Boston University
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Rooftop Solar Monitoring System

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Abstract

Solar energy systems are becoming increasingly popular as the world moves toward a common goal of environmental conservation. Photovoltaic system deployers seek to reduce its operating costs while improving performance of these systems. One way of accomplishing this task is to create a solar energy monitoring system to analyze the productivity of their rooftop solar panels and be updated on their situation wirelessly.

Solar power systems are commonly employed on building roof tops. Currently, the only way for the company to analyze solar panel performance is to send someone to the roof with a single solar sensor. Typically, measurements are made only upon initial installation, and there is no long-term data analysis for the solar panels. We seek to create a viable system that allows daily updated analysis on the light intensity of each solar panel during the day and to be able to monitor any unexpected fluctuations that could be an indication of a problem requiring maintenance.

Our solution uses a wireless mesh network comprised of Moteiv T-mote sky wireless motes that can measure parameters including light intensity, battery voltage, and temperature; and transmit that information to a base station. Subsequent analysis of the collected data can then be performed by a user accessing the system.

The system can alert an operator of any of any physical obstacles, which may get in the way of sunlight, and it also allows the company to get updated information of the current readings of each panel thus providing a way to ensure the system's performance and prevent degradation.

Introduction and Background

Solar energy is one of the highest technologically exploitable potential of all the types of regenerative energy. As a growing environmental and economical concern, seeking alternative energy sources has become an extremely important issue, and solar energy is on the forefront.

Our sponsor has expressed that it is eager to maximize energy production per dollar invested. As a result, a new rooftop solar energy monitoring system was proposed to replace the old system of solar energy monitoring. Currently, measurements made to monitor the rooftop solar panel's energy are performed manually upon the initial installation through a single solar sensor. No long term monitoring is available for a changing roof environment. If new measurements need to be taken, workers need to be hired to climb to the roof and check manually. This task is as tedious as it is expensive.

Our team's project is to create a low-power wireless rooftop solar energy monitor system using motes, to create a two-dimensional grid of data displaying light intensity and energy. The system helps maximize energy production at a low cost to the company. We

want to minimize costly trips to the roof by using motes to wirelessly relay any data about environmental feedback to an easily accessible PC. Our system will look similar to the illustration in figure 4. Using motes with attached sensors, wireless solar monitoring units will be created and placed on each panel. Each monitoring unit will report its collected data to a nearby base station wirelessly, which will be remotely accessed by a PC or laptop for easy analysis and interpretation.

The system will be used to sense solar energy, intensity, and temperature. Time values and location will also be added to the data to analyze environmental degradation. The data will be logged to a nearby base station wirelessly, and the output will be remotely accessed through a PC. A graphical snapshot of relative sunlight intensity, energy, and temperature will be the final result. The new system will provide far more data than a single sensor, and also save time and money.

The new monitoring system technology will ultimately be available for many different applications. The system can be used as a preliminary test for placement of solar panels to maximize the energy absorbed by each panel. The monitoring system will also be able to be installed in existing rooftop solar panels to measure performance and identify obstructions. The technology can be used in many environmental applications to detect environmental events. Future upgrades to the system could include warning messages from the base station in response to specific detected events.

