Solar Energy Harvesting Solution for the Wireless Sensor Platform the UWASA Node

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Abstract: This paper presents a solar energy harvester and energy management prototype developed for the UWASA Node wireless sensor platform. The prototype was designed using a modular approach, requiring only minor hardware modifications in order to allow harvesting from different energy sources. The primary sensor network application for which the design was developed is wind turbine monitoring. The energy harvesting prototype and the performance level it enables for the sensor networking are evaluated through experiments, and methods of optimizing energy harvesting and energy management are discussed.

1 INTRODUCTION

Wireless sensor networks enable a range of completely new kinds of monitoring and control applications as a part of the Internet of Things concept. Even though wireless sensor nodes have been developed rapidly during the last decade, their power supply still constitutes a significant bottleneck for their applicability. Having to service a wireless sensor node and change its battery can be prohibitively expensive or difficult due to the location and means of installation of the sensor node. This greatly limits the number of feasible applications in which wireless sensor nodes would otherwise be perfectly suited for monitoring and control. Different types of energy harvesting systems have been developed to overcome this problem. A common challenge related to them is that the energy resources they are able to harvest usually enable a remarkably lower sensor node performance level compared with powering from a battery without energy harvesting. This level might not be enough to fill the requirements of the particular monitoring or control application.

In this paper we present a solar energy harvesting solution for the UWASA Node wireless sensor platform (Yigitler et al., 2010). It was developed as a part of our wireless automation research activities, and it is primarily targeted for wireless sensor network (WSN) applications for wind turbine monitoring (Höglund, 2014a; 2014b). It would be beneficial to collect information about different kinds of forces and vibrations that affect the wind turbine structures. The dimensions of the wind turbines used for industrial-scale electricity generation are so large that energy harvesting capability is a necessity to make wireless sensor nodes feasible for monitoring and control installations. In addition to solar energy, energy harvesting from vibrations was also considered, and with small modifications, the developed energy harvester could be adapted to harvest vibrational energy.

The rest of this paper is organized as follows: The UWASA Node wireless sensor platform is introduced in Section 2. Methods of energy harvesting are discussed briefly in Section 3 and general requirements of the energy harvester in Section 4. The developed energy harvester prototype is described in Section 5 and the applied solar cell in Section 6. Maximum power point tracking is discussed in Section 7. The implemented energy management and storage is explained in Section 8, and the system performance is evaluated trough experiments presented in Section 9. Finally, Section 10 concludes the paper.

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2 THE UWASA NODE

The UWASA Node, shown in Figure 1, is an open source wireless sensor node developed by Aalto University and the University of Vaasa (Yigitler et al., 2010). It is a modular and stackable platform, the software and hardware design of which allow it to be used for different types of applications with minimal changes to the main architecture. The possibility to stack different slave boards onto the main board allows the creation of custom solutions for any application. In its simplest form, called the basic stack, only the main module and the power module are used. These are sufficient to comprise a wireless sensor node that consists of processors, a wireless communication interface, peripheral interfaces, and power management and distribution (Çuhac, 2012; Virrankoski, 2012).

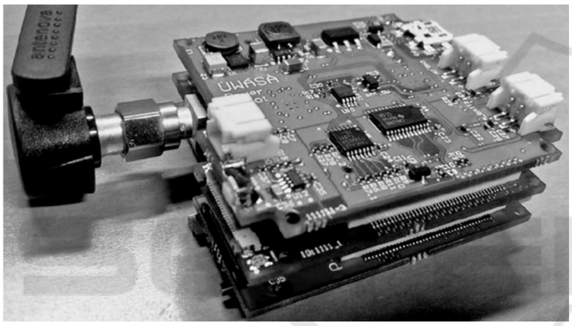

Figure 1: The UWASA Node with power module.

