GNOMES: A TESTBED FOR LOW POWER HETEROGENEOUS WIRELESS SENSOR NETWORKS

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ABSTRACT

Continuing trends in sensor, semiconductor and communication systems technology (smaller, faster, cheaper) make feasible very dense networks of fixed and mobile wireless devices for use in many different sensing and decision-making systems. In this paper we present the design and development of GNOMES, a low-cost hardware and software testbed. This testbed was designed to explore the properties of heterogeneous wireless sensor networks, to test theory in sensor networks architecture, and be deployed in practical application environments. We also present an overview of architectures for extending the lifetime of individual nodes in the network, along with the design tradeoffs that this presents.

1. INTRODUCTION

This paper describes the development, initial testing and deployment of a low-power and inexpensive testbed for wireless sensor networks - GNOMES. In the past few years, as the costs and sizes of sensors and wireless communications devices has rapidly decreased, several such testbeds have been created to explore and verify the properties of these systems. These hardware testbeds - such as the SmartDusts project at UC Berkeley [1] and the μ Amps project at MIT [2] - were designed to test theories of power aware computing, distributed sensor data gathering, data analysis, ad hoc routing and communication. Our GNOMES testbed has many similar features to these, but it also adds some new elements that are being used to boost new theoretical research at Rice University. In addition, the testbed is also being deployed in practical application scenarios.

Our design goal was to create a system of low-cost ($\leq$ \$25 each, in quantity) sensor nodes that are self-organizing and can work in a collaborative manner to solve a given problem. Cost and power consumption were the overriding design constraints for this development effort. These constraints were based on the following assumption: traditional macro sensor devices are bulky and expensive but extremely accurate. Because of the high cost per sensor, they are also not generally fault tolerant. Therefore, by flooding an application area with many small cheap devices, one can overcome the weaknesses that are inherent in this kind of system. Data collected from multiple sensors can be combined to improve the accuracy through the use of advanced DSP algorithms (e.g. creating a high-resolution image by combining multiple low-resolution

images). The system is inherently fault tolerant because of the many nodes that are in use. If a few nodes become inactive, overall system performance should not suffer much.

It is important to note that in our system, nodes are not homogeneous, but rather heterogeneous. That is, each node in the network may not be sensing the same thing. This has benefits in keeping down the cost of each node since each one will not need a full complement of sensors. Sensors can be distributed in such a manner that adequate coverage is maintained for all measured system properties, while keeping the cost of each node relatively low. Organization of similar types of heterogeneous sensor networks have been previously discussed [3, 4], and this approach to system design opens up new research opportunities which are currently being explored at Rice [5].

2. POWER CONSIDERATIONS

In almost all applications of sensor networks, there is a desire to achieve maximum node lifetime (e.g 1 year or more). Many of these nodes will be located in areas where battery replacement may not be an option. This problem of node lifetime and accessibility is often cited in the literature [6], and many researchers tend to combat this problem by concentrating on low-power node design or through energy-aware routing algorithms [7, 8]. We extend this body of work by exploring supplemental and alternate power technologies, such as solar power, in an attempt to extend the life of each node indefinitely.

In addressing the longevity problem, the system designer can consider several approaches:

Make use of exotic, cutting-edge battery technologies. These technologies - e.g. Lithium Ion or Lithium Polymer - have extremely high energy densities. Using batteries alone however, even exotics, has several disadvantages. First, these new technologies tend to be very expensive, which defeats the purpose of a low-cost system with potentially hundreds or thousands of nodes. Second, as is shown in [9] battery technology does not adhere to Moore's law, which is a given in the semiconductor industry. There are clearly diminishing returns in each new generation of battery technologies. Additionally, it is shown in [10, 11] that current advanced battery technologies such will not even meet the standby power requirements for one year of operation for most systems. In these systems, batteries alone will not be adequate.