System Overview

Physical Description

T-Mote Sky:
The heart of the system, Tmote Sky, is a low power "mote" with integrated sensors, radio, antenna, microcontroller, and programming capabilities.
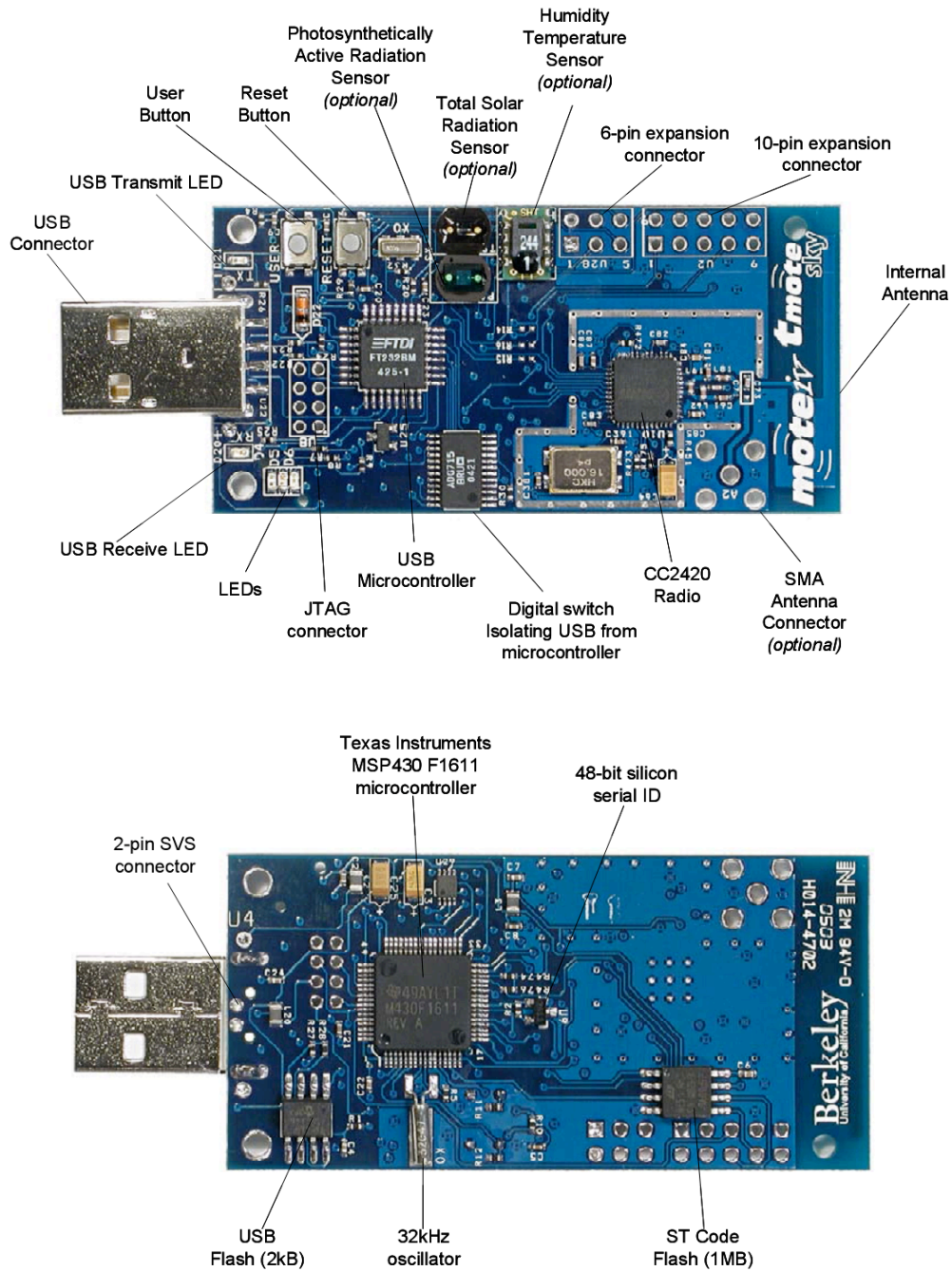
Figure 1: Front and Back of the Tmote Sky Mote

PCB: Sensor and Power Supply Circuit:

Sensor Circuit:
The solar radiation sensor circuit momentarily disconnects the solar panel from the power supply using a relay and connects it to a 0.22Ω resistor. Using an Operational Amplifier

we amplify the voltage across the small resistor to a level suitable for the A/D converter on the MCU.

Power supply:
Our solar panel will provide a maximum of 200mA at 3V. Then a switching type (step-up) DC-to-DC converter will step up the voltage from the solar panel to 3.3V and charge the batteries when needed.

