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November 16, 2005

Dr. Andrew Rawicz
School of Engineering Science
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Burnaby, British Columbia
V5A 1S6

Re: ENSC 340 Design specifications for a Bicycle Energy Measurement System

Dear Dr. Rawicz:

The enclosed document, *Design Specifications for a Bicycle Energy Measurement System (BEMS)*, outlines the design specifications of our device for the ENSC 340 project. We are in the process of designing a device which will allow the user to measure the energy expended while cycling. The Bicycle Energy Measurement System will include a simple user interface allowing the cyclist to enter personal information similar to the menu system in a basic bicycle computer.

This design specification provides the detailed description of how we intend to implement the capabilities of our product stated in our functional specification. Included in this document are the hardware and firmware designs of each block of the proof-of-concept device. Also included are our plans for testing of individual components and of the complete system. The proof-of-concept device will be delivered by December 14th, 2005.

Exigo Technologies consists of two fifth year engineering students: Denis Dmitriev and Mimi Wu. If you have any concerns or questions in regards to our proposal, please do not hesitate to contact me by phone at (778)835-8539, or by e-mail at mwua@sfu.ca.

Sincerely,

Mimi Wu

Mimi Wu
Exigo Technologies

Enclosure: Design specifications for a Bicycle Energy Measurement System

Exigo Technology

Design specification:

Bicycle Energy Measurement System

Project team: Denis Dmitriev
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Submitted to: Dr. Andrew Rawicz
Brad Oldham
Steve Whitmore
Mike Sjoerdsma

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Executive Summary

Exigo Technologies recognizes the emerging need for devices that make exercising enjoyable. Our product retains the recreational aspects of cycling as well as provide detailed output information. The BEMS is meant to provide detailed information about the current cycling conditions at an affordable price, so as to reach the mass public. The prototype of our product will be completed by December 2005.

The BEMS will be developed in two stages. The first stage is the development of the proof of concept device and the second stage is the development of the production prototype. In the first stage, the proof of concept will allow the user to enter personal information through the display. It will collect data from the sensors in real time, perform the necessary calculations and display the results on the display unit. In the second stage, the production prototype will be weatherproof and will comply with all relevant CSA and Federal Communications Commission rules. The accuracy goals set in the functional specifications will also be attained in the production prototype.

The development of the proof of concept device will be based on the design specifications outlined in this document.

Contents

List of Figures

Glossary

BEMS	Bicycle Energy Measurement System. The product discussed in this document.
DIP	Dual-in-line package. A particular type of IC packaging, especially well-suited for prototyping.
IC	Integrated circuit.
OLED	Organic light-emitting diode. An emerging technology for making liquid crystal displays that emit rather than reflect light.
PCB	Printed circuit board.

1 Introduction

BEMS is a product that measures the energy expended by the cyclist during an exercise session. This is done by an indirect measurement of the power based on the speed, acceleration, and inclination of the bicycle at any given moment. BEMS is intended to provide detailed energy expenditure information to the cyclist while doing so on a budget. The project is being developed in two stages, including the proof of concept device set to be delivered in December and additional development of the production prototype.

1.1 Scope

This document outlines the proposed design specifications for the Bicycle Energy Measurement System. It encompasses all parts of the project including the hardware, the software, the user interface, and the test plan.

These specifications implement the functional requirements listed in the *Functional Specifications for a Bicycle Measurement System* to the extent of the proof-of-concept device. The proof-of-concept device will not fulfill all the functional requirements listed in the functional specifications document. Please refer to the *Functional Specifications for a Bicycle Energy Measurement System* for the detailed list of concessions made for the proof-of-concept prototype.

1.2 Intended audience

Design engineers will use this document to further develop the project. This document will also allow the project manager to measure project success as well as to verify the design. The marketing department may use these design specifications for promotional purposes.

1.3 Objectives

The specifications listed in this document aim at outlining the design of BEMS to its potential users and to guide further development of the system.

The design specifications listed in this document will apply to the proof-of-concept device.

2 System overview

Figure 1 shows the overview of our energy measurement system. The system consists of a sensor unit attached to the front fork of the bike, a display unit attached to the handlebar, and a cable connecting them. The user inputs personal information, such as weight, through the display unit. As the cyclist pedals, the sensors transfer the gathered information into BEMS, which calculates the amount of energy expended by the cyclist. This information is tallied and displayed on the unit at regular intervals.