2.1 The Main Module

The main module of the UWASA Node contains two processors: one main controller and one radio frequency controller. The radio frequency controller can handle all computation and communication in simple applications, and then the main controller need not be used. For more demanding applications, the main controller is preferable. The main controller is an LPC2378 ARM7TDMI-S-based high-performance 32-bit RISC microcontroller from NXP Semiconductors.

2.2 Operating System and Software

The modularity of the UWASA Node is realized by both the hardware and the software architectures. The FreeRTOS (Free Real Time Operating System) was chosen for the UWASA Node in order to enable real-time operation and preemptive multitasking. The UWASA Node can thus handle many communication, measurement and control tasks simultaneously.

Middleware has been written for the UWASA Node to provide device drivers and hardware abstractions that are used to establish a uniform programming interface for both the main controller and the radio frequency controller. The same API functions can thus be used for programming both controllers. Automated daemons run in the background, taking care of tasks related to power management, time synchronization and system diagnostics (Çuhac, 2012).

2.3 Auxiliary Hardware

The UWASA Node can be connected to a number of slave modules by using the hardware stack connectors with a total of 160 pins per module. These connectors provide all necessary inter-modular connections for signals and power supplies. The slave modules can be any peripherals such as sensors, actuators and drivers.

2.4 Power Source and Energy Management

The energy management of the UWASA Node is handled by the power module, which is a separate module that can be stacked onto the main module. The power module features dynamic power path management and is capable of choosing the most suitable power source and charging a battery if one is connected and sufficient power is supplied. There is a battery monitoring chip that accurately measures current, voltage and temperature. This can be used for calculating the energy state of the battery and for measuring the power consumption of different applications (Çuhac, 2012).

The battery input of the power module is designed for one-cell lithium ion batteries with a nominal voltage of 3.7 V. It accepts voltages between 1.8–4.2 V. A charger input features an undervoltage lock-out (UVLO) that cuts the power when the charger voltage is below 3.3 V. During undervoltage lock-out a very small, but nontrivial current (tens of milliamperes were measured) is drawn from the charger input. Similarly, a very small but nontrivial current flows into the battery input when the battery voltage is below 1.8 V and the charger is in short circuit mode. To eliminate this loss, an external, very low-power UVLO circuit is proposed for energy harvesting applications.

3 METHODS OF ENERGY HARVESTING

For outdoor WSN applications, such as wind turbine monitoring, solar energy harvesting is the most suitable energy harvesting method because of the good availability of sunlight and the proven technology of solar cells. Energy harvesters using sunlight as their energy source can provide power on the order of 10 mW/cm^2 under ideal circumstances (Höglund, 2014a).

The most efficient method of energy harvesting is always case-specific because of the large differences in the availability of energy over time from different sources and locations, and because of the highly varying power consumption of wireless sensor nodes (Höglund, 2014a). There are three methods of energy harvesting that were deemed feasible for supplying the UWASA Node with power in wind turbine monitoring applications: solar energy harvesting using photovoltaic (PV) cells, vibration energy harvesting using a piezoelectric cantilever, and wind energy harvesting using a microscale wind turbine with an electromagnetic generator. These three methods could also be used in parallel in a hybrid energy harvester.

3.1 Solar Energy Harvesting

Using a PV cell as the energy source would be a safe choice, because it is a well-established technology. Solar cells are readily available in all sizes and in many different configurations with conversion efficiencies around 15% (Gilbert and Balouchi, 2008). A suitable number of photovoltaic fingers should be connected in series in the cell to yield an optimum nominal output voltage and more fingers can be connected in parallel to cover the rest of the available area. The generic 92 × 61 mm, 0.45 W solar cell sold by SparkFun Electronics (Niwot, Colorado) is a suitable choice, because its open circuit voltage is approx. 5 V and its size roughly matches that of the UWASA Node. If more energy is required, it is possible to connect more than one such cell in parallel to the energy harvester, while still keeping the maximum power point (MPP) voltage and energy harvesting circuit the same.