Figure 2: Front of the Printed Circuit Board that includes one of the two super capacitors, the mote's connector, DC/DC converter, operational amplifier, resistors, and filter capacitor.
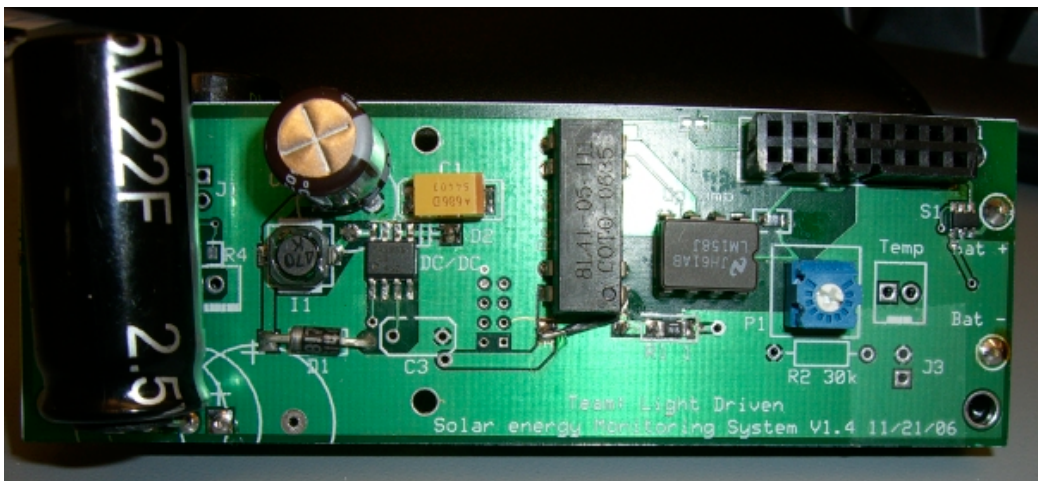
Figure 3: Back of the Printed Circuit Board that include second super capacitor the rechargeable batteries and the analog switches.

Enclosure

The box that houses the system is made by Hammond Mfg. (model # 590WSF). It is a die-cast aluminum box, has a silicon gasket and is IP65 rated. The reason we use a metallic enclosure is its better heat transfer characteristics and more resilience in harsh conditions. Also the side walls of the box have a low draft angle (2 degrees or less) that allows the precisely measured PCB to snugly wedge in the box with no need of any special mounts. Finally the box has a bottom flange that greatly simplifies mounting.
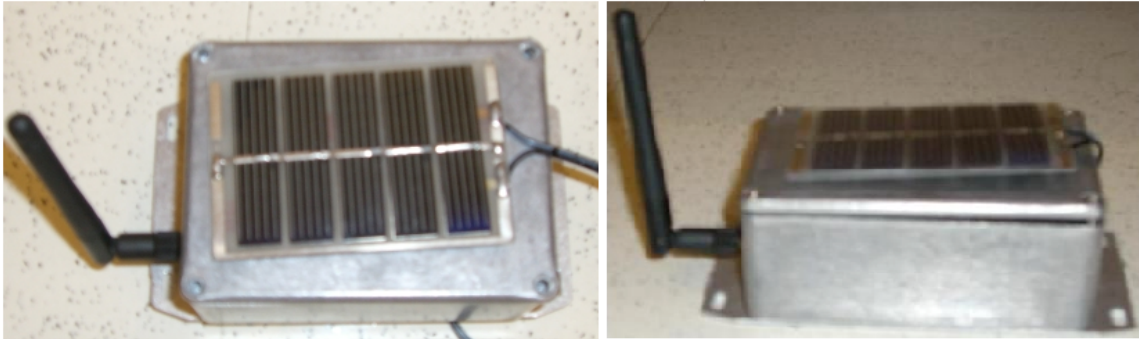

Figure 4: Final Enclosure Setup

Figure 5: PCB and Mote mounted inside the enclosure

Field placement

Every node is comprised from a Telos mote, a battery pack and a circuit board that will include the power supply and the sensing circuit, all packed in a small aluminum box. The node's solar panel will be mounted on as separate piece on the main solar cell array that could also serve as a mount for the antenna for increased range. A pair of stainless steal clamps will be used to attach the small solar panel to the main panel.

The electronics box should preferably be located under the main panels to take advantage of the shade created by the panels. Possible locations: On the support structure that holds the main panels or on the underside of the panes.
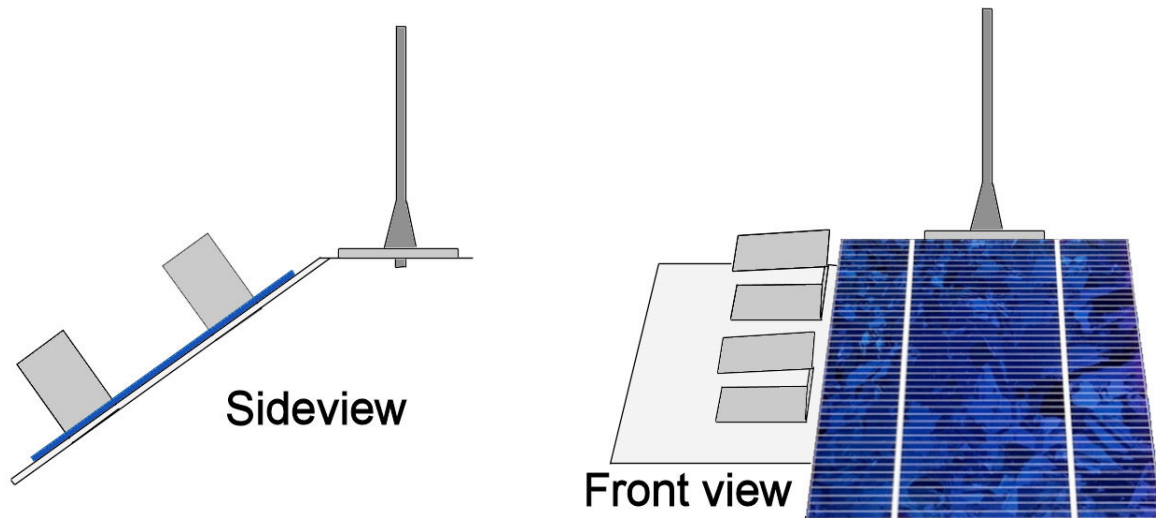

