Low-cost Wireless Sensor Network for Coastal Monitoring as Undergraduate Research Project

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Abstract

Wireless sensor networks have experienced a fast development and extended their fields of application since their appearance for military uses about two decades ago. Research on sensor networks, and wireless sensor networks (WSN) in particular has grown substantially in recent years. The range of WSN applications is wide, from vehicle traffic, environmental, and patient monitoring to target tracking, building, and health control. The monitoring of physical parameters in natural habitats is an important and critical application of such technology for assessing the risks on such ecosystems. Among natural environments with scientific interest, there are the coastlines and marine zones in front of the cities or heavy populated areas whose industrial and human activities impact on them. The development of sensory systems that allow us to scan and monitor the state of an environment is a research field in continuous evolution. The technology has a great potential to serve as research or industrial instrumentation, as well as for education purposes. It offers powerful opportunities for science, technology, engineering, and mathematics (STEM) education. This paper documents our early experiences developing a WSN for environmental monitoring. The novel aspect of our work was the high level of involvement at all technical levels by undergraduate students. Highlights of their efforts and the lessons learned are reported in this paper. Future undergraduate research areas are explored with suggestions on how WSN topics can permeate into undergraduate education. Lessons learned from this multi-year undergraduate project are presents and feedbacks form other instructors considering or already involved similar projects are welcomed.

1. Introduction

Monitoring of the coastal and marine environment has become a field of strong scientific interests in the last decades, as such these areas are very important for economic and social point of view as more people and business are located or relocated there. The environment areas are under ever increasing pressures from human activity, accidents and natural disasters. However, the coastal areas are particularly vulnerable to the effects of the human activity, industrial, tourist and urban development. However, the advances in the information and communication technologies offer solutions for monitoring of such ecosystems in real-time and on extended scale. The instruments used in this work have ranged from small-scale sensor networks to complex observation systems. Wireless sensor networks (WSNs) are a highly attractive solution in that they are easy to deploy, operate and dismantle and are relatively inexpensive. Wireless networks have freed us from miles of cumbersome wiring needed to carry information, but the electronic 'nodes' of such networks still need power. If geologists want to place hundreds of sensors on a mountain to monitor seismic activity, for example, they either have to supply electricity using cables or hike out to each sensor every six months or so to replace batteries.

The aim of this paper is to identify, appraise and select high quality research evidence relevant to the coastal monitoring use of WSNs to serve as educational engineering project. Before the project started an extensive literature reviewed was conducted to offer an overview of the present state of this field of study and identify the principal resources that maybe used to implement our project. A WSN is an autonomous network system consisting of large number of sensor nodes, have the capabilities of sensing, computation, communication and an expected low-cost, low maintenance and power requirements. A WSN is a “smart” system that can accomplish varied monitoring tasks, according to different environment conditions. Monitoring of water or air environment are ones of its typical WSN applications. Compared with existing real-time automatic water environment monitoring systems, WSNs-based marine monitoring has strong point as follows[3, 5-7]: 1) Less effect of the system on ecological environment: nodes transmit water environment parameters to base station by low power and low radiation wireless channel and multi-hop communication protocol. WSNs offer an unmatched option to a wide range of applications. The significance of the aforementioned research lies in the fact that it opens the door for a variety of applications as well as new areas of relevant research in wireless networks. The possibility of having hundreds of thousands of sensor nodes diving in the ocean or coastal areas, collecting data about the different inhabitants or parameters offers unique opportunities for ocean, marine or coastal studies and researchers in the field.

We are presenting here the development and designed of a low-cost environmental energy harvesting system that can be used to provide power to a WSN for marine or coastal environment monitoring system. Energy harvesting or the process of acquiring energy from the surrounding environment has been a continuous human endeavor throughout history. Unlike the conventional electric power generation systems, in energy harvesting concept, fossil fuels are not used and the generation units might be decentralized. There are many sources for harvesting energy, such as solar, wind, ocean, hydro, electromagnetic, electrostatic, thermal, vibration, and human body motion. Even the energy of radio frequency waves, propagated due to television and radio broadcasting in the environment, can be harvested. However, advanced technical methods should be developed to increase the efficiency of devices in harvesting energy from various environmentally friendly resources and converting them into electrical energy. These developments have sparked interest in engineering community as well as the engineering education community to develop more energy harvesting applications and new curriculums for renewable energy and energy harvesting topics. These days there is an increasing interest to harvest energy at a much smaller scale, for applications such as the ones found in many embedded systems the power requirements are often small (less than 100 mW). Today, sustaining the power requirement for autonomous wireless and portable devices is an important research and technical issue. However, this progress has not been able to keep up with the development of micro-processors, memory storage, and wireless technology applications.

