

Self-Sustaining Meteorological Wireless Sensor Networks

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Abstract: Greater distributed production of energy from renewable resources such as solar radiation has increased fluctuations of power on the electrical grid. Current infrastructure has limited ability to handle continued increases in fluctuations. Predicting weather patterns in areas containing a high penetration of solar photovoltaic installations can allow time to switch to energy storage and inform consumers to conserve energy thereby mitigating such fluctuations. Accurate prediction requires data at a high spatial and temporal resolution in hard-to-access areas such as on the rooftops of commercial and government buildings. A low-cost, autonomous, and easily maintained meteorological sensor network can meet these requirements. Through rapid prototyping techniques, specifically in-house 3D printing and open-source technologies, sensor modules are reported that achieve a high degree of durability under direct sunlight and high thermal loads while accurately measuring parameters such as temperature, pressure, humidity, and solar irradiance. The modules are inexpensive, portable, and self-powered. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Self-sustaining, Smart grid, Built environment, Meteorology.

1. Introduction

As of the third quarter of 2012, the United States (U.S.) had an installed peak capacity of 5.9 GW of solar power with an annual increase in utilization by an estimated 70 % [1]. Various facilities have installed or plan to install large solar arrays to handle their power requirements. For example, the U.S. Air Force Academy has installed a 6 MW, 30-acre solar array [2]. Jeju Island, in South Korea, plans to build a 450 MW array by 2050 [3]. With plans to rely more heavily on solar energy production, the large intermittency of solar energy will be felt more strongly by power network operators and consumers especially on smaller electrical grids such as those found in island communities [4].

Since many countries derive most of their energy from coal, oil, and nuclear sources, integrating renewable energy into the existing infrastructure presents challenges. If, for example, an industrial district in a city has a high density of solar arrays powering a significant portion of the facilities, these facilities will be dependent on conventional electricity sources through the night. A more acute problem is intermittent cloud cover during peak hours of the day. If a large photovoltaic array is overcast by clouds, the conventional power plant needs to compensate for the loss in local power production. This situation is further magnified by a high degree of spatial correlation between installations in the same vicinity. In the extreme case, an additional boiler or power plant may be needed to take up the

extra load. If the environmental effects on power consumption and production could be predicted on a sub hour timeframe, the electrical grid may be able to reduce fluctuations by bringing online lower cost energy storage such as batteries, informing consumers to conserve energy or pay a greater price at that time, or shifting production to other renewable energy means [5].

In order to reliably model, predict, and control a smart grid installation, a large amount of data is required. This data needs to contain a sufficient number of observations both in time and at as many useful locations across the power system and in the local operating environment as possible. This is especially important in complex terrain such as the UH Manoa campus, where different buildings may experience different combinations of wind, rain and sun, even in a small geographic area. (Collating data from a dense network of sensors also makes it possible to directly estimate cloud cover in the vicinity of the sun, and provides the opportunity for sophisticated statistical prediction of near-term irradiance and variability.)

In other words, in order to imbue the grid with smart-sensing capability, a second data network of significant complexity must be overlaid across it. This network design presents a complex problem. The network will be subject to environmental degradation, dropped packets, and changes in topology. These threats to the integrity of the network increase with the size of the network.

The sensing network must efficiently send traffic, be robust against network device failures, and be resistant to the environment in order to mitigate these threats. In other words, the network should be made up of inexpensive, simple, distributed devices that cooperate to deliver data over a large area for an extended period of time. Current solutions exist for self-sustaining wirelessly-networked modules [6-10] but do not attempt to achieve high spatial density over the harsh environment of building rooftops where panels are likely to be placed.