PV cells are made for outdoor use and are not damaged by rain or large temperature changes. Energy can reliably be harvested from them whenever the ambient illuminance is sufficiently high. A suitable harvesting schedule can be estimated by analyzing weather data to determine how much energy can be generated on average at a given time of day and time of year. A large fraction of the available energy is lost when the PV-cell is not oriented directly against the sun, but this is typically unavoidable. If possible, the PV-cell should be oriented in the direction of average maximum sunlight. The reflectiveness of the surroundings highly influences the received energy and a heavy cloud cover reduces the available energy by approximately an order of magnitude (Gilbert and Balouchi, 2008). In the worst case, the PV-cell will experience sufficiently bright conditions for so short a time that it cannot harvest enough energy for the load to operate. Seasonal and weather conditions may make it impossible to harvest a sufficient amount of energy for a long time and therefore it is important to store enough energy in the sensor nodes for them to be able to operate during such times.

3.2 A Hybrid Energy Harvester

Several different energy sources can be harvested simultaneously by using a modular energy harvester. Harvesting both solar and wind or vibrational energy would reduce the downtime of the harvester and produce power more evenly. The largest drawback of using several sources is the increased requirement for space. Park and Chou (2006) developed a modular energy harvesting system called AmbiMax. They propose to use a reservoir capacitor array, i.e. a separate supercapacitor for each energy harvester. These supercapacitors need to be able to reach the same voltage in order to power the common voltage rail. If the voltage over one of the capacitors is higher than that of the others, only that one will supply the voltage rail. If more than one capacitor is used like this, diodes may be necessary to prevent backflow from the voltage rail to the capacitors. Diodes should be avoided when possible, because they cause a small voltage drop and power loss. An energy harvester that outputs less power than the other harvesters needs to have a smaller supercapacitor so that it can reach the target voltage quickly enough to be efficient (reaching its maximum power point). The voltage rail can be used to power the wireless sensor node and/or a battery charger.

4 ENERGY OPTIMIZATION

When using an energy harvester to power a wireless sensor node, there are many aspects that must be considered when seeking optimal performance to harvest as much energy as possible and to store and use the harvested energy as efficiently as possible. If one part of the system is wasteful, it is not very helpful to get another part of the system to operate efficiently. Some of the parts of the system that must be considered when seeking optimal overall system performance are: harvesting location and schedule, size of the electronics, energy conversion, voltage conversion for storage, electrical switching, energy storage, voltage conversion for consumption, energy consumption of the load circuit, sensor node program execution, wireless communication scheme, and transmission power.

There are complex tradeoffs to be considered when selecting components for the energy management and storage connected to an energy harvester. When the values of the voltage and current of an energy source result in a maximum power output, the circuit is said to be operating at the maximum power point (MPP). The MPP voltage varies with ambient conditions. This voltage may not be optimal for the energy harvesting circuit and voltage regulator that drain the source and supply the voltage rail or storage device with a suitable voltage. Thus, significant power may be lost if the source and the harvesting circuit are not well matched.

The energy harvesting circuit is also optimally efficient at a certain output voltage. For example, step-up DC/DC converters are the most efficient when their output voltage is only slightly below the input voltage. When such a converter is charging a battery or a supercapacitor, its output voltage will gradually increase as the load is charged, and the conversion may be efficient only for a short time. For this reason, supercapacitors are commonly used as buffers to allow the output voltage to rapidly climb to a suitable voltage when harvesting, and then battery charging begins when the optimum voltage is exceeded, thus keeping the output at this voltage until the battery is charged to a higher voltage, after which the efficiency again decreases as the voltage closes in on the setpoint.

Voltage regulators supplying the sensor node cause an additional power loss that depends on the regulator type and its input and output voltages. It can be very difficult to optimize the overall system performance when so many components must be considered. As a rule of thumb, in electronics design, the optimum voltages of all components should be as close to each other as possible.

