

Designing, Building, and Testing a Microcontroller-Based System for Industrial Applications

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Abstract

The current paper describes designing, building, and testing of a microcontroller-based system that is cost effective and can be programmed without software compatibility constraints. The system is designed to replace a PLC (Programmable Logic Controller) that is used to automate and control an inkjet-cartridge refilling machine manufactured by FAES USA in Franklin, Tennessee. The preliminary research indicates that by using a Microcontroller-Unit-Board (MUB) in automation and control, the cost of some controllers may drop by 50%-70% on average. Due not only to the immense cost reduction, but also to the benefits of a more tailored automation solution, this research project has vast potential applications and might become the automation of choice for mid and small-size manufacturing companies. The system requirements and components justification along with the designing, building, programming, and testing stages of this microcontroller-based system are described. The work is partially funded by an undergraduate research grant that promotes undergraduate research and scholarly activities at Middle Tennessee State University.

Introduction

FAES USA, a mid-size manufacturing company based in Franklin, TN, is currently using PLCs (Programmable Logic Controllers) to automate and control the inkjet cartridge refilling equipment that the company is manufacturing and selling worldwide. PLCs today are very powerful and are deployed in all mixture of machine control in everyday life. Today, however, there are significant drawbacks to using PLCs in mid-size and small companies. PLCs are most always high in cost since they are manufactured to serve an extremely wide range of applications. The makers of these PLCs have integrated a large number of options and functions that are not required by most applications. Naturally, these costs are passed on to the consumer who is essentially buying functions and features that he or she does not need. Another disadvantage of PLCs is that they are based on a proprietary programming language that forces companies to buy the manufacturer's software to program these PLCs. This in turn makes it a nearly impossible task for a company to convert to a competitor's product because this change would entail

buying new programming software, learning to use the new software and then reprogramming the machine logic from scratch, which in many cases is not worth the investment.

A newly emerging technology that is recently available for mid-size companies is PC-based control. PC based controllers are very flexible and do not require proprietary software. However, their actual implementation is expensive and time consuming. Currently, however, this solution is only cost effective for large manufacturing companies such as in automotive plant production lines, oil refineries, and specialty packaging machinery to name a few. The Saturn automotive plant in Columbia TN, uses such a PC-based control system for their engine production of the 2004 VUE model. From the above, the authors believe that a better solution, which fills the gap between the rigid PLC world and the costly PC, is needed and might be found by designing a microcontroller-based system for general industrial applications. An initial preliminary cost analysis indicates that savings of 50-70% in material costs is possible by using the MUB solution versus PLCs as seen in Table 1. Because of this potentially large cost saving, the authors believe that the availability of such a microcontroller-based system has many possible applications, especially in small to mid-size manufacturing companies. With this in mind, the lead author has approached FAES USA, started a detailed cost and requirements analysis, and used that to create the design requirements and testing specifications to enable a true replacement of a PLC device by a microcontroller-based system. The designing, building, programming, and testing of such a microcontroller-based system (MUB) is discussed in more detail in following sections.

Preliminary Cost Analysis:

FAES USA PLC	MUB
JetDry100 (PLC materials) \$831.00	~\$200.00 Savings of ~76%
ColorFill330 (PLC materials) \$624.00	~\$190.00 Savings of ~70%
MultiFill800 (PLC materials) \$238.00	~\$170.00 Savings of ~29%
The costs of PLC materials mentioned above are current and are in production at this time.	

Table 1 – Preliminary Cost Analysis

Design Procedure

The design steps including the MUB specifications, component selection, circuit design, and Printed Circuit Board (PCB) layout are described here. These steps have resulted in the fabrication, assembly, programming, and field-testing of the MUB as will be discussed at the end of this section.

Specifications

The lead author began first by defining the specifications of the MUB. A list of the input and output (I/O) requirements of the four most popular machines at FAES USA was created. From this list, the I/O requirements and other peripheral needs for the MUB were defined. By analyzing the gathered data, it became evident that the MUB should have a minimum of 32 inputs and 24 outputs to ensure its compatibility with currently used

PLCs and to enable possible future projects and equipment upgrades. Moreover, the outputs should be capable of providing 24 V DC, a standard industrial voltage that is used to control relays, valves, indicator lights, as well as other devices. Due to the requirement of the valves and relays, each output channel/connection has to provide up to 400 mA of current, which can be achieved by using power driver IC chips. These power drivers are essentially Darlington pairs packaged on IC chips that were obtained from Allegro Microsystems™ Inc.

