AN996

Designing a Digital Compass Using the PIC18F2520

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INTRODUCTION

Digital compasses have become popular in the past few years due to the advancement of magnetic sensors and feature-rich microcontrollers. Compass applications have increased from simple, hand-held navigation devices to automobile navigation systems with voice recognition and up-to-date global maps.

This application note will focus on a simple, low-cost, hand-held digital compass design using a Microchip PIC18F2520 microcontroller. This compass application can be integrated into your own design, or as a building block in an advanced navigation tracking device similar to one you would find in a sporting goods store or automobile.

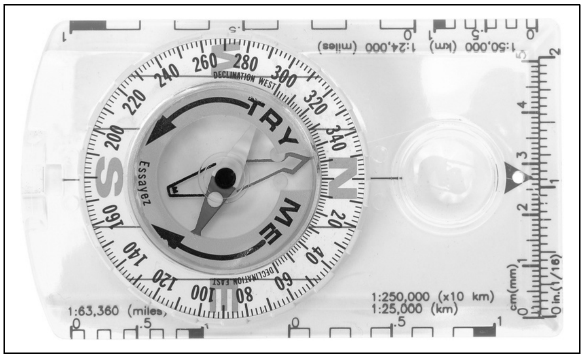
Compass Theory

Before we get into the specific design of the digital compass, let’s talk about compassing fundamentals. The information available on this topic is seemingly endless. Perform a search on the World Wide Web and you will find an abundance of information. In this section, we will cover enough of the basics of compassing needed to develop a digital compass.

The use of a compass dates back at least 2000 years when a magnetized stone, known as a lodestone, was used to determine direction. During the 12th century, mariners were using lodestones placed on wood floating in water. Prior to this, the primary method for determining direction was the stars by night, and the sun by day.

Typically, we don’t think of rocks when we hear the term compass. What usually comes to mind is a magnetic needle, free to rotate in a plastic housing similar to the compass shown in Figure 1. The needle aligns itself with the Earth’s north/south magnetic field lines to establish the north direction. The horizontal direction of the Earth’s field is always pointing north. This field has a magnetic intensity of 0.5 to 0.6 Gauss. In comparison, a 230 kV transmission line, under average load, yields a 20 mGauss field at 50 feet. Considering the needle is magnetic, objects containing iron, such as belt buckles, nails in a table, automobiles and mineral deposits in the ground, can affect the needle’s orientation. When measuring direction with an analog or digital compass, objects like these must be avoided to maintain accuracy.

FIGURE 1: COMPASS



In this application note, three angle terms are introduced that are popular within the aviation industry: Heading, Pitch and Roll. These angles are always referenced to the horizontal plane, which is perpendicular to the Earth’s gravitational force.

- Heading – the angle in the horizontal plane measuring clockwise from a true north direction (1°-360°).
- Pitch – the angle between an aircraft’s longitude axis (tail to nose) and the horizontal plane. For example, if the nose of the aircraft is pointed up, the pitch angle is positive (see Figure 2).
- Roll – the angle about the longitude axis between the horizontal plane and the actual flight orientation. For example, if the right wing of the aircraft is down in relation to the left wing, then the roll angle is positive (see Figure 3).

Pitch and roll, as shown in Figure 2 and Figure 3, are referred to as the tilt angles. As you will read later, the digital compass in this application is tilt-compensated, indicating that the pitch and roll angles of the hand-held device are accounted for in the overall heading measurement. The tilt angles are measured with an accelerometer. In addition to measuring the tilt angles, the X, Y and Z magnetic components will be measured. These are the axes relative to the Earth's north/south magnetic lines discussed previously. They are measured with magnetoresistive sensors.

FIGURE 2: PITCH

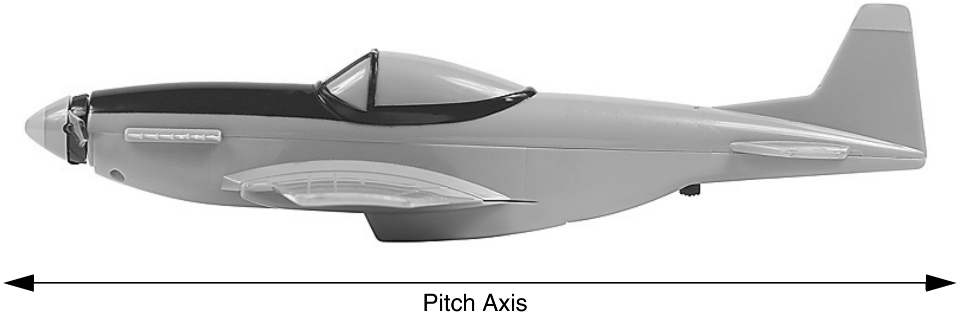
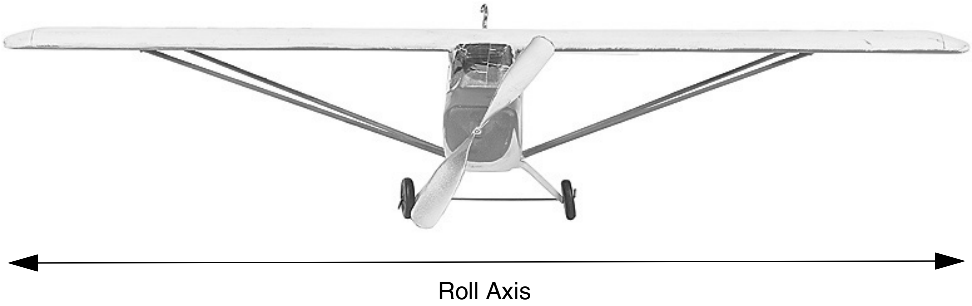


FIGURE 3: ROLL



SENSORS

We have discussed how to measure direction and the components involved in obtaining a measurement. Now on to the actual devices.

We mentioned the simple compass with a magnetic needle, and although this is a tried and true device, technology has brought us into the digital age of sensors, providing us with faster and more accurate solutions. Before we discuss sensor details, the following is a quick summary of the operating conditions of the digital compass described in this application note:

- Operating Voltage (V_{DD}): 3.3V
- Operating Frequency (F_{OSC}): 4 MHz Crystal (1 µs T_{CY})
- Power Supply: 9V Battery
- Development Tools: MPLAB® IDE 7.0, MPLAB C18 C Compiler, MPLAB ICD 2 (available from Microchip)
- Heading Refresh Rate: ≈300 ms
- 12-Bit A/D Results

Earlier, we discussed the need to measure the tilt angles (pitch and roll). To measure these angles, we used a 2-axis accelerometer. Accelerometers are available in different varieties (including 1, 2 or 3 axes), and different types (including piezo-electric, piezo-resistive, capacitive and thermal). They are also available and preferred in single-chip digital solutions, which means that the output of the accelerometer chip can be directly interfaced into a microcontroller's I/O pin.

