINPoint data logger again until the red light flashes. This concludes the collection phase of the experiment.

Plug the µPINPoint data logger into an available USB port on the computer and copy the .csv file with the most recent date and time to a convenient location. Log into iSENSE and upload your .csv. Using the "Visualize" button, display acceleration and light versus time.

Observations



1. What did you notice about the pendulum and the µPINPoint data logger during the experiment? Was there any rotation or movement of the setup besides the normal swing of the pendulum that could effect the data?

____

____

iSENSE Analysis

1. Use the Scatter Plot visualization to examine your data session in iSENSE.
2. Add data contributed by other participants to your Scatter Plot.
3. Save any visualization that you find particularly interesting.

Discussion Questions

1. What do the data suggest about orientation of the µPINPoint data logger with respect to its x, y, and z axes?
2. What physical phenomena would explain the events recorded on the graph?
3. What questions might you specifically investigate if you were to repeat this experiment?
4. How might you use the µPINPoint data logger with your students to examine the motion of a swinging pendulum?

iSENSE is a collaborative project of the University of Massachusetts Lowell and Machine Science Inc.
The project is supported two grants from the National Science Foundation (IIS-1123998 and IIS-1123972).

Figure A-3: Pendulum experiment handout provided to workshop participants.

iSENSE

Solar Oven Design and Test

Purpose

1. Engineer a simple solar oven and compare its performance to a control.
2. Record the change in temperature using a µPINPoint data logger.
3. Use iSENSE to visualize the change in temperature over time.
4. Use iSENSE to compare data sets with others and to draw conclusions about the best design.

Materials

1. Box
2. Tin or aluminum foil
3. Lamp
4. µPINPoint data logger
5. Computer with internet access

Method

Using the box and foil construct a solar oven of your own design. Leave the lamp turned off and orient the lamp such that it is directed at your oven. Place a µPINPoint data logger in the oven. Carefully press and hold the button on the side of the µPINPoint data logger until it flashes green and begins recording data. Turn the lamp on and wait three minutes, allowing the oven to heat up. Press and hold the button on the side of the µPINPoint data logger again until it flashes red and stops recording data. Turn off the lamp. Allow the µPINPoint data logger to return to room temperature and repeat the experiment with the µPINPoint data logger sitting directly on the table without the oven.

Plug the µPINPoint data logger into an available USB port on the computer and copy the two .csv files with the most recent times to a convenient location. Log into iSENSE and upload your files. Using the "Visualize" button, display the two temperature curves.

Observations

1. How well did your solar oven work in comparison to directly heating the µPINPoint data logger? Did it reach a higher maximum temperature? How does your design compare to others in the class?

____
____
____
____

iSENSE Analysis

1. Use the Scatter Plot visualization to examine your data session in iSENSE.
2. Add data contributed by other participants to your Scatter Plot.
3. Save any visualization that you find particularly interesting.

Discussion Questions

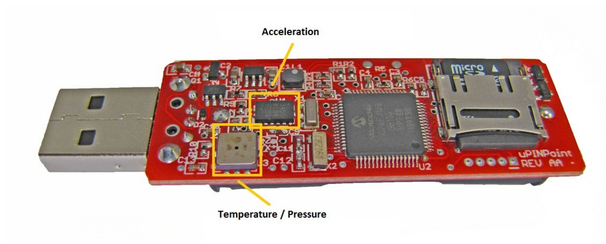
1. What physical phenomena would explain the events recorded on the graph?
2. From the graphs, are you able to spot where the lamp was turned on and off
3. What questions might you specifically investigate if you were to repeat this experiment?
4. How might you use the µPINPoint data logger with your students to examine solar oven design?

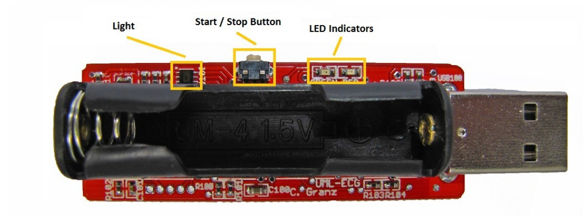
iSENSE is a collaborative project of the University of Massachusetts Lowell and Machine Science Inc.
The project is supported two grants from the National Science Foundation (IIS-1123998 and IIS-1123972).