The PLCs used at FAES USA are capable of converting and interpreting analog signals, which are used for temperature, weight, and pressure control. These types of analog

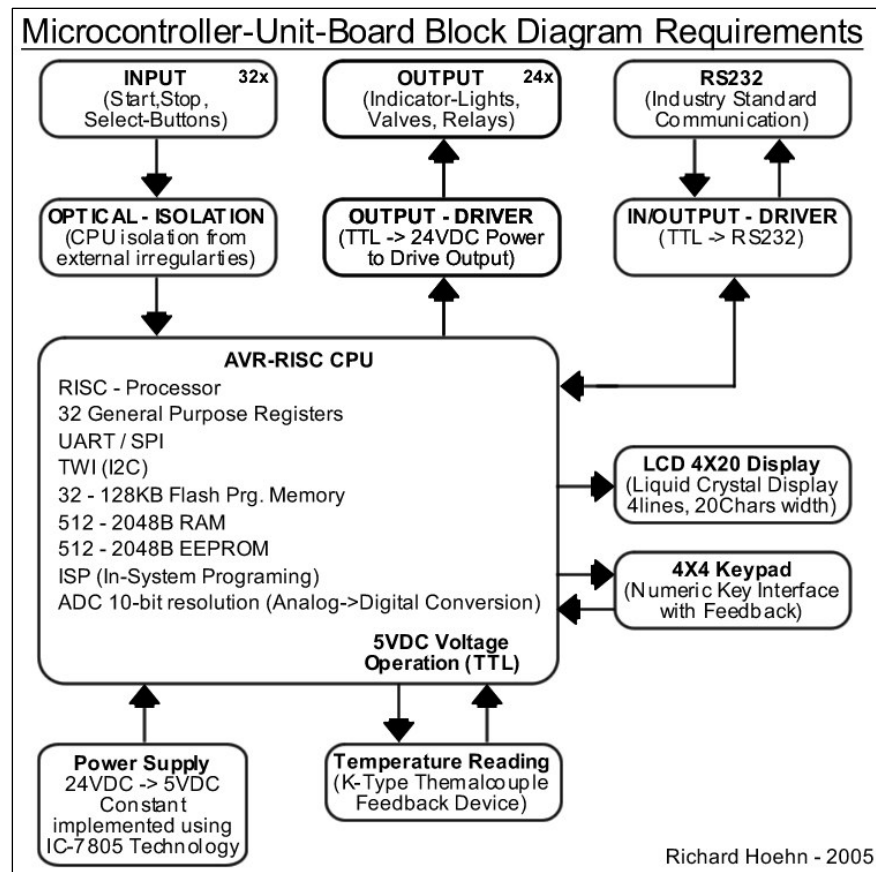


Figure 1 – Requirement Block Diagram

signalprocessing requirements can be achieved by using additional analog to digital converter IC chips, which are serially interfaced to the CPU. The entire MUB was also required to contain its own power supply. By choosing a 24 V DC power supply to power the MUB and its associated devices, the need for more than one power supply inside the machine has been eliminated. In addition to the power supply, the MUB should include one RS232 serial interface, which allows the board to communicate with PCs and other control and logging equipment. As for the Human-Machine-Interface (HMI), an economic way that includes a 4x20 LCD display and a simple 4x4 matrix keypad was chosen. A basic block diagram of the requirements of the MUB is shown in Figure 1. The Microcontroller-Unit-Board is based on an AVR®-RISC (Reduced Instruction Set

Computing) architecture by Atmel Corporation. Because the AVR-RISC technology is new, AVR microcontrollers hold numerous peripheral features such as I2C, SPI, UART and on board EEPROM memory, which are very useful for automation and control environments. In addition to the peripheral benefits, there is an exceptional IDE (Integrated Development Environment) for their AVR-RISC microprocessors that is user friendly and better yet, it is free. The programming and testing of the MUB are described in more details later on in this paper. The MUB itself was required to be capable of saving data settings and logging other activities of the program, which are also adjusted by means of the included HMIs such as the keypad and start and stop buttons. This type of parameter saving and editing required the CPU to have an internal EEPROM memory in order to allow the user to easily change and save program settings.