Use a combination of power sources. This solution uses a battery technology that is rechargeable combined with an alternate power source that can be used to charge the battery at times when it is not needed. This secondary power source could be one of several possibilities and highly application dependent. For environ-

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Figure 1: Average Output Voltage of Solar Cell across a 1kOhm Load

ments where outdoor operation is predominant, a solar cell could be used to recharge the battery as needed, provided that there is enough sunlight to do so. Outdoor structures such as bridges and skyscrapers could also use small and inexpensive wind turbines to harness energy. In addition, other forms of energy could be converted to electrical potential. For example, the Piezoelectric effect allows mechanical stress to be converted into electricity, and it would be possible to store this charge in a battery.

Make use of “non-battery” technologies. In extremely embedded and low-power systems, the designer may have to forgo batteries completely. Such an example scenario may be the embedding of sensors into the concrete foundation of a building for long term measurement. In such a scenario, it may be necessary to rely completely on batteryless operation, such as the Piezoelectric effect or some other exotic power technology [12]. One could also envision powering medical sensors with body heat as the sole power supply [13]. Exploring such systems is a goal of ours at Rice, and the GNOMES project is merely a step in that direction.

Our system employs a simple solar cell as a proof of concept device to show that mixed-power nodes are a viable solution in large scale sensor networks. There are clearly some design consequences with this approach, however. A node could possibly spend much of its time in an inactive/recharging state, with little or no participation in the network. This will affect system performance as nodes become active and inactive at varying time intervals. To combat this, efficient routing and distributed computation algorithms will be necessary, which are also being studied at Rice. The system we have designed will allow the node to switch between one of two on board batteries. This will allow the node to use one battery for power to perform computations, collect sensor data and communicate with other nodes while the other battery recharges.

To test the feasibility of our architecture, we ran an experiment with the 5 Volt, 30mA solar cell used in our design. With solar cells, the output voltage is proportional to the intensity of the sunlight received. For our experiment, we placed the solar cell on the end of a rod, facing skyward in our engineering quad. In this unobstructed position, the cell received direct sunlight for most of the daylight hours. We then measured the output voltage across a 1kOhm load at 1 min. intervals over a 1 week period in early January. Figure 1 shows these readings.

To determine the useable voltage level, we have to take into

Figure 2: GNOMES Block Diagram

consideration that our charging circuit requires a minimum of 3.5 Volts to provide enough current to charge a battery. The data show that in this location we could expect about 5 hours of useful sunlight each day. Of course, the amount of sunlight received has many dependencies: time of day, weather, season, geographical location, etc. Because of this, each node’s exposure to sunlight will vary. According to official records, the total amount of daylight during the experiment was approximately 10 hours and 39 minutes, with two sunny days and three cloudy, rainy days. To combat the fact that there will not always be enough time to sufficiently charge the battery, we are developing intelligent adaptive algorithms to regulate a nodes activity in the network. The effect that this will have on the sensor network architecture can be dramatic. Nodes that have little chance to recharge their batteries will not be very active participants in the network. Perhaps they will be forced to sense less often and transmit fewer bits of data in order to conserve power.

In addition to solar power, we are also exploring other possibilities, such as wind, hydro and electromechanical power, and have recently obtained some very promising preliminary results using wind power.

3. SYSTEM HARDWARE

A block diagram of the node we have designed is shown in Figure 2. Our GNOMES node resembles the COTS Dust node designed as part of the SmartDusts project at UC Berkeley [14] occupying approximately 55 cm³ (3.8 cm by 5.7 cm by 2.5 cm). While our design was inspired by this project, we have added several unique features that improve upon the original design and allow for greater system flexibility and performance.

The heart of the GNOMES node is a 16-bit MPS430 microcontroller from Texas Instruments. The particular chip that we chose, the MPS430F149, offers an impressive array of features while consuming very little power (about 3.5 MIPS/mA).

- 16-bit Operation, with Hardware Multiplier
- Up to 7.3728MHz Operation, Dynamically Controllable
- 60KBytes of Code Memory, 2KBytes of Data Memory
- 8 Integrated Channels of AD Conversion with 12 Bit Precision
- 2 UARTs for Serial Communications

In addition, our GNOMES node offers the following capabilities, as shown in Figure 2.

