An Intelligent Breadboard for Electronics Experiments

H. Randolph Holt

Department of Technology
Northern Kentucky University

Abstract

This paper develops the functional specification and preliminary design for a system that can enhance “hands-on” learning in electrical and electronic programs with the inclusion of a microcontroller-based system and software. When implemented, it can be used for a wide assortment of classes such as circuit analysis, analog electronics, digital electronics, microprocessors, assembly language, and higher-level programming. For programs having capstone experiences, this system could also be used in senior projects. This type of device can be used in traditional classes but will be most useful for distance-learning classes because of its ability to direct the student and collect data.

Introduction

Before attempting any design, it is important to specify what the design will accomplish, not how it will be implemented. This is typically done with a document called a functional specification. Once it is completed (and approved by shareholders, if necessary), work can begin on the actual components that make up the design.

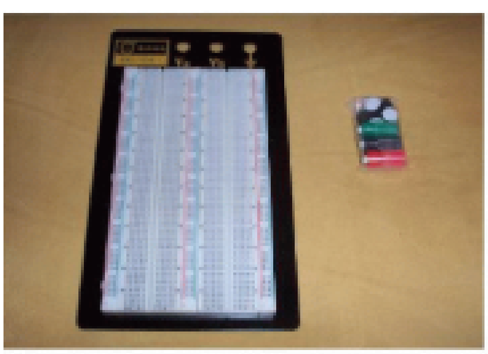

Figure 1: Breadboard

Many “hands-on” academic programs, like those in engineering technology, require laboratory courses or components within courses to acquaint students with actual hardware components, instrumentation, and software. Breadboards are used to serve as a way of connecting devices in electrical and electronic programs. Breadboards like the one shown in Figure 1 are often used to make connections easier. Spring-loaded entry points and tracks within the breadboard minimize the number of wires required to wire up a laboratory circuit. Unfortunately, especially for new students, it is still necessary for instructors to oversee the actual placement and wiring on these breadboards; and this is a valid argument often used to question the validity of providing such courses remotely.

Several approaches have been implemented to provide “hands-on” experiences to students by providing remotely-controlled systems on the Internet. Many of them use Labview and virtual instruments from National Instruments[7]. MIT has also constructed several remotely-controlled experiments as a part of their iLab Project that is part of Microsoft’s iCampus Project. A batched experiment[8], a sensor experiment[9], and an interactive experiment[10] are parts of this endeavor. An interesting article in *Online Cl@ssroom* discusses how Dr. Thomas Lehman has developed hybrid courses at Morgan Community College in Colorado that permit some lab experiments to be done remotely while then having the riskier or more equipment-intensive ones done on campus[11]. These approaches are too expensive and too complicated for many universities.

Other institutions have used web cameras and conferencing software to enable instructors to observe students performing experiments[12]. Bandwidth, resolution, and timing make this approach cumbersome for many students and programs.

The purpose of this paper is to propose a less expensive alternative to many of the current approaches while still providing instructions, tutorials, and data feedback mechanisms that enable students to perform “hands-on” experiments in electricity and electronics. A microcontroller-based approach coupled with a general-purpose computer and the Internet is suggested to permit customization and a graphical user interface that provides and displays information.

Significant steps have been taken to provide intelligence in systems using low-cost microcontrollers that also include other essential functions for generating and collecting signals from an experiment: analog-to-digital converters, digital-to-analog converters (or PWM outputs), and timers. When embedded in a system, these devices can function as voltage sources and meters. If the microcontroller-based systems are then connected to general-purpose computers, they can be loaded with programs that customize the microcontroller for specific experiments; results from the experiment can be transferred to the external computer for storage, display, printout, or delivery to the instructor via e-mail. The package received by the instructor can then be reviewed to verify that the experiment was performed correctly.

Computer programming languages and libraries have been developed and provided to simplify the development of programs that run on general-purpose computers, providing attractive user interfaces and functions that accomplish the tasks mentioned in the previous paragraph. Based on these languages and libraries, software can also be developed to allow instructors to write customized scripts for their own experiments, defining any tutorial material and microcontroller “reprogramming” to implement that exercise. The tutorials can be designed to assist the student in performing the given experiment, and the reprogramming allows the user interface to be customized specifically for this experiment.

Of course, one primary goal is to make this intelligent breadboard relatively inexpensive. Since it would be used for many different laboratories, the cost would be shared over these courses. A student price in the vicinity of $100 to $200 would be acceptable in most colleges and universities.