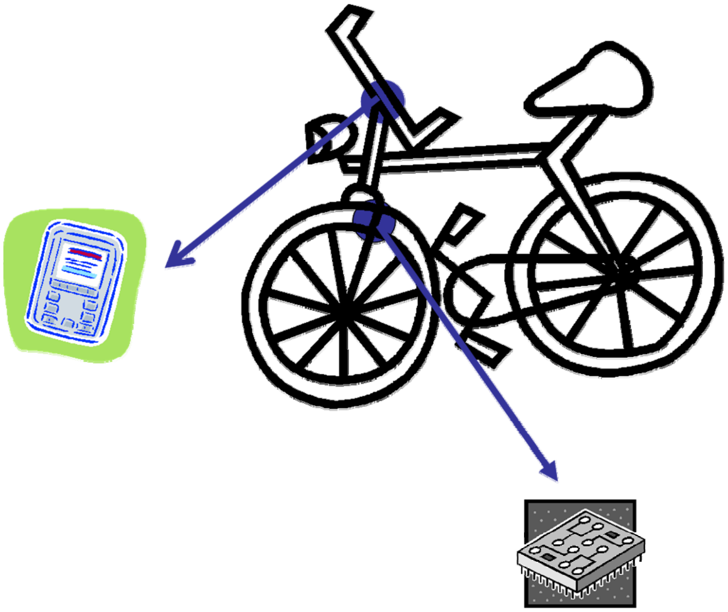

Figure 1: Conceptual system overview

3 Hardware design

BEMS is composed of two interconnected units—the sensor and the display. Proposed designs of both will be examined in the following sections.

3.1 Sensor unit

The primary function of the sensor unit is to monitor two pieces of information that BEMS uses to compute the energy expenditure—bicycle speed and inclination.

The most common way of measuring bicycle speed in bike computers employs a small magnet on the rim of a bike wheel and an appropriately positioned sensor that detects the magnet passing under it. This produces one impulse per revolution, which is sufficient for purposes such as measuring the total distance, providing a rough approximation of the velocity. However, we were concerned that such solution might prove unsatisfactory for our purpose.

First, we are not confident how the sampling rate of measurements will affect our energy-computing algorithm. If we were to commit to a low rate sensor for the prototype, we face the risk of the resolution being insufficiently fine, thus necessitating an extensive redesign. Secondly, since such a sensor only detects the frequency of revolutions, it would have to be individually calibrated for each bike to produce the actual speed.

With this in mind, we decided to measure the speed directly by coupling a small wheel onto the rim of the front wheel of a bicycle. An optical encoder then converts the sensor wheel's revolutions into a pulse train, which the microcontroller then uses to determine the velocity.

Since the circumference of the small wheel is known, the sensor can be calibrated to report speed in any convenient units regardless of the bike it is installed on. The resolution can also be easily made as fine as one pulse per centimeter (the actual resolution of our design), thus allowing very accurate measurements of the instantaneous velocity.

The most common way of measuring inclination is by using an accelerometer. This is exactly the approach we chose.

3.1.1 Physical design

The sensor unit is the part of BEMS most exposed to the elements. The enclosure needs to be rugged enough to protect the circuitry inside in the event of a crash. The attachment method must ensure that the sensor wheel is always in contact with the bicycle wheel's rim, but at the same time it must be sufficiently flexible to handle the wheel's imperfections without subjecting neither the bike nor the sensor to undue stress. These requirements resulted in the design shown in the figure 2 below:

The enclosure is made out of a piece of stainless steel tubing. The adjustable clamp on the side of the tube is used to attach the sensor unit to the bike. The clamp is not rigid but allows some degree of rotation around the axis perpendicular to the main axis of the enclosure. The spring ensures that the sensor wheel stays in contact with the bicycle, but at the same time

