Designing a Low-Cost Embedded System Development Board with Convertible Intelligent Layers

Gang Sun, Paul Simmons, and Brain Decker

Engineering Technology Program
Northern Kentucky University
Highland Heights, Kentucky

Abstract

Recently, the rapid advancement of computer, sensor, wired & wireless communication, data storage, and integrated circuit (IC) technologies has had a tremendous impact on embedded systems design in many different types of industries. Integrating those new devices and technologies into current embedded systems development processes can enhance the competitiveness of products. Additionally, universities need low-cost and practical embedded systems development tools for their engineering students to learn new knowledge and skills in embedded systems design. Three years ago, with the support of TI and NASA, the author developed a novel modular integrated stackable layer-analog system environment (MISL-ASE) platform for embedded systems research and education. Although other universities and students have expressed interest in the MISL-ASE boards, they could not afford to use them as each board is very costly. Therefore, there is a need to design, develop, and test a low-cost embedded systems development board with the most useful analog, digital, and new wired and wireless peripherals on it. This paper discusses in greater detail the board development including schematic and printed circuit board (PCB) design, testing, and overall system requirements.

1. Introduction

Recently, the rapid advancement of computer, sensor, wired & wireless communication, data storage, and integrated circuit (IC) technologies has had a tremendous impact on embedded systems design in many different types of industries [1]. Integrating those new devices and technologies into current embedded systems development processes can enhance the competitiveness of products, facilitate product design, development and test, and make companies gain a better position in the global marketplace than their competitors. Moreover, educational programs need low-cost and practical embedded systems development tools for engineering undergraduate education from entry-level courses at the sophomore level to final capstone/senior design projects. Such development tools are also significant value to support not only embedded systems software courses, but to have the ability to be used in other courses such as instrumentation, control, and communications, etc. With the support of TI and NASA, Sun et al. [2] developed a novel modular integrated stackable layer-analog system environment (MISL-ASE) platform for embedded systems research and education. The MISL-ASE platform can provide a comprehensive hardware development environment as well as fully support the rigorous demands of harsh operational environments found in aerospace, automotive, oil and gas, or medical or communications systems prototyping, etc. Although other universities/companies and our students have expressed interest in MISL-ASE boards for their product development and embedded systems education, they could not afford to use them as the platform is very costly (over $800/each). Thus there is a need to design, develop, and test a low-cost development board that still encompasses the most useful analog, digital, and new wired and wireless peripherals on it. Additionally, when students study microcontroller courses, development boards are usually purchased or made for them to learn embedded system design in the lab. It should be pointed out that every university teaches different brands of microcontrollers (such as TI-MSP430, ATMEL-AVR, Microchip-PIC, NXP, Silicon-8051, and ARM, etc.). All the existing development boards are typically designed for a specific microcontroller model. None of them can meet students' needs if they are interested in learning multiple microcontroller families using the same development board. In this project, a novel design of convertible intelligent layers facilitates several popular microcontrollers being interfaced to the main board, which makes it possible for students to learn a number of microcontrollers using the same on-board devices and peripherals.

2. Materials and Methods

Compared with the MISL-ASE platform, this low-cost development board still consists of the most useful peripherals and new devices, but the size and cost of the board are reduced significantly. Figure 1 shows the overall functional block diagram of the development board, which is divided into four major sections: 1) convertible intelligent layers containing Texas Instruments MSP430F5438A and Atmel-ATMEGA2560V microcontrollers, 2) GPIOs (general purpose outputs/inputs), 3) signal conversion, and 4) wired and wireless communications, etc.