In addition, the lead author met with the technical support staff of FAES USA to get a more detailed account of what the MUB should be capable of doing from a technical support side. The team recommended that the MUB have LEDs on all inputs and outputs so that field troubleshooting would be easier to conduct. In addition, the MUB connectors should be easily accessed so that service technicians can effortlessly replace the controller if needed. Since the MUB costs a small fraction of the total equipment, it is economically sound to have one spare controller in case of an emergency. Such small but invaluable details like the LED status indicators and removable connectors can make the designed product better and hence improve its usability and marketability.

Board Design

After defining the specifications of the board and selecting its components, the design of

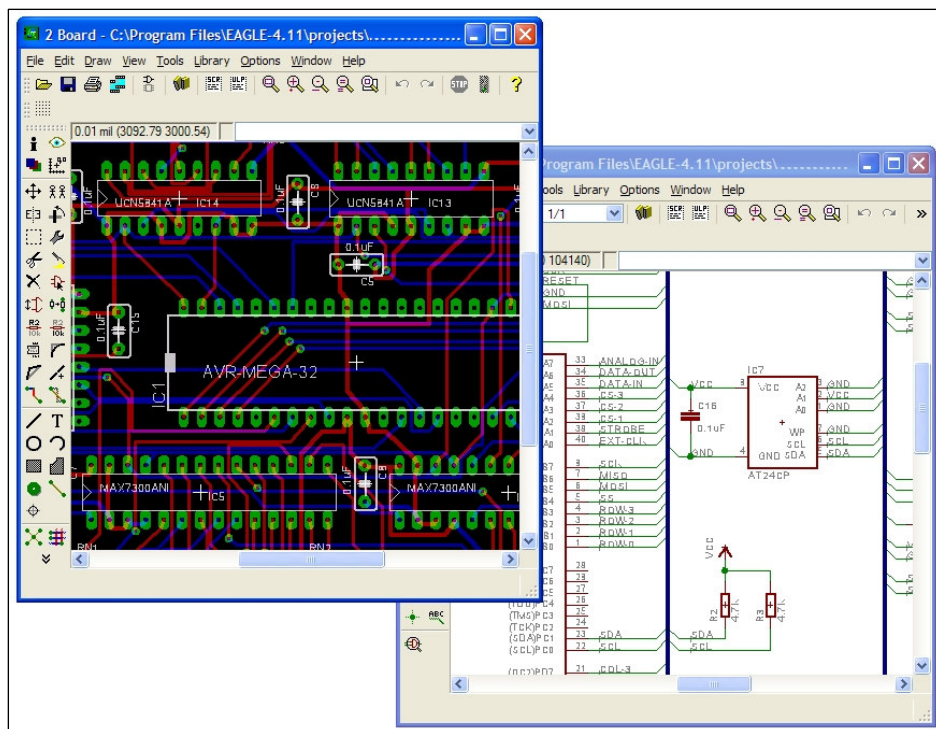


Figure 2 – EAGLE Editor

the MUB took place by first creating the electrical and Printed Circuit Board (PCB) layout schematics.

The author used a software package called EAGLE. The name EAGLE is an acronym that stands for **E**asily **A**pplicable **G**raphical **L**ayout **E**ditor. The EAGLE Schematic and PCB Layout Editor is an easy to use, yet powerful tool for designing printed circuit boards (PCBs). A screen sample is shown in Figure 2. The program consists of three main modules Layout Editor, Schematic Editor, and Auto router, which are embedded in a single user interface. Therefore, there is no need for converting netlists between schematics and layouts¹. EAGLE is an inexpensive software tool designed for PCB projects of all complexities.

The basic design was completed in two stages: Different components were tested first individually in order to ensure that they satisfy the design specifications such as current draw limits, temperature handling, and power supply stability. It is important to note here that the MUB system was not breadboarded in its entirety since this would be too cumbersome and time consuming. After the successful breadboarding and testing of the individual components and their interfacing with the outside world and the CPU, the schematic for the MUB was designed using EAGLE as mentioned previously. This allows the design in a schematic capture environment that builds netlists “on the fly” for an easy placement on the PCB layout editor.

There are several different ways to design PCBs and several different types of IC packages to mount on PCBs. The author chose to use Through-Hole-Technology known as Positive-Dual-Inline-Position (PDIP), which is used for prototype designs. An alternative is called Surface-Mount-Devices (SMD). SMD is a very popular method since it does not require holes to be drilled in the PCB, hence, lowering the manufacturing time and cost of PCBs. Due to this fact, however, the devices are not held in place by holes, which makes hand-soldering very difficult. If the MUB were to prove itself worthy of mass production, however, converting the MUB to SMD technology would be an easy task.