- An 32KByte I²C EEPROM for Persistent Data Storage
- Support for Multiple Power Supplies (e.g. Battery and Solar)
- Support for an Optional Integrated GPS Module
- Modular Communications Header - Bluetooth or 900MHz Radio
- Modular Sensor Header
- Two Expansion ports (14 GPIO total; 5 interruptable & I²C)

The following features are unique to GNOMES. First, as we previously mentioned, we designed this node to explore the longevity of sensor nodes. Our device draws its main power from one

Figure 3: Maximum Lifetime of a GNOMES Node (Accounting for Power Supply Inefficiency)

of two AA NiMH cells. In addition, auxiliary power can be supplied via an external device such as a solar cell in order to charge the battery that is not being used for main power. An adaptive software algorithm monitors system performance and battery voltages to determine when to switch sources, such that the longevity of a node can be extended indefinitely. This dual battery approach imposes little restriction on system operation. However, the node must curtail its operation if it cannot recharge for long periods of time and both batteries become low. This places some constraints on the design and operation of the sensor network, and we are currently exploring the issues that this raises in both theory and in practice.

Second, we have designed this node to include a modular sensor header, so that changing the functionality of a node is as simple as plugging in a new sensor module. In addition, this modularity allows us to design and test heterogeneous wireless sensor networks, in which each node may sense a different property of the environment than its immediate neighbor. This design approach also lowers the cost of each node since not every one of them will need to have many sensors. Our first sensor module includes accelerometers that measure two axes of acceleration from -5g to +5g. It also includes temperature sensors to aid in calibration of the accelerometers. Other sensor modules are currently in design.

Third, we designed the communications subsystem to be modular as well. Currently, it can function with either a 2.4GHz Bluetooth radio or a 900MHz radio module. For our first communication module, we chose to design around a Class 2 Bluetooth module [15]. We made this design decision for several reasons. Primarily, Bluetooth is a relatively low-power radio device that offers moderately high data rates (up to 721kbps for user applications). In addition, many low-level communications functions are already built into the hardware link and physical layers, such as power efficient modulation, device discovery, smart packet detection and intelligent sleep scheduling [16]. We have also found in our previous work that typical Bluetooth radios far outperform the specifications for device range without adversely affecting data throughput. For example, we have observed Class 2 Bluetooth modules maintain connections at 5 to 10 times the specified distance of 10m [17]. We have also developed a 900MHz radio module. However, we are still running tests on the module, after which it will be ready for production.

Using data gathered from lab tests, we performed an analysis

Scenario #	1	2	3	4	5	6	7	8
Sense & Process	50%	50%	100%	98%	50%	50%	98%	96%
Communication	0%	2%	0%	2%	0%	2%	0%	2%
GPS	0%	0%	0%	0%	2%	2%	2%	2%
Sleep	50%	48%	0%	0%	48%	46%	0%	0%
Avg. Current (mA)	2	3	4	4.9	2.6	3.6	4.5	5.4
Avg Power (mW)	6.7	10	13.2	16.2	8.7	12	14.9	18

Table 1: Operation Scenarios for a GNOMES Node (Irrespective of Power Supply)

and placed some upper bounds on the lifetime of a node. These data are shown in Figure 3 and Table 1. Although our nodes recharge a battery through solar power, these tables present baseline data without any recharging of the batteries. Figure 3 shows the maximum lifetime in days for a node for three different modern battery technologies and eight different scenarios. The scenarios are described in Table 1 and show percentage of time devoted to certain activities. Average current and power consumption are also given for each scenario. We picked percentages that seemed reasonable for some of our applications.¹ These percentages are being verified in field tests.

Even in the absolute worst case scenario (#8 with the NiCd battery), we predict that a node could achieve an uptime of 25% and operate indefinitely. That is, with using the solar cell to charge the system battery, a node would have to spend 3 days recharging the battery for every 1 full day it spent sensing processing and communicating.

Our cost goal for GNOMES was to keep each node under \$25 in large quantities (> 1000). Cost depends largely on the sensors, and we expect the nodes to become cheaper as the semiconductor industry continues its pace of device integration and miniaturization. Currently a GNOMES node with 2-axes of acceleration sensing costs around \$50 without GPS and \$80 with GPS.