A truly optimized energy harvesting system should take into account the limitations of the energy storage circuit and the draining schedule of the storage over time. The wireless sensor node needs to work intermittently and go into sleep mode at certain times in order to conserve energy for future measurements, data logging, and transmissions. The schedule could also be changed by the sensor node based on measurements of the environment. For example, the system has to take into account that no power is harvested from a photovoltaic harvester at night. Schedules of harvesting and consumption can be simulated using computer models before they are tested in hardware in order to make the best use of the harvested energy.

5 THE ENERGY HARVESTING PROTOTYPE

After measuring the typical power consumption of the UWASA Node and investigating what forms of energy harvesting would be suitable, the energy harvester prototype shown in Figure 2 was designed and built. The design was made with modularity and expandability in mind. The harvester was designed to work with a small solar cell, but other sources can be added in parallel if some modifications are made (Höglund, 2014b).

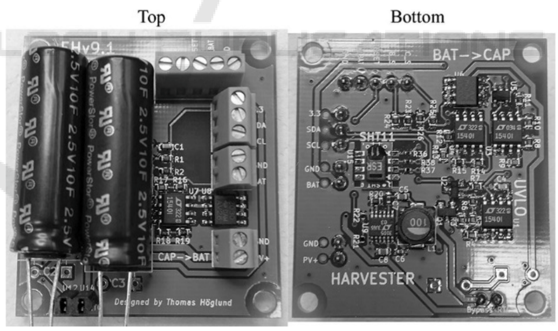

Figure 2: Developed energy harvester prototype.

The chosen implementation is based on the AmbiMax system described by Park and Chou (2006). It is an entirely analog energy harvesting system that was relatively efficient when it was made in 2006, but the power consumption of common, low-power digital controllers has since dropped significantly, making them a viable alternative. The maximum power point tracking was not implemented in the same way in this project as in the AmbiMax. The LTC3105 energy harvesting IC was chosen to perform the harvesting. Since 2013 when this choice was made, some even more efficient energy harvesting ICs have become available (Höglund, 2014b). The energy management was designed with components similar to those of the AmbiMax, but slightly more efficient (Höglund, 2014b).

The architecture of the AmbiMax platform is shown in Figure 3, reproduced from Park and Chou (2006). It consists of a comparator with hysteresis that performs MPPT with the aid of a sensor and controls a boost regulator. The regulator charges a supercapacitor that is connected to the voltage rail. All of these components can be grouped as a subsystem and used in parallel if more than one energy source is used. The supercapacitors are connected to the voltage rail via optional protection circuitry, and the voltage rail powers the sensor node. If the voltage of the voltage rail increases above a certain threshold, the battery is charged from the voltage rail via a current limiter. Conversely, if the voltage of the voltage rail drops to below a certain threshold, the battery feeds the voltage rail as long as its voltage is above another fixed threshold. This, in short, is how the AmbiMax and the developed energy harvester work. Additionally, a low-power undervoltage lock-out circuit and a real-time clock-controlled latch switch were designed to cut off the voltage rail from the sensor node when it drops below a threshold or when the node signals it to shut down for a length of time; these were not part of the AmbiMax.

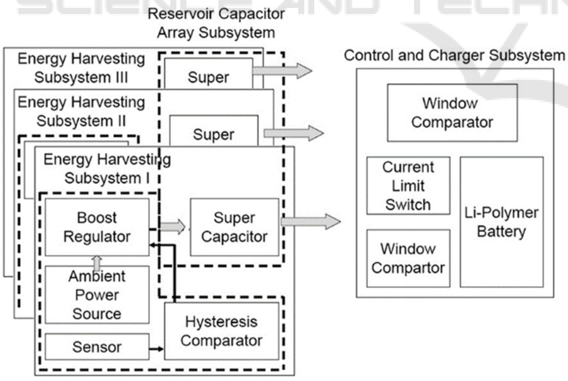

Figure 3: The architecture of the AmbiMax Platform (Park and Chou, 2006).