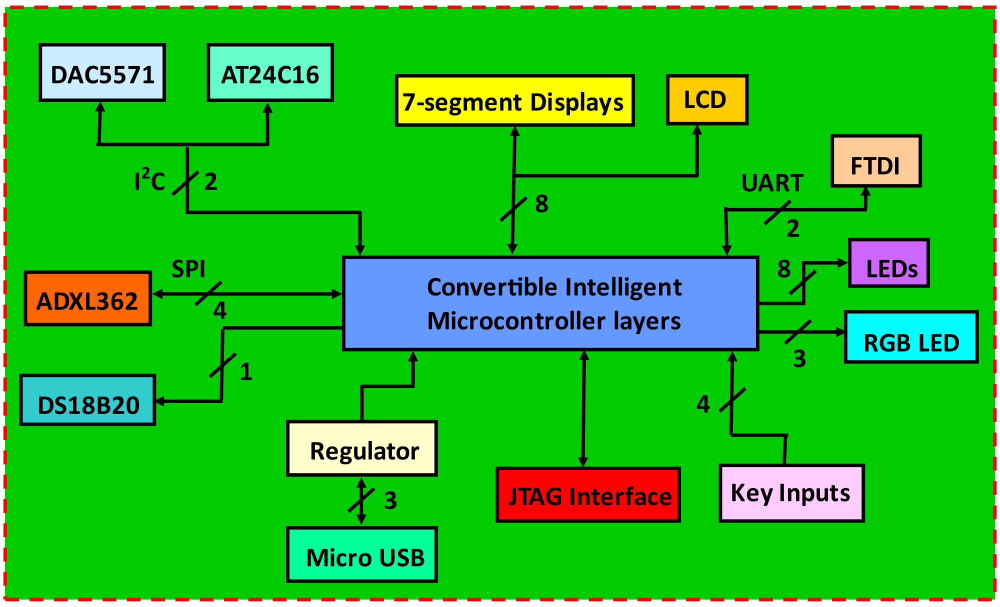

Figure 1. Overall functional block diagram of the development board

I. Schematic Design of the Development Board

(1) Convertible Intelligent Layers

In this project, two intelligent layers were created. One is a TI-MSP430F5438A microcontroller layer; the other is an Atmel-ATMEGA2560V layer. Figure 2 depicts the layout of a TI-MSP430 intelligent layer and the location of 100 pin data bus/connectors.

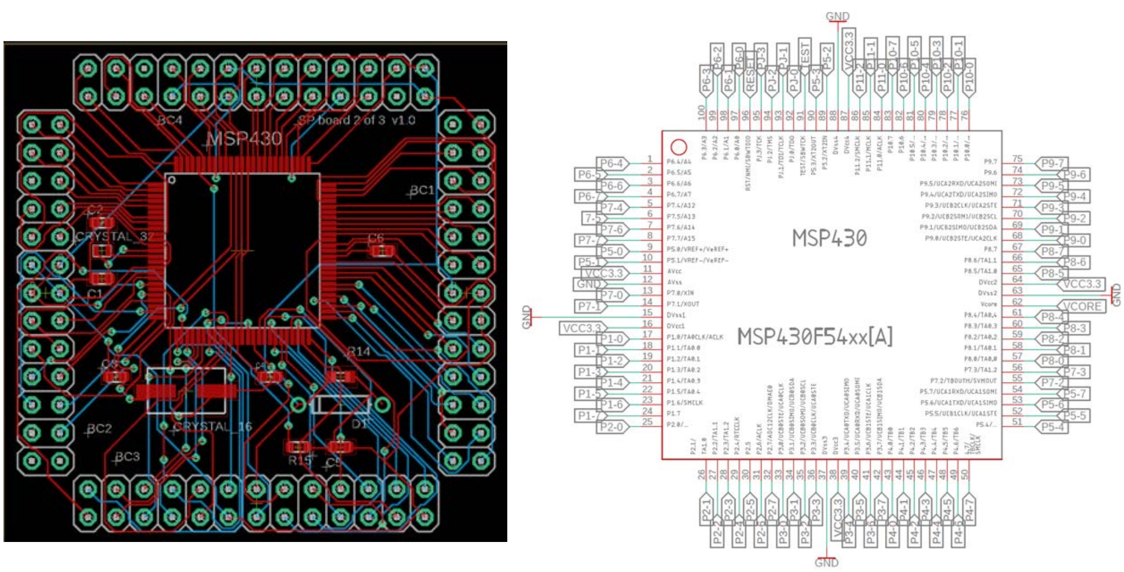

Figure 2. The layout of a TI-MSP430 intelligent layer

The MSP430F5438A [3] is an ultralow-power microcontroller, which features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. It has three 16-bit timers, high performance 12-bit analog-to-digital (A/D) converters, up to four universal serial communication interfaces (USCI), hardware multiplier, DMA, real-time clock module with alarm capabilities, and up to 87 general purpose I/O pins. On this layer, two external 32.768K and 16M crystals are connected with the oscillators XT1 and XT2 pins to generate clock signals for the microcontroller. A reset circuit includes a 47K Ohm pull-up resistor, a 2.2 nF capacitor to ground, and a N4007 diode. All the 100 pins of the TI-MSP430 microcontroller are pulled out to four female connectors that are plugged into the corresponding male connections on the main board. This type of design would allow for different brands of microcontrollers to be directly interfaced to the main board to share the same devices and peripherals. In other words, students can use this development board to study multiple microcontrollers and their peripherals without spending extra money on purchasing multiple microcontroller development boards.

(2) General Purpose Inputs/Outputs (GPIOs) Section

GPIOs are one of the most valuable resources in embedded systems providing the ability to communicate with the external world through digital lines that configured to operate as either inputs or outputs.