In this application note, we chose the dual axis MXD2020EL available from MEMSIC (see **"References"**), which has a range of ±1g and an operating voltage of 3.0V to 5.25V. The outputs are digital signals with varying duty cycles proportional to acceleration. These outputs are directly interfaced into the PIC18F2520 device's RA5 and RB4 I/O pins.

The operation of the MXD2020EL is based on heat transfer by natural convection. Changes in acceleration result in a change in the temperature profile within the chip and as a result, the duty cycle changes. As you will read later, the PIC18F2520 measures the high pulse to determine the angle. The MXD2020EL has a temperature output that is connected to AN3 on the PIC18F2520.

After the analog voltage is converted, the digital value is applied to an equation to determine how much the pitch and roll values should be compensated based on a change in temperature. In order to derive an equation, voltage measurements from T_{OUT} were taken at 25°C and 85°C. The values were then plotted on a graph using a spreadsheet, or a plotting freeware program which can be found on the Web.

The next components requiring sensor measurement are the magnetic X, Y and Z axes. These are important measurements because direction can be measured without tilt compensation; however, the results will not be as accurate if the compass device is not horizontal to the Earth's surface.

Two magnetoresistive sensors from Honeywell (see **"References"**) were selected, the HMC1051 (single-axis) measures the Z axis and the HMC1052 (dual-axis) measures the X and Y axes. These sensors are configured in a 4-element Wheatstone bridge to convert magnetic fields to differential output voltages. The output voltages are referenced to one-half V_{DD}. They have a ±6 Gauss field range with 1.0 mV/V/Gauss sensitivity and an operating voltage of 1.8V to 20V. These sensors are interfaced to three instrumentation amplifier configurations and then into the PIC18F2520 I/O pins. These sensors are feasible for this application considering our goal is a one degree resolution compass.

The HMC1051/1052 sensors are made up of permalloy (NIFE) thin films that create changes in resistivity with respect to external magnetic fields. These films can be compared to magnetic recording tapes. When exposed to a strong magnetic field, the data on the tape can be corrupted. The same applies to the sensor; a strong magnetic field can upset the magnetic domains of the film particles.

To realign the particles on the films, a Set/Reset condition will have to occur. This is accomplished through extra circuitry on the chip itself, as well as on the application's PCB. A sufficient power supply will be required due to the current demand. For this application, the MOSFET receives the current directly from the 9V battery (see Figure B-2). This is known as the Set/Reset strap, which is an input pin on the sensor's package. The Set/Reset strap circuit requires a 0.4 to 4A, 1 µs pulse to recover the films that have been disoriented by an external source. External source examples include speaker magnets, CRT monitors, or high-current carrying cables, among others. See **Appendix B "Schematics"** for circuit specific information.

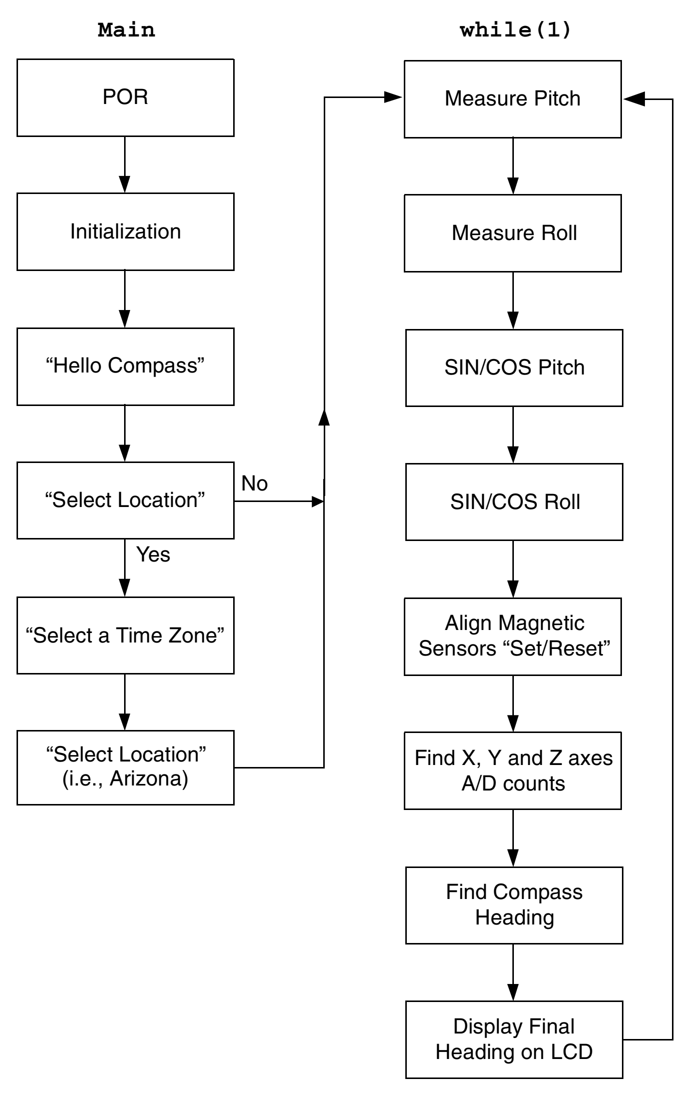
The remaining components not directly specific to compassing are the 2x8 LCD, and the MCP6022/MCP6024 operational amplifiers. The MOSFET responsible for creating the Set/Reset pulse is an IRF7509. Power is regulated by an LM1117 supplying 3.3V for the analog and digital circuits. Communication with a PC's HyperTerminal is handled by a MAX3232 transceiver. Refer to **"References"** for information on the components used in this design.

FIRMWARE

The firmware for this application is written in C using Microchip's MPLAB C18 C Compiler. Code utilization is 36 percent of the PIC18F2520 device's memory, which translates to 12172 bytes of 32 Kbytes (approximately 140 bytes of data memory is required). This application note focuses on the main code routines specific to compassing. The other routines, such as hexadecimal to BCD conversion, are general in nature and are not specific to this application. The segments discussed below are outlined in Figure 4.

Note: The source code and any application examples described in this application note are available for download from Microchip. See **Appendix A "Source Code"** for more information.

FIGURE 4: CODE FLOW DIAGRAM



The pitch and roll firmware is straightforward considering that the output of the MXD2020EL is a duty cycle proportional to acceleration with a 10 ms (100 Hz) period. Timer1 was configured to count the high pulses of the duty cycle captured by the I/O pin.