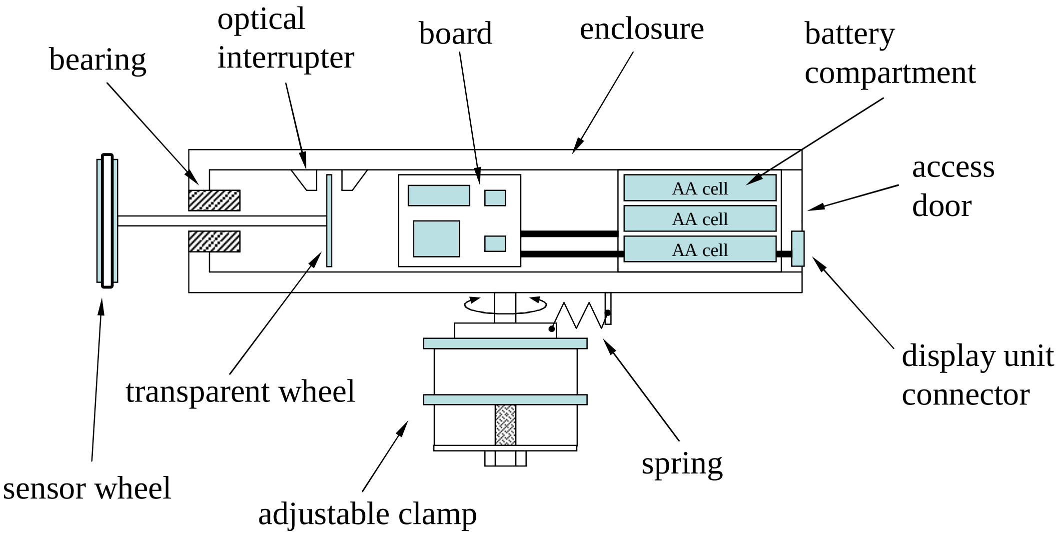

Figure 2: Conceptual diagram of the sensor unit

limits the pressure on both the bike and the sensor to safe levels. Finally, the rubber band on the sensor wheel ensures non-skid contact with the rim.

Inside the enclosure, an optical switch monitors the motion of the sensor wheel by looking for the marks on the disk made of transparent plastic, which co-rotates with the outer wheel. The rest of the enclosure is occupied by the board, which hosts the accelerometer and the signal conditioning circuitry, and the battery compartment.

The finished prototype of the sensor unit is shown in figure 3.

3.1.2 Electronic design

The complete schematic of the sensor unit can be found in figure 7 of the appendix.

Power to both the sensor and the display units come from 3 AA batteries housed in the sensor block. While in operation they provide voltage ranging from approximately $4.5V$ when fully charged to approximately $3.3V$ near the end of life. To power the circuitry this voltage is regulated down to $3V$ by the TPS7230 micropower low-dropout voltage regulator [1]. This particular regulator was chosen for its low dropout voltage (less than $200mV$), low quiescent current (less than $200\mu A$), shutdown capability, and the fact that it comes in DIP. The latter is important because if in case of the display unit we were forced to use a PCB, the sensor unit's circuitry can be assembled on a protoboard.

Velocity of the bicycle is ultimately sensed by the optical interrupter Q2. The current through the infrared diode is set by the resistor R8 and the ON resistance of the switch U5 to roughly

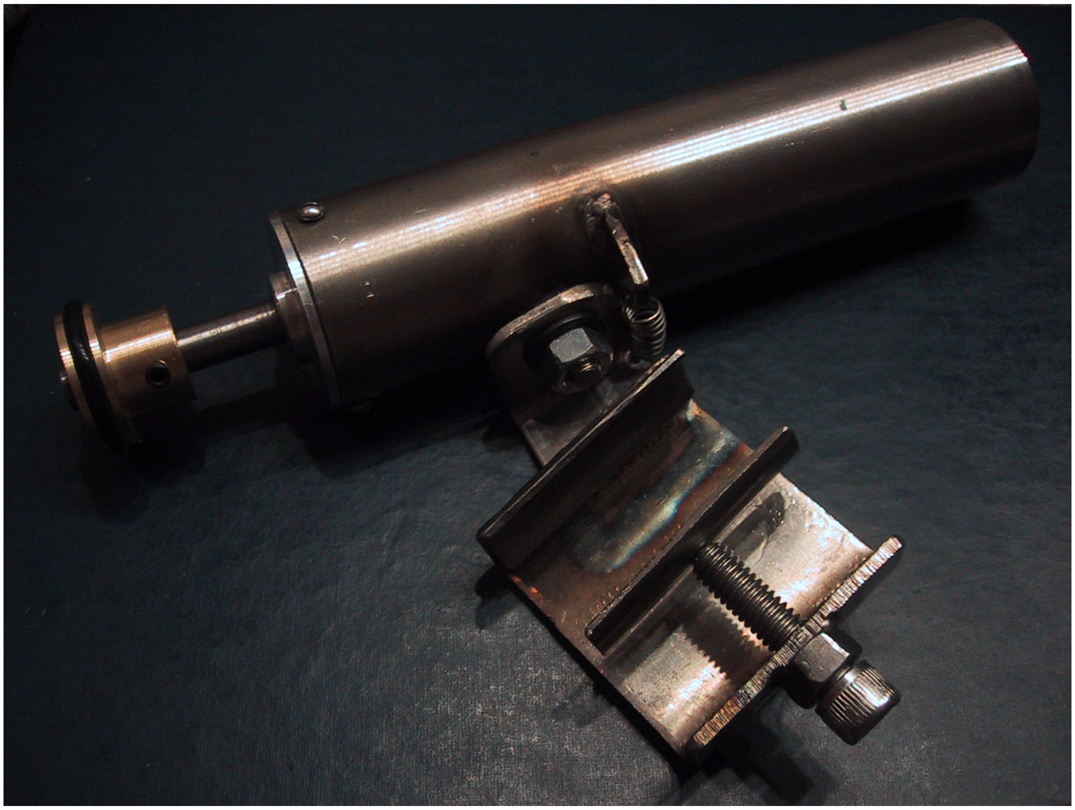

Figure 3: Completed prototype of the sensor unit

$15mA$. Resistor R10 then converts the current output of the interrupter to a voltage pulse train. The particular optical interrupter H22A3 was chosen for its relatively low operation current (diode currents upwards of $50mA$ are not unusual among optical switches) and its ability to work off $3V$ supply voltage [2].