For GPIO-outputs, GPIOs can control the binary status of external devices by setting an external voltage level to either a logic high or logical low. The typical external devices are LEDs, 7-segment displays, buzzers, LCDs, and relays, etc. On this development board, eight red-color LEDs, one tri-color LED and four common-cathode 7-segment displays are used to indicate the on/off status and display numerical digitals or characters (Figure 3).

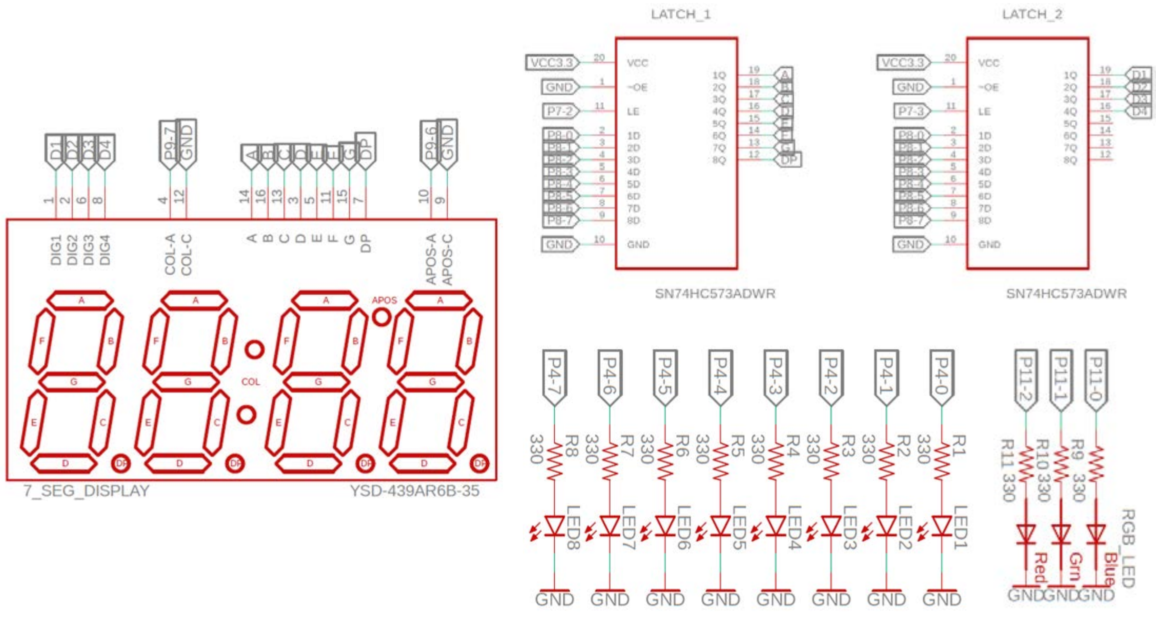

Figure 3. GPIO-outputs schematic

Due to the limits of the GPIOs' drive strength, two octal D-type latches (74HC573) are used. One latch is to drive a ~ dp segments (i.e., what to display) and the other is to select which display to use. Both of the latches are controlled through the latch enable (LE) pins to prevent the latches from overriding each other. In addition, an external LCD (1602) is interfaced to one of GPIO ports to illustrate images and information on the screen.

For GPIO-inputs, four independent mechanical pushbuttons are connected to the GPIOs of the microcontroller as a typical GPIO input example.

(3) Signal Conversion Section

The common task for embedded systems is to measure analog signals (e.g., temperature, pressure, flow rate, level, density, etc.) from the outside world and convert them into digital signals that microcontrollers can understand. Reversely, digital signals also must be converted to analog signals.

Signal conversion section (Figure 4) includes 1) a potentiometer: It is used to simulate a varying analog input voltage that will be fed into one of internal 12-bit analog-to-digital (A/D) converters so students can learn and practice A/D converter programming and 2) a 3-axis MEMS acceleration measurement system (ADXL362). It measures both dynamic acceleration resulting from motion or shock and static acceleration so it is widely used for home healthcare devices, hearing aids, and motion-enabled metering devices, etc. The ADXL362 communicates with the microcontroller over SPI (serial peripheral interface) interface and operates at extremely low power consumption levels. The built-in digital logic enables autonomous operation for sleep and wake-up operation that can run as low as 270 nA current at a low measurement rate (e.g., 6 Hz); and 3) a 8-bit digital-to-analog (D/A) converter (DAC5571): It is a low-power, single-channel, 8-bit buffered voltage output DAC. The DAC5571 utilizes an I^2C (inter-integrated circuit bus) interface that operates at clock rates up to 3.4 Mbps to convert digital signal to analog output voltage. The output voltage is changed from 0 v to Vcc (power supply) to alter the LED density. Additionally, some pcb terminal blocks are reserved on the main board for connecting with several typical analog sensors (e.g., temperature/humidity, pressure, flow rate sensors) so that their outputs can be converted into digital signals via internal A/D converters inside the microcontroller.