After Timer1 collects the total count of the high pulse, the value is checked to determine if it's greater, less or equal to 5000. If the count is greater than 5000 (angle is positive or compass housing is pointed up/right), 5000 is subtracted from the counter value and then divided by 33. If the value is less then 5000 (angle is negative or compass housing is tilted down/left), 2690 is subtracted from the counter value and then divided by 33. If the counter value is equal to 5000, the angle is 0 degrees. The equation produces a value in one degree increments, separated by 33 Timer1 counts, based on a 1 µs instruction cycle.

Once the pitch and roll angles are captured, the SIN and COS value of each angle must be calculated. These values are necessary for the overall heading calculation. The SIN and COS values are stored in program memory in the form of a table accessed by each of the tilt angle's routines. Firmware has been written to warn the user if the tilt angles are too excessive to retrieve a usable result. For instance, if the user is holding the compass where it is leaning too far to the left or right, then a message is displayed on the LCD to tilt toward the opposite direction. The same idea applies to the compass leaning too far to the front or back.

The next step is to measure the analog voltage output delivered by the HMC1051 and HMC1052 sensors. Before the actual A/D value is measured, each axis must be offset. This is accomplished by creating a low-cost DAC with an operational amplifier (see Figure B-1). The output at V_{REF} is an analog voltage proportional to the applied PWM signal. Each axis (X, Y and Z) will have its own specific duty cycle value which is determined in the calibration step.

After the axis duty cycle has been loaded, a short delay is executed to allow the sensor to stabilize with the latest PWM value and then the analog voltage is measured. Extra firmware has been implemented for A/D oversampling, which accomplishes a 12-bit firmware result (4096 counts) from a hardware 10-bit (1024 counts) A/D.

After the digital value is calculated and stored, it is plugged into the formulas for Xheading and Yheading as detailed in Equation 1. After the Xheading and Yheading values are calculated, the results are plugged into the formula shown in Equation 2.

From here, the ARCTAN value of the XYheading result is found by accessing a tangent table stored in program memory. Due to the limits of ARCTAN being 0 to 90 degrees, the quadrant in which the angle is located must be determined, which is performed with the `QuadrantDecode` routine. Finally, the magnetic heading value is obtained. Refer to **"References"** for the source of Equations 1 and 2.

EQUATION 1: X AND Y HEADING FORMULAS

$$\text{Xheading} = (\text{AxisValue}[X] * \text{PitchCOS}) + (\text{AxisValue}[Y] * \text{RollSIN} * \text{PitchSIN}) - (\text{AxisValue}[Z] * \text{RollCOS} * \text{PitchSIN})$$

$$\text{Yheading} = (\text{AxisValue}[Y] * \text{RollCOS}) + (\text{AxisValue}[Z] * \text{RollSIN})$$

EQUATION 2: XYHEADING FORMULA

$$\text{XYheading} = \text{Yheading}/\text{Xheading}$$

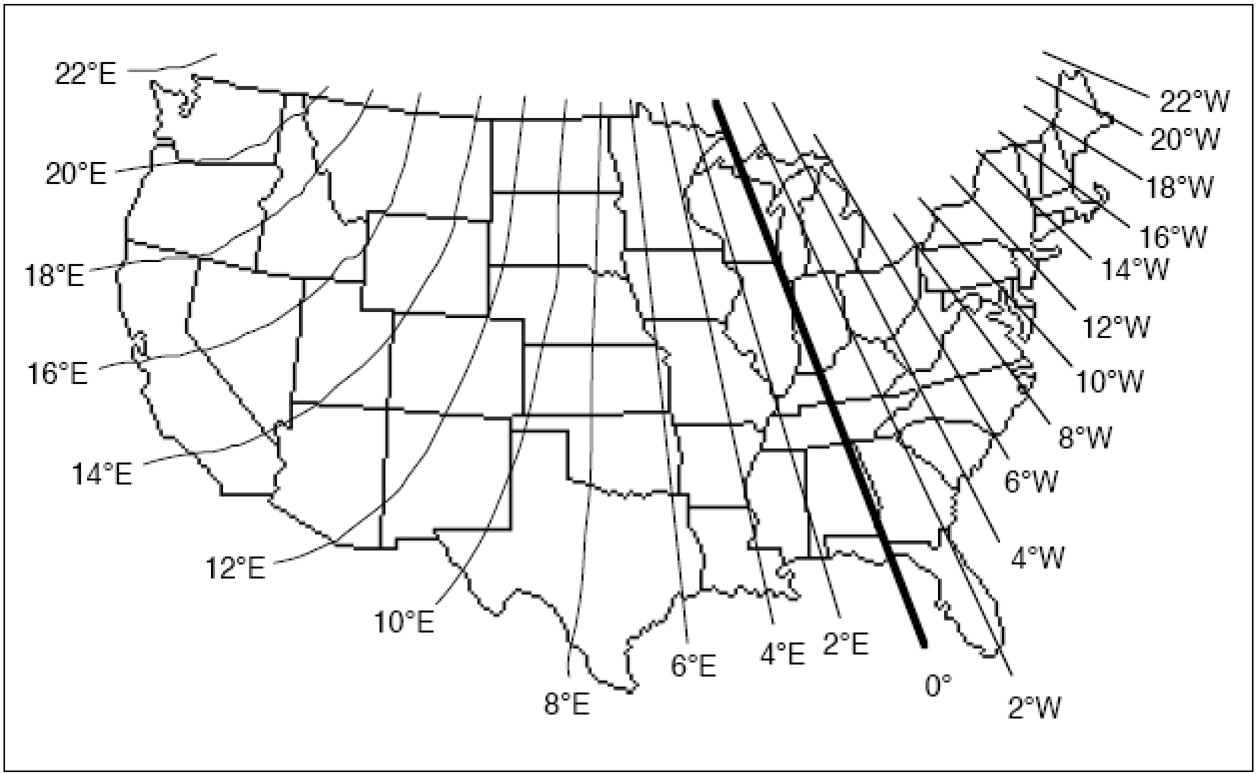
Although the magnetic heading is obtained, it may not necessarily be the correct heading. The reason for this is that there are two types of poles on the Earth: geographic and magnetic. The northern and southernmost points of the globe are the geographic poles (true north). The magnetic poles are the origin of the Earth's magnetic field and the pull is the strongest at these locations (magnetic north).

Compasses with a magnetic needle, which were discussed earlier, will point to magnetic north. To determine the difference between magnetic north and true north, we can reference an isogonic chart (see Figure 5), which is a map containing lines that indicate points of equal magnetic variation between magnetic north and true north. These lines are known as isogonic lines.

