Designing a Digital Compass for Inertial Navigation System (INS)

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Abstract – This paper presents the design of a digital compass for Inertial Navigation System (INS). The compass application can be implemented as a functional building block in navigation tracking device. The design is simple and low cost, made it suitable to be embedded on the control system of an aircraft or gliders, among others. Using magnetic sensor and accelerometer, the digital compass will give the heading and attitude of the aircraft which is the pitch and roll. It is programmed on the PIC18F2520 microcontroller using C language. The application is intended for the use in Malaysia.

Keywords – Inertial Navigation System (INS), digital compass, magnetic sensor, accelerometer.

1. INTRODUCTION

Commercial aircraft control system uses a very expensive equipment to determine the attitude and heading of the aircraft. It costs millions of dollars and this is costly for personal use; especially to the serious amateur rocket enthusiast and potential aerospace engineer to build an Inertial Navigation System (INS) for their aircraft.

The use of compass in aviation is quite different from the sea and land navigation. Aircraft move freely in space and it has six degree of freedom. Therefore, six variables have to be considered to determine the position and attitude of an aircraft. The position is given by x, y and z and the attitude will be specified by θ, ψ and φ which stands for pitch, yaw and roll respectively. Here comes the inertial part of INS, which is to obtain these variables. The variables are than manipulated using a microcontroller and desired output of the compass will be produced.

2. THEORETICAL BACKGROUND

Compass is initially used in *feng shui* by the Chinese. The first use of compass as a direction pointer was in the 4^{th} century. A needle is magnetized by rubbing its tip with lodestone, hung freely and it will always point to the north. Since then, compass is used in sea navigation, just like using the sun and stars to determine direction. The use of compass in sea navigation is then spread out to the Arab countries and then Europe later in the 12^{th} century.

Nowadays, compass is always associated with a magnetic needle, free to rotate in a plastic housing. The needle aligns itself with the Earth's magnetic north to establish the reference north direction. The use of compass has also diversified from sea to land and space navigation.

In aviation, compass is used to determine the attitude parameters of an aircraft. The parameters are heading, pitch and roll angles. These angles are always referenced to the horizontal plane which is perpendicular to the Earth's gravitational vector. Heading is defined as the angle in the horizontal plane measuring clockwise from the true north direction. Pitch is the angle between an aircraft's longitude axis that is from tail to nose and the horizontal plane. For example, if the nose of the aircraft is pointed up, the pitch angle is positive. On the other hand, roll is 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. [5]

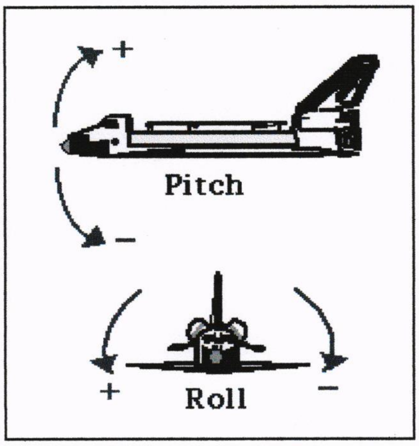


Figure 1: Pitch and roll

Determination of heading must consider the declination angle. Declination angle refers to the angle between the compass needle point and the true north point. There are two types of poles on the earth, namely geographic and magnetic poles. The geographic poles (true north) are the northern and southernmost point of the globe and the magnetic pole (magnetic north) refers to the origin of the earth's magnetic field. Needle of the compass will always point to the magnetic north since there have the strongest magnetic pull. The declination angle can be obtained from the isogonic map. The isogonic lines on the map represent the declination angle of places. The final heading must be plus or minus the declination angle. This can be configured in the PIC programming, discussed later in Section 3.2. Referring to the isogonic map in Figure 2, Malaysia has 0^{o} declination which means there is no angle difference between magnetic north and true north.