Switch U5 allows the microcontroller to shut the interrupter down to conserve battery when not in use. The switch selection was not critical—in the end, it all came down to packaging.

The inclination sensor is implemented using ADXL320—a dual-axis accelerometer with a full-scale range of $\pm 5g$ [3]. The particular chip was selected for its low cost and optimal measurement range. The ability to measure accelerations up to $5g$ in magnitude ensures that the sensor's accuracy will not be overly affected by vibration, minor drops and jumps, or hard braking, while at the same time providing high enough sensitivity (approximately $174mV/g$) so as not to place unreasonable demands on the analog-to-digital converter that will be interpreting its outputs. For simplicity of assembly, an accelerometer evaluation board was used. It is entirely self-contained, hosting the accelerometer U8 and the filtering capacitors C8 through C10, and requiring only power for operation. The board generates a pair of voltage signals proportional to the acceleration/gravity. Since the accelerometer's output impedance of $32k\Omega$ is much higher than the maximum of $2.4k\Omega$ allowed by the microcontroller's analog-to-digital converter [4], a low-power rail-to-rail dual operational amplifier U7 is used to buffer the outputs. Virtually any rail-to-rail amplifier would work for this purpose, and we settled on MCP6002—a rail-to-rail input and output operational amplifier from Microchip—because it met all our requirements, was available as a sample, and came in DIP [5]. R11 and R12 decouple the buffers from the capacitive load of the cable interconnecting the units.

Finally, an offboard connector P3 is used to communicate with the display unit. The connector's pin assignment is described in table 1 below:

Pin	Direction	Description
1	Output	$+3.0V$
2	Output	Ground
3	Output	X-component of gravity, as reported by the accelerometer
4	Output	Y-component of gravity, as reported by the accelerometer
5	Output	Pulse train from the optical interrupter
6	Input	Interrupter enable signal from the microcontroller
7	Output	Unregulated battery voltage
8	Input	Connection sensing

Table 1: Sensor unit connector pinout

At the sensor unit, pin 8 is very weakly pulled up to $3V$. However, the same pin is connected to ground at the display unit. As a result, pin 8 informs the sensor unit whether it is connected to the display or not, and correspondingly whether it should enable its power supply or shut down to conserve battery.

3.2 Display unit

Display unit is the central processing centre of BEMS. It performs calculations on the data supplied by the sensor unit, monitors user input, and displays the information.

3.2.1 Physical design

The conceptual drawing of the display unit design can be found in figure 4.

The enclosure is a handheld 3.5” × 2.5” × 1.2” Pactec box. Holes have been made to accomodate the display, six buttons, and the cable connector. The display is an OSRAM Pictiva$^{\text{TM}}$ 128×64 OLED module [6], chosen mostly because it is capable of displaying graphics and does not need a backlight. The buttons were taken from a calculator.

The prototype display unit will attach to the handlebars with a clamp mechanism similar to the one used in the sensor unit, except non-rotating.

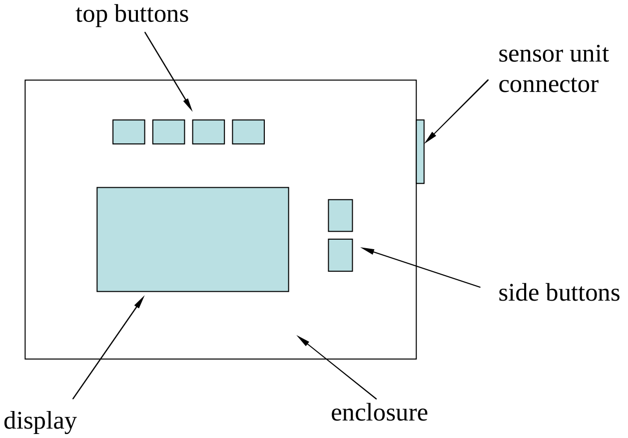

Figure 4: Conceptual diagram of the display unit

3.2.2 Electronic design

The complete schematic of the sensor unit can be found in figure 8 of the appendix.

The central element of the design is the microprocessor. For the prototype, we settled on the Microchip PIC18LF2320 [4]. The reasons behind this choice include availability of tools, such as programmers and compilers, ease of integration, sufficient number of available input/output pins, bountiful memory, and the ease of obtaining it as a sample. It is quite possible that using this particular device will prove to be excessive for BEMS—it is highly unlikely that we will make use of all of its $64kB$ of program memory or nearly $4kB$ of register memory. However, we chose to err on the safe side.