The LTC3105 energy harvesting IC by Linear Technology (Milpitas, California) was chosen from many alternatives to be the energy harvester used in the prototype of this work. It is listed as a 400 mA step-up DC/DC converter with MPP control and 250 mV start-up voltage. It is capable of supplying up to 5.25 V. The prototype is designed to supply 4.2 V, which is the maximum voltage of a one-cell lithium-ion battery. The very low start-up voltage of the LTC3105 allows it to harvest from a photovoltaic cell that outputs a low voltage due to low ambient illuminance. The low input voltage compatibility can also be useful for other types of energy harvesting sources such as thermoelectric, electromagnetic, or magnetostrictive sources, which output a low voltage.

6 THE SOLAR CELL

A 92 mm × 61 mm solar cell, with a nominal power of 0.45 W, was chosen for the energy harvester prototype, because its open circuit voltage is approximately 5 V, which is suitable for the LTC3105 and the battery, and its size is approximately that of the UWASA Node's. If more energy is needed, it is possible to connect more than one such solar cell in parallel with the other cells to the energy harvester, while still keeping the MPP voltage and energy harvesting circuit the same. Protection diodes could be used to allow operation with solar cells of higher voltages, but the LTC3105 operates most efficiently at input voltages slightly lower than its output voltage, and therefore the MPP voltage of the solar cell should be lower than the desired output voltage.

In order to measure the MPP of the solar cell, it was connected to a potentiometer used as a variable load. It was then placed under a constant illuminance of 2.8 klx and its output current and voltage were measured while varying the load. The output power was calculated, and the result is plotted in Figure 4. The MPP occurs at approximately 3.6 V and 6.3 mW. The MPP varies slightly with the illuminance, but after a few attempts at maximum power point tracking, it was decided that a fixed MPP voltage is sufficient for this application.

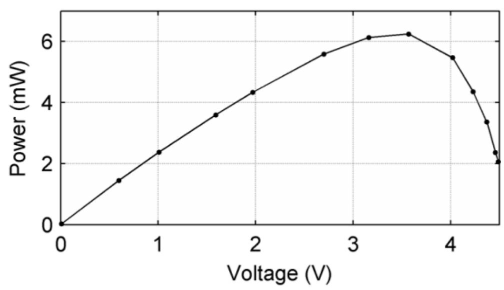

Figure 4: Power vs. voltage for the 0.45 W solar cell at 2.8 klx.

7 MAXIMUM POWER POINT TRACKING

Maximum power point tracking (MPPT) aims to adapt the energy harvesting load to the ambient conditions so that the input voltage of the energy harvester is always equal to the MPP voltage as it varies, in effect performing impedance matching.

In the case of the LTC3105, the MPPT is integrated on the chip and there is a pin named MPPC. The LTC3105 keeps the source voltage the same as the voltage on the MPPC pin, which constantly outputs 10 µA. If MPPT is not necessary, this pin can be connected via a fixed resistor R_{MPPC} to ground in order to set the MPP to a fixed voltage (U_{MPPT}) according to (1). In the prototype, a 360 kΩ resistor was used to achieve a U_{MPPT} of 3.6 V.

$$U_{MPPT}=10\ \mu A * R_{MPPC} \tag{1}$$

The datasheet of LTC3105 proposes to use a diode thermally coupled to the solar cell for MPPT, but this is unlikely to work well over the large temperature range of this application; it would also be difficult to achieve thermal coupling.

MPPT could also be performed digitally by a low-power microcontroller, digital signal processor, or field-programmable gate array. It is easier to calculate the MPP digitally and take several factors into account, such as illuminance and temperature, but unless such a digital control system is carefully designed, not much power can be saved.