As the chart in Figure 5 shows, the isogonic lines each have an angle associated with them for the United States. For maps of other areas of the world, see **"References"**. The 0° line indicates the geographic location where there is no angle difference between magnetic north and true north. This angle is known as the declination angle. If this is known, it can be easily implemented in a digital compass to account for the declination angle.

As described in this application note, firmware has been added to account for the declination angles associated within the United States. Upon a Power-on Reset (POR), the user is asked if a location should be selected, implying that a declination angle will be chosen by the user's location. If the user declines to select a location, the prior value stored in the PIC18F2520 device's EEPROM will be used as the declination angle. This may be a default value, or a value from a previous user when the device was last used. If the user decides to select a location, the next prompt on the display is to select a time zone (Pacific, Mountain, Central or Eastern). Once the time zone is selected, the firmware is configured to automatically scroll through the states within that time zone waiting for the user to make a selection.

FIGURE 5: ISOGONIC LINES



The accuracy of adding the declination to the heading can vary by a few degrees. If we look at the state of Texas, which has three isogonic lines running through it, it is possible to have a difference of four degrees in the heading. There are a couple of ways to address this:

1. Have more selections in firmware for the state of Texas (i.e., West Texas, Mid-Texas and East Texas).
2. If the compass application was integrated with a Global Positioning System (GPS), then the user's exact location could be detected and an algorithm to determine the declination angle could be implemented.

Unfortunately, options like these increase cost and development time and may not be feasible for a low-cost compass.

This brings us to the last main calculation – obtaining the final heading which reflects a true north measurement:

EQUATION 3: TRUE NORTH MEASUREMENT

$$\text{FinalHeading} = \text{FinalHeading} + \text{decl\_angle}$$

This measurement is displayed on the LCD which is continually updated by the main loop of the firmware.

At this point, all of the compassing specific firmware has been discussed, which leaves the generic functions, including the LCD, A/D and hexadecimal to BCD conversion routines. Some of these routines have been taken from the PIC18 library where they are used for a variety of applications.

The firmware for the Set/Reset function is very simple; it consists of setting RA4 for one instruction cycle and then clearing it. This is executed in the main loop; therefore, it is occurring approximately every .38 seconds. This number is fast, so for applications with minimal battery capacity, the Set/Reset pulse can be timed by a timer interrupt (i.e., every 2 seconds). This will greatly reduce the current drain on the power source.

PCB/CIRCUIT DESIGN

Layout should be taken into account considering magnetic sensors, high-current pulses and A/D conversions will be occurring. The sensor manufacturers have made recommendations for device connection and positioning; however, in addition to this, competent layout practices should be followed. The 2-layer PCB measures 3 inches by 2 and 3/8 inches, with most of the components being surface mount.

Positioning

The analog section of the compass is partitioned off with a ground plane in the upper right corner. The PIC18F2520 and power supply circuits were located in the upper left corner. User switches were located in the lower left corner to keep them easily accessible. The MOSFET responsible for driving the Set/Reset pin was kept relatively close to the HMC1051/1052 devices, limiting the length on the high-current pulse line. The HMC1051/1052 devices were positioned towards the middle of the PCB with no close proximity to any of the other major components.

The HMC1051/1052 devices do not require a ground plane, as this would alter the capabilities of measuring magnetic fields. MEMSIC has several recommendations for the layout of the MXD2020EL, which include placing a ground plane under the device's footprint (PCB: bottom layer) and liberal use of ceramic bypass capacitors. The physical orientation of the HMC1052 and MXD2020EL is important. If the manufacturer's instructions are not followed, the risk of having measurements out of phase is possible.

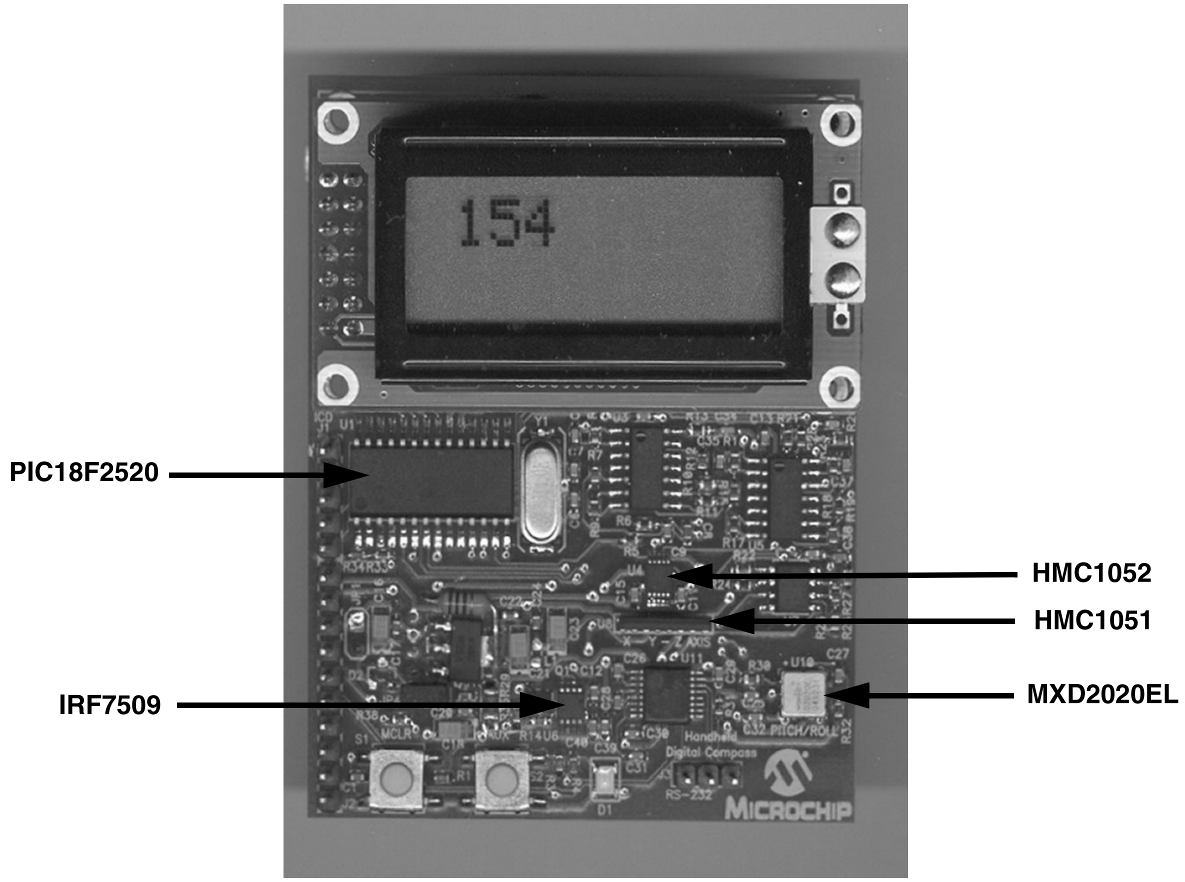
Traces

The MOSFET feeds the Set/Reset pin with an extra heavy trace for the high-current pulses. The X, Y and Z analog lines out of the operation amplifiers are routed parallel to each other, back to the PIC18F2520, while avoiding noisy and/or power traces. The power traces have all been widened.