We have taken a design approach to reduce costs and allow flexible deployment on rooftops while maintaining accurate measurements that could be used for prediction. Furthermore, we have required that the module designs be self-sustaining to reduce maintenance costs. The sensor modules leverage rapid-prototyping technology including Arduino-based open-source hardware, 3D printing equipment that is readily available (MakerBot Replicator 2 [11]), commercial-off-the-shelf (COTS) parts, and a laser cutter. These technologies enable rapid iterative improvement of designs. A prototyping iteration has been executed for miniaturizing the design onto a specialized printed circuit board (PCB) with surface mount components. This iteration will help to reduce the power footprint and size of the modules as well as improve robustness to failure of the sensor modules.

As a first and primary testbed, we have chosen the University of Hawaii at Manoa (UHM) campus to implement a sensor network that would be able to

predict weather patterns over the rooftop of Holmes Hall, the engineering building, as well as other campus rooftops where solar panel installations are being planned. The sensor network is deployed over a relatively small geographic area as Hawaii is subject to many micro-climates over small distances due to the mountainous terrain creating rainfall amounts that vary by more than an order of magnitude over distances of a few miles. At UHM there is considerable variation in cloudiness as UHM lies along the breadth of Manoa valley from lower campus area which is close to Waikiki (approximately 20 inches of rainfall per year) to Lyon Arboretum which lies at the back of Manoa valley (approximately 150 inches of rainfall per year) [12]. The modules are linked across campus via a wireless mesh network creating a rooftop area network (RAN) and data is collected in a 48 TB database system. To further our educational goals, we have involved many undergraduate and graduate students on the project to help design, build, and deploy the sensor network.

2. Module Design

The two approaches that we have investigated include a laser cut module using readily available plexiglass sheets (Lasercut) and a 3D printed module using a Replicator with polylactic acid (3D-Printed). The sensing module is a small, low cost, low power, wireless module intended for mass field deployment. Information from each sensor can be sent via nodes along a mesh network to a centralized computer for data collection and analysis. Each sensor module can monitor temperature, barometric pressure, and humidity. The sensor also includes a GPS module for location and time stamping of data. Critical innovations include:

- 3D printed passively ventilated meteorological module housing to handle rooftop temperatures;
- Laser cut passively ventilated meteorological module housing utilizing COTS components;
- Low cost, low power, self-sufficient, meteorological sensor platform using open-source designs;
- Custom Arduino shield for hardware integration.

The electronics of the modules are laid out according to the block diagram shown in Fig. 1. All sensors and associated hardware send their respective data to the Arduino microcontroller. The Arduino utilizes an XBee library to assemble all data in a payload. Each module sends its data payload in a packet over the IEEE 802.15 network. The XBee radios send their packets in API mode and the coordinator node manages the mesh network via the ZigBee protocol. All data is received at the server and organized in the database. This data will be analyzed for real-time micro-climate monitoring. Prediction algorithms will allow the possibility of anticipating a reduction or loss of power production via local solar arrays.

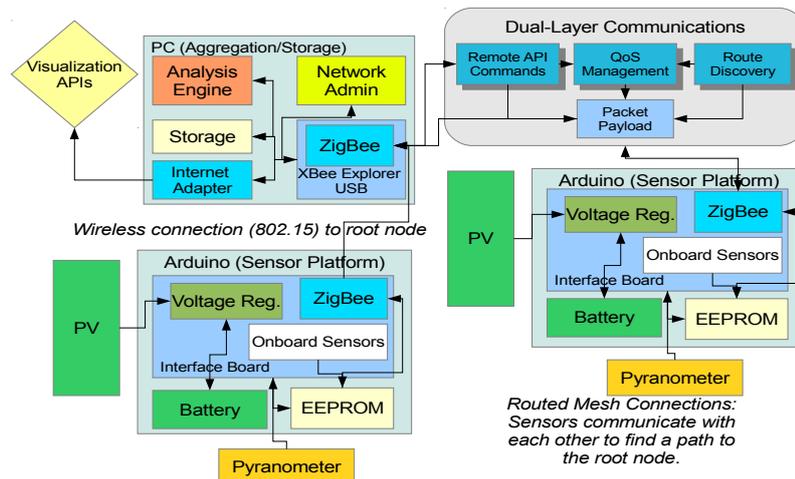


Fig. 1. Block diagram of sensor network communication layers and hardware layout.