Using the files created by PCB Layout Editor, PCB makers can manufacture 1-5 PCBs in less than a week turn around time. In this case, three MUB PCBs were made for \$30.00/board, which is a good price for such a low quantity. Usually, PCBs are manufactured in quantities of 100 pieces or more. When ordering high quantities, the PCB fabrication cost drops dramatically. For this MUB, the PCB would have cost \$4.50 apiece when ordering 100 or more.

Board Assembly

Assembling the MUB took about 4-5 hours using a standard soldering iron. Since the PCB was manufactured with a solder mask, the solder joints created were excellent in form and size, which enables trouble-free mounting/soldering of the components. The good connections resulted in a very low to mostly negligible resistance, which makes the MUB a more stable and efficient controller. The soldering was also an easy task because

the MUB was designed using through-hole technology. The completed board is shown in Figure 3.

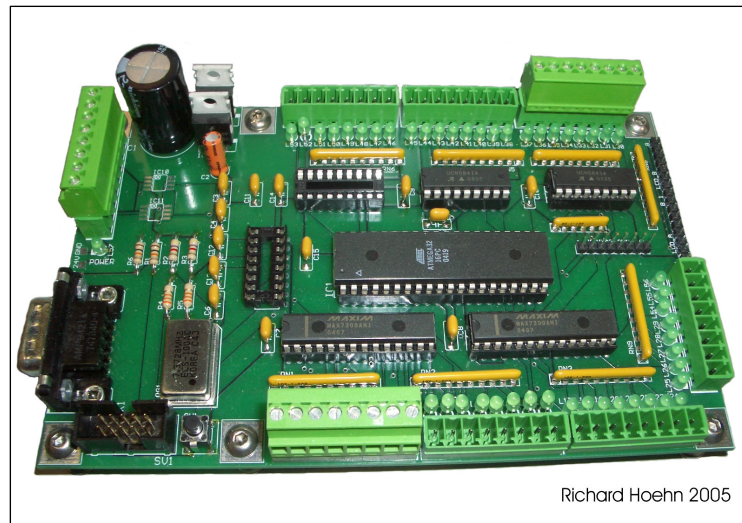


Figure 3 – Completed MUB

As seen in Figure 3, the green user-access connectors around the board edges allow for inputs and outputs hookups to be easily disconnected if need be. The LED status lights also can be seen next to the I/O connectors. These are used to indicate to field technicians which inputs and outputs are ON or OFF at any given moment. According to the FAES USA service technicians; this saves them a great amount of troubleshooting time since they do not have to connect a Digital Multimeter (DMM) nor a multi-channel logic probe to the MUB in order to troubleshoot field problems.

In the top left of the MUB, one can see a simple power supply that converts an input voltage between 6-30 V DC down to 5 V DC for the entire board using IC7805 and filter capacitors to ensure low ripples. Other board components include I/O and temperature control, HMI connections, and frequency generator.

In the middle of the MUB is the AVR-RISC processor, which executes a memory-saved program and controls all peripheral devices. It is positioned in the middle of the PCB since it is the heart of the MUB and all other peripherals are connected to it.

Programming

Two languages were used to program the MUB, assembly language and ANSI C. According to Barrelo: “The AVR[®] RISC chips are easy to use, extremely powerful and well suited for both assembly and higher level languages.²⁻⁵” It was decided that assembly language be used at the board level since this low level language allows the programmer to have full control over the registers and peripheral ports on the AVR-RISC

processor. This ability to know exactly what is occurring at any given moment in time is crucial for testing and simulating different operation scenarios.

When programming more complicated test applications such as testing PC communication with the MUB over the RS232 interface, however, the ANSI C language was heavily used. In this case, a test program was written so that the host PC sends random numbers to the MUB. After receiving these numbers the MUB multiplied the received number by a factor of three and sent the products back to the PC. The PC kept a log to check if the MUB sent the correct numbers back. This test was performed over a period of 24 hours with a 99.998% accuracy, which is satisfactory for the MUB specifications.

The use of ANSI C is also another advantage since it is non-proprietary and is a standard language. Moreover, the MUB can be also programmed in many different languages such as Basic, COBOL, Pascal, Bascom, and QBasic. The C language was chosen since it is an industry standard and many free IDE environments are available to choose from for the programming of the AVR[®] microcontroller chips.