Power

The main power source (9V battery) has been divided into two subsources: analog and digital. The main reason for this was to isolate digital noise from the analog circuits.

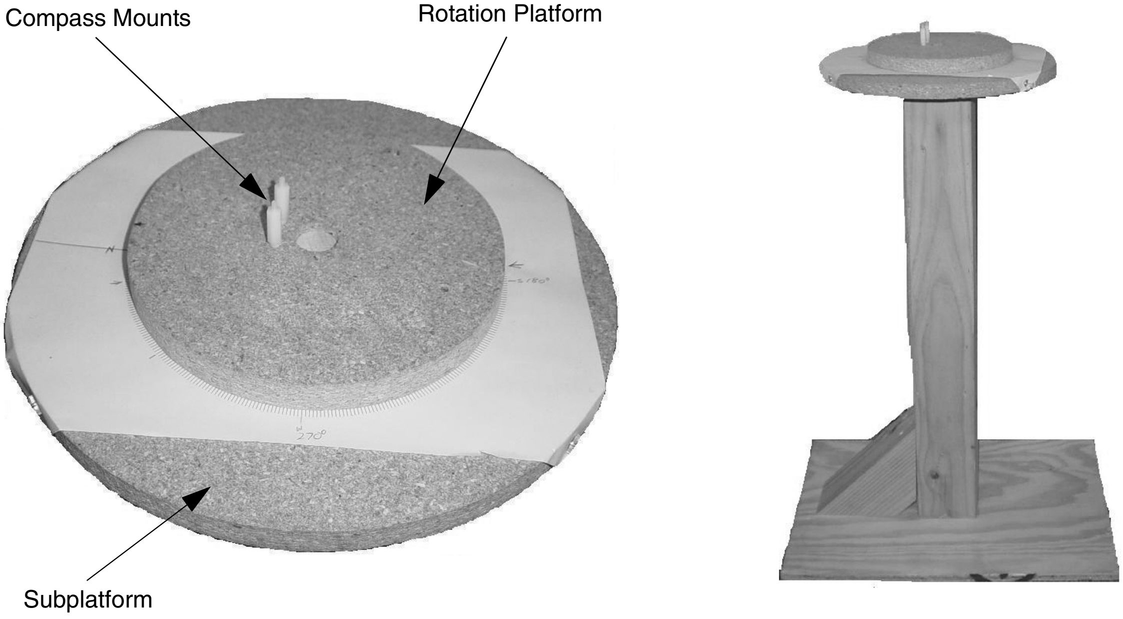
FIGURE 6: DIGITAL COMPASS



CALIBRATION

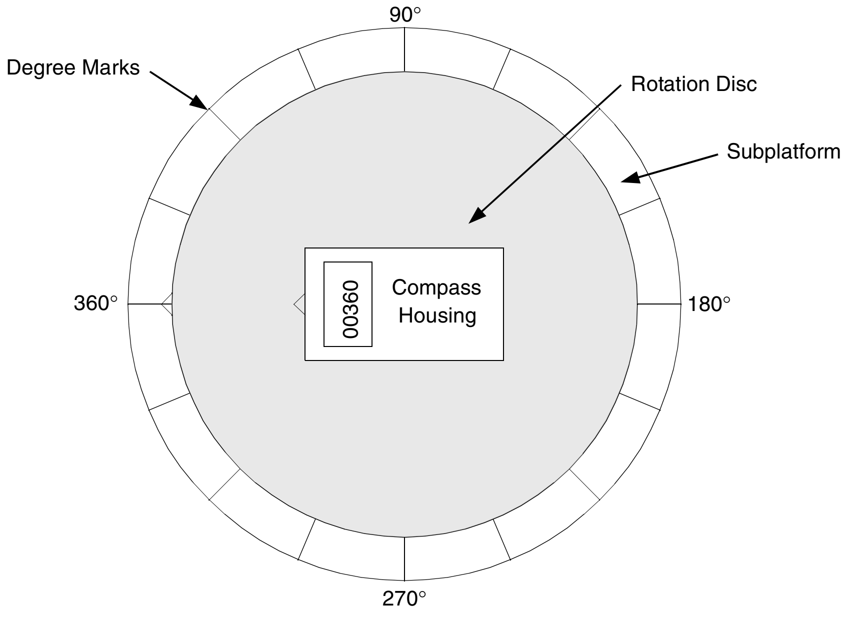
The compass is calibrated by attaching it onto a horizontal platform to eliminate any tilt angles. The mounting platform (Figure 7) used for this application was made perpendicular to the Earth's surface before any measurements were taken, and was constructed out of wood and glue to avoid any magnetic distortions created by metal fasteners. The compass was mounted to a disc that could spin freely on top of the platform. Then, 360 equidistant points were printed onto a sheet of paper using CAD software (as shown in Figure 8) and laid under the movable disc. The 360 points simulate 360 degrees of rotation and are needed for the calibration process. A tick mark was placed on the rotational disc. The compass housing was aligned with this tick mark. Therefore, when the rotational disc is positioned at the 360° mark, the compass would be as well.

FIGURE 7: COMPASS PEDESTAL



MOUNTING PLATFORM **PEDESTAL**

FIGURE 8: CALIBRATION MARKS



Calibrating a digital compass can be done in several ways. In this application note, the following approach was taken, which is recommended by the magnetic sensor manufacturer (see **"References"**):

1. Configure the PIC18F2520 device's USART to communicate with the HyperTerminal program on a PC and display the X and Y A/D results. These values would be the final A/D counts after the quadrant math is completed. As the compass is rotated, you will observe a change in the counts. This can also be displayed on the on-board LCD.
2. Establish direction (i.e., north) using a calibrated compass, analog or digital.
3. Rotate the compass at a constant speed one full turn (360°) on the horizontal pedestal while collecting as many X and Y readings as possible. The rule of thumb is to collect a reading every few degrees. If enough readings have not been collected in the one full rotation, then complete one or two more rotations.
4. From the readings collected in step 3, find the min/max values for each axis.
5. Place the min/max values into the following equations:

   $Xsf = 1$ or $(Ymax - Ymin)/(Xmax - Xmin)$, whichever is greater,

   and

   $Ysf = 1$ or $(Xmax - Xmin)/(Ymax - Ymin)$, whichever is greater
6. Place the values obtained in step 5 into the following equations:

   $Xoff = [(Xmax - Xmin)/2 - Xmax] \bullet Xsf$

   and

   $Yoff = [(Ymax - Ymin)/2 - Ymax] \bullet Ysf$
7. Xoff and Yoff represents the values by which the X and Y outputs must be shifted. This is accomplished by applying the correct duty cycle value for the PWM signal to obtain the Xoff and Yoff shift.