The microcontroller provides its own clock, thus obviating the need for an external crystal. However, since we are planning to vary the internal clock frequency depending on the computational demands of a particular task to reduce average current consumption, some external timing mechanism is necessary. For simplicity, this is done with a regular 555 timer U3 set up as an astable multivibrator. R6, R7, and C5 set the oscillation frequency at around $50Hz$. This frequency is then used by the microcontroller to keep track of time. Such an arrangement is not precise enough to maintain real-time clock; however, it should be sufficiently stable to not perceptibly affect the precision of the energy calculations.

All six buttons are implemented as switches with one leg connected to ground and another individually pulled up to $3V$ (nets T1 through T7 on the schematic, with T7 reserved). When closed, a particular net goes low. Priority encoder U4 detects this condition and generates the index of the corresponding button for the microcontroller.

Since the display needs $+12V$ to power the LEDs, a switching power supply based on MCP1650 boosts the unregulated voltage from the battery to $12V$. The schematic and the parts for this supply were taken directly from the datasheet for the switching regulator [7].

R1 and R3 halve the unregulated battery voltage, so the microcontroller can sample it and use it to estimate the remaining charge of the batteries. This method is not perfect, but it is simple to implement and it should provide the user with at least some information regarding the state of the batteries.

Finally, connector J1 is used to connect the Pictiva display to the board—its pinout was taken directly from the design datasheet of the display (not publicly available); connector P1 is used to link the display and the sensor units—its pinout matches the one in table 1, and connector J2 is used to perform in-circuit programming and debugging of the PIC microcontroller.

3.3 Inter-unit cable

The cable connecting both units is an 8-wire cable with male DIN plugs on both ends. Prototype cable will be unshielded. The wires will either be merely braided or put through a length of heatshrink, depending on the thickness of the bundle.

4 Firmware design

4.1 Interpreting sensor data

Information regarding bicycle velocity comes to the microprocessor in the form of a pulse train with each pulse signifying one centimeter of movement. The pulses are counted by the PIC microcontroller's asynchronous hardware counter T1, and the number of pulses per unit of time set by the timer U3 is then used to estimate the instantaneous velocity of the bike. Since the raw result of such computation is expected to be rather noisy, the velocity information will be filtered by a simple digital low-pass filter before use.

The microcontroller receives the current inclination in the form of two perpendicular components of gravity, as shown in figure 5 for the case of a stationary bike. These components are digitized by the built-in analog to digital converter and then analyzed to extract the current angle of incline.

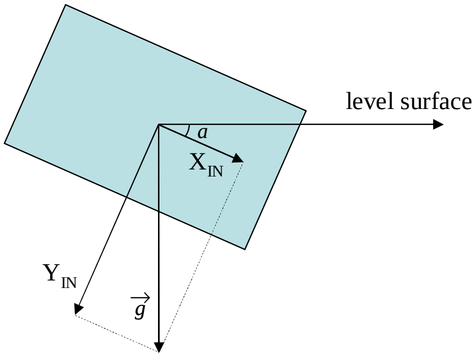

Figure 5: Interpreting the X_{IN} and Y_{IN} signals

In this case, the angle of incline α can be calculated as $\alpha = \tan X_{IN}/Y_{IN}$. In reality the bike will not be stationary when measurements are performed, thus the bicycle acceleration will have to be removed from the gravity components before applying the formula above. Luckily, doing so is a simple matter of subtracting the acceleration obtained by differentiating the data from the velocity sensor from X_{IN}.

4.2 Computing energy expenditure

With information about the current velocity v, measured acceleration a_m, and the angle of incline α of the bicycle at hand, the instantaneous power expended by the rider can be estimated by comparing the measured acceleration a_m with the acceleration expected given the current incline $a_e = g \sin \alpha$. This gives the force estimate F developed by the cyclist as $F = M(a_m - a_e)$, where M is the combined mass of the cyclist and the bike. Finally, the instantaneous power is

$$P = \max\{Fv, 0\} = \max\{Mv\left(a_m - g\sin\alpha\right), 0\} \tag{1}$$

Integrating P over time gives the total energy expended by the rider. To ensure that the no information is missed due to undersampling, the calculation will be performed at least ten times a second—every fourth cycle of the timer.

While the expression derived above does not account for air resistance or for variations in the surface types (the latter can potentially be estimated from the power σ_n^2 of the high frequency noise in the accelerometer outputs), these effects can be added as empirical “fudge factors,”, such as $F = M\left(a_m - a_e\right) + k_a v^{\beta_a} + k_r \sigma_n^{\beta_r}$, where k_a, β_a, k_r, and β_r are experimentally determined coefficients. Refinements of this sort are certainly possible and will be considered if time permits.