Figure A-4: Solar oven experiment handout provided to workshop participants.

iSENSE

µPINPoint Quick Start Guide





<u>Collecting Data with the µPINPoint Data Logger</u>

1. Insert a AAA battery into the µPINPoint and note that the red and green lights on the side of the device flash for a moment.
2. Optionally, plug the µPINPoint into a computer USB port and note that it appears as a storage device – this verifies that the device is ready and working.
3. Prepare the experimental setup which you will be collecting data from.
4. Press and hold the single button on the side of µPINPoint until the green light flashes – the device is now RECORDING.
5. Perform the experiment.
6. Press and hold the single button on the side of µPINPoint again, until the red light flashes – the device is now STOPPED.

<u>Copying Data to a Computer</u>

1. Plug the µPINPoint into a USB port and note that it appears as a storage device.
2. Locate the .csv file with the most recent date/time – this file contains your data.
3. Copy the file to a convenient location on the computer and rename, if desired.

<u>Uploading Data to iSENSE</u>

1. On a computer with internet access, go to http://isenseproject.org
2. Follow the instructions on the web site to upload a .csv data file.

Figure A-5: µPINPoint quick-start guide provided to workshop participants.

Appendix B

Manufacturing Documents

Shown in Figure B-1 is the qoute for 100 μPINPoint units (second prototype), assembled, programmed and tested. The cost per unit would decrease as quanity is increased.

Proforma Invoice

Ver1.10

Schotry Business International Co., Ltd
Addr: Baoxingyuan 102-21E, Wangjing Dongyuan Area 1, Chaoyang District, Beijing, China
Zip Code: 100102
Tel: +86-13910820254
Fax: +86-10-58850516

Quote Num.:	QT_US231120925A	**Order Num.:**	US231120925A
Order By:		**Payment Info: (By Check)**	
Company:	University of Massachusetts Lowell	**Pay to:**	Schotry Business International Co., Ltd
Contact:	Fred Martin	**Address:**	Baoxingyuan 102-21E, Wangjing Dongyuan Area 1, Chaoyang District, Beijing, China
Address:	Room 302, 3nd floor, Olsen Hall 198 Riverside Street, Computer Science		
City:	Lowell	**Zip Code:**	100102
State:	MA	**Payment Terms:**	NET 30
Country:	USA		
Zip Code:	01854		
Tel:	+1(978)9341964		

Item List:

No.	Item Name	Description	Lead Time (Calendar Days)	Qty (pcs)	Unit Price (USD)	Sub Total (USD)
1	PCB NRE Cost.	2.4mm thickness, standard FR4, ENIG(gold flash) finish, green soldermask, white silkscreen.	5	1	175.00	175.00
2	Assembly NRE Cost.	200$ for tooling setup and making stencil which will be used in re-flow process. No need for repeated order(s).	2	1	100.00	100.00
3	uPINPoint boards	PCB Fabrication, BOM processing, Assembly, Test	14	100	33.14	3,314.00
4	Shipping Cost	DHL Air Express	-	1	100.00	100.00

Total Price: 3,689.00 USD

Extra Requirements or Notes, if any:

None.

Terms: 1. Information listed herein follows the contents of confirmed order. 2. Quantity information listed herein is subject to change, and is just for reference purpose. Exact quantity information will be presented in future packing list included in the shipment. 3. Amount information listed herein is subject to change, and is not for accounting purpose. Final and accurate amount will be decided and presented in future formal invoice, prior to trading closure. 4. Customers should confirm the information listed, or shall be responsible for possible delay or any mistake caused by the information errors.

Signature:

Supplier:	***Schotry Business Int'l Co., Ltd***	**Buyer:**	***University of Massachusetts Lowell***
Signature:		**Signature:**	
Name:	***Mutong Zhang***	**Name:**	***Fred Martin***
Title:	***Sales Director***	**Title:**	
Date:	***2012-9-25***	**Date:**	

Figure B-1: Manufacturing quote.

