

Teaching Optical Communications Concepts in Embedded Systems Courses

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Abstract – There have been significant technological developments and advancements in areas related to telecommunication, medicine, and computing. Optical engineering has played an important role in all of these. Optical engineering is becoming more prevalent because of its wide range of applications in almost every field. The goal of a teaching effort was to create embedded system lab exercises that could be used to teach optical communications hardware interfacing and control. This paper identifies pedagogy for teaching these concepts and conducting laboratory exercises. It then presents the experiences of introducing board-to-board communications using simple infrared and fiber optical communications devices in the classroom. Specific assessment of student skills that were needed as a prerequisite and successes are also addressed.

Index Terms – Embedded systems, fiber, hands-on lab exercises, infrared, optical engineering.

INTRODUCTION

Wireless communications has been an important commercial product feature and research topic for more than twenty years. Radio communications is one area of importance, but optical communications is also gaining prominence. Technology advancements are providing smaller, faster and more cost effective devices for integrating computational processing, optical 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.

There have been significant technological developments and advancements in areas related to telecommunication, medicine, and computing. Optical engineering has played an important role in all of these. Optical engineering is becoming more prevalent because of its wide range of applications in almost every field [1,2]. As an example, communication using optical fiber is becoming one of the fastest growing areas and is in use extensively through out the world.

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 optical 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 an embedded system that could be used to teach optical communications hardware interfacing and control. This paper establishes the requirements of knowledge that an embedded optics engineer must possess. This paper also identifies the ideal pedagogy for teaching these concepts and conducting laboratory exercises. It then presents the experiences of introducing board-to-board communications using simple infrared and fiber optical communications devices in the classroom. Specific assessment of student skills that were needed as a prerequisite and successes are also addressed.

OPTICAL ENGINEERING

Just recently optical engineering has emerged as one of the most significant areas for technological research and development. Starting from the small Light Emitting Diodes (LEDs) and photodiodes to optical fibers and laser electronics, optical engineering applications are found in almost all industrial and research areas. Typically the field of optical engineering is related to photons and light and their interaction with matter. The traditional optics of lenses and prisms have merged with semiconductor technology, detectors, lasers, and thin optical fiber to give rise to modern optical engineering. Until recently the field of optical engineering was not considered to be a part of electrical engineering, although the fundamental laws for electromagnetic waves, which are followed in optics, are also governed by the Maxwell's equation. Optical engineering has, however, now revolutionized the electrical engineering field due to the technical developments in the area of integrated optics, fiber optics, electro magnetic optics, and optical computing. With this new technology, the knowledge about optical engineering has become important for electrical and computer engineering students. To understand the general concepts in the field of optics, a student needs to have knowledge about physics and should be familiar with electromagnetic theory and Fourier transforms.

Although there are many advanced applications of optics, only one application of optics has revolutionized the field of communication: optical fiber. Optical fibers are thin, transparent strands almost the size of a human hair made from a dielectric cylinder surrounded by another transparent dielectric cylinder [3]. The fibers are used as light wave

guides to transmit light energy at optical wavelengths. The light travels inside the fiber using a series of reflections from wall to wall between the two transparent cylinders. The reflections inside the walls are possible because of high refractive index material of the inner cylinder and the low refractive index of the outer cylinder, also known as total internal refraction. The light can thus be transported from one end connected to a light transmitter to the other end connected to a light detector. A typical optical fiber communication system consists of a transmitter with a light source, which is typically a LED or a laser diode, length of optical fiber and a receiver with a light detector, like a photodiode. Within the transmitter the input signal is converted from an electrical signal into an optical light source signal. This modulated light, after a series of reflections through the length of the optical fiber, reaches the receiver, where the light signal is converted back into electrical signals with the help of detectors. The detector is typically either a phototransistor, a PIN diode (positive, intrinsic and negative) or an APD diode (Avalanche photodiode). The use of optical fibers as a means of communication is mainly because of their very low fabrication cost, low signal loss, and extremely low interference and capability of high data transfer rate at very low power. The light traveling through the fiber is totally confined inside the fiber resulting in almost zero cross talk between the fibers. An example of a fiber optic cable and two transceiver devices are shown in Figure 1.