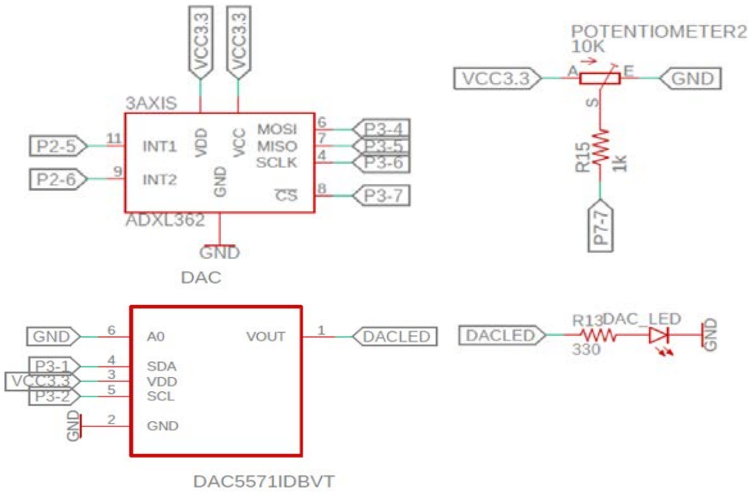

Figure 4. Signal conversion schematic

(4) Wired and Wireless Communications Section

Most new wired and wireless communication interfaces and protocols are available on this development board (Figure 5): four-wire communication networks: SPI (3-axis accelerometer ADXL362); b) two-wire communication networks: UART (USB/RS-232 FTDI); c) two-wire communication networks: I^2C (EEPROM 24C16, D/A converter DAC5571); and d) 1-wire communication networks: DS18B20.

SPI: The serial peripheral interface (SPI) is a synchronous serial bus standard with full-duplex capability to support communications between a master (e.g., microcontroller) and one or multiple slave peripheral devices. On this development board, a 3-axis accelerometer ADXL362 is able to communicate with the microcontroller via SPI to measure dynamic and static acceleration. Also, on-board SPI headers can be used to connect to external Wi-Fi chips. With this design, many different devices and equipment can be remotely accessed, monitored, and controlled through internet and Wi-Fi, such as web-based home automation, remote environmental monitoring, Voice Over IP, etc.

UART: The universal asynchronous receiver/transmitter (UART), is a very useful feature of microcontrollers for communicating serial data (text, numbers, etc.) to computers or devices. A 6-pin FTDI header is made on the board to convert RS-232 or TTL serial transmissions to USB signals so that the microcontroller can communicate with other computer systems via UART interfaces.

I^2C: The inter-integrated circuit bus (I^2C) is a synchronous serial communication protocol to support on-board interconnection of integrated circuit devices. On this development board, the I^2C uses two lines (SDA and SCL) to establish a half-duplex communication bus between the master (microcontroller) and two slave devices: 16K EEPROM (24C16) and D/A converter (DAC5571).

One-wire communication: A digital thermometer (DS18B20) is employed so students can develop distributed temperature monitoring systems through one-wire communication bus in lieu of the traditional measuring method using temperature sensors, signal conditioning circuits, and A/D converters.