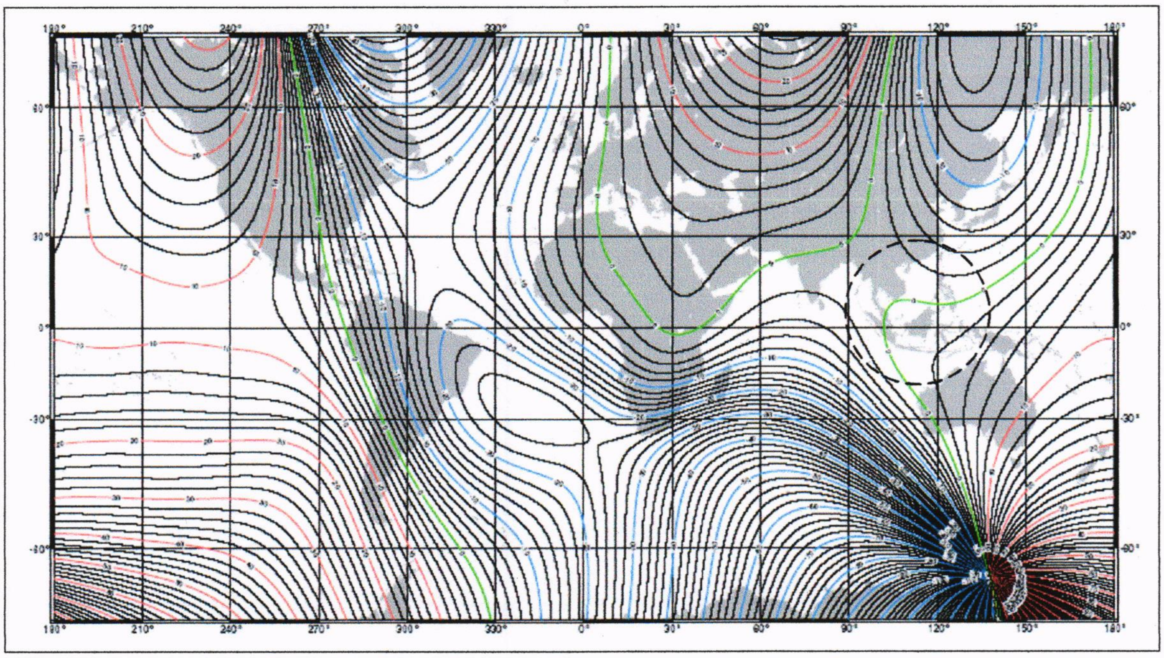


Figure 2: Isogonic Map – Malaysia in dotted circle

3. SCOPE OF WORK

3.1 Hardware Implementation

Older version of aircraft was equipped with compass (with magnetic needle), barometric altimeter and a relative air speed sensor. However, the modern type is equipped with a lot of sensors for the use in flight control system. These sensors together with the digitalization contribute to the need of precision and accuracy in the aviation industry.

Before going into detail, let's look at the operating condition of the digital compass described in this project:

- Operating Voltage (V_{DD}): 3.3V
- Operating Frequency (F_O): 4 MHz
- Power Supply: 9V battery

- Development Tools: MPLAB® IDE 7.30, MPLAB C18 C Compiler, MPLAB ICD 2

The digital compass is tilt-compensated so that it can give the direction to the aircraft even when it is not horizontal to the Earth's surface. This means that the pitch and roll, or also known as the tilt angles, are accounted in the overall heading measurement. An accelerometer is used to measure these angles. There are many types of accelerometer such as piezo-film, MEMS, thermal, null balance and many more. In this design we use MXD2020EL dual axis thermal accelerometer from MEMSIC. It is low noise, low cost and has a range of $\pm$ 1g. The accelerometer uses the force of gravity as an input and gives digital signals output with the duty cycles proportional to the acceleration. This makes MXD2020EL simpler since there is no need for additional A/D converter circuit as interface to the PIC. Pitch directly gives input to the RB1 of the PIC I/O pin and roll to the RB4. The temperature output, T_{OUT}, is a PWM signal. A simple RC filter is used to convert it to analog signal before connected to the PIC's AN3 pin. The operation of MXD2020EL is based on heat transfer by natural convection. As the acceleration changes, it will change the temperature profile. This will cause the duty cycle to change. In order to determine the angle, PIC will count the high pulses and put into equation with the digital value of the temperature to determine how much the pitch and roll value should be compensated.