2. Projects in Engineering and Technology Education

The engineering, science, and technology field, at present, is very dynamic due to recent advances in computer and other technologies. These advances have resulted in numerous computer programs to solve traditional and novel problems. The fundamental challenging problems in engineering and technology education are related to the improving the student–instructional technologies interactions to incorporate the required learning tools and new advances in fundamental and applied sciences, management, etc. Engineering and technology graduates must have a comprehensive background covering a wider range of technical subjects. The graduates must be proficient in the use of engineering and scientific equipment, conducting experiments, collecting and analyzing data, and effectively presenting the results[1-7]. Engineering graduates must be well-trained in theory as well as in experimentation. However, it is often difficult to provide useful, hands-on practical, modern and attractive experience for our students. One way to increase the student exposure to recent advances in technology, computing, IT, microelectronics, etc. is to research projects. Engineering and technology senior or capstone design courses fill a critically important role in the curriculum, forming a bridge between school and the workplace and have been extensively researched. These courses bring to the forefront many of the ABET outcomes such as lifelong learning, design, teamwork, and contemporary issues.

The senior graduating from 4-year engineering or engineering technology program must complete some type of capstone design project in order to graduate. It is of utmost that the project selected is not any project, but rather one that simultaneously enhances the learning experience of students, prepares the graduating ones for the real world, increases freshmen retention and strengthens relationships between universities and industries. The key to making the most out of capstone design projects is to carefully select ones that will accomplish all of the above. After completing a 4-year engineering program, most students are proficient in the principles they studied in the classroom. Whether recent graduates are able to apply these principles to various situations upon entering "the real world" is another story. The capstone senior deign project can be the vehicle to help solving these issues. ABET defines Engineering Design as: "The process of devising a system, component, or process to meet the desired needs. It is a decision making process, in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet stated objective. Among the fundamental elements of the design process are: the establishment of the objectives and criteria, synthesis, analysis, building, testing and evaluation"[6]. In our senior design classes we have placed this definition at core of senior design courses[7.8]. Each project involves elements of several engineering disciples, mechanical and electrical engineering, electronics and computer engineering, or system design, etc.. First we focus on the word objectives and criteria and ask the student to write a paragraph stating the objectives, principles, and the decisive factors to reach the stated objectives. The second step is conceptualization and laying down the foundation for how to achieve the stated objectives. The students are encouraged to draw a block diagram showing different components of the system they want to design. A set of questions are posed to students to further understand the task at hand. These are typical questions:

- What are the input signals to system and, what are their characteristics and magnitudes?
- Do the inputs require signal conditioning?
- Do the inputs dictate to system to be designed how to behave, or just activates the system?
- What is, voltage, current and power requirements for the load?

Once the students compile the answers to these questions, they are directed to perform system analysis, design, component purchase and fabrication, building and testing of the prototype, as well as the overall design improvements.