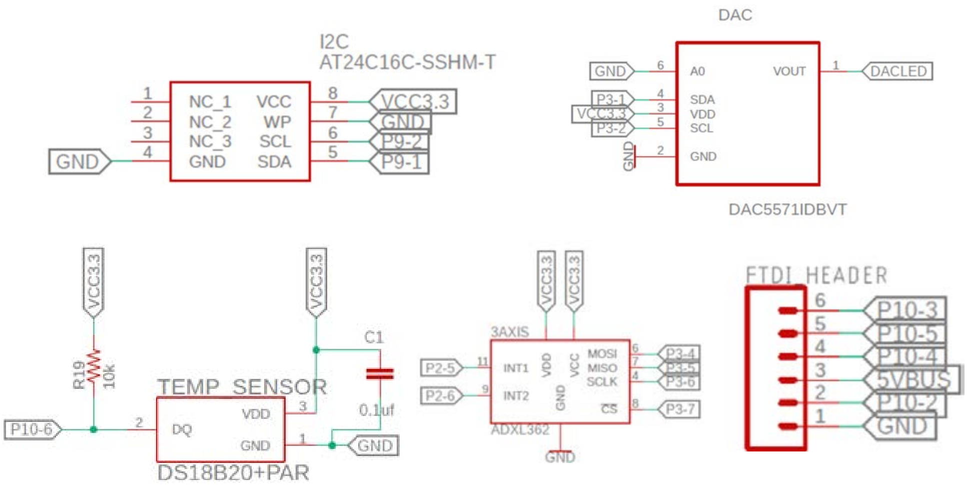

Figure 5. Wired and wireless communications schematic

II. PCB Layout Design of the Development Board

(1) Overall Layout

The printed circuit board (PCB) layout of this development board has four layers: top, bottom, power, and ground layers, which were designed using Autodesk Eagle [4]. Eagle is used to translate the schematic capture and all circuit connections into a file that can be laid out to accommodate the best design. Throughout the board layout, a number of design rules needed to be generated such that a design rule checker can be run on the layout and ensure that the design can be manufactured by the board house. The output of board layout software is a set of Gerber files that have been checked by the software's design rule checker and are then submitted to be verified by the board manufacturers design software. Figure 6 shows the overview of the entire board PCB layout.

