Software and Hardware Tools for Teaching Communications Concepts and Introducing Students to Low-Power Wireless Communications

Authors:

James M. Conrad, University of North Carolina at Charlotte, USA, 704-687-2535, jmconrad@uncc.edu
Ivan Howitt, University of North Carolina at Charlotte, USA, 704-687-3887, ilhowitt@uncc.edu

Abstract — *Wireless communications has become an important commercial product feature and research topic within the last ten years. There are now more mobile phone subscriptions than wired-line subscriptions. One area of commercial interest lately has been low-cost, low-power, and short distance wireless communications used for "personal wireless networks." Technology advancements are providing smaller and more cost effective devices for integrating computational processing, wireless communications, and a host of other functionalities. These embedded communications devices will be integrated into applications ranging from homeland security to industry automation and monitoring, and will also enable custom tailored engineering solutions, creating a revolutionary way of information dissemination and processing. With new technologies and devices come new business activity, and the need for employees in these technological areas. Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable development environments available for classroom use, so students often do not learn about these technologies during hands-on lab exercises. The goal of a development and teaching effort was to create a low-power embedded system that could be used to teach wireless communications hardware and protocols. This paper presents the experiences of introducing board-to-board communications, Infrared communications, and finally wireless communications concepts and hardware into the classroom. Specific assessment of student skills that were needed as a prerequisite and successes based on prerequisites are also addressed. A design of additional hardware is presented. Also, a future class that builds on these tools is suggested.*

Index Terms — *Embedded Systems, Wireless communications, hands-on learning, IEEE 802.15.4, Bluetooth.*

INTRODUCTION

Experts say that embedded systems are "everywhere" around us. Embedded Systems Development is the field of putting small computers in everyday items, like microwave ovens and wireless phones. Wireless communications has become an important commercial product feature and research topic within the last ten years. There are now more mobile phone subscriptions than wired-line subscriptions. One area of commercial interest lately has been low-cost, low-power, and short distance wireless communications used for "personal wireless networks." Specifically, Bluetooth components have been included in mobile phones, head sets, Personal Digital Assistants (PDA), PCs, printers, and other devices. A new communications standard, IEEE 802.15.4, has been created to further reduce the power requirements and cost of devices.

Technology advancements are providing smaller and more cost effective devices for integrating computational processing, wireless communications, and a host of other functionalities. These embedded communications devices will be integrated into applications ranging from homeland security to industry automation and monitoring, and will also enable custom tailored engineering solutions, creating a revolutionary way of information dissemination and processing. The wireless embedded network is context aware, taking into account the power restrictions, the application's information flow rates, the network's location, as well as reliability and survivability. Development of wireless embedded networks requires a detailed understanding of the RF environment, low power circuit design and advancements in energy efficient network design.

With new technologies and devices come new business activity, and the need for employees in these technological areas. Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable development environments available for classroom use, so students often do not learn about these technologies during hands-on lab exercises.

The goal of a development and teaching effort was to create a low-power embedded system that could be used to teach wireless communications hardware and protocols. The specifications of these new teaching tools were that:

- The base embedded microcontroller environment should be a very low cost off-the-shelf development board. Two were selected: the Renesas M30262 SKP board ($40) and the Atmel STK500 board ($40). These two boards have accompanying development software and compilers.

- The communications electronics should be low cost Bluetooth and 802.14.5 devices that are attached to the development board via removable daughter boards.
- Basic communications protocols should be implemented to allow the boards to work and communicate, as identified by the standards specification. The use of these basic protocol software libraries should be documented so that students, with the correct development board and communications daughter board, could use this software.
- The basic protocols and daughter boards should be used by students in an embedded systems or computer interfacing course.

This paper presents the experiences of introducing board-to-board communications, Infrared communications, and finally wireless communications concepts and hardware into the classroom. Specific assessment of student skills that were needed as a prerequisite and successes based on prerequisites are also addressed. A design of additional hardware is presented. Also, a future class that builds on these tools is suggested.

AN EMBEDDED SYSTEMS AND AN ADVANCED EMBEDDED SYSTEMS COURSE

The IEEE Computer Society and the ACM formed a joint task force to create a model curriculum for computing. They have developed guidelines for a Computer Engineering curriculum [1], of which embedded systems and communications are core disciplines, or "knowledge areas." The task force also states that, "*Computer engineering must include appropriate and necessary design and laboratory experiences.* A computer engineering program should include "hands-on" experience in designing, building, and testing both hardware and software systems."