2.1. Sensors

All of the sensors (Table 1) are digital and have been calibrated by the manufacturer. Pressure, solar irradiance, and power sensors communicate via the I²C protocol. The temperature sensor of the Lasercut module, humidity sensors, and GPS communicate via a 2-wire TTL. The temperature sensor of the 3D-printed module communicates via the Maxim 1-Wire protocol.

Table 1. Sensors Included in Respective Modules

Parameter	3D-Printed	Lasercut
Pressure	BMP085	BMP085
Ambient Temp.	DS18B20	SHT11
Humidity	SHT11	SHT11
Location	MTK3339	MTK3339
Solar Irradiance	none	SP215
Battery monitor	INA219B	none

The pressure sensor, BMP085, has the range of 300 – 1100 hPa with a resolution of 0.03 hPa [13]. The humidity sensor, SHT11, measures relative humidity from 0 – 100 % with an accuracy of 3.5 % and a resolution of 0.03 % [14]. The temperature sensor, DS18B20, has a range of -55 °C – 125 °C with an accuracy of +/-0.5 °C (at -10 °C – 85 °C) and a resolution of 0.05 °C [15]. The GPS module can track up to 22 satellites and updates at a rate between 1 Hz and 10 Hz with a -165 dBm sensitivity [16]. The current/voltage sensor is capable of measuring a voltage of -26 V – 26 V with a maximum current of +/- 3.2 A. The 12-bit ADC allows for a resolution of 0.8 mA [17]. The sensor module hardware is shown in Fig. 2.

2.2. Power

The module is powered by a 3.4 W, 6 V solar panel. Output current from the solar panel passes

through a current sensor and battery charging circuit that tracks the peak power point of the solar panel and charges an installed battery when feasible. The installed battery is a 4.2 V, 6600 mAh lithium ion polymer battery, which supplies power when sufficient solar power is not available. It has been calculated that the battery can power the module for a maximum of 44 hours without any sunlight from full charge.

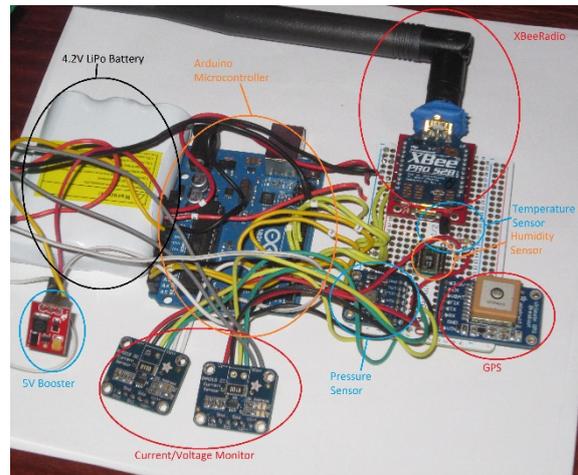


Fig. 2. Sensor module internal hardware of 3-D printed module.

To further reduce power consumption, electronics on the board may be dynamically switched off to save power during low-sunlight periods.

2.3. Network

The wireless network is controlled by Xbee radios using the ZigBee protocol (an extension of IEEE 802.15). The modules communicate in a mesh configuration, using Ad-Hoc On-Demand Distance Vector Routing (AODV). Radios within communication range of the central coordinator node

relay any information from nodes further out in the network, using routes established on demand. This routing protocol allows network nodes to renegotiate routes periodically, granting a degree of resilience against device failures.

The initial field deployment is to consist of multiple nodes in a mesh network. A visualization of a potential mesh network configuration superimposed across the UHM campus is provided in Fig. 3.