Appendix C

Example Data File

Shown in Figure C-1 is an example of the type of file produced by the µPINPoint data logger.

```
Time, ElapsedTime, Temperature, Pressure, Altitude, AccelX, AccelY, AccelZ, AccelMag, Light
02/12/2012 12:31:24.000000, 0.000000, 26.2, 102.131, -66,  -2.45,  -2.60, -11.18,  11.74,  108.8
02/12/2012 12:31:24.125000, 0.125000, 26.5, 102.126, -66,  -1.22,   0.00, -10.72,  10.77,  108.8
02/12/2012 12:31:24.250000, 0.250000, 26.5, 102.121, -66,  -0.30,  -1.07,  -9.96,  10.00,  108.8
02/12/2012 12:31:24.375000, 0.375000, 26.5, 102.126, -66,  -3.21,  -1.37,  -7.20,   8.00,  108.8
02/12/2012 12:31:24.500000, 0.500000, 26.5, 102.126, -66,  -0.91,  -0.45,  -8.73,   8.77,  108.8
02/12/2012 12:31:24.625000, 0.625000, 26.5, 102.121, -66,   0.76,  -1.99, -10.26,  10.48,  108.8
02/12/2012 12:31:24.750000, 0.750000, 26.5, 102.107, -64,  -2.14,  -1.37,  -7.81,   8.18,  108.8
02/12/2012 12:31:24.875000, 0.875000, 26.5, 102.121, -66,   0.00,  -2.29,  -9.96,  10.19,  108.8
02/12/2012 12:31:25.000000, 1.000000, 26.5, 102.132, -66,  -2.45,  -2.60, -10.88,  11.44,  108.8
02/12/2012 12:31:25.125000, 1.125000, 26.5, 102.129, -66,  -0.15,   0.76, -11.34,  11.35,  108.8
02/12/2012 12:31:25.250000, 1.250000, 26.6, 102.147, -68,  -0.30,  -1.07, -11.49,  11.53,  108.8
02/12/2012 12:31:25.375000, 1.375000, 26.6, 102.129, -66,  -2.45,  -2.45,  -7.81,   8.54,  108.8
02/12/2012 12:31:25.500000, 1.500000, 26.6, 102.135, -67,  -1.07,  -0.15, -11.95,  12.00,  108.8
02/12/2012 12:31:25.625000, 1.625000, 26.6, 102.126, -66,   0.15,  -2.14,  -9.35,   9.59,  108.8
02/12/2012 12:31:25.750000, 1.750000, 26.6, 102.129, -66,  -1.22,  -0.15, -11.80,  11.83,  108.8
02/12/2012 12:31:25.875000, 1.875000, 26.6, 102.129, -66,  -1.37,  -0.15, -11.80,  11.87,  108.8
02/12/2012 12:31:26.000000, 2.000000, 26.6, 102.126, -66,  -2.45,  -2.45,  -7.35,   8.12,  108.8
02/12/2012 12:31:26.125000, 2.125000, 26.6, 102.121, -66,   0.00,  -2.91,  -9.81,  10.19,  108.8
02/12/2012 12:31:26.250000, 2.250000, 26.6, 102.129, -66,  -1.22,  -3.21,  -9.35,   9.94,  108.8
02/12/2012 12:31:26.375000, 2.375000, 26.6, 102.121, -66,  -0.76,  -0.15, -10.72,  10.72,  108.8
02/12/2012 12:31:26.500000, 2.500000, 26.6, 102.129, -66,   0.61,  -2.91,  -9.96,  10.39,  108.8