Over the last decades, the research on environmental energy harvesting techniques to extend the lifetime of miniature low power wireless sensor nodes/network (WSN) became very popular. Even though there are significant advancements in the low-power electronic circuits design, high energy density storage devices and optimized power-aware network protocols, the amount of energy provided by the finite-energy storage element still constraints the autonomy of distributed embedded systems. In practical applications, longer lifetime is an important goal of many WSN systems. To achieve this objective, there is a need to make a paradigm shift from the battery-operated conventional WSN, which relies on batteries, toward a truly self-autonomous and sustainable energy harvesting WSN (EH-WSN). For EH-WSN, the sensor nodes are integrated with some form of energy-harvesting mechanisms, such as wind, solar, vibration, etc., directly from the surrounding environment of the remote deployment site for recharging the onboard batteries/super-capacitors of the sensor nodes, so very little maintenance is required for extended period of operation. An energy harvesting system must reliably and autonomously operate for several years after installation with almost no maintenance while capturing enough energy to power the communication end node of the sensor network. . It must be resistant to the weather, wildlife, and others affecting or damaging treats These are challenging factors and make these types of projects very interesting, providing useful learning experience. As ultra-low-power circuits and micro-systems develop, conventional batteries used for these systems could be replaced with smaller-sized and longer lifetime candidates. In this sense, energy harvesters hold great advantages such as unlimited lifetime, and no need for recharging or power cables. In this project, students will conduct energy scavenging experiments with a photovoltaic module and a micro wind turbine. The design process can be broke into the following steps: 1) The design and construction of a power electronic circuitry of the harvester; and 2) The experimental measurements, data acquisition and analysis. Once the students compile the answers to these questions, they are directed to perform system analysis, design, component purchase and fabrication, building and testing of the prototype, as well as the overall design improvements. The use of an energy harvesting circuitry first to charge a battery and a super-capacitor bank, and later to provide power to a sensor node, designed to measure, collect and transmit air and water temperature, humidity and pressure. The paper presents the design, testing and implementation of such EH system, supplying power to a WSN node, and the lessen learned during this project.

3. Low-Coast Energy Harvester for a Costal Monitoring Wireless Sensor Node

This project is an underway project for MET 421/422/423 (Senior Project Design), preformed by a team of four students, two electrical and two mechanical seniors. MET 421/422/423 is a sequence of three-quarter capstone project design courses required for all the BSET majors. The course focuses on planning, development, and implementation of an engineering design project, which includes formal report writing, project documentation, group presentations, and project demonstrations. The goal of these courses is to demonstrate the ability to manage a major project involving the design and implementation of products with a mixture of electrical and mechanical elements as a member of a product development team. In these project-based courses, the students are expected to effectively manage their time and team efforts to produce a finished product in three ten-week quarters. Progress and formal reports, and oral presentations constitute integral components of this course sequence. Before beginning the projects, student teams are provided adequate training in project formulation and resource analysis, performance goals and team expectations, public presentations of project work, and individual project supervision[9-11].

3.1 Project Description

The team decided to use solar PV and a micro wind turbine as the energy sources to power the load, the sensors and the RF transmitter because of their high energy density and wind and solar radiation availability in most of the costal locations. A lithium phosphate battery provides and two super-capacitors are used as energy storage elements because of their many characteristics that suggest they can operate 10 years without maintenance. Also, maximum power point tracking (MPPT) controllers for both PV module and micro wind turbine and a battery protection circuit allow the energy buffers (super-capacitors and battery) to be charged and to regulate the energy flow. For the attachment method of the harvester the project team decided to clamp to the buoy or a platform used for monitoring. Wind load, fatigue, and stress calculations were performed to ensure the system was rugged enough to last for several years. Sensing block include several sensors for temperature, humidity and pressure monitoring. Commercial transceivers are used for wireless communications, usually transmitting in the free-licensed ISM band. Power must be provided to different system stages. Nodes that only relay or receive data can skip functions such as processing. Transceivers are one of the most power consuming parts of a wireless sensor node. The power of a transceiver in active mode is four to five orders of magnitude than in sleep mode[10-14]. The system block diagram is presented in Figure 1.

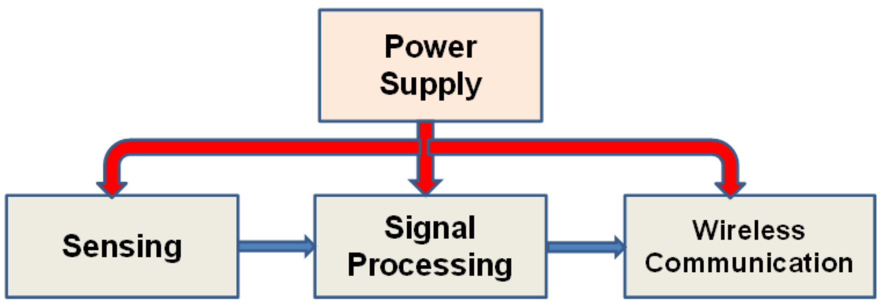

Figure 1 Block diagram of a wireless sensor node

However, power can also be dominated by the sensor stage[14-19]. Low-power sensors and electronic interfaces can help in the reduction of the power consumption of a WSN. Average power consumption ($P_{average}$) for a wireless sensor node[6] is estimated by:

$$P_{average} = DP_{active} + (1 - D)P_{sleep} \qquad (1)$$

Here $D = t_{active}/T$ is the duty cycle, when the sensor node is operating, P_{active} and P_{sleep} are the power used by the WSN in active and passive mode, respectively, T is the period. One way the lower $P_{average}$ is by reducing the duty cycle. The power supply stage must be able to provide both the total energy demanded during the expected lifetime and the instant power at the active time. Fig. 2 shows generic block diagram of the proposed low-cost wireless sensor in this senior design project. Load is accounting for sensing, processing and communication in Fig.1[12-15]. Conversion efficiency of the system in Fig. 1 is defined as follows:

$$\eta = \frac{P_{Transferred}}{P_{MPP}} \qquad (2)$$

Where P_{MPP} is the power at the maximum power point (MPP) and $P_{Transferred}$ is the average power transferred to the energy buffer. When the super-capacitors are used, as is the proposed system, $P_{Transferred}$ is usually computed as the value needed to increase the energy level from $E(t - T)$ to $E(t)$ during a given period T. Only harvester that always operates on the correct MPP can achieve efficiency over 90% and losses are only caused by the power dissipation of the system components. In this project, η was computed considering the DC-DC converter intrinsic losses.

3.2 System Architecture and Design

Typical design issues for solar and micro-wind harvesters are: micro wind turbine and PV module size are limiting the maximum power budget, while the power consumed by the MPPT and control circuits (usually taking large part of the harvested energy), and the powered system (load) that interact with the energy harvester[19-21]. The energy harvesting system architecture, designed after several steps is shown in Figure 2. The harvester architecture consists of four main subsystems: a) PV and micro wind turbine; b) the MPPT systems that sense and control the buffer stage forcing the PV module and micro wind turbine to work in most efficient conditions; c) buffer stage stores the energy collected form the solar module and/or micro wind turbine into the super-capacitors and battery; and c) output stage generates a stable voltage supply for the low-power WSN applications. In the following we introduce the building blocks providing design guidelines and considerations, which help to optimize the performance of the harvester.

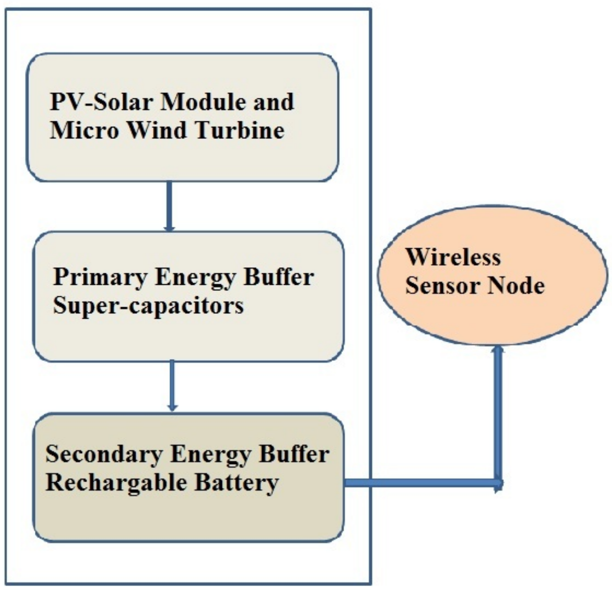

Fig. 2 Generic block diagram of the proposed WSN system

PV solar subsystem consists of PV module, MPPT subsystem, including a DC-DC converter to regulate the voltage delivered to the energy buffer stage. While, the wind-powered sensor node in Fig. 2 consists of two main building blocks: 1) the wind turbine coupled to the electrical generator; and 2) power management unit, which consists of power conditioning circuit and energy storage. From the energy buffer the power is delivered to the wireless sensor node itself. The energy harvester converts the raw wind energy and/or solar radiation harnessed from the ambient environment into electrical energy in DC from form in this project. The power management unit is employed to take care of the dynamics of both the wind turbine generator subjected to environmental condition variation such as varying wind speeds as well as the power-aware wireless sensor node operating at the deployment site. Inside the power management unit, super-capacitors, which has fast dynamic response, is employed to decouple the interrelationship between the fluctuating energy supply of the wind turbine generator and PV module and the duty-cycling operation of the wireless sensor node. It is necessary to optimize the power management unit with consideration of the characteristic of the wind turbine generator and the performance of the sensor node in order to meet the application requirement. Details of the proposed energy harvesting system and electronics are shown in Figure 3.