Figure 6: Small solar panel with mounting bracket.

Specifications

Specification	Value, range, tolerance, units
System operating voltage	2.1V - 2.6V
Max allowed solar panel voltage	3.4V
Max allowed solar panel wattage	0.5Watts
Radio frequency	2.4Ghz
Enclosure	Diecast aluminum alloy, IP65 rated
Systems life expectancy	2 Years
Mote radio range	100 feet / 30 meters
Operating temperature	-20 to 60 °C
Operational Amplifier Gain range	2-100

User interface

Matlab, and Tmote tools should be installed on the computer first. The user interface is designed to make logging and analysis of the data simple for the user. Open the directory where the installation took place. Open the file DataAcquisition.fig. A grey screen will pop up with three push buttons and a graphical panel. It will look like this:
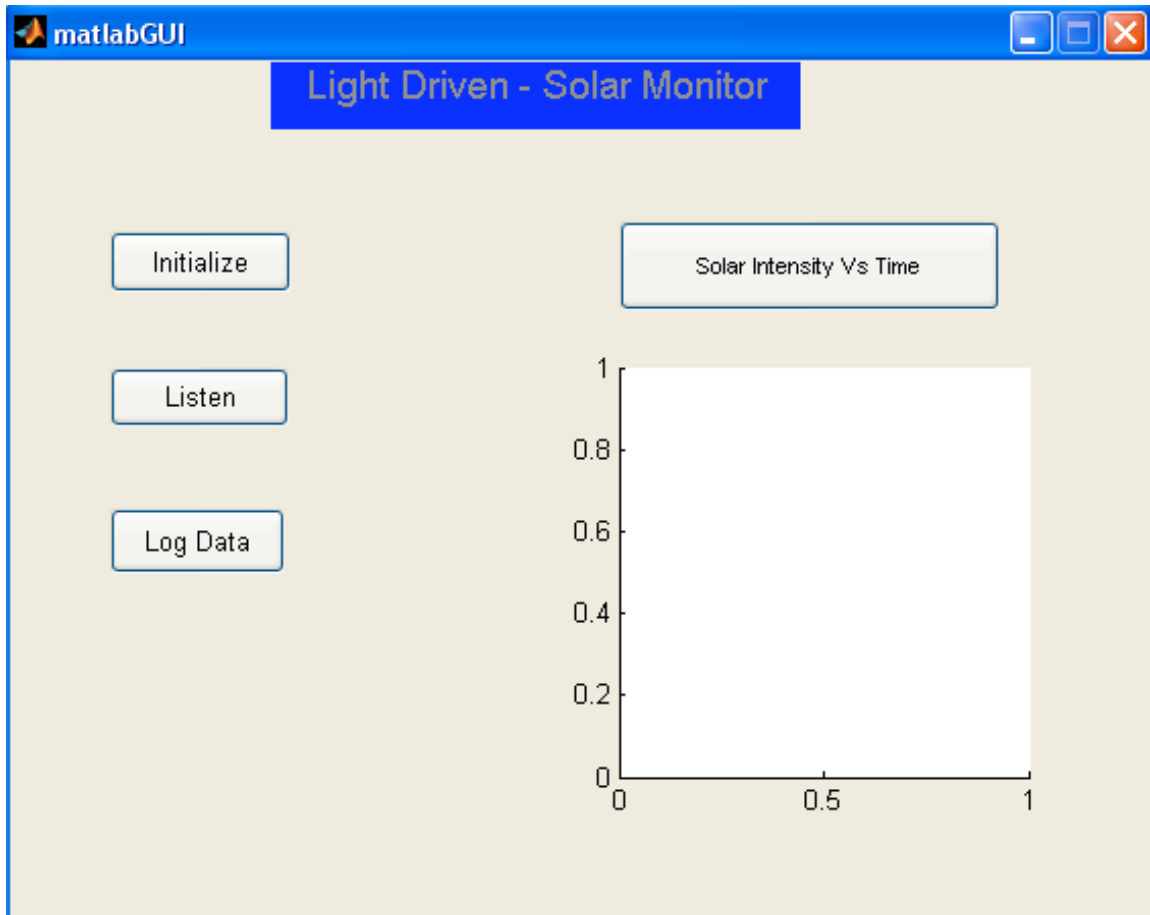
First push the initialize button. This connects the serial port from the computer to the mote spitting raw data packets. Once this is done, press the Listen button to collect the raw data. The listen button allows the data packets to be logged in a clean format organized by byte. Once you have logged enough data press log data to get a plot of the solar panel voltage vs. time.
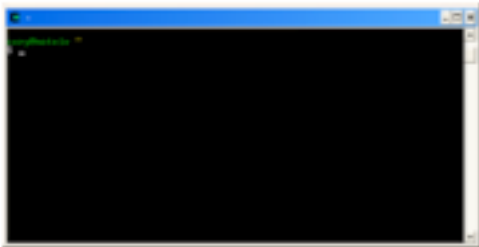
Displaying Live Data