02/12/2012 12:31:26.625000, 2.625000, 26.6, 102.132, -66,  -0.91,  -3.98,  -1.83,   4.47,  108.8
02/12/2012 12:31:26.750000, 2.750000, 26.6, 102.116, -65,   2.60,   0.30,   1.22,   2.82,  108.8
02/12/2012 12:31:26.875000, 2.875000, 26.6, 102.121, -66,   0.15,  -0.76,  -3.98,   4.00,  108.8
02/12/2012 12:31:27.000000, 3.000000, 26.6, 102.129, -66,   1.07,   2.29,  -8.12,   8.48,  108.8
02/12/2012 12:31:27.125000, 3.125000, 26.6, 102.122, -66,   4.44,   6.43, -16.70,  18.43,  217.6
02/12/2012 12:31:27.250000, 3.250000, 26.6, 102.132, -66,  14.40,   2.45, -26.05,  29.86,  272.0
02/12/2012 12:31:27.375000, 3.375000, 26.6, 102.129, -66,   9.65,  13.18, -30.19,  34.32,  272.0
02/12/2012 12:31:27.500000, 3.500000, 26.6, 102.132, -66,   1.83,   0.45,  -1.07,   2.00,  217.6
02/12/2012 12:31:27.625000, 3.625000, 26.6, 102.129, -66,   2.45,   0.15,  -1.22,   2.64,  326.4
02/12/2012 12:31:27.750000, 3.750000, 26.6, 102.122, -66,   1.83,   0.00,   0.00,   1.73,  326.4
02/12/2012 12:31:27.875000, 3.875000, 26.6, 102.116, -65,   0.91,   0.76,  -1.07,   1.41,  272.0
02/12/2012 12:31:28.000000, 4.000000, 26.6, 102.116, -65,  -0.91,  -1.53,   1.83,   2.44,  163.2
02/12/2012 12:31:28.125000, 4.125000, 26.6, 102.119, -65,   0.15,   1.53,  -1.99,   2.44,  163.2
02/12/2012 12:31:28.250000, 4.250000, 26.6, 102.116, -65,  -4.44,  -7.35,  -4.29,   9.59,  108.8
02/12/2012 12:31:28.375000, 4.375000, 26.6, 102.130, -66,  -3.98, -12.72,  -6.13,  14.66,    0.0
02/12/2012 12:31:28.500000, 4.500000, 26.6, 102.132, -66, -10.26,  -6.28,  -7.05,  13.92,   54.4
02/12/2012 12:31:28.625000, 4.625000, 26.6, 102.116, -65,  -8.43,   0.00,  -8.58,  12.00,   54.4
02/12/2012 12:31:28.750000, 4.750000, 26.6, 102.130, -66,  -5.67,  -2.60,  -7.81,  10.00,  108.8
02/12/2012 12:31:28.875000, 4.875000, 26.6, 102.130, -66,  -5.05,  -1.83,  -5.82,   7.87,  108.8
02/12/2012 12:31:29.000000, 5.000000, 26.7, 102.127, -66,  -3.21,  -1.68,  -9.96,  10.58,   54.4
02/12/2012 12:31:29.125000, 5.125000, 26.7, 102.127, -66,  -2.75,  -2.91,  -9.19,  10.00,   54.4
02/12/2012 12:31:29.250000, 5.250000, 26.6, 102.130, -66,  -2.45,  -3.21,  -7.81,   8.77,   54.4
02/12/2012 12:31:29.375000, 5.375000, 26.7, 102.122, -66,  -1.53,  -2.29, -11.18,  11.48,   54.4
02/12/2012 12:31:29.500000, 5.500000, 26.7, 102.116, -65,  -5.05,  -2.29,  -7.81,   9.53,   54.4
```