In addition to the steps outlined by the manufacturer, these steps can also be used to verify the compass headings:

1. Looking at the quadrant diagram in Figure 9, we know that the X measurement should be at the point of going either positive or negative. A negative result is when the A/D measurement is greater than 2048, whereas a positive result is when the A/D measurement is less than 2048. In terms of the A/D measurement, this translates to a result of X = 2048-A/D in quadrant 1, or X = measurement-2048 in quadrant 2.
2. The measurement should be at or near 2048 counts.
3. The same procedure can be done for the Y axis, in quadrants 2 and 3, at the 90 degree mark on the pedestal.
4. In an ideal situation, the four points would have equal values of magnitude:

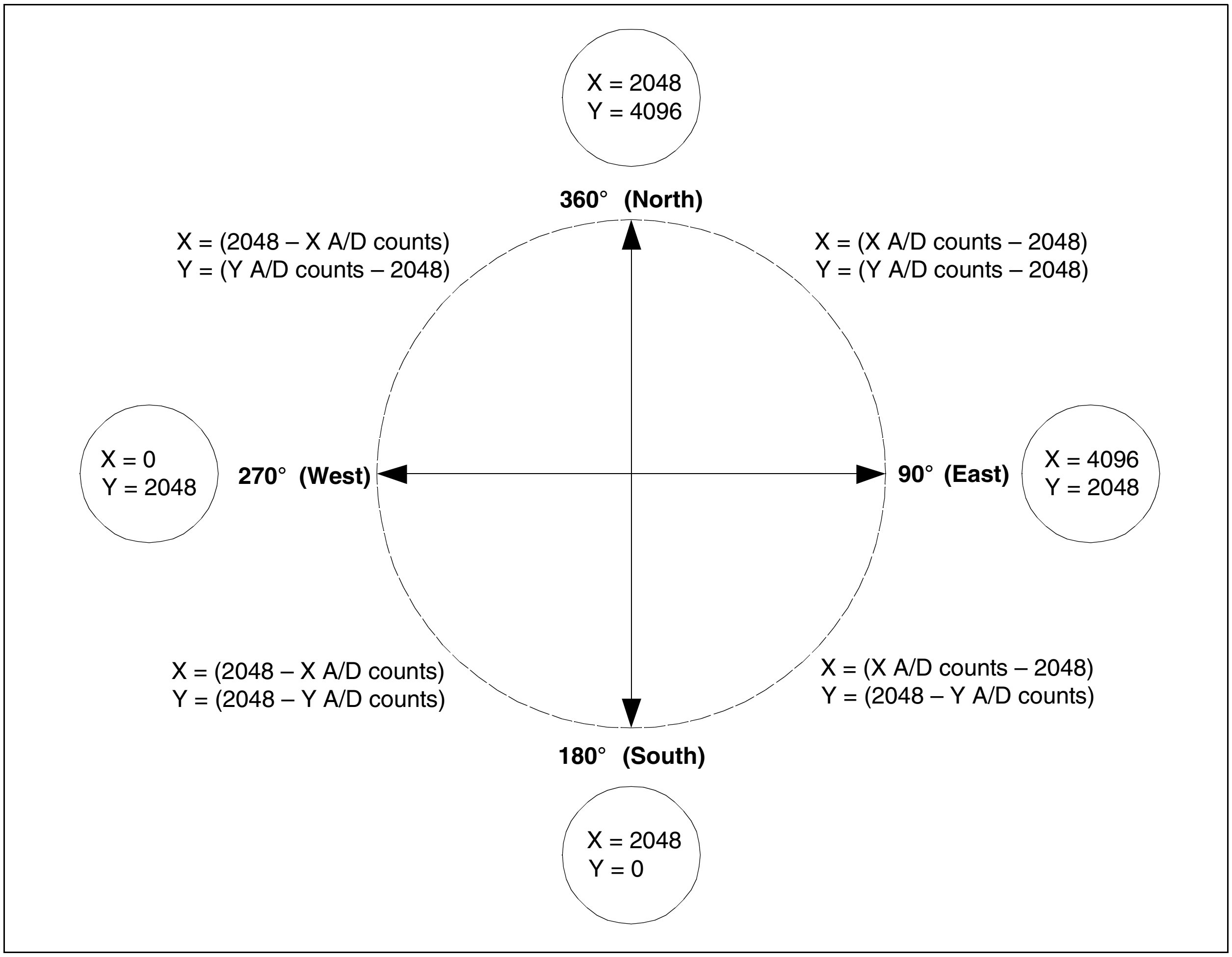
   North X = 2048, Y = 4096;
   East X = 4096, Y = 2048;
   South X = 2048, Y = 0;
   West X = 0, Y = 2048

   In reality, magnetic compasses must deal with soft/hard iron deposits, variations in magnetic field and so on.

The following considerations should be taken into account when calibrating:

- Are high-power devices/lines nearby?
- Does the calibration area have metal rebar encased in the floor, or metal studs in the wall?
- Is the compass housing in horizontal plane in relation to the Earth's surface?
- Has a known reference been established (i.e., north)?

FIGURE 9: QUADRANT DIAGRAM



CONCLUSION

Implementing a digital compass can range from the simple to the complex. This is determined by how sophisticated an application is required. A low-cost digital compass application requires mid-level design experience.

Application requirements are the driving factors behind the level at which it is developed. Some of these factors include accuracy, speed, features and size.

For this application, accuracy will be within ±4 degrees, and speed is relatively fast for hand-held devices with minimal overhead. Size must be kept small for the application.

There are several key decisions to be made when defining your application requirements. Consider the type of sensors to be used and how they can be interfaced to the PICmicro® microcontroller. If you are striving for a 360 degree compass (one degree increments), then the PCB must be designed to eliminate and/or suppress noise. For an 8-point cardinal system (N, NW, W, SW, S, SE, E, NE), the PCB design is not as critical because higher noise levels can be tolerated. Calibration techniques must be considered, including whether it will be calibrated once by the manufacturer or contain calibration firmware. Calibration cannot be taken lightly as it directly affects the performance of the compass. Practical engineering in all of the aforementioned areas will result in a successful application.