4.3 User interface

The cyclist will interact with BEMS using the six buttons positioned around the display. The buttons will not have fixed functions. Instead, their current function will be shown on the display beside the buttons themselves. The main display will look very similar to figure 6.

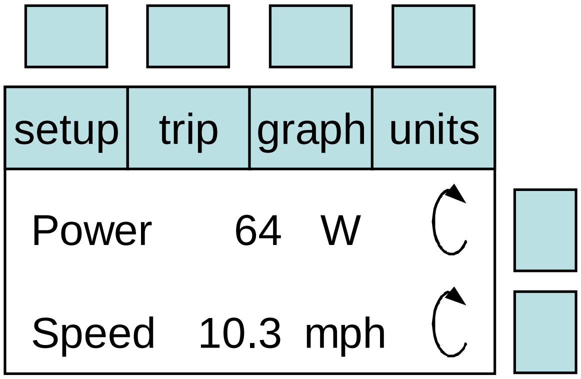

Figure 6: Main display

From figure 6, it can be seen that pressing either of the four buttons above the display will invoke the corresponding menu of functions, while pressing the buttons on the right side of the display will cycle through the list of available measurements.

The exact behaviour of the interface has not yet been finalized—refinements will be made as the development progresses. However, the basic functionality of the interface will reflect Section 2.6 of *Functional Specifications for a Bicycle Energy Measurement System*.

4.4 Power saving features

In its current form, the design incorporates several features, which will allow the microcontroller to selectively reduce the power consumption of BEMS depending on circumstances. If the microcontroller detects that the bicycle has been stationary for some preset period of time, e.g. 10 minutes, it will disable the screen and the optical interrupter and reduce the frequency of its internal clock to approximately $32kHz$. Doing this lowers the current consumption of the entire product to approximately $1.5mA$, which a set of rechargeable batteries can provide over a period of two months. BEMS will resume normal operation if the accelerator detects a movement or if any of the buttons are pressed.

Current consumption of BEMS during normal operation is estimated to be approximately $50mA$–$80mA$ depending on the percentage of lit pixels on the display. Given $2200mAh$ rechargeable batteries, this sets the expected operation time to at least 27 hours on a single charge.

5 Test plan

Initially, each of BEMS's units will be tested independently. When the basic functionality of both units has been verified, they will be connected and testing of the whole product will proceed.

5.1 Preliminary hardware test plan

5.1.1 Power supplies

Both the logic and OLED power supplies will be tested to confirm that they are capable of indefinitely sustaining the full range of expected loads and at least a 50% overload without going out of regulation or overheating. Short-circuit testing will not be carried out for fear of destroying the components.

5.1.2 Sensors

The optical encoder assembly will be tested to ensure that it produces a stable pulse train with no spurious transitions in response to motion. Rise and fall times will be tested to ensure proper operation at velocities of up to $100mph$ (equivalent to rise and fall times not exceeding $100\mu s$).

Accelerometer will be tested to verify that it generates appropriate signals in response to changes in orientation.

5.1.3 Shutdown logic

Shutdown of the sensor unit's power supply upon disconnection from the display unit and the proper operation of the optical interrupter's switch will be tested to ensure correct functionality.

5.1.4 Timer

The timer will be tested to ensure that it generates a stable square wave with a frequency of appproximately $40Hz$ to $60Hz$ with negligible day-to-day drift.

5.1.5 Buttons

Buttons will be verified to generate appropriate inputs to the priority encoder. Additionally, priority encoder will be tested to generate correct outputs in response to button presses.

5.1.6 Microcontroller

The microcontroller will be tested to respond to in-circuit programming and debugging. Also, its ability to receive information from the priority encoder and the timer will be verified.

5.1.7 Display

Display will be tested to respond properly to the microcontroller signals. We will verify the ability of the microcontroller to write data to and read data from the display. Lighting individual pixels will also be tested.

5.1.8 Inter-unit cable

The cable will be tested for proper pin assignment and connectivity.

5.2 Hardware test plan of BEMS as a whole

5.2.1 Communication with the sensor unit

The ability of the microcontroller to properly receive information from the sensor unit will be verified. This will involve testing that the processor counts the pulses from the optical encoder properly and that it correctly digitizes the accelerometer's outputs.

Additionally, the ability of the microcontroller to disable and then re-enable the optical encoder at will will be tested.

5.2.2 Operation time on a single charge

To test the operation time on a single charge, power saving functionality of BEMS will be temporarily disabled, and it will be left working in what will be considered to be the most power intensive mode. The time it takes for the device to cease normal operation will then be taken as the desired value.