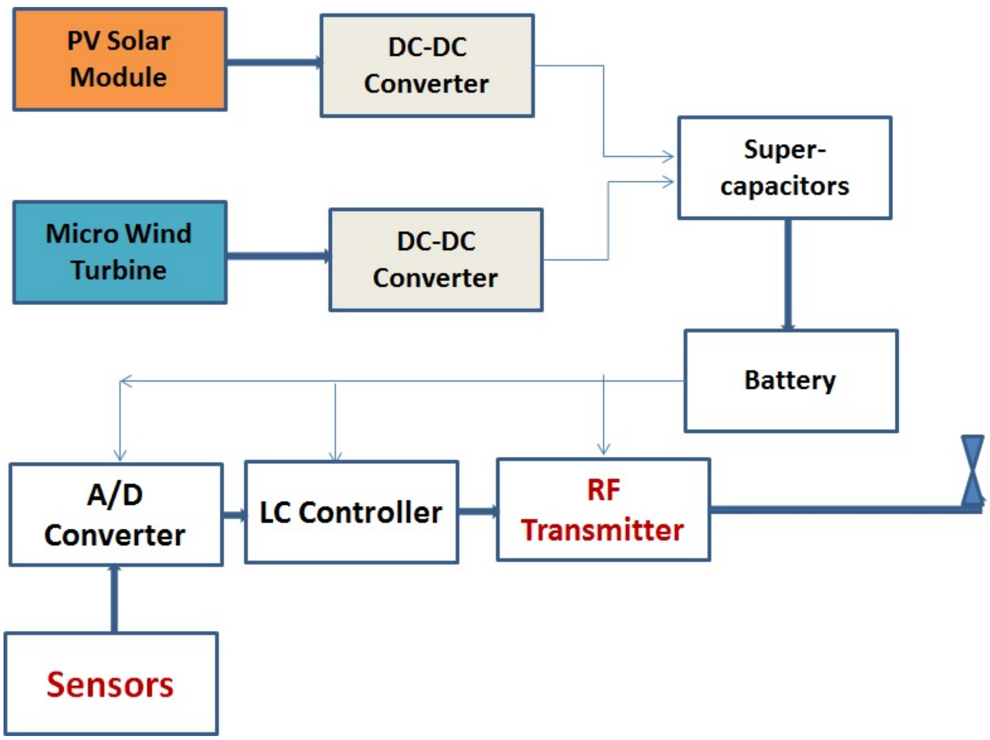

Figure 3 Wind and PV-solar energy harvesting system block diagram

The MPPT algorithm for PV subsystem is designed to automatically find the operating point (V_{PV}, I_{PV}) at which a PV module should operate to obtain the maximum output power under a given temperature and irradiance, following is when the light intensity changes. There are several algorithms to the track the maximum power point (MPP) voltage[14-18]. The most popular ones are Perturb and Observe (P&O) and Fractional Open-Current Voltage (FOCV)[20,21], which was adopted in this project. The P&O method requires complex control is suitable WSN applications. The short-comings of this method are the high cost and complexity. On the other hand, FOCV is largely used in small-scale and low-power PV applications. This method exploits the nearly linear relationship between PV module operating voltage at MPP V_{MPP} and its open-circuit voltage V_{OC}:

$$V_{MPP} \cong K_{FOC} \cdot V_{OC} \quad (3)$$

K_{FOC} is a constant that ranges from 0.71 to 0.78, depending slightly on irradiance conditions[14]. Since the linear factor depends on the characteristics of the solar cell that is being used, it usually has to be computed in advance by empirically or experimentally determining V_{MPP} and V_{OC} for a specific solar cell at different irradiance and temperature levels. However, this is only an approximation and a solar cell rarely operates in its exact MPP, but this MPPT technique is easy and inexpensive to implement and most important does not require a microcontroller, uses lower power to operate. The MPP can be approximated measuring periodically V_{oc} by a temporary disconnection of the PV module from the circuit. Unlike standard voltage regulating boost converters, the main functions of the DC-DC converters in the power-management unit of the harvester are: 1) to step-up the low DC voltage output of the wind turbine *V*dc to charge the energy storage device and 2) to perform MPPT so that maximum power transfer takes place.