An embedded systems course was developed at North Carolina State University in 2002 to better prepare Computer Engineering students for the design challenges of today's marketplace. The course was brought to the University of North Carolina at Charlotte in 2003 [2]. The goal of an embedded systems course is to solidify and build upon a student's knowledge of computer organization by presenting hands-on experience with microcontrollers. Students also examine a few sensors that are used in commercial and medical products and learn how to interface them in a microcontroller system. Specifically, the course performance outcomes are that students will:

1. Recognize and identify the constraints facing embedded system designers, and determine how to assess them.
2. Program a modern microcontroller in assembly language and operate its peripheral devices.
3. Interpret how the assembly code generated by a compiler relates to the original C code.
4. Practice thread-based program design with a real-time operating system.
5. Develop programs controlling embedded systems using quick and efficient methods.
6. Predict, measure and manipulate a program's execution time.

Laboratory assignments are an integral part of the course and are intended to provide experience in applying the design techniques discussed in lecture. Because almost all of us learn by doing, the laboratory is probably the most effective method for learning the material. These assignments use the embedded systems board required for the class. Lab exercises can be performed in the Embedded Systems Teaching Lab or on a student's own home PC, but the successful implementation has to be demonstrated to a Lab TA. The laboratory setup includes networked PCs, bench power supplies, multi-meters, and 350 MHz mixed-signal oscilloscopes. The laboratory board kit is purchased by each student in the class through the university bookstore and includes the board, a ROM monitor daughter board, a USB cable, and two Integrated Development Environment (IDE) software disks. Students keep this board after the class ends for use in other classes (e.g. Senior Design, Advanced Embedded Systems). Students work in pairs. The first few assignments require only one board for development and demonstration, but later lab assignments require board-to-board communications, so two boards are needed. The last assignment uses concepts from all of the previous labs, and also requires code reuse.

An advanced course in embedded system design utilizes the same 16-bit microprocessor board and development environment described above. In this course students:

- Recognize and identify the constraints facing embedded system designers, and determine how to assess them.
- Program a modern microcontroller in assembly language and operate its peripheral devices.
- Interpret how the assembly code generated by a compiler relates to the original C code.
- Practice thread-based program design with a real-time operating system.
- Develop programs controlling embedded systems using quick and efficient methods.
- Predict, measure, and manipulate a program's execution time.
- Learn software development techniques and tools used in embedded system development, including working with configuration management tools and software repositories.

- Design and build embedded systems, including architecture, schematic capture and layout, board manufacture, population, test, and system integration.

The goal of this advanced course is to solidify and build upon a student's knowledge of computer organization by presenting hands-on experience with microcontrollers. Students also examine a few sensors that are used in commercial and medical products and learn how to interface them in a microcontroller system. Students in this course continue to utilize the mixed signal oscilloscopes and PCs with software development environments described above. They also use configuration management tools available via the campus local area network.

INTRODUCING COMMUNICATIONS INTO EMBEDDED SYSTEMS COURSES

The approach to teach communications to students is bottom-up with respect to the OSI layer model. In the introductory embedded systems course students implement basic serial I/O communications using polling by transmitting data between a PC and a M30262 SKP development board. They learned the importance of setting up the physical data communications including speed, number of data bits, start and stop bits, and parity. Next they used interrupts to perform serial I/O between two M30262 SKP development boards. Students learned the importance of relying on the hardware and interrupt service routines to handle the physical transmission of large blocks of data.

In the advanced embedded course, students continued their experiences with data communications by designing their own communications circuit to interface with the development board. Their first lab introduced students to interfacing two M30262 SKP board via an Infrared (IR) link. In this lab students utilized onboard timers, serial UARTs, and I/O ports of the board to create an IR communications device. The main objective was to create a board that can attach to a PC and transmit/receive data via an IR link. Two boards were programmed with the same code and had the same IR hardware. IR hardware was provided. Two serial cables and one PC with two serial ports were needed. The first effort simply sent a single byte, and waited for an acknowledgement (ACK) or non-acknowledgement (NAK) byte to be returned. Students also implemented a time-out function to allow resending the byte if an ACK or NAK was not received in sufficient time after transmission. An example of the lab set-up for the Infrared communications experiment is shown in Figure 1A.

The next effort involved creating packets of data and transmitting these between boards. The packets had a sync byte, source and destination bytes, a packet size byte, the data payload, and a checksum byte. In this exercise, the students learned the value of building packets, then buffering data and decoding packets.

The last effort in this series of exercises was to involve a packet store-and-forward exercise, where any received packet that was not intended for the device would be forwarded to the next device, but the success rate of the packet exercise was too low to allow groups to easily reuse code.