Next is the magnetic sensor which is used to determine the X, Y and Z axes. The HMC1053 3-axis magnetic sensor was chosen for this application. It is a Wheatstone bridge device to measure magnetic fields. When the power is supplied to the bridge, the sensor converts any incident magnetic field in the sensitive axis direction to a differential output voltage. Using LMV324M operational amplifier, the output voltages are referenced to the V_{REF}. The resultant of X, Y and Z are sent to the AN0, AN1 and AN2 pins respectively. The magnetic sensor is made of Permalloy thin film placed on a silicon wafer. When it is exposed to the magnetic field, it will change the bridge resistive elements that cause a corresponding change in voltage across the bridge output. The Set/Reset condition has to occur in order to realign the particles on the film. HMC1053 has a built in Set/Reset strap. The IRF7509 MOSFET gives a high current pulse to the strap to recover the films that has been disoriented by external sources such as temperature and high voltage cable.

Other components are not directly involved in the compassing application. However, they are essential to make the device functions. The LM117 power regulator is used to supply 3.3V to the analog and digital circuits. Communication with the PC's HyperTerminal is handled by DS232A transceiver from Dallas Semiconductor. The receiver receives the output from the TX pin of the PIC and transmits signal to the RX pin of the PIC.

3.2 Software Development

The software for the compass is written in C language and compiled using Microchip's MPLAB C18 Compiler. The program consists of the main program, headers and linker. Some of the routines are obtained from the MCC18 library.

To determine the pitch and roll angles, the output from the accelerometer is considered. Timer is used to count the high pulses of the duty cycle captured by the I/O pin. There are three possible conditions:

a. Timer count > 5000 (Positive angle)

$$Pitch/Roll\ angle = \frac{Timer - 5000}{33} \quad (1)$$

b. Timer count < 5000 (Negative angle)

$$Pitch/Roll\ angle = \frac{Timer - 2690}{33} \quad (2)$$

c. Timer count = 5000

$$Pitch/Roll\ angle = 0 \quad (3)$$

The resultant angle is in one degree increments divided by 33 of timer count, based on 1µs instruction cycle.

For overall heading calculation, we need to determine the Sin and Cos value of these tilt angles. The Sin and Cos tables are created and stored in the program memory. The tables will give the value for 0° to $\pm 70^{\circ}$. If the reading is more than $\pm 70^{\circ}$, warning message will be displayed. It means that the compass has a tilt angle limitation of $\pm 70^o$.

Next, the program is to get the X, Y and Z component from the magnetic sensor for heading calculation. The outputs from the HMC 1053 are analog voltages. Calibration has to be made so that each axis will have their duty cycle value respectively. This is configured by setting the PWM value. The value will set *Vref*, compare with the HMC 1053 output and produce duty cycle. A function for oversampling is implemented to get a 12-bit result from hardware. This is done by taking and averaging number of samples from the A/D which will give a higher accuracy conversion value. The resultant digital value is put in the equation for $X_{heading}$ and $Y_{heading}$ as shown in "Equation (4) & (5)". Thus the final heading can be determined as in "Equation (6)".

$$X_{heading} = (X \times Cos\ \theta) + (Y \times Sin\ \varphi \times Sin\ \theta) - (Z \times Cos\varphi \times Sin\theta) \quad (4)$$

$$Y_{heading} = (Y \times Cos\ \varphi) + (Z \times Sin\ \varphi) \quad (5)$$

$$Heading = Tan^{-1}(Y_{heading} / X_{heading}) \quad (6)$$

Where θ and φ is the pitch and roll angle respectively.

The arcTan value of the $XY_{heading}$ result is found by accessing a tangent table stored in program memory. Due to limitation of $0^o - 90^o$ of arctangent, a routine is implemented to determine the quadrant in which the angle is located. Finally, the magnetic heading value is obtained.