FIGURE 1
FIBER OPTIC CABLE AND TRANSMISSION DEVICES

The wide range of applications of optics in almost every field, and particularly in the field of electrical and computer engineering, makes it important that engineers have certain knowledge about optics. Many universities offer optical engineering courses both at the Masters as well as at the PhD

level. The degree program covers the basics of optics, which includes topics like modern physics, electromagnetic waves, optical properties of materials and mathematics. The program also covers the advanced fields in optics like optical fiber communication, quantum optics, holography, and lasers. A large amount of research is also taking place at the university level.

The University of North Carolina at Charlotte offers both Masters and PhD degrees in Optics [4]. The program is an interdisciplinary effort involving the Physics, Chemistry, Mathematics, Electrical and Computer Engineering, and Mechanical Engineering departments. Besides a large number of courses being offered there is much research conducted in the field of Optical Engineering as well. Some of the research that is taking place in the Department of Optics includes fields like optical imaging, optical communication, optical metrology, nanostructured optical devices and much more.

AN INFRARED WIRELESS COMMUNICATION SYSTEM

INTRODUCTION TO INFRARED FOR LAB EXERCISES

Wireless infrared (IR) transmission has many applications like remote control, telemetry and health care. For those applications, infrared transmission has many advantages over RF (Radio Frequency) transmission techniques [5,6]. Since intensity modulation and direct detection receivers are used, the multipath-fading problem can be avoided. In addition, building walls block infrared waves, so that interference rarely occurs. Furthermore, there are no regulations over the used bandwidth. Infrared transmission has some drawbacks as well: path loss could be high, it is limited to short range applications, and it has transmission power restrictions so as to not affect human eyes or skin.

Infrared emitters and detectors capable of high-speed transitions are available at a low cost, so it was simple task to create labs to introduce students to the basics of IR communications systems [7]. The main outcomes of lab exercises were an understanding of modulation, transmission, and demodulation techniques through establishing a board-to-board communication using two SKP-30262 microcontroller evaluation boards, LEDs, photo detectors and some transistor level devices.

Their first lab introduced students to interfacing two evaluation boards 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 2.

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.

Prerequisites for these lab exercises are an introductory course in analog and digital communications and an introductory course in embedded systems or computer organization.

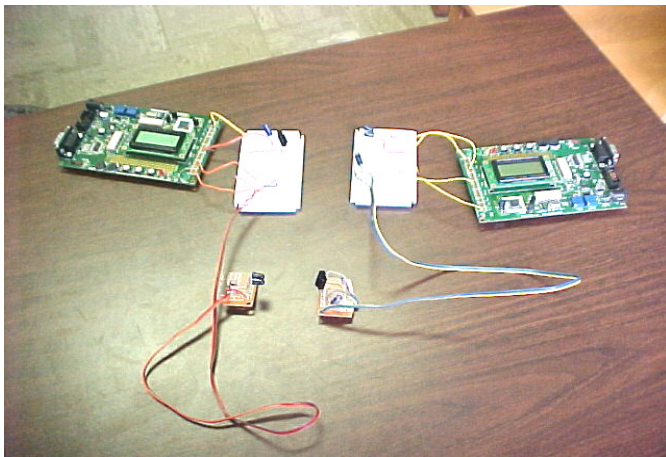


FIGURE 2
TRANSMITTER AND RECEIVER SIDE CIRCUIT.

TRANSMITTER SIDE

The transmitter side of the IR lab is shown in Figure 2 and consists of the following parts:

- Power supply.
- SKP-30262 board.
- 2N2222A, NPN Transistor.
- High-powered IR (TSAL6100) LED.
- 8 K Ω resistor.

The Vishay TSAL6100 is a high efficiency infrared emitting diode in GaAlAs on GaAs technology. The main features of the TSAL6100 are extra high radiant power and radiant intensity, high reliability, low forward voltage, suitable for high pulse current operation, angle of half intensity $\phi = \pm 10^\circ$, peak wavelength $\lambda_p = 940$ nm, and good spectral matching to Si photo detectors.

On the transmitter side, data bits are modulated to be sent, utilizing A0, A1, A2, and A4 timers on SKP-30262 board. A0 (Figure 3) works as free running timer, generating 30 kHz, which triggers timers A1 and A4. Those timers work in the

event counter mode and they are loaded by calculated values that define the time for 20 pulses and the 10 msec period of shutdown. A2 works in timer mode also and is used to trigger the LED, its output goes through the 8 K Ω -resistor to the base terminal of the 2N222A transistor, which is used as a switch to turn the LED ON and OFF.