Figure 4 Physical implementation of the circuitry.

Depending upon the energy storage level of the super-capacitors, the output voltage of the wind generator *V*dc is manipulated to transfer maximum power to the super-capacitor by adjusting the duty cycle of the pulse width modulation gate signal of the boost converter such that *V*dc is as close as possible to V_{MPPT}, the voltage at which the harvested power is at its maximum. Since most of the conventional MPPT algorithms are not suitable for the micro wind turbine, an alternative MPPT technique based on the concept of emulating the load impedance to match the source impedance was used. This technique is also known as resistor emulation or impedance matching. When the load resistance matches the source resistance, power harvested by wind turbine-generator is always at a maximum for different wind speeds. However, for other loading conditions shifting away from the internal resistance of the wind turbine generator either very light or heavy electrical loads, the electrical output power being generated drops significantly. This exhibits that the MPPT technique based on resistor emulation is a possible option to assist the small-scale wind turbine to achieve maximum power harvesting from the wind turbine generator. The physical circuit implementation is shown in Figure 4.

The proposed solution uses a super-capacitor from PowerStor that present a very high energy density (100 times that of electrolyte caps) and power density (10 to 100 times that of batteries)[14-16]; equivalent series resistance (ESR) extremely low compared to activated carbon super-capacitors; relative low leak current; ample operating temperature range; and may be recharged hundred thousand times. Considering a duty cycle typical to WSN of 1%, an active node current of 20 mA and a sleeping current of 5μA, the average current is 0.01×20 mA + 0.99×5 μA = 0.205 mA. The sensor node operating voltage is 2.80 V and the super-capacitors will power for 10 hours (estimated period without sun light).Two super-capacitors of 22 F / 2.5V each in series are used in our design, providing the 2.80 V and minimizing the leak current.

Embedded systems, including WSNs contain advanced ICs that require a stable supply voltage to operate correctly and properly. This requirements demand a properly designed output stage with regulated voltage to deliver the power supply to the whole WSN node. A DC-DC regulator combined with a custom enabling and insulation circuits has been selected to maximize the output regulator efficiency. A Buck-Boost converter was selected to give more flexibility in providing a 3.3 V stable voltage with ~ 90% efficiency. Note that efficiency depends also on super-capacitor, battery and the rest of the harvester components. Even with the same irradiance, usually there are significant changes in PV power (P_{PV}) output due to various reasons. The MPPT methods discussed in previous subsections can be used to find the maximum P_{PV} regardless of the irradiance.