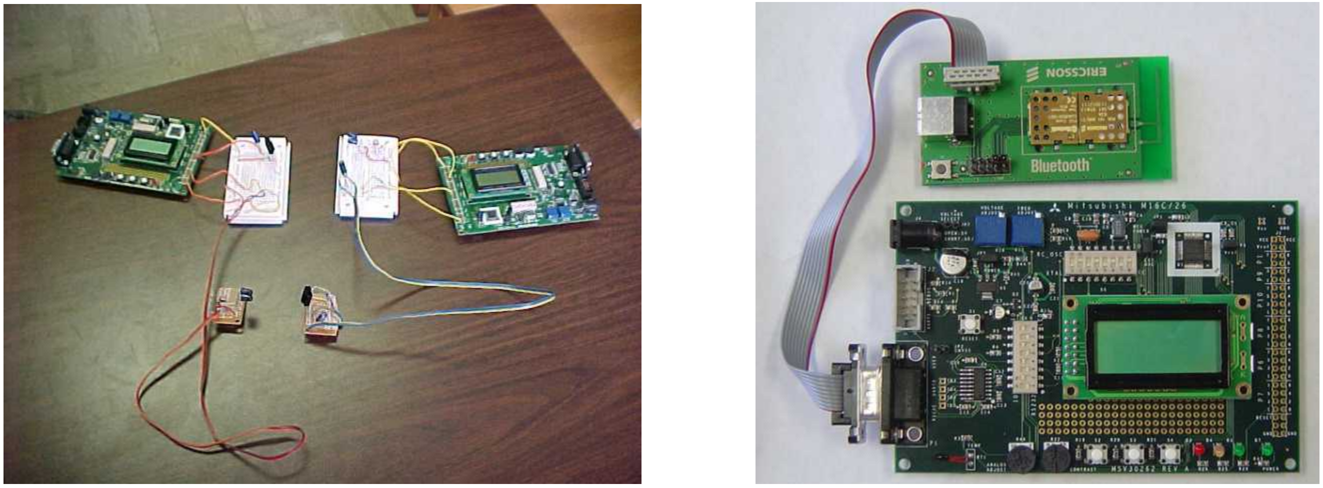

FIGURE 1
A) A LAB SETUP FOR THE INFRARED COMMUNICATIONS EXERCISE B) A LAB SETUP FOR THE BLUETOOTH COMMUNICATIONS EXERCISE

The next communications experiment involved building transmission packets for the Teleca (Ericsson-made) Bluetooth module. Students set up the Bluetooth module for data communications, then continuously transmitted the temperature value (in ASCII) of the development board's thermistor to another Bluetooth module connected to a PC. Again students needed to build packets with the destination address and payload. One aspect that they did not program was the Bluetooth discovery process - they had to rely on an already written PC program to do this. See Figure 1B for an example of the Bluetooth lab setup.

One effort that was started but not completed was the creation of an IEEE 802.15.4 "daughter board" which could plug into the class development board. This daughter board would contain only the radio transceiver chip and supporting circuitry for IEEE 802.15.4 communications, and rely on the development board for the software stack needed to communicate between boards. We would provide the students with the necessary libraries needed to build messages for transmission, and decode received messages. We are currently completing this work and hope to have it available for the last lab exercise of the Fall 2004 semester.

FIGURE 2
SAMPLE EMBEDDED DEVELOPMENT BOARD WITH ATTACHED IEEE 802.15.4 COMMUNICATIONS DAUGHTER BOARD

Student success of each exercise was measured by grading each lab based on the functionality demonstration, code content, code structure, and lab report. A score of 85% of possible lab exercise points was considered a successful implementation of the lab. The five efforts described above had the following success rates: serial I/O-Polling = 100%; serial I/O-Interrupts = 95%; IR communications - basic = 100%, IR communications - packets = 50%, Bluetooth communications = 100%. The reason the packet communications lab exhibited a low success rate was due primarily to the difficulty of synchronizing the bits of the entire packet between the two boards. Students learned that the timers and system clocks of individual boards were often too far apart to allow synchronization based on only the synchronization byte. Nonetheless, this is an important concept and in future labs we may incorporate this concept through discovery-based learning.

FUTURE WORK – AN WIRELESS ENABLED EMBEDDED SYSTEMS COURSE

A new senior technical elective course will be developed to address issues associated with designing and implementing wireless sensor networks. The course builds upon and is motivated by extensive educational literature which supports the integration of classroom learning with laboratory experience for educating students in communications [4-16]. The proposed course will have the following five educational objectives:

1. Issues and design practices for integrating sensor, control logic, and RF communications for low cost and low power sensor applications.
2. Introduction to low power and low cost RF communication standards. Specifically, the IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (LR-WPAN). These two standards will be compared and contrasted to examine trade-offs in transceiver design for wireless sensor network (WSN) applications.
3. Introduction to low power network protocols for WSN. Current routing and scheduling schemes for WSN will be covered based on techniques addressed in the literature as well as methods being developed by the authors.
4. Environmental issues including RF signal propagation, multipath and interference as well as coexistence issues based on operating the WSN in an unlicensed frequency band.
5. Context aware design, i.e., understanding the WSN application and exploiting the characteristics of the problem to achieve an improved design.

Prerequisites for the new course will be an introductory course in analog and digital communications and an introductory course in embedded systems.