8 ENERGY MANAGEMENT AND STORAGE

The energy management part of the circuit takes care of routing the power in an optimal way between the energy harvester and sensor node components for maximum performance and optimal schedule of operation. The energy management of the energy harvester prototype consists of supercapacitors, a Li-ion polymer battery, nanopower voltage comparators, a logical AND gate, two MOSFETs and a few current limiters.

The LiPo battery is charged by two supercapacitors connected in series when the supercapacitors reach a voltage threshold. The charge current is limited by a current limiter that also works as a switch. Charge current flows intermittently due to a configured hysteresis, until 4.2 V is reached. The voltage thresholds at which power is transferred in the prototype between the supercapacitors, the battery, and the UWASA Node are governed by LTC1540 nanopower voltage comparators by Linear Technology (Milpitas, California). These comparators feature an ultralow quiescent current of nominally 0.3 µA, a voltage reference, and a hysteresis, both adjustable by resistor voltage dividers.

One comparator is used for activating the current flow from the voltage rail (supercapacitor) to the battery when the rail voltage is more than 3.7 V. Another comparator is used in the undervoltage lock-out (described in Section 8.3), and a pair of comparators with an AND gate is used for activating the current flow from the battery to the voltage rail. All comparators were configured for a hysteresis of approximately 100 mV.

The comparator that activates battery charging and the AND gate that activates battery draining are connected to the enable pins of two separate current limiters that, when enabled, permit a limited current flow through them in one direction. These current limiters were implemented using TPS2030D power distribution switches by Texas Instruments (Dallas, Texas). They allow 300 mA to pass through them when activated.

8.1 Supercapacitors

Supercapacitors can act as a buffer and be used to store the first energy delivered by the energy harvester until there is enough energy to begin charging the battery or supplying the sensor node. The voltage of the supercapacitor can rise quickly to a voltage where the step-up (or step-down) converter operates the most efficiently because of its much lower capacity compared with a battery. Connecting the harvester directly to the battery would cause its voltage to rise very slowly and energy would be harvested less efficiently because of the step-up inefficiency at lower voltages. Supercapacitors can also smooth out the wide dynamic range of energy harvesters and the node load, especially if more than one harvester subsystem is connected in parallel. Another advantage of using supercapacitors is that they can be used to preferentially supply the sensor node before the battery is needed. This keeps the battery voltage more even, which slows down battery aging.

According to Mars (2009), (2) gives an approximation for the necessary capacitance C of the supercapacitor assuming there is a constant load current I_L and that the supercapacitor needs to be able to supply I_L for time t. When current is drawn from a supercapacitor, there is an instantaneous voltage drop due to its equivalent series resistance R_{ESR}. The load voltage is allowed to decrease from U_{max} to U_{min}. Equation (2) shows that an approximately 12 F supercapacitor is necessary to supply 250 mA for 60 seconds with the voltage limits of the developed prototype. In the actual case, the current would vary significantly over time, but this equation provides a useful indication of how large a capacitor is required.

$$C = \frac{I_L t}{U_{max} - U_{min} - I_L R_{ESR}} = \frac{250 \cdot 10^{-3}\ \mathrm{A} \cdot 60\ \mathrm{s}}{4.2\ \mathrm{V} - 2.9\ \mathrm{V} - 250 \cdot 10^{-3}\ \mathrm{A} \cdot 200^{-3}\ \Omega} = 12\ \mathrm{F} \quad (2)$$

8.2 Switch Controlled by Real-Time Clock

A real-time clock (RTC) was added to the prototype so that the sensor node can cut off its own power supply in order to avoid consuming any energy on the node side while it is in sleep mode. The RTC has an alarm output that can be set to trigger at the point in time when the node should be powered on. The RTC consumes only a few microamperes of current. The alarm output is connected to a latch IC that turns on or off the current flow through two MOSFETs that supply the node with power. The sensor node can request the RTC to activate the latch at a specific time in the future, turning the power supply on at that time, and then use the reset line of the latch to shut itself down. An SHT11 temperature and humidity sensor was also included on the PCB on the same I^2C bus as the RTC because temperature and humidity measurements are needed in wind turbine monitoring.