5.3 Firmware test plan

5.3.1 Sensor data interpretation

The firmware will be tested to correctly interpret data received from the sensors. It must report the correct angle of incline whether the bicycle is moving or not, and it must also report appropriate velocities when in motion. Correctness of the velocity computation will be tested using a commercial bicycle computer, while the correctness of the angle computation will be verified using a level and a protractor.

The acceptable tolerances of individual measurements are yet to be established; however, the tolerance of the overall result is specified in the functional specification.

5.3.2 Energy and power calculation

Currently we have no method of directly testing the energy calculations under all conditions; however, in certain situations theoretical results are available. One such setting is riding up a hill in the absence of wind and stopping at a known height. In this case, theoretical energy expenditure can be calculated as a function of the height and the combined mass of the bike and the cyclist, and this can be compared against the result produced by BEMS.

We will also consult the Department of Kinesiology at the Simon Fraser University regarding availability of more precise testing approaches.

5.3.3 User interface

The user interface will be tested to ensure that it provides the rider with convenient means of accessing different features of BEMS and adjusting settings. We will also ensure that the response delay of the interface is imperceptible to the user under all operating conditions.

5.4 Overall system test plan

The entire unit will be mounted on a bike and taken for test rides by the employees of Exigo Technologies. If time permits, the unit will also be tested by objective bystanders. The unit will undergo testing in different riding conditions. Different weather conditions, such as wind, will be tested as well as road conditions, such as pavement and gravel. Riding on different inclinations will be tested as well.

The proof of concept device will not undergo testing in heavy rain as it will not be completely waterproof.

6 Conclusion

This document outlines the design specifications for the proof-of-concept device. The design approach proposed in this document describes how we plan to implement the functionality specifications covered in the *Functional Specifications for a Bicycle Measurement System*. The proof-of-concept device is scheduled to be tested in December. Once it is complete, this document will serve as a guide to assist in further development of the product.