Since the digital compass is for the use in Malaysia (declination = 0 degree), the heading value obtained is without considering the declination angle. If declination exists, the heading can be determined using the "Equation (7)".

$$Final\ heading = Heading + Declination \quad (7)$$

This measurement is displayed on the PC which is constantly updated by the main loop of the software.

Another function is the Set/Reset. The program will set the RA4 pin to execute an instruction cycle and then clearing it. Besides the program relates to compassing, there are other routines to be included such as hexadecimal to ASCII and A/D conversion.

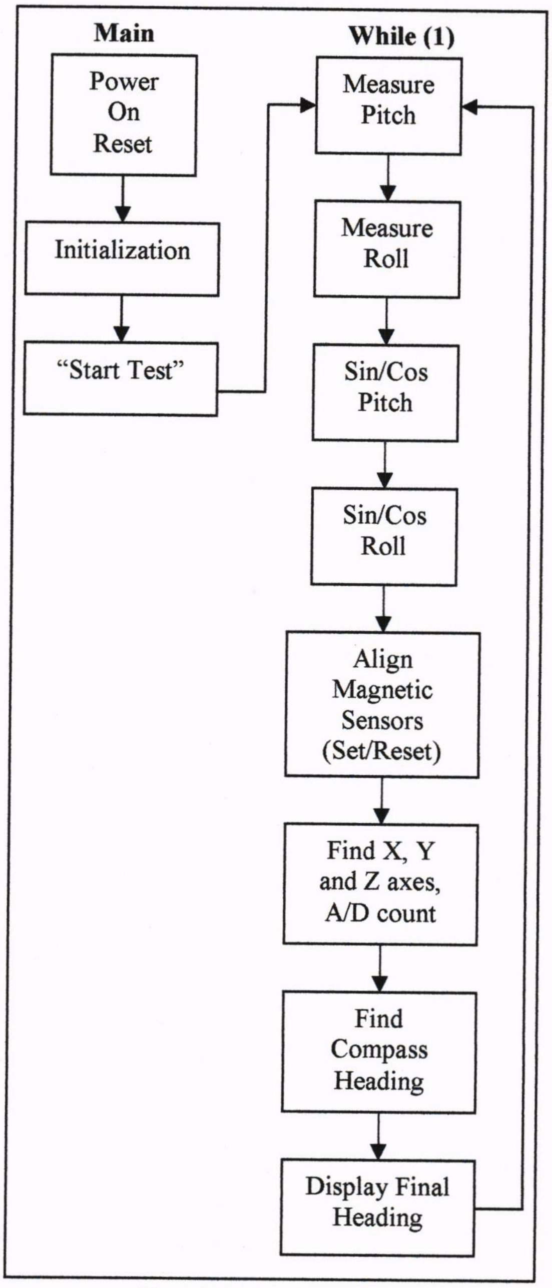


Figure 3: Program flow diagram

3.3 PCB Design

In designing the PCB, there are some factors to be considered namely the position of the component, track size and the power supply. This is because the design consists of analog and digital part. Careful measures are taken to keep the accuracy of the compass and to avoid interference between components.

The PCB is divided into three parts – the compass board, the transceiver and the power supply unit. Most of the components are surface mount and both sides are used to place the components. The size of the boards is kept as small as possible for it to be light in weight. They should not be a burden for the aircraft.

Compass board is made of important components related to compassing application. The analog section of the compass is positioned on the right side and separated with a ground plane. On the other hand, the PIC is placed on the left side. The switch is at the lower left make it reachable by the user. MOSFET is located near to the magnetic sensor to keep the high-current pulse line short. The position of magnetic sensor is important since it is very sensitive to magnetic field. The magnetic sensor is placed in the middle of the PCB and far from other main components. The sensor also did not need ground plane to maintain its accuracy. For the accelerometer, ground plane is applied under the footprint. Finally, the position of these magnetic sensor and accelerometer is very crucial. If else, there is possibility to get the angles out of phase.

Next is the track size. The line between the MOSFET and the magnetic sensor is made intense as it carries high current pulses. The lines for X, Y and Z to the PIC are routed away from power traces to avoid noise. The signals are analog and therefore sensitive to noise. Another way to avoid noise is to isolate the digital noise from the analog circuit. This is done by dividing the 9V power supply into two parts which is analog and digital voltages.