Connect the base station mote to the usb port of your computer. Power on all other motes with rechargeable alkaline batteries

Open a shell, invoke the Cygwin shortcut that the installer placed on your desktop.

This is an initial Cygwin bash shell prompt. The installer configures

Use the motelist utility to show which COM ports actively have Tmote modules. Just type "motelist" at the command prompt:

Then type:
 MOTECOM=serial@COM3:tmote java

com.moteiv.trawler.Trawler

This example uses COM3. Yours may vary depending on what COM Port used. A java screen will come up with sensor data for each onboard sensor for every mote.

When Trawler starts, it will begin the process of establishing an ad-hoc mesh network and display the network topology on the screen.

Be patient, it may take several minutes for the entire network to come online and establish stable, reliable routes to the Tmote device connected to your PC.

Trawler will have Sensor Readings tab displaying all sensor data.

Trawler also includes network topology and Mesh network data.

Matlab Configuration

Matlab can be configured to connect directly to TinyOS through Java.   This is how the data logging and analysis will be performed. To configure matlab to work with java follow these instructions:

Edit Classpath in Matlab:

• Add 'comm.jar' to 'c:\tinyos\cygwin\opt\tinyos-1.x\tools\java'.

- Open Matlab classpath by Typing edit classpath.txt , and add the line :

    c:/cygwin/opt/tinyos-1.x/tools/java/comm.jar

- **Replace all contents startup.m with this :**

[flag, value] = system('ncc -print-tosdir');

run('C:/cygwin/opt/tinyos-1.x/tools/matlab/defineTOSEnvironment.m');

cd C:\cygwin\opt\tinyos-1.x\tools\matlab;

- **Replace TOSDIR in defineTOSEnvironment.m with the correct directory of Matlab**

addpath([TOSDIR '/../tools/matlab']);
addpath([TOSDIR '/../tools/matlab/comm']);
addpath([TOSDIR '/../tools/matlab/apps']);
addpath([TOSDIR '/../tools/matlab/lib']);
addpath([TOSDIR '/../tools/matlab/util']);
addpath([TOSDIR '/../tools/matlab/tools']);

becomes:

addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab');
addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab/comm');
addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab/apps');
addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab/lib');
addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab/util');
addpath('C:/cygwin/opt/tinyos-1.x/tools/matlab/tools');

- **Replace Group ID with correct group ID programmed on the motes (7d):**

    o   defineTOSEnvironment.m
COMM.GROUP_ID = hex2dec('7d');

    o   defineCOMM.m
elseif ~isfield(COMM,'GROUP_ID')
    COMM.groupID=hex2dec('7d');

- **Add 'jmi.jar' to classpath in cygwin type:**

CLASSPATH="${CLASSPATH};c:\MATLAB6p5\java\jar\jmi.jar"

- **Since using MATLAB7 patch MatlabControl.java with MatlabControl-R13-R14.patch provided by TinyOS:**

  o cd C:\cygwin\opt\tinyos-1.x\tools\java\net\tinyos\matlab
  o Apply patch MatlabControl-R13-R14.patch

Setup for Data Acquisition and analysis

The installation CD-ROM includes the required applications and files for data acquisition.