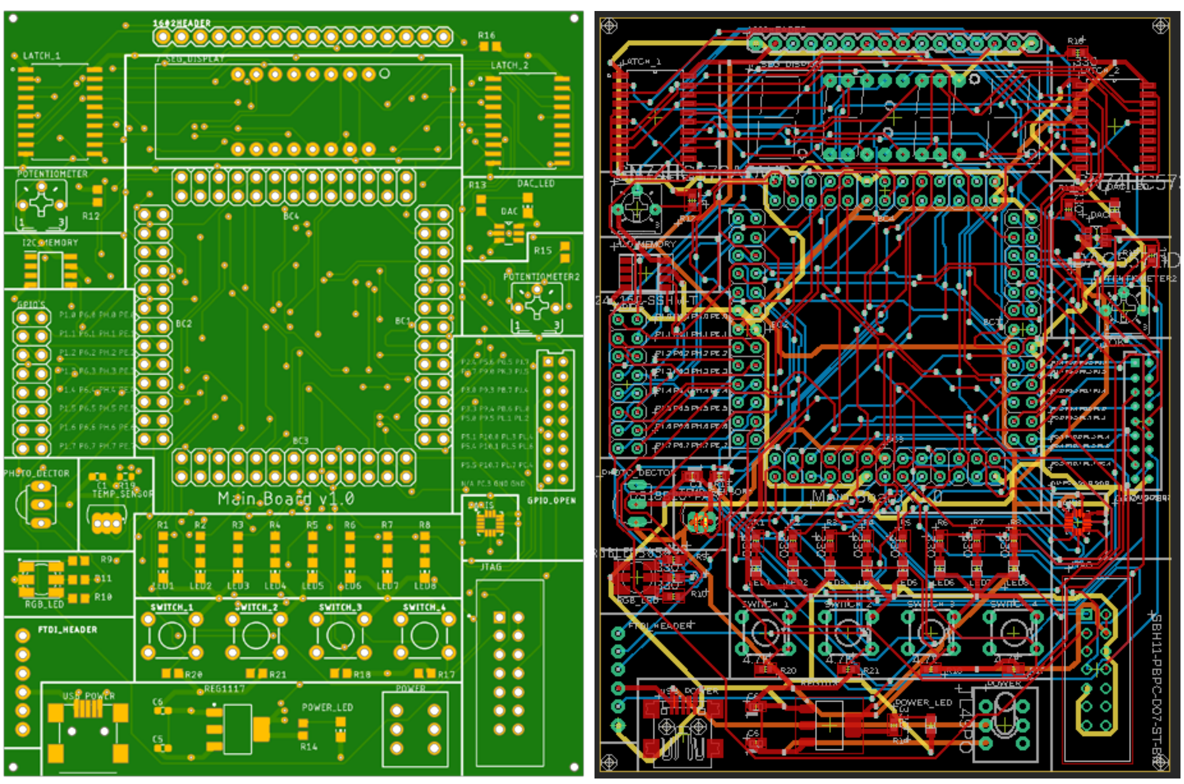

Figure 6. Overview of the entire board PCB layout

As can be seen in Figure 6, there are many different isolated circuits on the main board. These include LEDs, LCDs, push buttons, 7- segment display, one-wire temperature sensor, I^2C memory, IR, 3-axis accelerometer, DAC, JTAG, and more. To power the board, a USB mini B port was installed on the board. Once the power button is turned on, the 5 volts from the USB port go to the voltage regulator (REG1117) that takes the 5 volts down to 3.3 volts. 3.3 volts are used to power all the components on all the boards and layers. Connected to the voltage regulator are two capacitors that filter the noise out and help improve the power output. The last component in the power section is an LED to indicate the power on/off status. To the right of the power components is the JTAG header. This is for programming and debugging on the microcontroller that is plugged into the board. To the left of the power components is the FTDI headers. This six-pin header converts the USB signal to serial communication (RS232). Above the FTDI header is an RGB LED with three colors (red, green, and blue). The infrared sensor used on this board can detect any infrared radiation in the surrounding area. The one-wire temperature sensor can determine the temperature of the area. This one-wire temperature sensor circuit made for this project is to provide students an opportunity to learn and practice new communication protocol and digital devices. To the right of those sensors is a row of four push buttons. Each push button is connected to one GPIO pin and each has a pull up resistor attached to it. Above the four pushbuttons is a row of eight red-color LEDs. Each LED is connected to one GPIO pin with a current limiting resistor in-between them. To the right of the eight LEDs is the three-axis chip. This is an accelerometer that can determine what angle the board is at. In the center of the board is four twenty-six pin connectors. This connects the main board to an intelligent microcontroller layer.

On the right side of the intelligent microcontroller layer is an 18-pin GPIO port. Seventeen of the pins are used as GPIO pins with the eighteenth pin being used as a ground pin. Also, on this side of the board is a potentiometer; a DAC. 3.3 volts is sent to the potentiometer, and there is a specific voltage drop for whatever resistance the potentiometer is set at. The microcontroller, when programmed to, can read the amount of voltage that comes out of the potentiometer and display that voltage on the seven-segment display or an LCD. Continuing up on the board is the DAC and its LED. This chip can convert a digital signal to an analog signal.

On the right side of the intelligent microcontroller layer connectors are several other components. The first of these components is a fourteen GPIO pin headers. This is a two-column header with the right column being connected to one whole GPIO port and the left side being connected to another whole GPIO port. Above that header is the I^2C EEPROM chip. Last component on the left side of the intelligent layer connectors is a second potentiometer that controls the brightness of an LCD screen. On the top of the main board are four components, a seven-segment display, a one row sixteen-pin header to connect an LCD screen to the board and two D-type latches. The D-type latches are used so that the seven-segment display can be used by one GPIO port instead of having to use multiple ports. The first latch would store what number is to be displayed, and the second latch stores the signal for which one of the four spots the number is displayed on.

(2) Signal Layers

Shown in Figure 7 are two signal layers: top and bottom. To potentially minimize cost of the board and make for a simplistic design, all components and silkscreen were placed on the top layer of the board. The bottom layer was used for routing of connections that could not be accomplished on the top layer or through the internal planes.