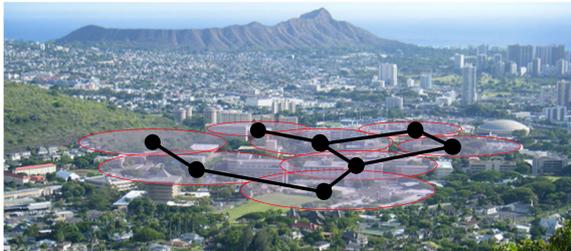


Fig. 3. Superimposed view of a mesh network across UHM campus.

3. Housing

The design of the housing is critical in maintaining a high degree of durability while allowing accurate measurement of external conditions. Wind temperature can be measured in shade as long as it is shielded from the roof temperature which can reach values over 120 °F. The top surface of the unit will experience the greatest degradation from exposure to direct sunlight and the sensing equipment should be separated from this top surface ideally using a shaded region and also reflective low-emissivity coating. The emissivity of the material controls how fast it can be heated and cooled to match the ambient conditions. The antenna must be placed high enough to allow good connectivity to the other nodes in the mesh network. The entire module can either be ballasted in an appropriate position on the roof or clamped to railing to improve ease-of-deployment as long as the clamping force exceeds the wind loading under hurricane-force winds which is possible using low-cost Irwin grips that can supply over 300 lbs of force in some cases¹. The housing must be designed to reduce effects of water which can result in dramatic corrosion of the electronics especially in environmentally corrosive environments like Hawaii. Yet the module cannot be entirely sealed in order to allow the environment to be probed with the sensors.

3.1. 3D-Printed Device Housing

The housing for this module was fabricated using a 3D-printer (Fig. 4). Polylactic acid (PLA) was chosen as the printed material due to its robustness under weather and the fact that it is more

environmentally friendly. The first version consisted of three compartments including individual spaces for the Arduino microcontroller (an Atmel AVR), sensor components, and the battery. The top plate of the housing is sized to accommodate one 3.4 W, 6 V solar panel. The solar panel provides both the protection from direct sunlight and contains a gap for natural ventilation to allow cooling of the panel. Underneath, a tray allows for the placement of a ballast to prevent the module from being jostled in heavy winds.



Fig. 4. 3D-printed module in the field.

3.2. Laser-cut, Passively Ventilated External Sensor Housing

The laser-cut housing is comprised of four main sections: the base, the ventilated compartment, the body, and the lid (Fig. 5). This housing design, fabricated primarily from laser-cut Plexiglas pieces, features a stacked electronics configuration in which electronics are fitted in layers on top of each other to allow for greater height and thus, improved antenna range. The ventilated compartment which houses the temperature, humidity, and pressure sensors has been designed to allow natural air flow for more accurate sensor data readings. Furthermore, the laser-cut housing lid design supports two 3.4 W, 6 V solar panels as well as a silicon-cell solar irradiance sensor to accommodate improved power capacity and more accurate solar irradiance measurements.



Fig. 5. Laser-cut module in the field.

¹ <http://www.irwin.com/tools/brands/quick-grip>

4. Measurement

Two graphs of data ranging over March 7, 2013 illustrate comparative findings (Figs. 6 and 7).

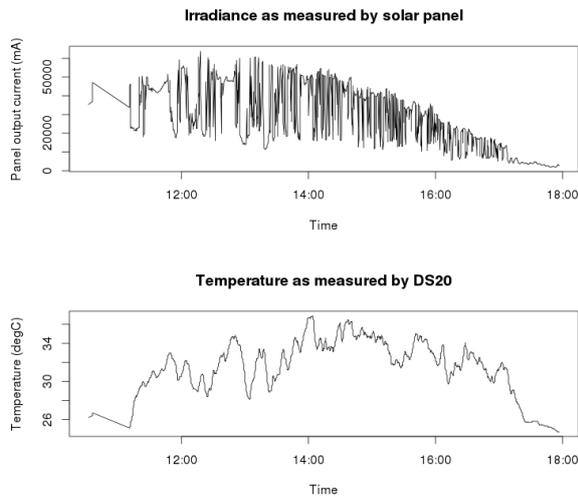


Fig. 6. Solar irradiance and temperature measured by solar panel and specialized temperature-only sensor (respectively).