To collect data follow these steps:

- Open Matlab

- Run defineTOSEnvironment.m to initialize the Java settings and Matlab Configurations.

- Run xlisten_tmote_delta.m*

- Type Ctrl C to end the data collection

- Run reading_delta_data.m*

- Your data is now saved in the specified file in "reading_delta_data" by default in delta_data.txt.

- *note that the file which xlisten_tmote_data.m writes into and the file which reading_delta_data.m reads from have to be the same as it is setup by default to logged_data.txt.

Operation of the Project

Operation Mode 1: Normal Operation
- The first step is to connect the base station mote to the base station computer that will log and process the information.
- The next step is to prepare and power on the individual nodes by connecting the small external solar panel and external antenna to the corresponding connectors and installing the batteries. The LED on the mote will start to blink red indicating that the system is active and in full power operation.

In normal operation, the motes automatically establish a mesh network and find the quickest path to the base station. Data is sent through RF to the base station mote periodically with a 1% duty cycle by default. With each LED blink, a packet of data is sent to the base station. Bad packets are automatically dropped. Every time each mote is

active it will send around 14 packets before it goes back into low power operation. In a full day the system will be active for about a total of fifteen minutes.

Operation Mode 2: Low Power Operation
99% of the time the system will be in low power mode. During low power mode the LED will be continuously illuminated. During low power mode, the mote will not be sending data over RF. The radio module consumes most power so the low power mode allows the system to conserve power (80% less power). During low power mode, the system switches from sensing to charging the battery if necessary.

Safety Issues
The major safety issue is the overheating of the system due to extreme sunlight exposure. Overheating inside the enclosure can cause batteries leakage. Battery's chemicals are toxic. Also, this can cause pressure buildup inside the box, requiring caution when servicing the system.

Technical Background

Tmote Sky
Our system is based on the Tmote Sky by Moteiv. It is a mote platform for low power, high data-rate sensor networks. It futures a powerful low power MCU by Texas Instruments, a large on-chip RAM size (10kB), IEEE 802.15.4 radio, and an integrated on-board antenna providing up to 125 meter range. It has a number of integrated peripherals including a 12-bit ADC and DAC, Timer, I2C, SPI, and UART bus protocols, and a performance boosting DMA controller. Also it may be wirelessly programmed for extreme flexibility. Finally it provides an easy-to-use USB protocol for programming, debugging and data collection.

Current sensing
The circuit uses a total of 0.21Ohms of resistors to sense the short circuit current of the solar panel. When sensing, the solar panel is isolated from the power supply using an SPDT reed relay. The internal resistance of the relay has been accented for in the total current sensing resistance to minimize the error. Then the small voltage drop across the relay and the resistor is amplified by a very low offset voltage Op Amp made by National Semiconductors (LM158J). The gain can be adjusted by a variable resistor to mach the solar panel in use.

Power supply
The main component of the PSU is the MAX856 step-up DC/DC converter. It can tack an input from as low as 0.7V up to 3.3V from the solar panel and step it up to 3.3V. This allows the system to charge the batteries even in low light conditions. The converter is controlled by the mote's internal voltage supervisor circuit that constantly monitors the incoming voltage and accordingly decides to charge the batteries. The threshold is set at 2.85V. The batteries are two AA rechargeable alkaline batteries made by Pure Energy Battery .inc.

These batteries have a very low self-discharge rate and 1.5V nominal voltage.

Capacity Loss	PE-XL	Reg. Rech. Alkaline	NiCd	NiMH
20°C/month	<1%	1%	20%	25%
45°C/month	3%	5%	60%	80%
65°C/month	10%	20%	100%	100%
Shelf Life	7 yrs.	5 yrs.	charge prior to use	charge prior to use

Figure 7: Rechargeable technology self discharge comparison.