Functional Specification

Both the hardware and software functions need to be enumerated prior to implementing them in the intelligent breadboard. It would be constructed around a basic breadboard (see Figure 1. already displayed above).

A microprocessor or microcontroller would be the best starting point for hardware since it provides the flexibility needed in such a project. Each experiment will probably require a different set of tasks, and this would be extremely difficult to achieve with hard-wired designs. To meet the price goal, many hardware functions would have to be provided within this intelligent component so as to avoid adding other components and additional cost. This may well affect the overall performance of the system, limiting the frequencies and data acquisition rates, but such limitations should be acceptable for most student laboratory experiments. Some changes may have to be made with existing experiments to accommodate such an intelligent breadboard system.
Software is perhaps the most difficult task to specify and will take the longest to develop. It involves the embedded code for the microcontroller device, user software to interface a general-purpose computer to the intelligent breadboard, and an application that makes it easy for instructors to translate their experiments for use in the proposed system and evaluate the work submitted by students.

Basic Features

The following lists describe what the Intelligent Breadboard system is to do and where it could be used:

- Performs all student experiments in
  - D.C. circuit analysis
  - A.C. circuit analysis
  - Analog electronics
  - Digital electronics
  - Microcontrollers
    - Assembly level programming
    - Interfacing
  - Embedded applications

- Assembly level programming
- Higher level programming

- Uploads scripts from a general-purpose computer that describe what the system is to perform
- Downloads student experiment data for
  - Printing
  - Graphing
  - Delivery of results to instructor
- Provides software to permit development of experiment scripts and editing of existing scripts by instructors
- Permits instructions and tutorials for a given experiment script
- Provides a graphic user interface on a general-purpose computer to facilitate
  - Selection of experiment
  - Display of results
  - Printing
  - Delivery of results to instructor
- Maintains cost target of total system within student financial limits, about $100
- Supplies script generation software that instructors can use to develop experiments, instructions, and tutorials

System Diagram

Shown below is a block diagram of the intelligent breadboard system, Figure 2. A sketch of how it might look is shown in Figure 3.

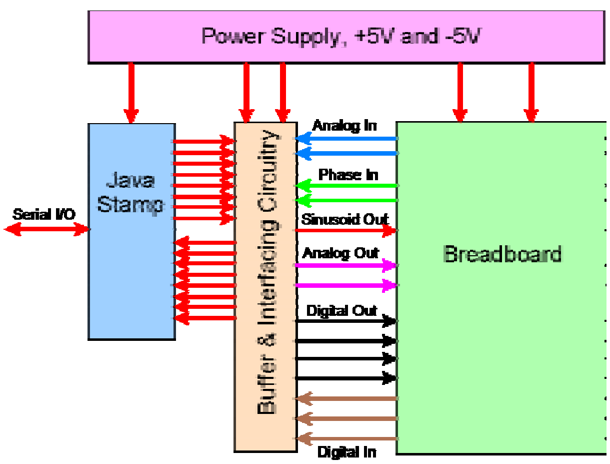

Figure 2. Intelligent Breadboard Hardware Block Diagram

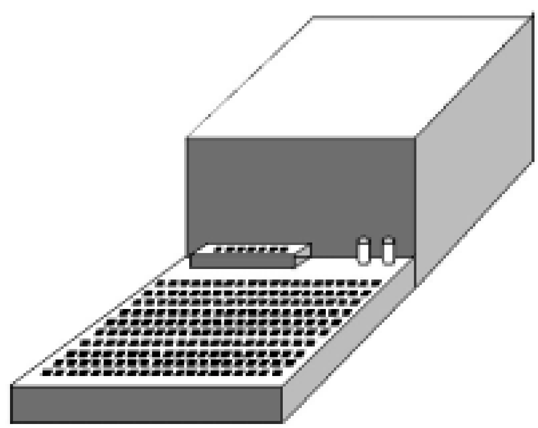

Figure 3. Sketch of Intelligent Breadboard

Hardware

Hardware Functions

Described below are the basic components in the Intelligent Breadboard hardware:

Microcontroller – The most cost-effective flexible solution will probably be with microcontrollers because they can include much of the peripheral hardware such as electrically-erasable memory, A/D converters, digital outputs, and timers in one monolithic package. The microcontroller chosen should also have development tools to permit easy programming. The 8051 family (available from a wide number of vendors) and the Motorola 6805/08 are two possible contenders. The Parallax Javelin Stamp family would also be of interest since it incorporates “virtual peripherals” that can be run concurrently with the embedded program.