Testing

In order to field-test the MUB, FAES USA has agreed to replace the PLC of one of their currently produced machines with the designed board. The SpinMaxx 240 is a high-speed centrifuge machine that is used to dry foam cores of diverse nature. For example, the SpinMaxx 240 is used to dry the foam cores of inkjet printer cartridges. In Figure 4,

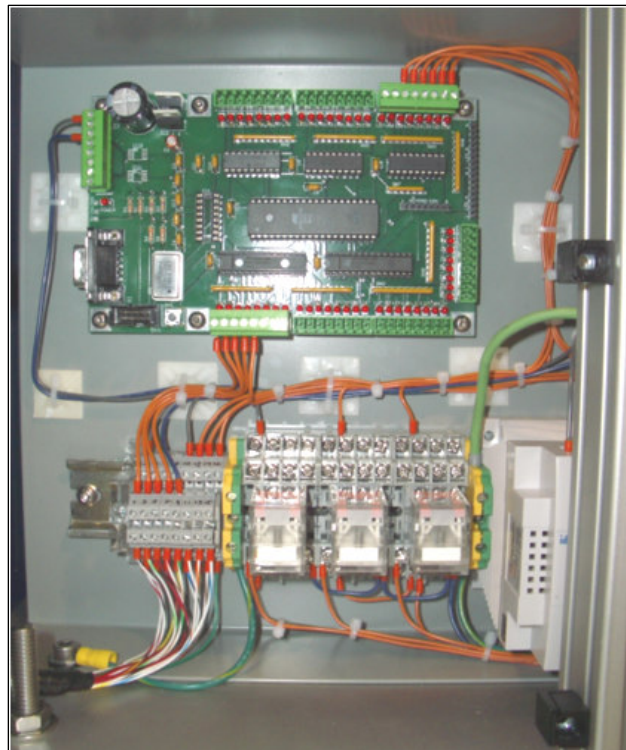


Figure 4 – SpinMaxx 240 MUB Implementation

one can see the MUB being interfaced to three relays that control the revolutions per second of the centrifuge. In addition, there were multiple START, STOP and safety buttons that are connected to the MUB. The entire controlling logic program was written in C. The keypad and 4-line 20-character LCD display allowed the operator to determine the speed, cycle-time, and rotating direction of the SpinMaxx centrifuge drying cycle. The programming of this device took about 20-30 hours of time including all libraries for the MUB board. Further software implementations will not take as long, however, since a great deal of interfacing protocols have already been created. As of the end of February 2005, the SpinMaxx with the integrated MUB has completed over 4600 cycles in the last two months without any problems. This reliability tests, in which the MUB controlled an actual real-life automated machine, has resulted in a stable track record over a long period of time and proved the successful end of this project.

Summary and Conclusions

In retrospect, the design of a Microcontroller-Unit-Board (MUB) and its application in system control have proven to be possible and economical. The research started by considering PLC and PC-based control in terms of cost and their advantages and disadvantages when used in industrial systems. With this data in mind, the authors were able to compare these solutions with a more cost effective design, the MUB namely. Through this process, a great deal of how to define specifications of a control system has been researched and learned. Communicating with different potential users and operators gave a vast account of non-documented yet very important specifications that can make a product more effective and better. This was clear from the feedbacks of the technical support staff at FAES USA.

The research, although has great industrial implications, has also shown to have more profound impacts on the author. With the designing and manufacturing of the MUB, the author has been able to effectively use what he learned in the classroom. It was very rewarding to recognize and then correctly apply methods of solving various problems. It was interesting, for example, to be able to get a good understanding of how to calculate the current drawn of devices and being able to make decisions on the maximum power consumption of the entire MUB. What thought to be “wasted time” that was used in problem solving in the classroom had to be revisited by “pulling-out” electronic textbooks and other reference materials used in courses before. Throughout the project, constant communication and consultation with the mentoring professor ensured the successful completion of this project. In addition to various challenges that were overcome, the lead author has realized the benefits and importance of classes such as Analog Electronics, Printed Circuit Board Design, Microprocessor Interfacing, and C++ Programming. Such courses in addition to the math and science classes have proven to be invaluable in the creation and production of the MUB.

The most rewarding experience to the student was being able to design and build the Microcontroller-Unit-Board from ground up, and that the board has a real-life purpose and application. The experience was also very rewarding to the mentoring faculty as well.

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