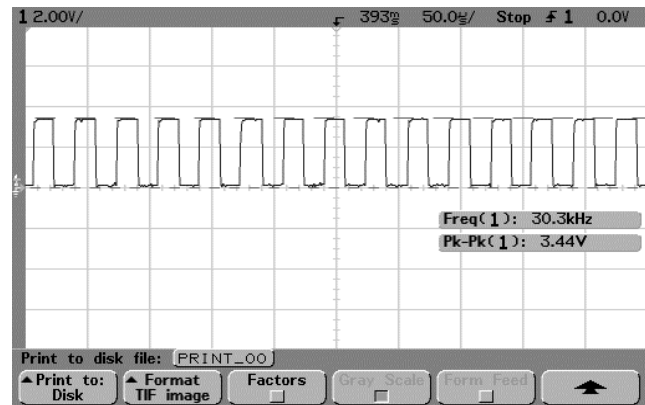


FIGURE 3.
TIMER A0 OUTPUT.

The software, which handles the communication, has three arrays; each has eight data bits and corresponds to just one switch on the SKP-30262 board. If any switch is pressed, the software configures the corresponding array and determines between 0 and 1 element. If it is 1, the required timers will start to get 20 pulses within 0.66msec and feed them to the LED, and then shut it down for a period of 9.34msec. If it is 0, the LED must be in idle mode for 10msec.

As an example, the generated signal on the transmitter side is shown below in Figure 4. Each pulse on this graph is a group of 20 sub pulses; the oscilloscope could not show all of them.

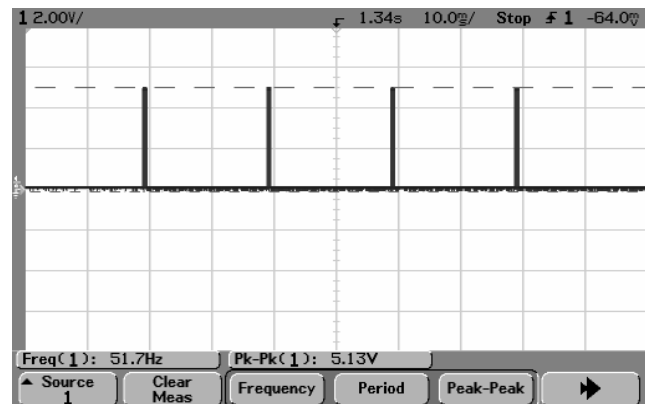


FIGURE 4
PART OF THE TRANSMISSION OF THE DATA {10101010}

TRANSISTOR CIRCUIT CALCULATIONS

To work properly, the IR LED needs to be supplied by 100mA. Regarding to 2N2222A transistor specifications,

$\beta=200$. Having this, the following equations determine the resistors values:

$$V_{BB}=I_B R_B+V_{BE} \quad (1)$$

V_{BE} needs to be 0.7V and $I_B = 0.5\text{mA}$, So $R_B=8\text{k-ohm}$.

$$V_{CC}=I_C R_C+V_{CE} \quad (2)$$

I_C needs to be 100mA and $V_{CE}=1.5\text{V}$, so $R_C=30\text{ohm}$.

The internal resistance of the IR LED is 15-ohm, cascading two of them results in the required 30-ohm and enhances the emitting operation.

RECEIVER SIDE

TSOP12 from Vishay Semiconductors is used as an IR receiver module in conjunction with the SKP-30262 board. TSOP12-series are miniaturized receivers for infrared remote control systems; PIN diode and preamplifier are assembled on lead frame, the epoxy package is designed as an IR filter. The demodulated output signal can be decoded directly by a microcontroller. TSOP12 is the standard IR remote control receiver series, supporting all major transmission codes and have the following special features:

- Photo detector and preamplifier in one package
- Internal filter for PCM frequency
- Improved shielding against electrical field disturbance
- TTL and CMOS compatibility
- Output active low
- Low power consumption
- Improved immunity against ambient light
- Suitable burst length ≥ 10 cycles/burst

Space around us is full of noise and disturbance signals that are eliminated in TSOP12 by using bandpass filters, integrator stage and automatic gain control. Those circuits need a unique carrier frequency, burst length, and duty cycle for each signal to be decoded as data.