8.3 UnderVoltage Lock-Out Circuit

An undervoltage lock-out (UVLO) circuit was designed to cut off the power from the sensor node when the voltage rail is below 2.9 V. There is a 20 MΩ feedback resistor that creates an extra high hysteresis of 350 mV to allow enough energy for the sensor node to wake up and measure the voltage without allowing the turn-on current surge and any startup tasks to drain the voltage rail below the UVLO threshold again. The switching is done using a 2N7002 small signal N-channel MOSFET and an IRLML6401 P-channel power MOSFET.

9 THE PERFORMANCE OF THE PROTOTYPE

The lowest level of illuminance at which the LTC3105 was able to harvest was a few hundred lux, depending on the voltage of the supercapacitor. The energy harvester prototype was tested in a long-term test that lasted six continuous days. The solar cell was located on a roof where it was not shadowed by any object at any time of the day. There was no load connected to the prototype. A data logger was connected and used for measuring time, illuminance, and the voltages of the supercapacitor, battery, solar cell, and MPPC pin of the LTC3105.

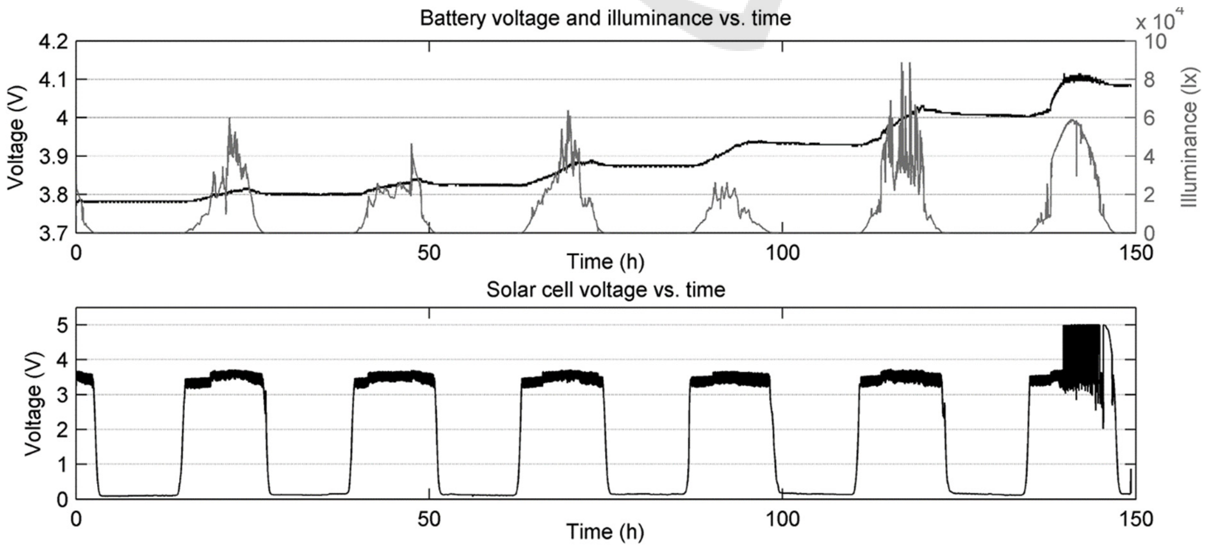

Figure 5: Energy harvester performance over six days.

During the test, the temperature was a few degrees C below the freezing point. Figure 5 shows how the prototype performed. On average, the energy harvester was active for 9.0 hours per day (the sunny hours) and harvested at 35.6 mW. On average, 1.16 kJ was harvested per day, or 2.14 J per minute active. In 6 days, the total energy harvested was 6.9 kJ, which corresponds to 51% of the capacity of the 1,000 mAh, 3.7 V LiPo battery. Once the battery was fully charged, the voltage rail reached the set point of the energy harvesting circuit and the solar cell was automatically disconnected, causing a voltage of more than 5 V over the solar cell.