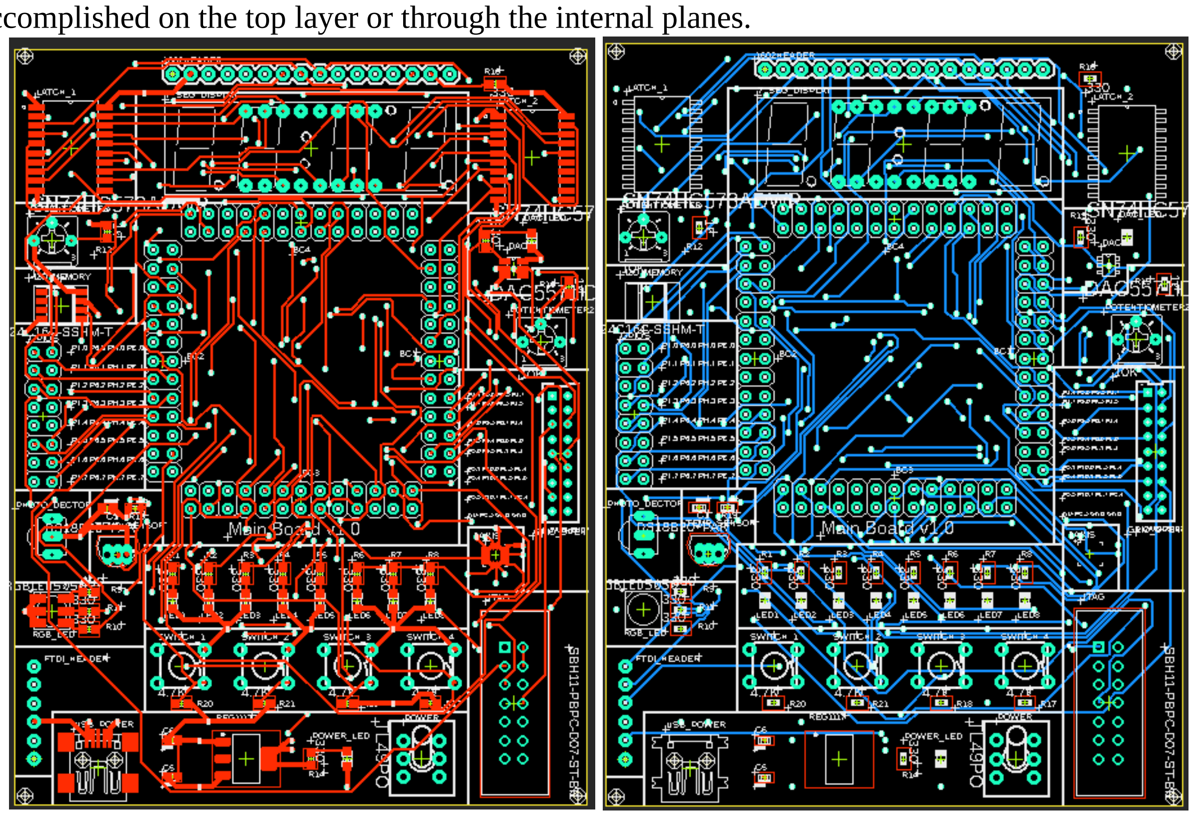

Figure 7. Signal layers (Left: top layer; Right: bottom layer)

(3) Power and Ground Layers

The power and ground layers are shown in Figure 8. The power layer is used to provide constant voltage throughout the design and minimize traces by providing a direct point of connection for any signal requiring a 3.3-volt signal. The ground layer is used to ensure that the whole development board has a good common ground. It also allows for less routing of all ground connections as they can be immediately connected to the ground plane through a via.

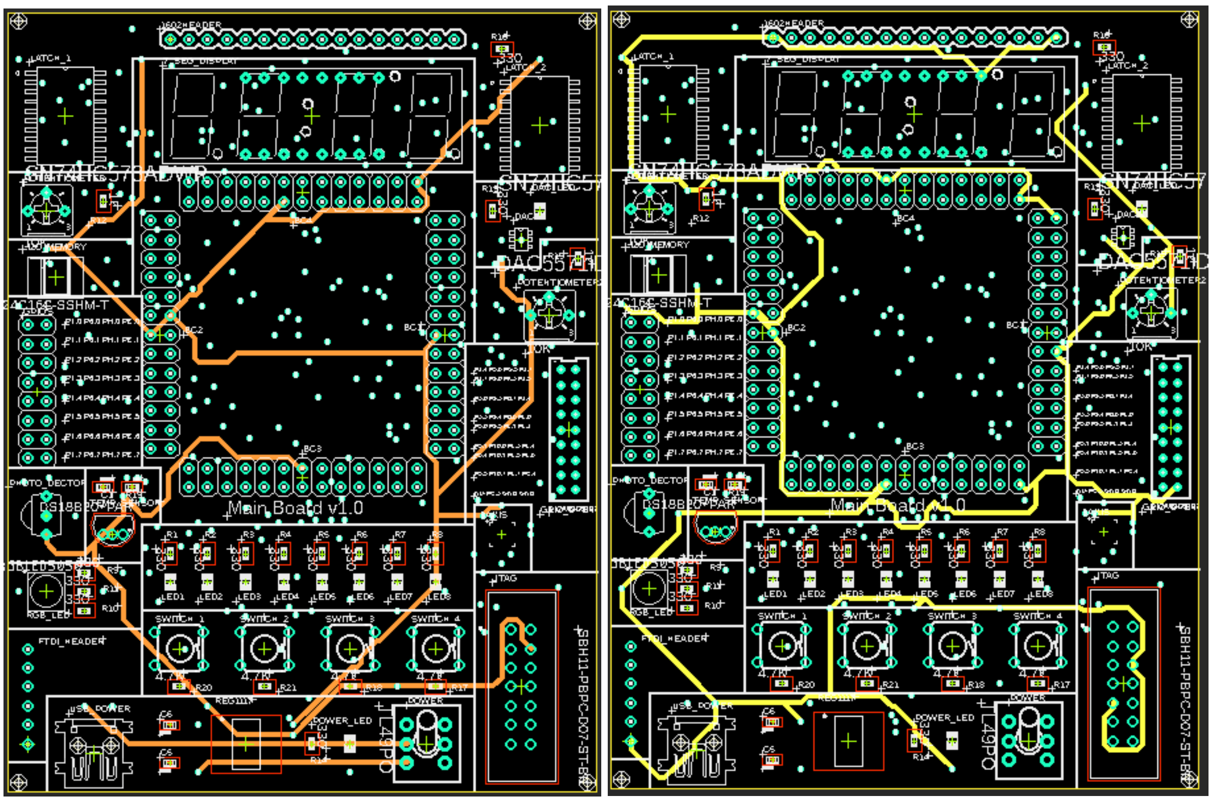

Figure 8. Power and ground layers (left: power layer; right: ground layer)