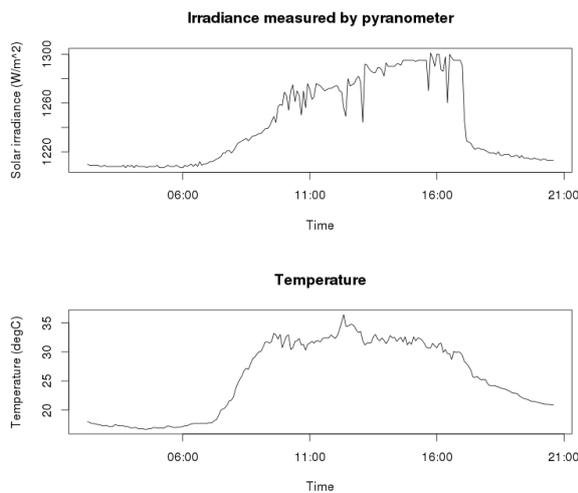


Fig. 7. Solar irradiance and temperature as measured by solar irradiance sensor and integrated temperature/pressure sensor (respectively).

The two enclosures were used as candidate test beds for slightly different components. Notably, the 3D-printed housing has a smaller profile, and does not have a solar irradiance sensor installed, instead relying on solar panel current to gauge solar irradiance. The laser-cut housing has two solar panels, and uses an integrated temperature/pressure sensor to give measurements of temperature.

As seen from figure 6, the solar panel response is noisier than that of the solar irradiance sensor due to its narrow sensitivity and primarily nonlinear characteristic. It does not make a good substitute for

a solar irradiance sensor, even in a narrow band. However, the increased sensitivity of the specialized temperature sensor (DS20) provides a more detailed plot of temperature throughout the day.

Most importantly, the measurements on the single-panel enclosure are cut off until 9am, well after sunrise. This result is due to the inability of a single 3.4 W panel to sufficiently charge the battery to capacity. Since the largest consumer of power on the sensor node is the XBee wireless adapter, this indicates that either better use of the XBee dynamic power control option or a larger panel area is warranted.

5. Network

Data is sent from the Arduino unit to the laboratory data store over a ZigBee mesh network (extended IEEE 802.15). Due to the mesh network's self-healing capability, the network is robust against single device outages. The installed XBee adapters are remotely configurable (through the provided API), including power control (hibernation and cyclic sleep), sampling rate adjustment, and numerous other parameters such as 128-bit AES encryption. The coordinator module controls the network. Each router is given a 16-bit address within the network. This allows for 65,536 potential radios on a single mesh network pan ID. Each node can act as a bridge for any nodes that are out of range of the coordinator. The coordinator manages the ad hoc network in real time in the event that a node, which was acting as a route for a more remote node, goes down. The broken path is rerouted through other nodes to maintain continuous data transmission from all modules.

The current XBee adapters communicate in the ISM (2.4 GHz) band using direct sequence spread spectrum, which allows for a higher data rate and interference resistance at the expense of range. The maximum rated range is 3200 m in ideal conditions with a clear line of sight. Current draw at full power is approximately 300 mA. This is at the high end of the unit's current daily power budget, making judicious use of the cyclic sleep function is a requirement. The cyclic sleep function allows a user to adjust the number of times a node is polled for a route, grants the ability to offer or not offer guaranteed traffic in a given period, and allows adjustment of the route poll rate. These settings allow fine control of network traffic. Coupled with hibernation state settings, device power consumption can be freely adjusted at any time [18].