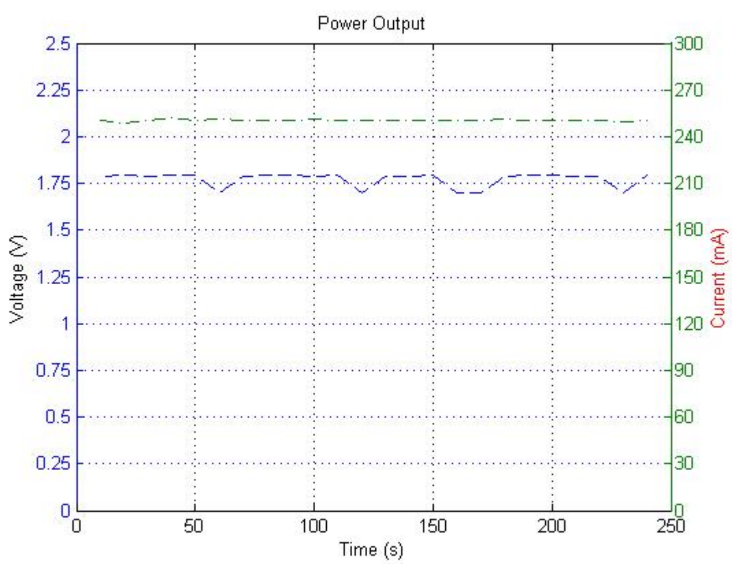

Figure 5 Waveforms showing PV voltage and PV current

Our energy harvester is targeted to supply low-power WSN devices for marine monitoring under typical environmental conditions, being very flexible and can be attached to commercial sensor nodes which are not designed with energy harvesting features. Circuit consumption and losses vary with the current flowing through the power switches. It is targeted to supply low-power WSN devices for environment monitoring under typical environmental conditions. Circuit consumption and losses vary with the current flowing through the power switches. In the most constraint conditions (low input power) the total power consumption is under 10μW making this architecture suitable for low power autonomous WSN. The power consumption for wireless sensor device provided by manufacturer with sensors and micro-controller in stand-by conditions is < 1 mW, while the power consumption reaches ~ 50 mW in active mode. Fig. 5 shows the experimental waveforms of the PV module voltage and current, and the output voltage and current for 1000 W/m^2 insolation. The PV voltage for both insolation values is kept at around

1.79 V. However, the out power for the second insolation values is only about 60% of the previous one. The power difference is supplied by the storage unit of the harvester.

3.3 Mechanical Design

To adequately collect the ambient solar radiation necessary to facilitate the operation of the WSN monitoring unit, there needs to be a way to modify the direction of the solar panel to compensate for the lack of light at a certain angle or time. The method we found to facilitate the maximum light irradiation of the panel is to mount the unit on a movable ball and socket mount, (see Figure 7). This ball and socket mount was required to be able to be adjusted to any direction in 360º. The design was originally chosen from one of our alternative designs for the solar panel mounting configuration after it was determined that a modular system would be optimal for the generalized applications that our system was to be used in.

Figure 6 Pivoting mount of the PV/solar panel

The ball and socket mount chosen is a speaker mount from a high end surround sound system. This specific mount was chosen for its range of motion as well as its mounting capabilities. The base plate is made from thick gauge steel cut from the chassis of an old Macintosh computer, with steel rack stock brazed to the back. This allowed the ball and socket joint to be attached to the base plate. A similar mount is used for micro wind turbine, attached similar to the energy harvesting system enclosure. It allows an the full turbine rotation following the wind direction. We are planning to use in the future a ducted micro wind turbine for enhancing the energy collection and for better protection of the rotor. The enclosure and the mounts are finished with automotive grade trim around the edges to provide a barrier against the metal and for durability. Because both mounts have multiple disconnect points, the ball and socket joint can be taken apart and reattached anywhere the power cord will allow. With the ability to relocate the solar panel assembly to an area off the base unit, we can set the panel in an area that would allow for the best ambient light collection, while monitoring an area that could possibly be multiple feet away from the base station. This configuration would also allow the placement of the base station at a distance closer to another node, facilitating better network communication. If necessary, the solar panel and the micro wind turbine can be mounted on the unit itself, utilizing the two holes on the top of the chassis assembly.

4. Conclusions and Future Work

Students learn, verify, and reinforce theoretical concepts by performing experiments in the laboratory sessions and through the project experience. In our approach we adopted the principles of the problem-learning methodology. The design experience develops the students' lifelong learning skills, self-evaluations, self-discovery, and peer instruction in the design's creation, critique, and justification. Students learn to understand the manufacturer data sheets, application notes, and technical manuals. The experience, which would be difficult to complete individually, gives the students a sense of satisfaction and the accomplishment that is often lacking in many engineering courses, using traditional teaching approaches. Furthermore, the design experience motivates student learning and develops skills required in industry.

The development, testing and implementation of a project solar and micro wind turbine energy harvesting system in our senior project design course sequence are presented here. The project is used to allow students to apply fundamental engineering concepts as well as principles of engineering design to attractive engineering topics, such as solar and wind energy harvester for a WSN coastal monitoring. The societal impact of the project, energy scavenging methods, also makes students more aware of what engineering can do to address current energy issues worldwide and how to provide long lasting power supply for environmental monitoring systems. Presently we are modifying the content of the project to address the main concern that the students of the project team expressed in their reflection papers, i.e. the level of complexity and the amount of time needed to complete the project. The project presented above, together with other projects proposed by the authors in the areas of renewable energy, energy harvesting and wireless sensor networks have been used to draw student's interest in the field of renewable energy sources, advanced and intelligent monitoring systems.

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