The output of the TSOP12 (IR receiver module) is connected to an input pin on SKP-30262 board. This pin is connected to high voltage (5 volts) and once a burst of pulses is received, this pin's voltage goes down for a time interval equal to all received sub pulses time intervals. Therefore, the start bit for any code must be one. Receiving the first burst of pulses generates an interrupt, this interrupt saves the first received bit as 1 and starts timer A. Timer A interrupts the microcontroller every 10 msec to sample the input pin and store either 1 or 0 in the assigned received pattern array. After the bits are received, start and stop bits are compared with the expected ones.

As an example, the received signal at the collector terminal was taken for {10101010} transmitted data and shown in Figure 5. The voltage is dropped from 5V to nearly 4V. Up to eighty characters can be sent using this wireless communication system within a range of 10m.

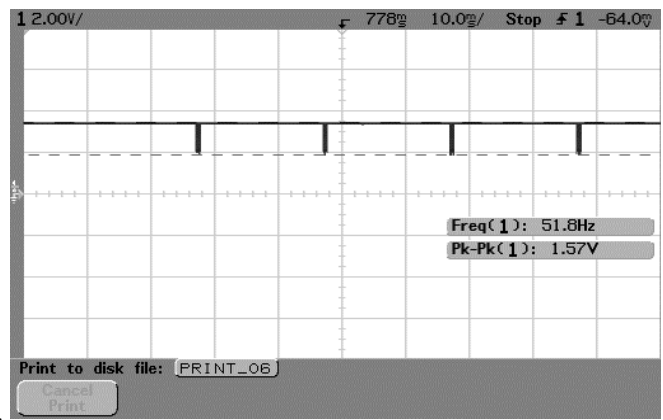


FIGURE 5
{10101010} DATA ON THE RECEIVER SIDE.

ACHEIVEMENT OF OBJECTIVES

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 two efforts described above had the following success rates: IR communications - basic = 100%, IR communications - packets = 50%. 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.

We also found that students that had a strong electronics background were able to better debug their circuit implementations than those who had strong programming/computer backgrounds. The ideal teams were those who had one member with a strong electronics background and one member with a strong programming background.

FIBER OPTIC LAB EXERCISE

BACKGROUND AND OBJECTIVES

The purpose of another educational effort was to create a cost-efficient lab exercise that helps students to learn the basics and benefits of optical communication. The optical link allows very high-speed (>100kbps) data transfer between two SKP-30262 microcontroller development boards.

Many attempts to find this kind of work done in the classroom area resulted in many sources of teaching optical theory [10], but not embedded-level optical communication. This lab was prototyped in the Fall of 2004 and was implemented in the Spring 2005 semester. The overall objective of this lab was to test the programmer's ability to create the most efficient code. The transfer speed for the Fall

2004 prototype exceeded 142kbps, which is greatly faster than other methods with the board in use.

PROTOTYPE LAB EXERCISE

The hardware for the optical communication consists of a transmitter and receiver module created by Agilent (Figure 6). The HFBR-1412 standard transmitter is capable of speeds in excess of 10Mbps. The HFBR-2412 TTL receiver is capable of speeds up to 5Mbps. This speed far exceeds what is possible by the development board. This is important because the efficiency of the programmer’s code determines the highest attainable transfer rate. More information can be found in the technical data sheet on the Agilent web site [8,9].

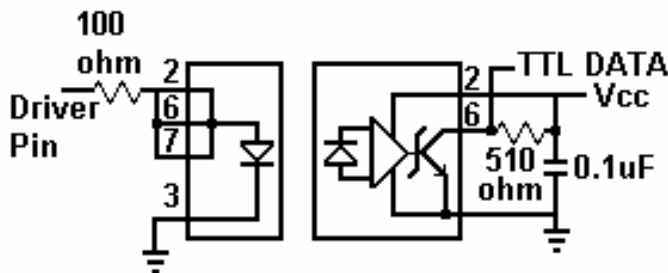


FIGURE 6
HFBR-1412 TRANSMITTER AND HFBR-2412 RECEIVER
SCHEMATICS (RESPECTIVELY)

The transmitter output is controlled by one output port of the microcontroller. When the output port is driven high, the light emitting diode (LED) emits light through the fiber to the receiver. The receiver module has a photodiode that creates a low signal (0 volts) when light is present at the module. The communication protocol therefore becomes similar to communicating serially over a wire. The following code demonstrates driving the optical transmitter through the p8_2 port of the microcontroller:

```
void timera1int() {
    p8_2 = tx_array[j][i];
    i++;
    if (i>=10) {
        i=0;
        j++;
    }
}
```

The communication protocol consists of 8-bit ASCII characters with a start and stop bit. The visual presentation of the transfer consists of two HyperTerminal windows communicating with the two respective boards via the UART ports. This communication takes place at 19.2 kbps. This slow UART rate is actually a “bottleneck” for the overall transfer. In order to maximize the optical transfer time, the characters are stored in the transmitting microcontroller until the return character is received.