Breadboard – The only decision for the breadboard is its size, including the number of vertical and horizontal connection points. This size must accommodate the experiments anticipated for the Intelligent Breadboard.

Power Supply – Most microcontrollers today are being designed to operate on 3.3 to 5 volts, so a power supply must be available for this voltage. This probably implies that the experiments should also be designed (and adapted, if necessary) for this single voltage; if voltage sources are generated in the microcontroller, they will be limited to the maximum microcontroller supply voltage, and any ADC inputs would also be constrained to this voltage. For those experiments that require AC sources, an auxiliary power supply would be necessary to provide positive and negative rails. Higher voltage supplies could be used, but this would introduce added cost and require some scaling for the microcontroller. Some electronic devices are also now being designed for 1.8 volts, but this low voltage would be a problem for wired connections on a breadboard and the inherent losses in those connections.

Miscellaneous – Because the ADC inputs on microcontrollers are unipolar (zero volts to a positive voltage), any AC measurements would have to include circuitry that converts information into a type that can be read by this unipolar device. Measuring alternating-current voltages would also necessitate circuitry to provide rms or average values and clipped waveforms for determining phase angle (see Figure 4).

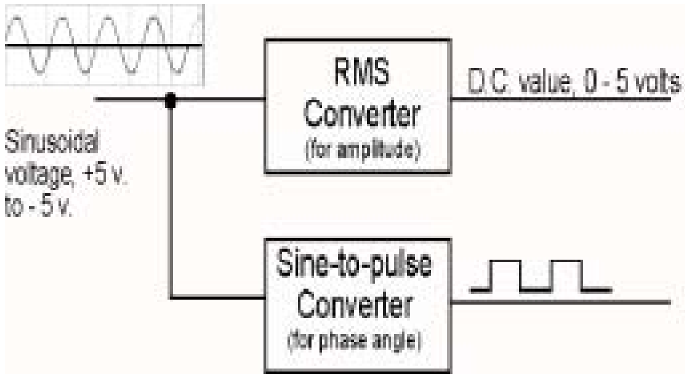

Figure 4. Converting bipolar sinusoid for amplitude and phase shift

Assuming that currents need to also be measured, circuitry would have to be included to translate that current to a voltage for input to the microcontroller. Generating a sinusoidal voltage source might also use an external device such as a VCO (voltage-controlled oscillator) or programmable waveform generator that is controlled by the microcontroller; a DAC output could produce a sinusoid if the selected microcontroller permitted interrupts for updating the output; additional hardware would then be required to condition that unipolar signal for a bipolar one. See Figure 5 below.

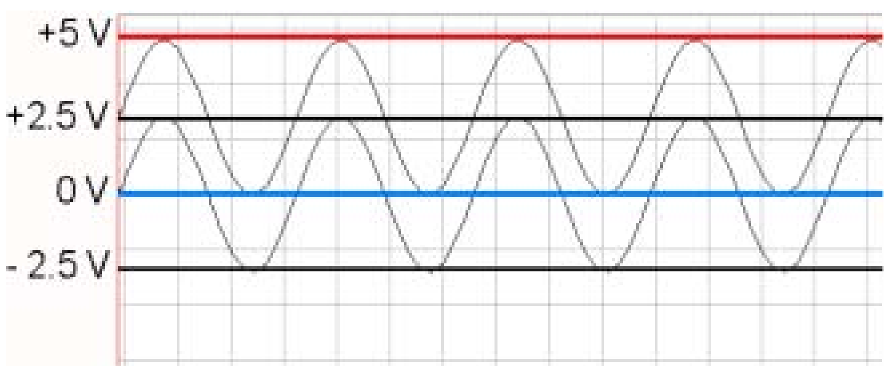

Figure 5. Shifting unipolar sinusoid to bipolar.

The overall goal would be to minimize the expenses of adding hardware to the system and to use basic capabilities of the microcontroller wherever possible.

Software

For a complete solution to this flexible system, three types of software would have to be developed: (1) Embedded -- for the actual intelligent breadboard hardware; (2) User -- to provide a user interface that informs the breadboard system of what is to be done, displays and packages results; and (3) Instructor -- that permits instructors to develop modules for the system and examine laboratory results submitted by the students. This paper will only address the first software type in detail.