Also their capacity is less affected from the extreme temperatures that this system may encounter.
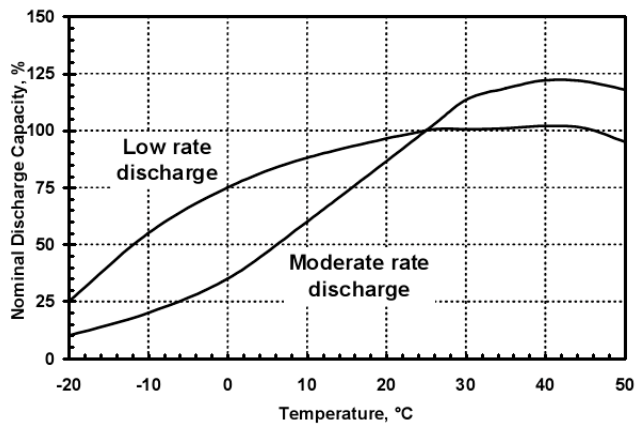

Figure 8: Effect of Temperature on Capacity of
XL RECHARGEABLE ALKALINE Cells**.**

Even thought alkaline rechargeable batteries have generally a low number of charge-discharge cycles, if they are not discharged more that 20% in every cycle they can provide more that 500 charge-discharge cycles.
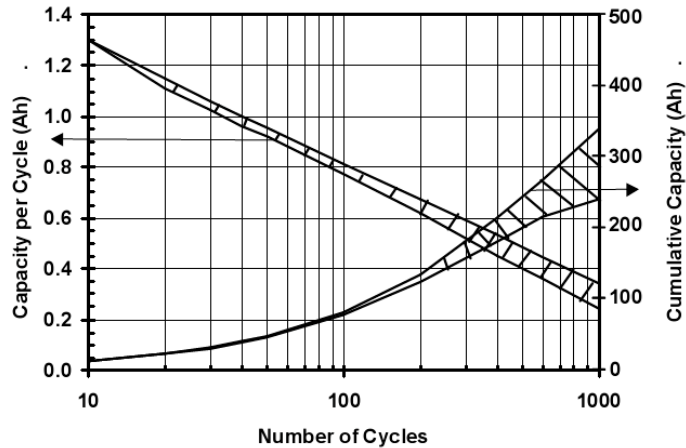
Figure 9: Performance Range of XL RECHARGEABLE
ALKALINE AA Cells as Function of Depth of Discharge on
Cycling, Full Recharge after each Shallow Discharge.

The batteries are complimented by two 22 Farad, 2.5V rated super capacitors in series to reach a 5V max voltage. These capacitors can power the system for at least 24 hours tacking it through the night without draining the batteries at all. This will decrease the number of charge-discharge cycles imposed on the batteries and greatly increase their lifespan. To control the energy source the mote monitors the voltage of the capacitors and when they have enough charge, it switches power to them. The system was designed based on the weather patterns in the Boston area.
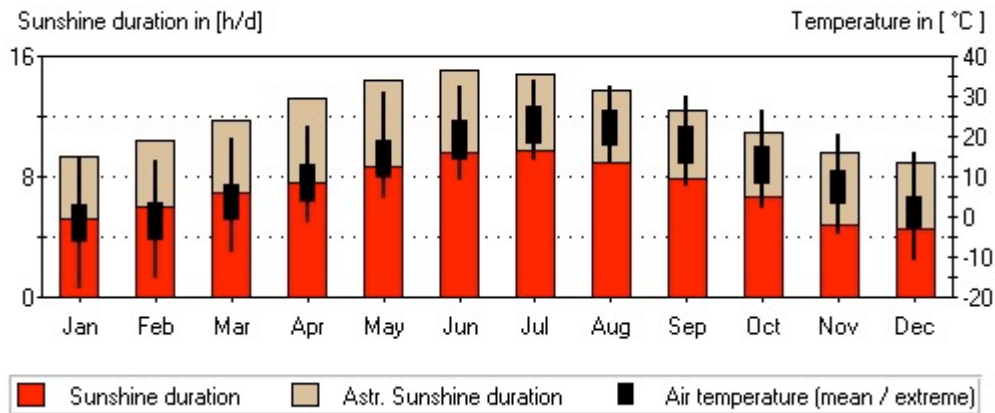

Figure 10: Sunshine duration in Boston.

Power Handling
All components have individual analog switches that only power them when they are needed. This minimizes the wasted power and maximizes battery life. The switches are low power mosfets that were designed for function. Four different models were used in this project.