A three prong approach is to be investigated for engaging the students and facilitating learning: 1) traditional lecture, 2) computer modeling & simulation, and 3) laboratory with empirical investigation. Communication theory and analytical models are often considered dry by undergraduate students leading to poor retention of the material. Understanding these concepts is an important part of understanding approaches required to solve real world problems. Therefore, a pedagogical goal is to develop learning modules for the topics in the course. Each module would use multiple approaches and multiple teaching approaches to engage the student to grasp difficult concepts and see underlying principles. To illustrate, radio frequency signal propagation is an essential component in designing WSNs and there are well-established analytical models that characterize signal propagation. The analytical models are involved and difficult for most undergraduates to grasp. A learning module for RF propagation could include the following: 1) Lecture introducing the concept of RF propagation at a high level with limited use of mathematical models, 2) Laboratory experiment which extends the lecture and requires the student to engage in discovery-based learning, 3) Follow up lecture which discusses the analytical models in detail, drawing upon the students observations from the lab, 4) Additional computer simulation assignment on RF propagation which reinforces the concepts discovered in the laboratory and presented in the classroom. Identifying the correct set of topics and the development of the learning modules is central to the objectives of the project.

CONCLUSIONS

Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable development environments available for classroom use, so students often do not learn about these technologies during hands-on lab exercises. We have provided students with hands-on lab exercises which represent some areas of communications and wireless communications used in industry. Several examples of communications lab exercises were described, including wireless communications. A future lab will investigate IEEE 802.15.4 in great detail. A follow-on Wireless Enabled Embedded Systems course is also suggested.

REFERENCES

[1] IEEE Computer Society/ACM Task Force on Computing Curriculum, *Computing Curricula - Computer Engineering "Iron -Man Draft"* , June 8, 2004 (http://www.eng.auburn.edu/ece/CCCE/)

[2] Conrad, James M., ECGR4101/5101 Course website, http://www.coe.uncc.edu/~jmconrad/ECE3090Fall2003/index.html.

[3] Conrad, James M., Infrared Experiment website, http://www.coe.uncc.edu/~jmconrad/EducationalMaterials/IR.html.

[4] Behnam Kamali, "Development of an undergraduate structured laboratory to support classical and new base technology experiments in communications," IEEE Transactions on Education, v 37, n 1, Feb, 1994, p 97-105.

[5] Behnam Kamali, "A Three-Level Structured Laboratory to Support Traditional and New-Base Technology Experiments in Communications," NSF Award No. 9153146, University of Texas at San Antonio, May 15 1991 to Oct 31 1993.

[6] Levent Sevgi, "EMC and BEM engineering education: Physics-based modeling, hands-on training and challenges," IEEE Antennas and Propagation Magazine, v 45, n 2, April, 2003, p 114-119.

[7] V.E DeBrunner, L.S. DeBrunner, S. Radhakrishnan, Khan Kamal, "The telecomputing laboratory: A multipurpose laboratory," IEEE Transactions on Education, v 44, n 4, November , 2001, p 302-310.

[8] Michael Munoz, Susan Garrod, "In process development of an advanced undergraduate communications laboratory," Proceedings of the 27th Annual Conference on Frontiers in Education, v2, 1997. Part 2 (of 3), Nov 5-8 1997.

[9] Ali Behagi, "Development of a wireless and satellite communication laboratory at Penn State Harrisburg," Proceedings of the 1997 ASEE Annual Conference, Jun 15-18 1997, Milwaukee, WI, USA, 5p.

[10] E. Bertran, F. Tarres, G. Montoro, "Experimental course on digital communications," Proceedings of the IEEE International Conference on Electronics, Circuits, and Systems, v 3, Sep 7-Sep 10 1998, p 321-324.

[11] William D. Lane, "Textbook principles to communications hardware: Making it work," Proceedings - Frontiers in Education Conference, v 3, Nov 6-9 1996, p 1504-1507.

[12] Brad Richards, Nate Waisbrot, "Illustrating networking concepts with wireless handheld devices," Proceedings of the Annual SIGCSE Conference on Innovation and Technology in Computer Science Education, 2002, p 29-33.

[13] Randy Smith, "Integration of Wireless Technologies into an Undergraduate Networks Exploration Laboratory," NSF Award No. 0125635, Jacksonville State University, Jun 1 2002 to May 31 2005.

[14] Fred L Fontaine, "Wireless Communications Systems Design Laboratory," NSF Award No. 9850785, Cooper Union, Jul 1 1998 to Jun 30 2000.

[15] P.M. Shankar, B.A. Eisenstein, "Project-based instruction in wireless communications at the junior level," IEEE Transactions on Education, v43, n3, Aug, 2000, p 245-249.

[16] P. M. Shankar, Introduction to Wireless Systems, Wiley, 2002.