Transceiver board consists of RS232 communication system. The connection to the PC is via serial port. Finally, the power supply unit. The supply is from 9V battery, which is then divided into 3.3V for each digital and analog circuit.

4. RESULT

Software simulation is done using the Microchip MPLAB SIM. During the simulation, the program being executed by the simulator which may require stimuli from outside sources. It could be a level change or a pulse to an I/O pin of a port. There are two types of stimulus – synchronous and asynchronous. Synchronous stimuli with a regular and repeating series of high and low voltages with adjustable duty cycle set by the number of clock. On the other hand, asynchronous stimulus let the I/O pin to be fired by the user. In this case, we use the synchronous stimulus.

Simulator Control Language (SCL) is used to execute synchronous stimulus. The registers RB1 and RB4 are injected with pulses to imitate the signal from the accelerometer. The number of pulses are counted, gone through some arithmetic calculation and return the pitch and roll angle. The output format is as in Figure 5.

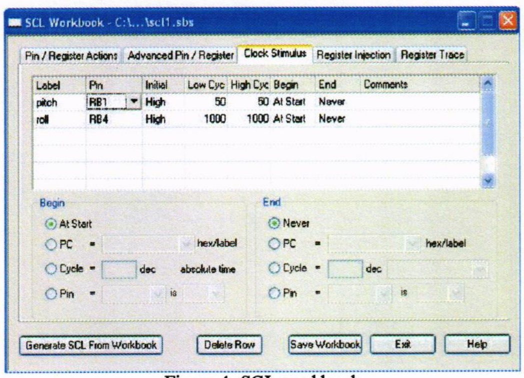


Figure 4: SCL workbook

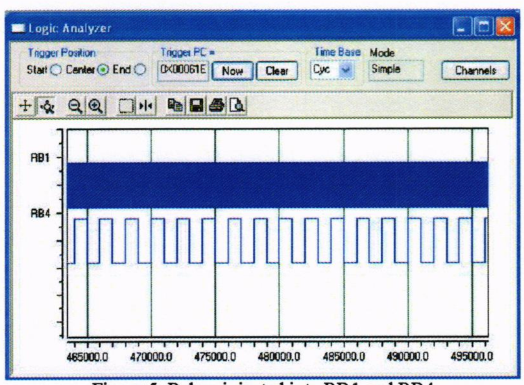


Figure 5: Pulses injected into RB1 and RB4

After the PIC is programmed, the digital compass is ready to be used. It is connected using RS232 and the output can be monitored from the PC HyperTerminal. The format is somewhat similar as from the UART output file.

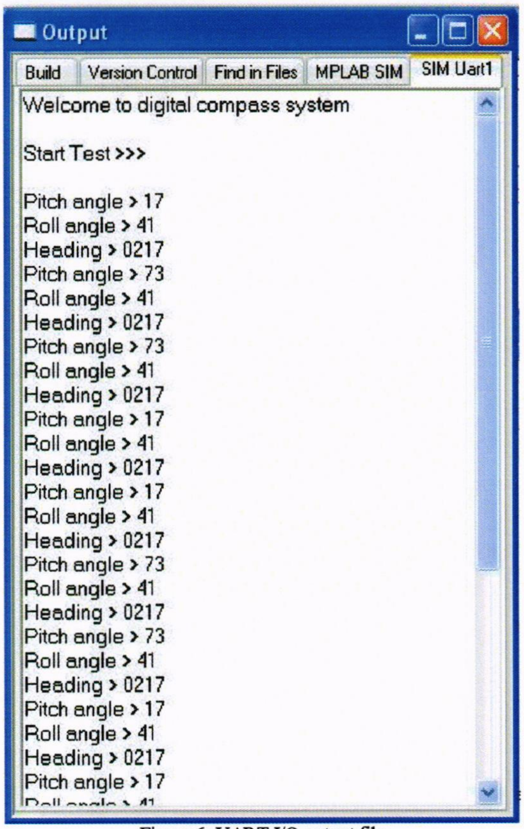


Figure 6: UART I/O output file

5. DISCUSSION

From the simulation, we know that the software developed is working and capable to give the heading, pitch and roll of an aircraft.