REFERENCES

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  http://www.magneticsensors.com
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  - IRF7509 Set/Reset pulse device
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  http://www.maxim-ic.com
  - RS-232 transceiver
- MEMSIC, Inc.
  http://www.memsic.com
  - MXD2020EL pitch/roll measurement device
- Microchip Technology Inc.
  http://www.microchip.com
  - PIC18F4520 microcontroller
  - MCP6021/2/3/4 operation amplifiers
  - *"PIC18F2420/2520/4420/4520 Data Sheet"* (DS39631)
  - *"MCP6021/2/3/4 Data Sheet"* (DS21685)
- Microtips Technology Inc.
  http://www.microtipsusa.com
  - 2x8 LCD MTC-S0802XFYNSAY
- National Semiconductor
  http://www.national.com
  - LM1117 3.3V regulator

APPENDIX A: SOURCE CODE

All source code and application examples described in this application note are available as a WinZip download from the Microchip web site at:

www.microchip.com

APPENDIX B: SCHEMATICS

FIGURE B-1: SHEET 1 OF 3

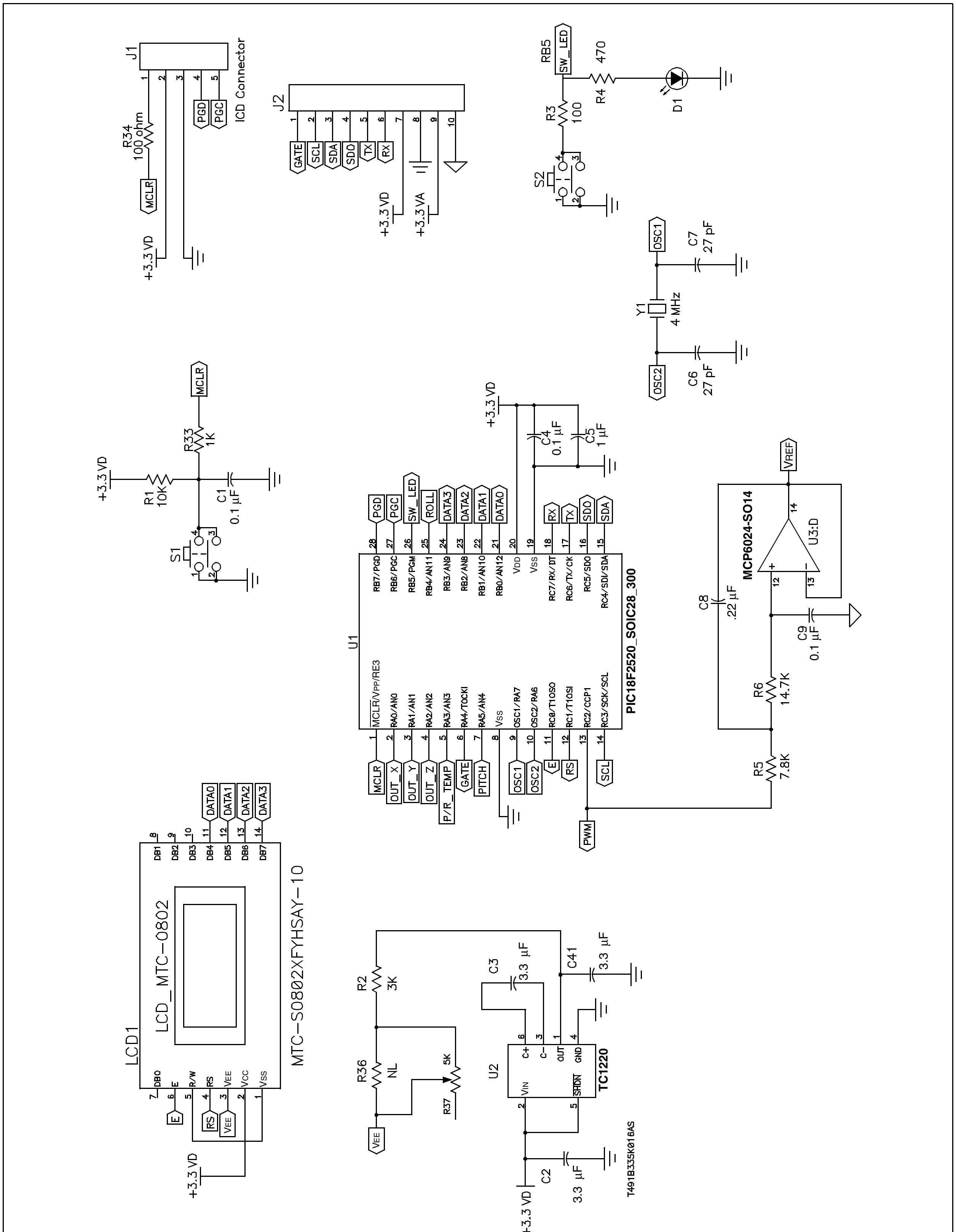


FIGURE B-2: SHEET 2 OF 3

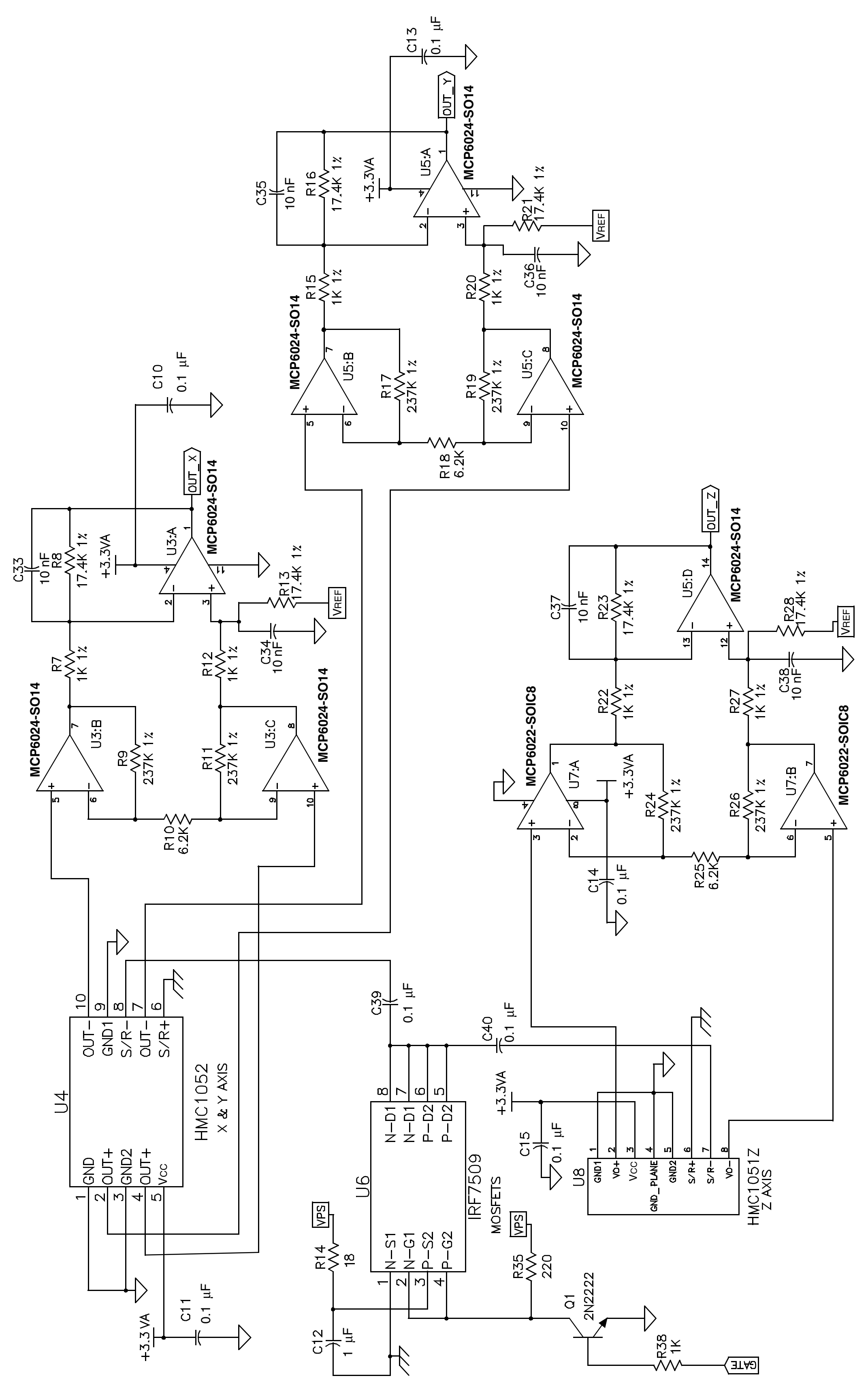
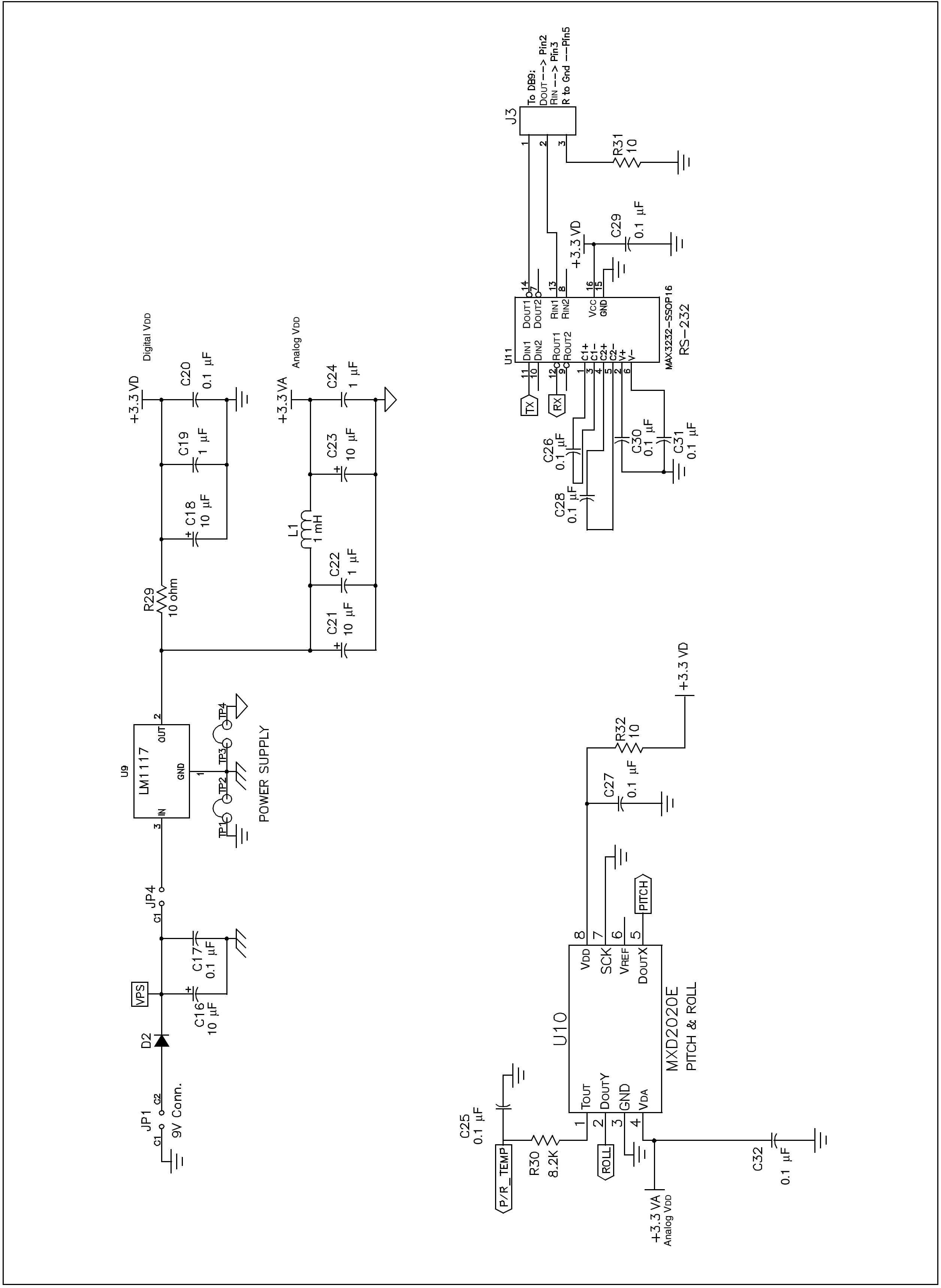


FIGURE B-3: SHEET 3 OF 3



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Microchip received ISO/TS-16949:2002 quality system certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona and Mountain View, California in October 2003. The Company's quality system processes and procedures are for its PICmicro® 8-bit MCUs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.

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07/01/05