Figure C-1: Example output CSV file.

Appendix D

Business Scan

Often it useful to formalize the business potential of an innovative device with an organized “Business Scan” which provides a way to quickly compare the features and strengths and weakness of the device. This has been done for the µPINPoint data logger and is shown below.

Innovation Business Scan

Device: μPINPoint Data Logger

Developer: Christopher D. Granz, University of Massachusetts Lowell

Issue Addressed: Inexpensive Electronic Instrumentation for Science Education

Date Prepared: December 2nd, 2012

Prepared By: Christopher D. Granz

Outlook:

+ Very simple to use
+ Inexpensive
+ Fulfills a need in a relatively new field, therefore there is essentially no competition

- May not provide enough sensors for all potential customers
- No market precedent for such a device, prospects are largely unknown

Recommendation:

The μPINPoint data logger has potential as an educational tool especially for classroom usage. Its low cost and simplicity should make it attractive to middle school and high school teachers as an alternative to more expensive electronic instrumentation.

To market the device, two different approaches may be followed. One is to sell the design and rights to a company which already markets educational products, such as Vernier Software & Technology Inc. or a company which sells hobbyist products, such as Sparkfun Electronics, Inc. This option requires the least effort on the part of the designer and also carries the least amount of risk, but also gives the least opportunity for profit. The other option is to form a start-up company to refine the prototype, setup large scale manufacturing, and market and distribute the device.

The option of forming a start-up company to sell the device would require financial investment. One possibility is to acquire funding and essentially "pre-orders" via the Kickstarter website. This website provides the ability for many individuals to contribute small amounts of money to a project in exchange for the product. Several thousands of dollars could potentially be raised in this way. Another possibility is to follow a more traditional path and seek private investment.

In the meantime, the prototype design can be sold immediately by the non-profit organization Machine Science, Inc., who was a collaborator during the development of the device.

This can help raise awareness about the device and give lead users a chance to use the device in their classrooms in the near future.

Preliminary Business Scan

SWOT Analysis

Strengths	Weaknesses
• Small size • Simple to use • Inexpensive • Significantly different than other devices on the market • Could potentially define a new market	• Type of electronic instrumentation unknown in classrooms – work needs to be done to generate awareness • Device loses date/time when the battery is removed (fix in revised prototype)
Opportunities	**Threats**
• Primary education market (middle school / high school) • Hobbyist market	• Small hobbyist data loggers if they become simpler to use

Business Potential

Invention/Product Description:

The µPINPoint data logger is a device slightly larger than a standard USB flash drive which includes a battery, and Micro SD card, and some sensors. It provides the ability to record readings of temperature, pressure, altitude (derived from pressure and temperature), light intensity, and acceleration in three dimensions at rates up to 64 samples per seconds. To retrieve the data from the device it is simply plugged into a USB port of a computer and the data file is dragged off. No special software is needed by the user.

What specific problem or need does this invention/product address?

The device addresses the need for inexpensive electronic instrumentation for science education. The µPINPoint is inexpensive and small enough such that all students in a science class can have access to their own device.

What Industry or Business Segment does this product address? Describe the industry/business segment.

The product addresses the educational industry and provides a tool for teachers of middle school and high school science subjects. Companies already exist, such as Vernier Software & Technology Inc., which market products in this industry.

Who is the specific target market? Who buys and who uses the product? How big is this target market? How are they best reached?

Private and public middle and high schools are the primary market for the device. The idea is that science teachers would have their institutions purchase the device for classroom use. This market is relatively small, so the goal would be to promote the product for hobbyist use as well.

The best way to reach the target market is through word-of-mouth and holding workshops which introduce educators to the product and the benefits it can provide for classroom education.

Does this product or similar products exist? What products/services/companies currently serve this target market?

No product like this product currently exists. Larger, more fully featured data loggers exist, but are not as simple to use. Small data loggers also exist with only a few sensors, like the µPINPoint, but none are as simple to use without the need to install special custom software to access collected data.

What portion of the market does the product address?

Primarily the low-end, low-cost portion of the education market.

What is the likely business model? Are there different business model options? What are they?

There are two basic options. One is to offer to sell the product design to a business which already markets related devices, such as Vernier Software & Technology Inc. This is the easiest option, but also gives the least opportunity for profit. The other option is to form a start-up company to market and sell the device. This second option requires more investment of time and money, but has the potential for the highest pay out.

What is the status of the Intellectual Property?

The product design is copyrighted to the University of Massachusetts Lowell, but no patents on the device exist. The hardware design and software which runs on the device are also open source.

What is the commercialization pathway? What needs to be done to bring a product based on this technology to market?

The prototype could use a few more refinements, but no major changes are needed. Manufacturing for the finished device needs to be secured, as well as product packaging and distribution.

Recommendations for moving this innovation forward:

The recommendation is to produce a promotional video for the Kickstarter website. Post the video and devise a pre-order scheme depending on contributions from individuals.