Budget

Item	Description	Q.	Unit Cost ($)	Total Cost ($)	BU provided ($)	Group2 ($)
1	Moteiv T- mote sky	3	130.00	390.00	390.00	0.00
2	External Antenna	1	9.99	9.99	0.00	9.99
3	Solar panel	1	24.95	24.95	0.00	24.95
4	Temperature sensor	1	3.81	3.81	0.00	3.81
5	Rechargeable Batteries	12	1.75	21.00	0.00	0.00
7	Hammond 1590WSF Enclosure	1	15.13	15.13	0.00	15.13
9	PCB	1	198.25	198.25	0.00	198.25
10	Super Capacitors	2	14.70	29.40	0.00	29.40
11	Relay	1	7.02	7.02	0.00	7.02
12	Op Amp NS LM158J	2	6.45	12.90	0.00	12.90
13	Various electronics		100.00	100.00	0.00	100.00
14	SMT to DIP adapters	4	18.00	72.00	0.00	72.00
	Total					**473.45**

Attachments

Fig. 11: Solar Panel

Fig. 12: Solar Panel with Motes
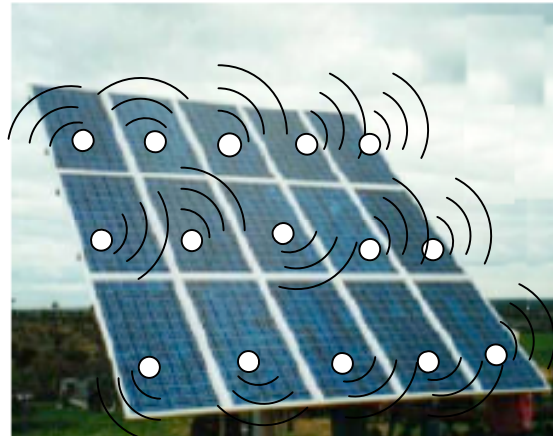
METEONORM Version 5.1

Site:	Boston US		
Situation:	sea/lake		
Horizon:	astronomic		
Type	Cities	Format	METEO

Month	Ta	Ta min	Ta dmin	Ta dmax	Ta max	RH
Jan	-1.9	-18.0	-6.6	2.9	14.3	60
Feb	-0.9	-15.4	-5.9	3.4	13.9	58
Mar	3.6	-9.0	-1.1	7.8	19.7	58
Apr	8.8	-1.5	3.5	13.2	22.6	57
May	14.5	4.7	9.4	19.0	30.9	61
Jun	19.7	8.8	14.0	24.1	32.6	65
Jul	23.0	14.1	17.9	27.5	34.2	65
Aug	22.1	13.5	17.4	26.6	32.5	67
Sep	18.1	7.6	13.1	22.3	30.1	68
Oct	12.7	2.0	7.8	17.6	26.5	64
Nov	7.3	-4.6	2.8	11.6	20.4	63
Dec	0.9	-11.2	-3.6	5.2	15.9	62
Year	10.7					62

Month	H_Gh	SDm	SDd	SD astr.	RR	RD	FF	DD
Jan	58	163	5.3	9.3	93	9	5.8	293
Feb	75	168	6.0	10.4	93	8	5.8	293
Mar	115	214	6.9	11.8	96	9	5.9	293
Apr	141	227	7.6	13.2	92	9	5.6	293
May	174	267	8.6	14.4	84	9	5.1	203
Jun	184	287	9.6	15.1	81	8	4.7	248
Jul	187	301	9.7	14.8	74	7	4.7	248
Aug	166	277	8.9	13.7	85	8	4.5	248
Sep	127	237	7.9	12.3	81	7	4.8	248
Oct	93	206	6.6	10.9	85	7	5.1	293
Nov	57	143	4.8	9.6	109	9	5.3	293
Dec	47	142	4.6	8.9	104	10	5.4	293
Year	1423	2630	7.1		1077	100	5.2	274

Legend:

Ta:	Air temperature	RH:	Relative humidity
Ta min:	10 y minimum (approx.)	Ta max:	10 y maximum (approx.)
Ta dmin:	Mean daily minimum Ta	Ta dmax:	Mean daily maximum Ta
SD:	Sunshine duration	RR:	Precipitation
RD:	Days with precipitation	FF:	Wind speed
SD astr.:	Sunshine duration, astronomic	DD:	Wind direction
H_Gh:	Irradiation of global radiation horizontal		

Temperature in [°C]
Wind speed in [m/s]
Sunshine duration in [h/day]
Radiation in [kWh/m²]