4. SYSTEM SOFTWARE

In order to easily create networking and other application specific software for the GNOMES testbed, we have also begun development of an embedded real time operating system and low-level software drivers to control each of GNOMES' subsystems. Modelled after TinyOS [18] from UC Berkeley and ADEOS, written by Michael Barr [19], the GNOMES operating system will offer process management and scheduling. This allows software developers to write multiple applications to be run on the node concurrently as well as allowing the operating system to take care of power management issues in the background.

We have also developed software drivers and common APIs to provide easy process-level control for each of the GNOMES subsystems. This includes: a partial implementation of a Bluetooth [15] stack to allow for device discovery and connection establishment; NMEA string parsing to better manage data from the GPS module for user applications; I²C driver to communicate with the on-board EEPROM; an intuitive interface to control the AD converter. We have also implemented a power management pro-

¹1% time devoted to communication yields a maximum data transfer rate of $\approx 1\text{Mbytes/hour}$, well more than we expect most of our applications to use. 2% times devoted to GPS is roughly equivalent to the time needed to sample GPS data once per hour.

cess that will run in the background and look for ways to conserve power on the node. Both the drivers and the operating system were developed in a mixture of C and assembly on the "IAR Embedded Workbench" from IAR systems, a Texas Instruments third-party company, which offers both an embedded development as well as debugging environments.

5. APPLICATIONS

The low cost and long lifespan of GNOMES make them ideal for investigating various approaches to traditional sensing applications. In addition, their on-board processing power, wireless capabilities and modular design allow us to explore novel and innovative uses:

Seismic monitoring of civil structures. GNOMES allows for the rapid deployment of dense sensing networks in structures otherwise unsuited for seismic monitoring. This gives valuable insight into the nature of building behavior under various excitations. Supplementary nodes equipped with strain gauges and force transducers will be able to monitor the local performance of individual members and connections. As this data is collected, the use of on-board computing power permits pre-processing of data, thereby decreasing the necessary bandwidth for the centralized collection of data. Furthermore, structures such as bridge towers and high-rise buildings are well suited to the employment of alternate power-sources, such as solar and wind power.

Tracking and routing of personnel and machinery. GNOMES, fitted with the optional GPS module, can help track and optimize the progress heavy machinery such as graders and excavators. In indoor environments, the radio modules can act as beacons, which in conjunction with signal strength maps [20] would permit the localization of personnel operating on site. This opens the possibility of providing context-aware services to the jobsite workforce. As the cost of these devices decreases, they could be attached to large pieces of equipment as identification badges, allowing their efficient tracking and routing on the way to installation.

Examination of contaminant levels and flow. Environmental regulations and awareness lead to a reduction of the allowable concentrations of pollutants released into air, soil, and water. Thus, to detect and identify these levels of pollutants, it is increasingly important to advance the capabilities of field monitoring methods and systems. The needs for fast and cost-effective environmental assessment have been addressed with a variety of chemical sensors [21]. With the addition of chemical sensing modules, GNOMES could be employed to monitor the levels and flow patterns of environmental contaminants.

Corrosion detection and cure-rate monitoring. We are currently investigating the use of GNOMES in embedded environments such as concrete members and asphalt roadways. Through the examination of moisture content and temperature, it is possible to estimate the maturity of concrete in structural components, providing a non-destructive complement to existing strength tests. The embedding of sensors in roadways is already being investigated and could detect corrosive subsurface conditions before serious damage is done. This application could be extended to include underground pipes and drainage tiles.

6. CONCLUSION AND FUTURE DIRECTIONS

In this paper, we have presented the complete design of and applications for GNOMES, a testbed for wireless heterogeneous sensor networks. This system was built to explore the various properties of and to test and develop theories for wireless sensor networks,

with a initial focus on increasing the longevity of sensor nodes and characterizing the performance this has on a sensor network. We are actively developing our testbed by creating new sensor and communication modules and by manufacturing a large quantity of the GNOMES nodes. In addition, we are considering designing a new node with either multiple MSP processors or a more powerful DSP. We realize that this will introduce more power consumption, but we also recognize that this will allow us to implement more sophisticated and interesting algorithms on each node. This will allow us to better explore the tradeoffs between local and remote data processing within a sensor network.

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