Embedded – The software contained within the intelligent breadboard would have to provide all input/output functions and adjust parameters to conform to the experiment being conducted by the student. This software would first look for macro "instructions" from the User Software to describe what is to be done and what is to be returned. This data would configure the embedded software for that experiment and regularly monitor its connection to the User Software for changes or termination.

User – Written in a high-level language and with tools that provide an excellent graphical user interface, this software would read a "script" created by the Development Software, provide the student with hookup and background data, and then inform the Embedded Software of the required operations to be performed.

Instructor – This software would again be developed with high-level programming language tools and would permit an instructor to describe what is to be done in an experiment as well as to provide information on how to connect the circuit and the breadboard hardware. Background or tutorial data could also be appended. A file would then be created for use by the student with the User Software. This software would also permit upload descriptions and mechanisms to have data sent to the instructor for examining the data collected by the students.

Preliminary Design of Embedded Module

Microcontroller Selection

There are a large number of microcontrollers that could be selected for this project, providing all of the peripheral subsystems like ADCs, DACs, timers, interrupts and development software. Cost is very low for the actual device, but most companies do not provide inexpensive development tools and compilers. Prior experience with the Parallax BASIC Stamp attracted me to the Javelin Stamp[1,2], a device that is pin compatible with the BASIC Stamp but is programmed using a Java interpreter and a free development environment. Unlike the BASIC version, this more powerful and faster microcontroller is supplied with "virtual" peripherals that enable the user to run some input/output tasks in parallel with the mainline code. As an example, a PWM (pulse-width-modulated) output can be created that will continually output that waveform until turned off; the BASIC version has PWM but it must be run within the program and is turned off when the next instruction is executed. The Javelin Stamp also has a delta-sigma analog-to-digital converter configuration that permits 8-bit resolution using two I/O pins, two resistors, and one capacitor; it is also a virtual peripheral and samples can be taken approximately every two milliseconds. The Java language for this device is a simplified and I/O enhanced version of a full Java implementation, but it is more than adequate for the tasks in this intelligent breadboard project. The “list” price for the Java Stamp is $89.00 in single quantities, but Parallax offers a 15% discount for educators and students. Any Parallax printed-circuit board can be used for prototyping, but probably the best one is the Board of Education at $65.00 in single quantities. Shown below (Figure 6. and Figure 7.) are pictures of the Javelin Stamp and the Board of Education:

Figure 6. Javelin Stamp Module

Figure 7. Board of Education PCB

Software

Software for the Embedded Module takes direction from the User and configures the hardware for the required tasks. It resides in EEPROM memory, so it will be nonvolatile unless revised by the Javelin Stamp IDE.

When initialized, the module looks for “instructions” from the User that are transmitted as bytes over a serial connection. These instructions describe what devices are being used and provide any parametric data on how those devices are to operate. The embedded software enters a mainline routine that performs the requested operations and collects and downloads any data requested by the User. During the actual operation of the Intelligent Breadboard, the embedded software will periodically look for a specific code from the User that terminates the operation.

A flow diagram of the embedded software is shown below:

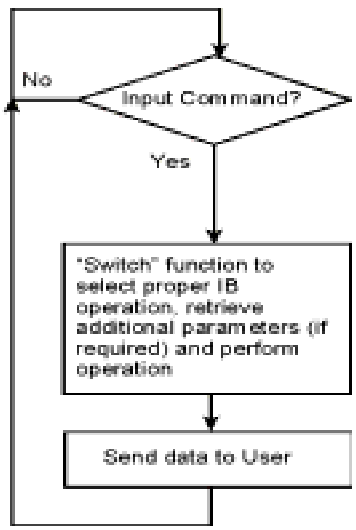

Figure 8. Flowchart

Power Supplies

The primary voltage for this system is +5 volts, but a second voltage of -5 volts would be necessary to generate a sinusoidal voltage. Current requirements are anticipated to be less than 1 amp for +5 volts and less than 100 milliamperes for -5 volts. A switching power supply[4] would be preferred for efficiency (and higher cost), but a linear supply could also be used.