However, the simulation result can be more reliable if the simulation is done using the compass hardware. This is because the number of pulses injected may be illogical and not in real time.

Caution should to be taken during handling the compass. Object containing iron such as watch and buckle must be avoided or it can affect the accuracy of the measurements.

6. FUTURE DEVELOPMENT

As described earlier, the digital compass can be a standalone device or to be integrated into a system. Together with an altimeter and GPS, they can perform a complete Inertial Navigation System. It can be implemented on an aircraft so that a control system can be established.

Instead of a series of figures output, a graphical user interface will give a convenient visualization of the heading, pitch and roll. Figure 6 shows an example of the graphic as used on aircraft. It can be developed using Visual Basic.

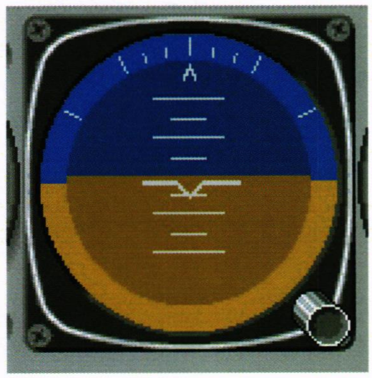


Figure 7: Graphical interface for the compass

Additional features of the compass can also be introduced through software. For example, to make the compass able to be used everywhere in the world by considering the declination angle. A list of places together with their respective declination can be stored in the program memory. A subroutine is needed to prompt the user to select the location and it will return the declination of that particular place.

7. CONCLUSION

Digital compass is very useful in determining the attitude and heading of an aircraft. This design is viable and cost very much less than the commercial one. The usage of PIC makes it practical as the software can be customized according to the need. Calibration can also be done through software.

The principle in designing of digital compass relies on the factor of accuracy, speed, feature and size. This designed compass has accuracy between ±4 degrees and the speed is quite fast