For most applications, one solar cell of the type tested should be sufficient and the 1,000 mAh battery capacity is useful to have to ensure the sensor node can operate during days of low illuminance. The solar cell, battery and energy harvester of the prototype were well-dimensioned.

Regarding the energy consumption of the UWASA Node, experiments showed that the startup and initialization of wireless communication and a few sensors consumes between 0.7 and 1.5 J. Measuring three voltages 10,000 times using the internal ADC consumes approx. 400 mJ (no peripherals turned off). Transmitting 100 bytes of data consumes ~850 mJ. Measuring 3-axis, 10-bit acceleration at a sample rate of 500 Hz for 2 s consumes 1.82 J. A typical program reading several sensors at a high rate will consume approx. 3-10 J for measurements and 50-100 J for transmission of thousands of bytes. If few bytes are transmitted, the node will consume less than 5 J and can thus operate intermittently at an interval of 3-4 minutes on harvested power.

10 CONCLUSIONS

The goal of this work was to build and test a small energy harvester and power management prototype optimized for the UWASA Node for outdoor use in cold weather, primarily for wind turbine monitoring applications. The developed energy harvester was tested using only a solar cell, but the prototype was designed so that more energy harvesting sources can easily be added. Every part of the energy harvester and power management was chosen to operate at voltages optimal for the UWASA Node with power module. The energy measurements presented in Section 9 can be useful for energy harvester developers. The presented prototype is an improvement on the AmbiMax system described by Park and Chou (2006). By integrating the RTC switch on the energy harvesting PCB, the power consumption of any connected sensor node can be eliminated when inactive.

Powering the UWASA Node by energy harvesting is a useful idea, as it makes the node self-sufficient and allows it to operate in places where servicing would be prohibitively expensive or impossible. By using energy harvesters, wireless sensor nodes can potentially operate independently for several years, if the rest of the software and hardware platform is sufficiently robust.

REFERENCES

Çuhac, C., 2012. UWASA Node Reference Manual 3.0.0. [Unpublished, internal document]25 August. Aalto University and University of Vaasa, ComSys group.

Gilbert, J.M. and Balouchi, F., 2008. Comparison of Energy Harvesting Systems for Wireless Sensor Networks. *International Journal of Automation and Computing*, [online]. University of Hull. Available at: <http://web.eecs.umich.edu/~prabal/teaching/eecs598-w10/readings/GB08.pdf>.

Höglund, T., 2014a. Energy Harvesting for the UWASA Wireless Sensor Node: Applications for Wind Turbine Monitoring. B.Sc. University of Vaasa.

Höglund, T., 2014b. Energy Harvesting Solution for the UWASA Node: Applications for Wind Turbine Monitoring. M.Sc. University of Vaasa.

Mars, P., 2009. Using a Supercapacitor to Manage Your Power. IDTechEx Ltd, [online]14 December.

Available at: <http://www.energyharvestingjournal.com/articles/using-a-supercapacitor-to-manage-your-power-00001921.asp>. [Accessed 24 August 2014].

Park, C. and Chou, P.H., 2006. AmbiMax: Autonomous Energy Harvesting Platform for Multi-Supply Wireless Sensor Nodes. *Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society,* [online]. Available through: IEEE Xplore Digital Library website [Accessed 18 March 2013].

Virrankoski, R. (Ed.), Generic Sensor Network Architecture for Wireless Automation (GENSEN), *Proceedings of the University of Vaasa*, Reports 174, Vaasa 2012.

Yigitler, H., Virrankoski, R. and Elmusrati, M.S., Stackable Wireless Sensor and Actuator Network Platform for Wireless Automation: the UWASA Node, *Aalto University Workshop on Wireless Sensor Systems*, November 19th, 2010, Espoo, Finland.