When a character is received via UART by the transmitting microcontroller, it is immediately converted and stored in an array of 1’s and 0’s. The reason for this is that it

cuts down on processing time for the actual optical communication. This procedure is shown in the following code:

```
void u0_rx_isr() {
    current=u0rbl;
    u0tbl=current;
    tx_array[size][1]=((current&0x80)>>7);
    tx_array[size][2]=((current&0x40)>>6);
    tx_array[size][3]=((current&0x20)>>5);
    tx_array[size][4]=((current&0x10)>>4);
    tx_array[size][5]=((current&0x08)>>3);
    tx_array[size][6]=((current&0x04)>>2);
    tx_array[size][7]=((current&0x02)>>1);
    tx_array[size][8]=(current&0x01);
    tx_array[size][9]=0;
    size++;
}
```

In a similar fashion, the microcontroller receiving the optical communication stores the received characters as an array of 1’s and 0’s until all bits have been received. Once all the characters have been received they are converted to characters as they are transferred to the computer via UART.

The bit duration for both the transmitting and receiving microcontroller are controlled by an overflowing timer interrupt. The value for the timer is kept the same on both microcontrollers in order to maximize the synchronicity of the communication. This value is made as low as possible until the processing between bits becomes longer than the bit period (about 7 μs for the prototype). The following prototype code shows the processing that occurs during the bit period of the optical transfer where p8_3 is the port connected to the data line of the optical receiver:

```
void timera3int() {
    if (p8_3 == 0) rx_array[k][value] = 1;
    else rx_array[k][value] = 0;
    value ++;
    if (value >= 9) {
        ta3s=0;
        recval=0;
        k++;
    }
}
```

ACHEIVEMENT OF OBJECTIVES

The Spring 2005 Advanced Embedded Systems class performed this optical communications lab exercise. Eighteen students in nine groups were given a lab exercise to perform data communication between two Renesas microcontroller boards.

The students performed two independent tasks. The first task was to send characters through the optical fiber from one board to the other using the board UARTs at a baud rate of 19,200 baud. This task had to be completed with minimum errors. This simple task was assigned to ensure the students built their hardware circuit correctly.

The second task was to perform a high-speed data transfer between two boards using the optical circuits at the greatest speed possible. The second task was more challenging

because of the fact that the speed at which the communication needed to be performed was not specified and the students could experiment and optimize their code in order to achieve the fastest speed possible.

Nearly all groups achieved the first task and all working implementation had zero errors. The results of the second task however, were disappointing. While the fastest speed achieved was a blazing 845,069 bps with few errors (using a 20 MHz processor), only 40% of the groups were able to transmit faster than using the 19,200-baud UART. The most common pitfall was that the groups had difficulty writing their own "software UART" to accurately clock their data through the board's I/O ports. However, the main objective of student learning was achieved. All students now have a better understanding of (and respect for) optical communications.

CONCLUSIONS AND FUTURE WORK

Engineers who have knowledge of embedded systems and optical communications will be in high demand. Unfortunately, there are few affordable lab exercises or development environments available for classroom use, so students often do not learn about these technologies during hands-on lab assignments. We have provided students with hands-on lab exercises that represent some areas of IR communications and optical communications used in industry. Several examples of communications lab exercises were described. These labs build upon and are motivated by extensive educational literature which supports the integration of classroom learning with laboratory experience for educating students in communications [11-17]. They do require prerequisite knowledge in electronics, programming, and communications.

Future work includes developing a printed circuit "daughter board" which contains an optical fiber transceiver as well as IR transmitter and receiver circuitry. This board could be attached to any microcontroller evaluation board and used by any university in their embedded systems or communications courses.

Examples of these labs can be found at <http://www.coe.uncc.edu/~jmconrad/EducationalMaterials/index.html>

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