Digital Inputs and Outputs

The sixteen I/O pins on the Javelin Stamp can be configured as either input or output and can be reconfigured within the program. For ease of use, however, it might be good to specify which pins will be used for inputs and outputs so that they could be properly marked and grouped on the Intelligent Breadboard. As a starting point, four of the I/O pins will be designated as outputs and four others as inputs. The Javelin Stamp has a limitation of 30 mA (source or sink) per I/O pin but 60 mA maximum for each group of pins; one group is I/O pins 0 through 7, and the second group is 8 through 15. Because of these limits, to increase current drive capability and to protect the electronics, it might also be good to buffer the digital outputs.

Analog Outputs

Pulse-width modulation is used by the Javelin Stamp to provide analog voltage. A simple R-C network is connected to that I/O pin to filter the PWM signal. A unity-gain amplifier could then be added to that output to provide isolation and better drive capability. The first prototype of the Intelligent Breadboard will have two such analog outputs. Such a circuit is shown in Figure 9. below:

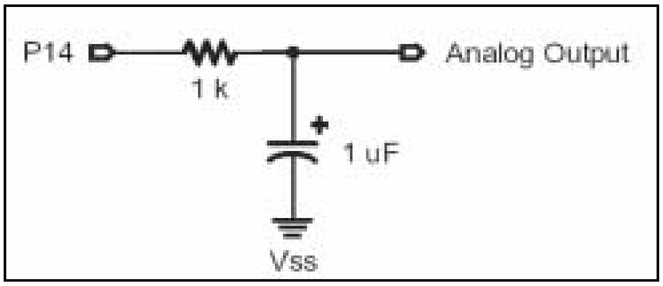

Figure 9. PWM-generated Analog Output

Some electrical/electronic experiments require a sinusoidal voltage. This can be generated from a table and software using a digital-to-analog converter, but a significant amount of overhead might be necessary for this. A relatively inexpensive integrated circuit chip can be included that automatically generates a sinusoidal or triangular voltage, and the frequency of that waveform is controlled by a single analog voltage input. This Intelligent Breadboard system will use such a chip, the MAXIM MAX038. The voltage for controlling the frequency will be supplied with a third PWM output, but a unity-gain amplifier will not be required. An example of the connection between the Javelin Stamp and the Maxim MAX038[3] is shown below as Figure 10. :

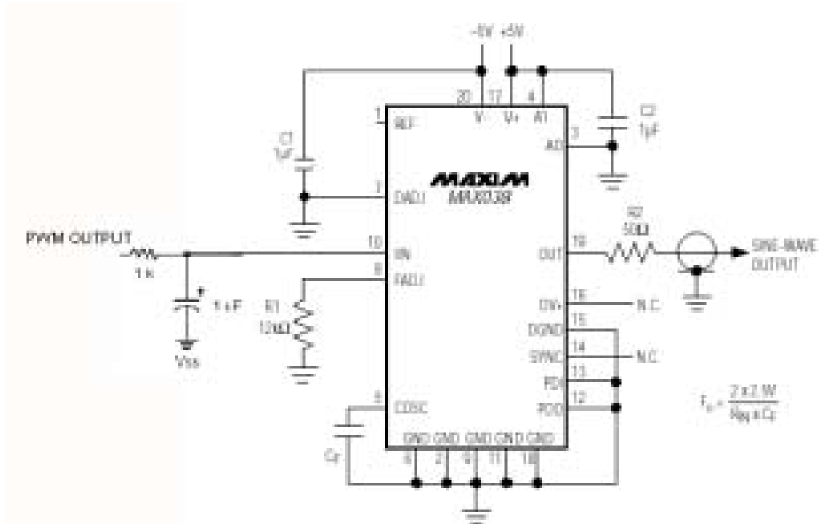

Figure 10. Sine-wave generation using Maxim MAX038

Analog Inputs

The delta-sigma analog-to-digital conversion that is part of the Javelin Stamp would be used for any analog inputs. They require two I/O pins per ADC, two resistors and one capacitor. Samples can be taken every two milliseconds. This design will initially have two such analog inputs, requiring four of the I/O pins. A unity-gain amplifier could also be included to reduce current and protect the electronics. Figure 11 shows such an analog input circuit:

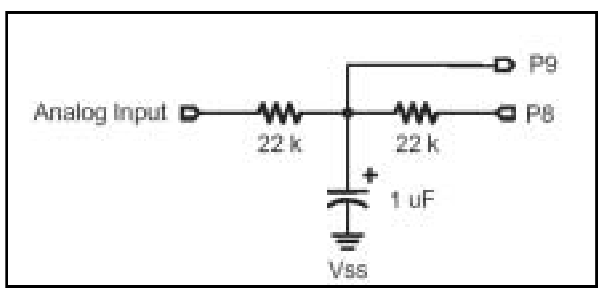

Figure 11. A-to-D Conversion

Limitations and Changes to Experiments

Limitations

This Intelligent Breadboard is replacing a wide range of instruments to provide a convenient vehicle for students, especially those in distance-learning classes. The cost goal can only be reached by limiting the capabilities of data collection, bandwidth, voltage range and component selection. Resolution is limited to 8 bits (256 values), so this is probably not as accurate as one would obtain with more sophisticated equipment.

As configured, this system is designed to provide a maximum of five-volt operation, and AC experiments will be limited to a sinusoidal voltage swing of +/- 2 volts because of the choice of programmable waveform generator.

Current limits in the system would require that some thought be given to the devices and device families used in experiments. Existing experiments would probably have to be rewritten to accommodate the Intelligent Breadboard.

Experiment Alterations

As mentioned above, there would have to be changes to most experiments to use the Intelligent Breadboard. The most significant changes would be made to limit the current required from the system and to limit the voltages to those generated.

Conclusions

In order for many electrical and electronic courses to be offered as distance-learning offerings, an intelligent system would have to replace the instructor in “hands-on” exercises. This paper has proposed such a system and has provided a preliminary design that can serve as the starting point for such a system. Combined with a general-purpose computer and interfacing software, the Intelligent Breadboard could be used to provide assistance for web-based classes as well as conventional ones.

References

1. *Javelin Stamp Home Page.* Parallax, Inc. Retrieved 16 February 2005 < http://parallax.com/javelin/>.
2. *Javelin Stamp Documents and Pricing.* Parallax, Inc. Retrieved 16 February 2005 < http://parallax.com/detail.asp?product_id=JS1-IC >.
3. *MAX038 High-Frequency Waveform Generator*. Dallas Semiconductor Maxim. Retrieved 16 February 2005 < http://maxim-ic.com/quick_view2.cfm/qv_pk/1257 >.
4. *MAX680/MAX681 +5V to +/- 10V Voltage Converters.* Dallas Semiconductor Maxim. Retrieved 16 February 2005 < http://www.maxim-ic.com/quick_view2.cfm/qv_pk/1530 >.
5. *LM6132/LM6134 Dual and Quad Low-Power 10 MHz Rail-to-Rail I/O Operational Operators*. National Semiconductor. Retrieved 16 February 2005 <http://www.national.com/search/search.cgi/main?keywords=LM6132 >.
6. *AD9833 Programmable Waveform Generator.* Analog Devices, Inc. Retrieved 16 February 2005 <http://www.analog.com/en/prod/0%2C2877%2CAD9833%2C00.html >.
7. *Distance Learning Solution Guide.* National Instruments, Inc. Retrieved 16 February 2005 <http://www.ni.com/pdf/academic/us/distance_learning.pdf >.
8. *iLabs Home Page.* Massachusetts Institute of Technology. Retrieved 16 February 2005 < http://icampus.mit.edu/iLabs/default.aspx >.
9. *Flagpole Home Page.* Massachusetts Institute of Technology. Retrieved 16 February 2005 < http://flagpole.mit.edu/
10. iLab Heat Exchanger Project Home Page. Massachusetts Institute of Technology. Retrieved 16 February 2005 < http://heatex.mit.edu/default.htm >.
11. Lehman, Thomas. *Hybrid Science Labs: Flexible and Hands-on*. Online Cl@ssroom, February 2004. Retrieved 16 February 2005 < http://www.spjc.edu/SE/newsletter/OnlineClassroom.pdf >.
12. Distance-Learning Remote Laboratories using Labview. National Instruments. Retrieved 16 February 2005 < http://zone.ni.com/devzone%5Cconceptd.nsf/webmain/7BD0B01FCF3CF61A86256B510059F0FB/$File/WP2238.pdf >

H. RANDOLPH HOLT

Mr. Holt is an Associate Professor of Engineering Technology in the Department of Technology at Northern Kentucky University. Teaching duties are at both the undergraduate and graduate levels. His primary research emphasis is on the application of environmental principles to electronic design. He is a Senior Member of the IEEE and a Professional Engineer in Ohio.