(4) Development Board Evaluation

The schematic and PCB design of this low-cost development board were completed during the Spring and Summer 2019. The PCB layout Gerber files were sent to the board manufacturing company (Seeed) and the first version (prototype board) was made and populated (Figure 9). Two senior electronics engineering technology students who have finished microcontroller courses are hired to access the value and acceptance of this new board. After debugging, testing, and modifying the prototype boards, 30 development boards will be procured and populated for our students.

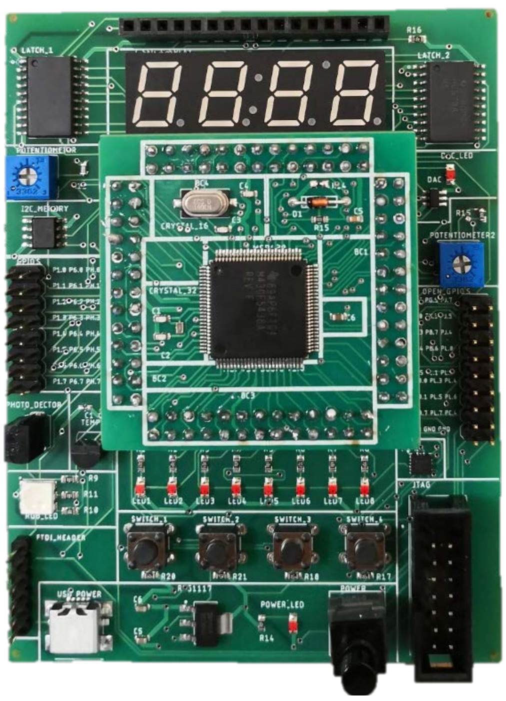

Figure 9. The first version (prototype board)

3. Conclusions

This paper presents the overall design of the low-cost embedded system development board with convertible intelligent microcontroller layers. The main board can be divided into four sections: the connector for intelligent layers, GPIOs, signal conversion, and wired & wireless communications. The convertible intelligence layers contain different brands of microcontrollers (e.g., TI-MSP430F5438A and Atmel- ATMEGA2560V), which can be directly interfaced to the main board. This novel design allows students to use the same devices and peripherals within various microcontroller development environment by simply changing the intelligence layer. It is expected that this new development board could provide an affordable hardware environment for students to learn, design, and test embedded systems using advanced microcontroller technology and a wide range of new communication protocols and devices.

Acknowledgment

The authors wish to acknowledge financial support from Center for Integrative Natural Science and Mathematics at Northern Kentucky University.

References

[1] Y.M.Roshan and M. Moallem, "Developing a course and laboratory for embedded control of mechatronic systems," *Proceedings of ASEE Annual Conference*, 2011.

[2] Sun, G., J. Morgan, J. Porter, and H. Yim. "Development of a novel modular integrated stackable layer – analog system environment (MISL-ASE) platform for embedded system education," *Proceedings of IEEE Frontiers in Education Conference*, El Paso, TX, 2015.

[3] "Texas Instruments MSP430F5438a microcontrollers," 2020. [Online]. Available: http://www.ti.com/product/msp430f5438a.

[4] "Autodesk-Eagle PCB layout design," 2020. [Online]. Available: https://www.autodesk.com/products/eagle/overview.

Biographical Information

Dr. GANG SUN is currently an assistant professor in Engineering Technology program at Northern Kentucky University. From 2013 and 2016, he was an assistant professor in the Department of Engineering Technology and Industrial Distribution at Texas A&M University. His research involves designing mechatronic systems that integrate embedded systems, programmable logic controllers, ubiquitous computing, real-time operation systems (RTOS), wired/wireless communication, sensor networks, and actuator control in various industrial, agricultural, and environmental applications.

PAUL SIMMONS is a senior student and undergraduate research assistant in the Electronics Engineering Technology program at Northern Kentucky University.

BRAIN DECKER was an undergraduate research assistant in Electronics Engineering Technology program at Northern Kentucky University. He graduated in May 2019 and continues to pursue his master's degrees in Computer Science and Business Administration at NKU.