A Schematics

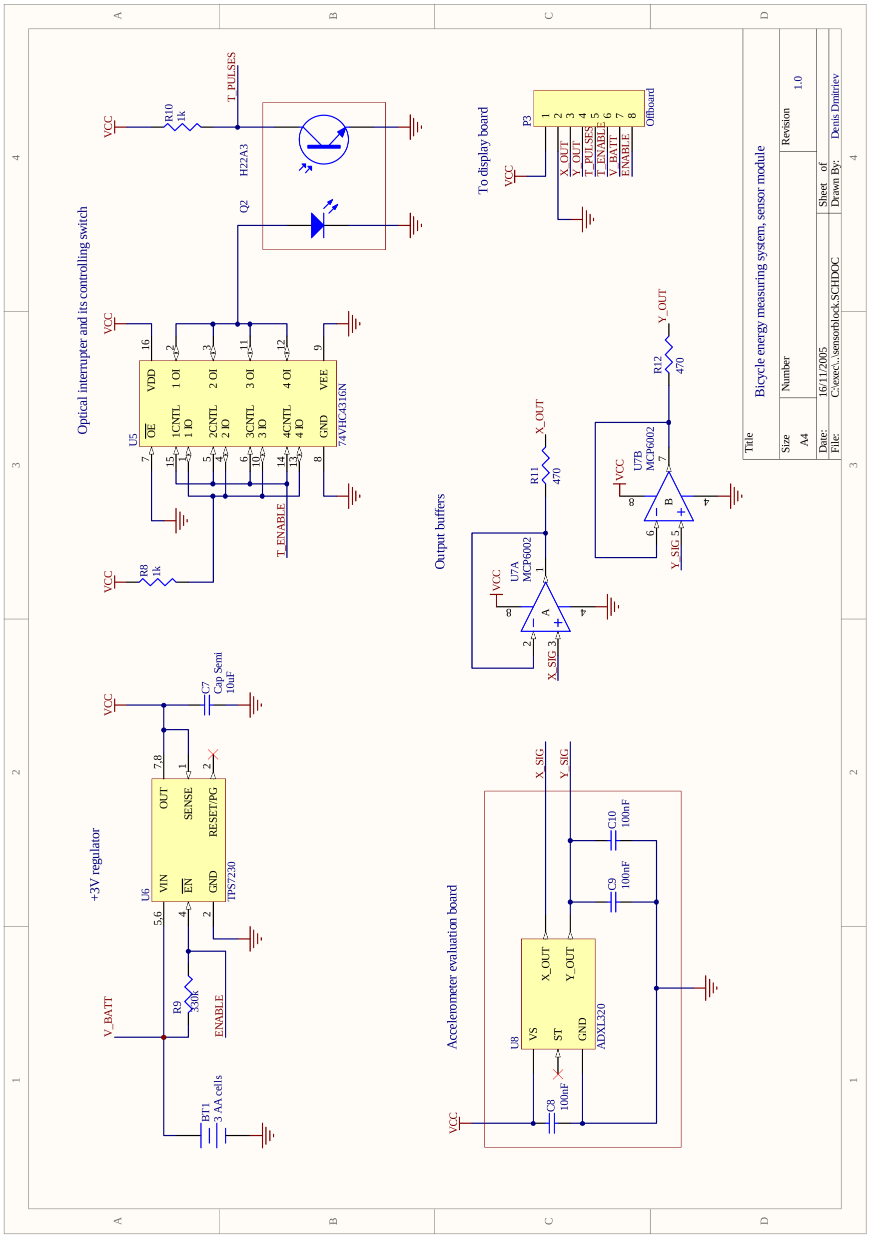

Figure 7: Sensor unit schematic

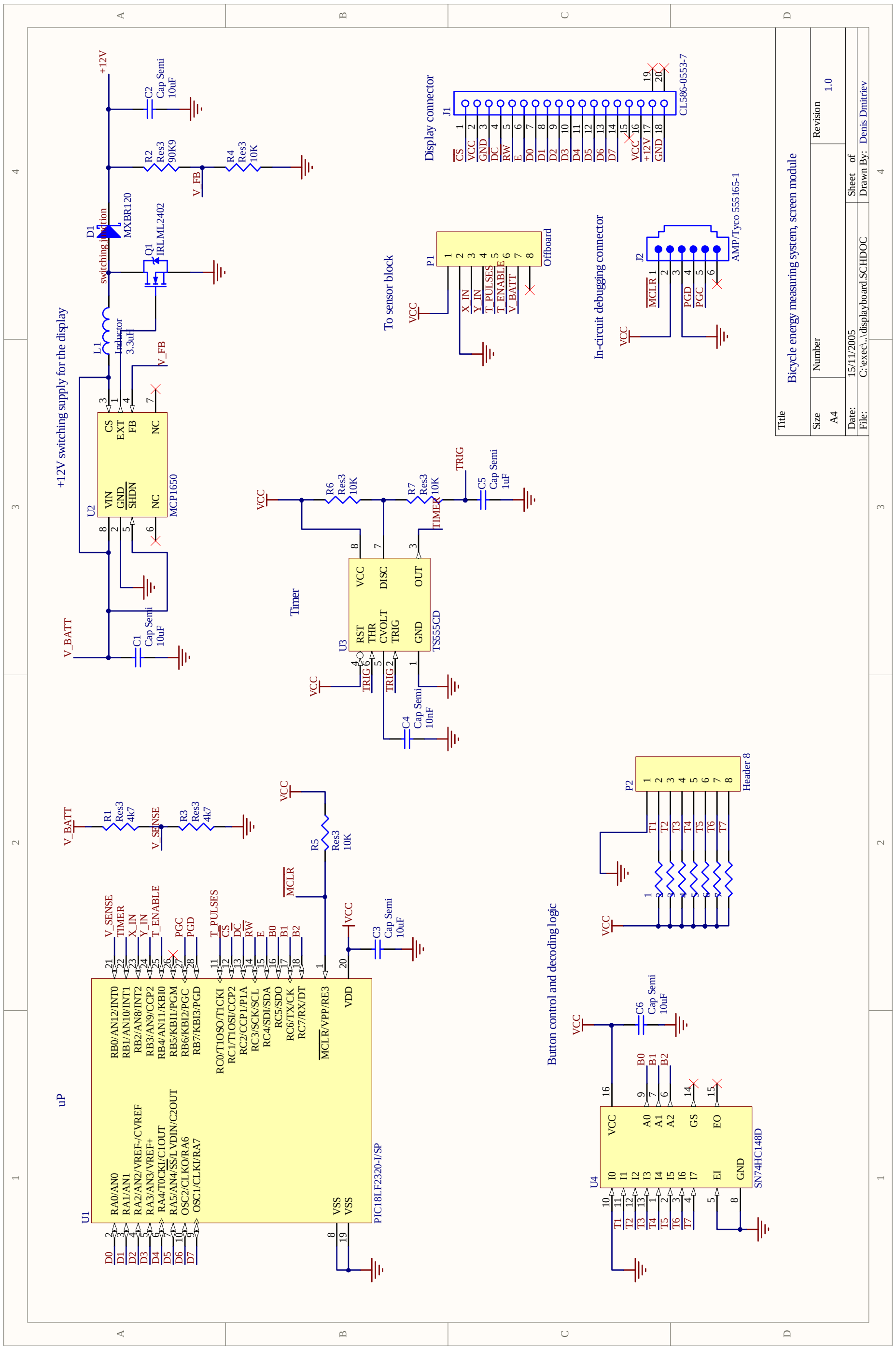

Figure 8: Display unit schematic

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