APPENDIX : SCHEMATIC

Figure 1: Compass

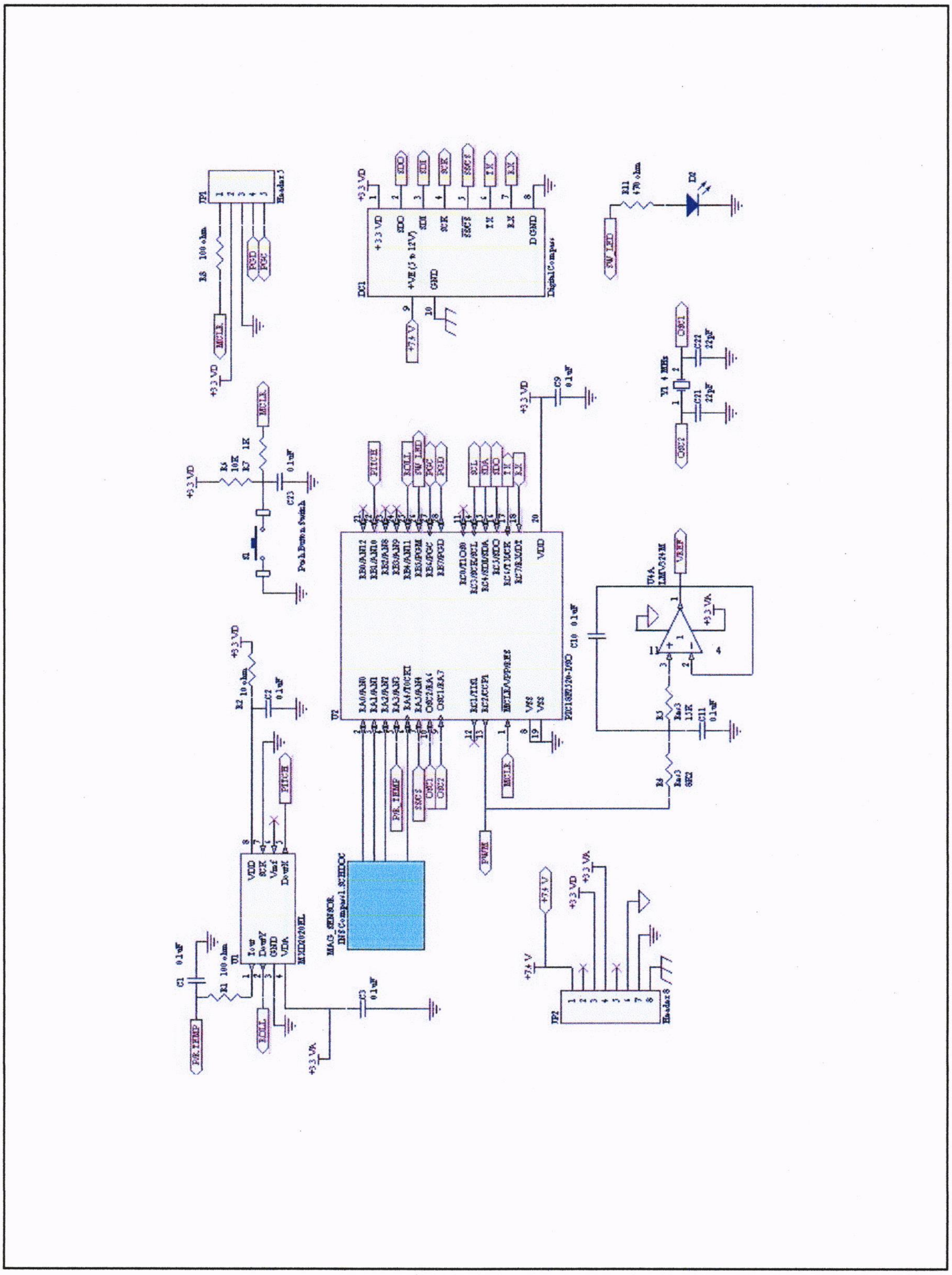


Figure 2: Magnetic sensor

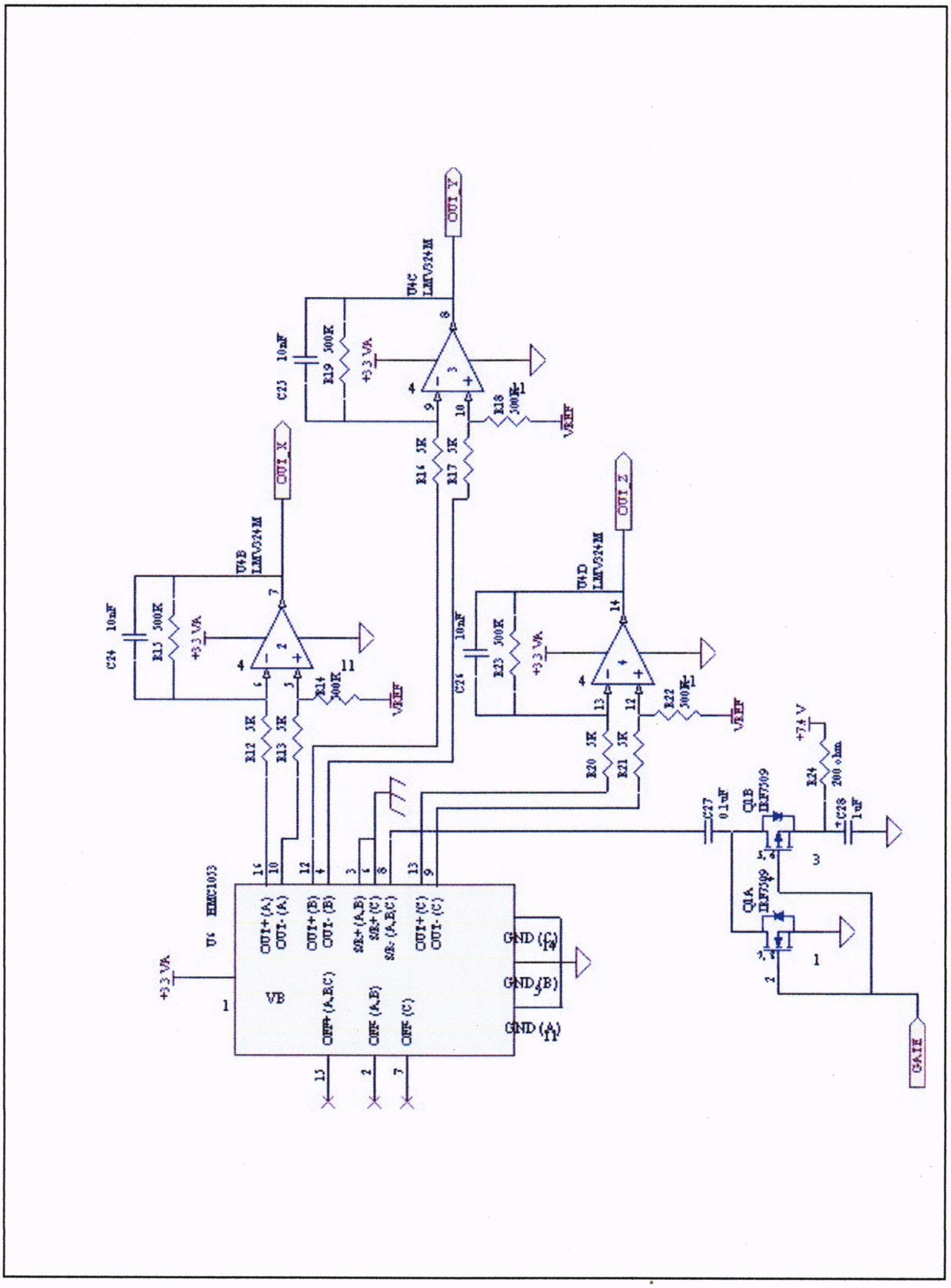


Figure 3: Power supply unit

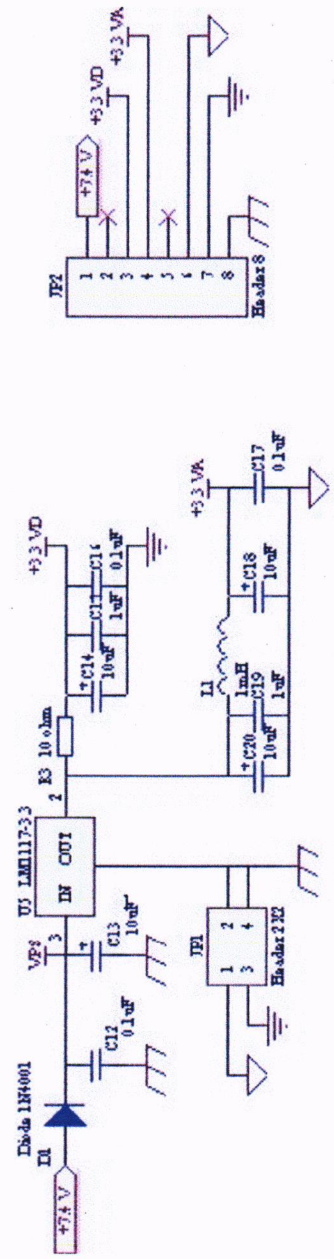
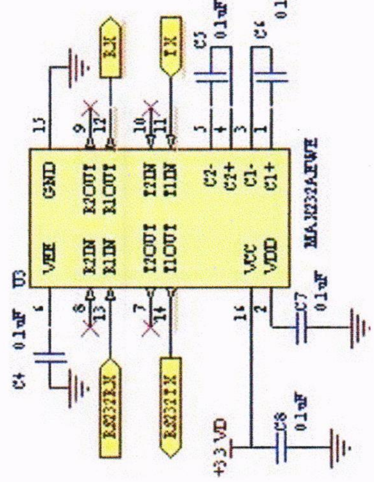


Figure 4: RS232 transceiver



for hand-held device. The size is kept small for the application in INS. Proper designing process and correct device handling during taking measurement will give a pleasing result.

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