6. Database

Captured data is stored on a high-capacity Linux server installation within the laboratory in a PostgreSQL database. This allows distributed access through SSH sessions to large chunks of data for

analysis both in the lab and around campus. Other parallel research projects make extensive use of the shared data. Exploratory analysis is being conducted on the initial data collected during the device testing period, and higher-complexity models can be run on the server as well as locally on user machines. A simple visualization routine written in a few lines of

R can query the database and produce graphs like the one below. Likewise, an XML-RPC client written in Java for Android allows administrators to check the status of data the server.

A slightly more detailed examination of the sensor data reveals possible correlations between environmental conditions and energy inputs (Fig. 8).

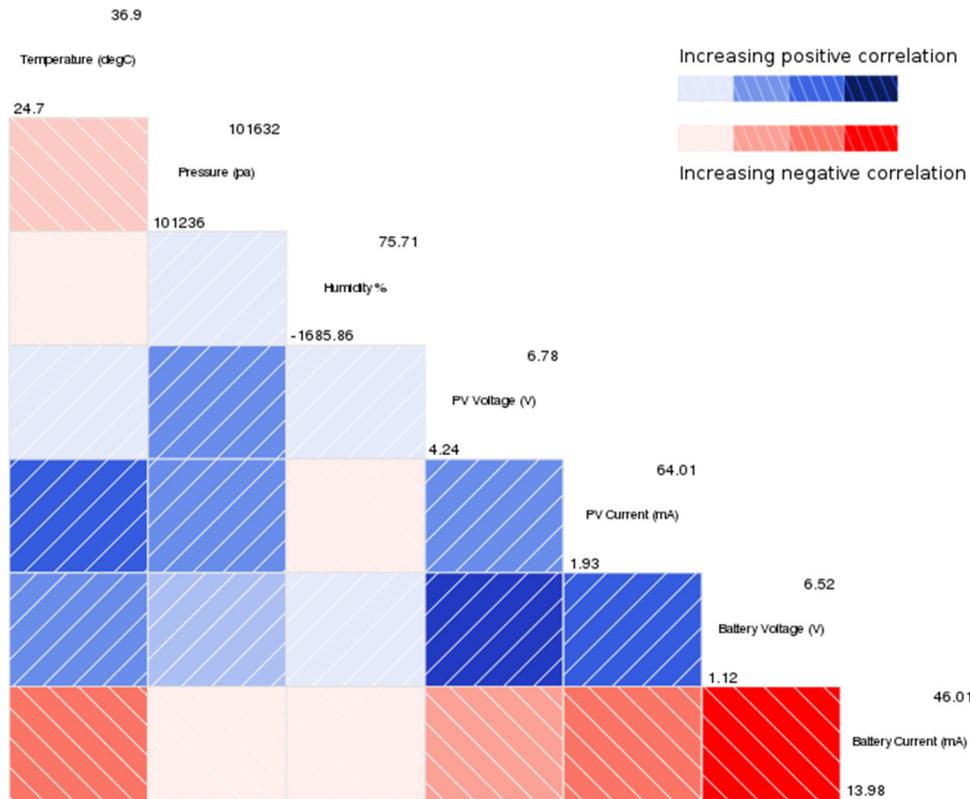


Fig. 8. Data correlations on 3/7/2013.

7. Future Work

The next version of the module will consolidate all of the sensors onto a more closely connected and organized substrate. Temperature and humidity sensors will be placed in a well-ventilated compartment, reducing the greenhouse effect inside the housing. Conversely, barometric pressure, GPS and current sensing modules will be placed in order to avoid exposure to the elements. Ultimately, the entire circuitry, minus the temperature, irradiance, and humidity sensors will be consolidated onto one board organized around the Atmel AVR microcontroller. A smaller module, a birdhouse, will also rise above the solar panels to provide thermal gradient information which can provide feedback to the air conditioning units inside of the building. The birdhouse will also contain a low-cost 3D anemometer to understand architectural wind and wind shear around the building [19]. These wind effects can be harvested with rooftop or parapet wind turbines or used to naturally ventilate the building.

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