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" This Thesis Submitted to Fulfill the Requirements for the Degree of Master of Science (M.Sc.) in Aeronautical Engineering (Avionics) "

Design of Digital Barometric Altimeter

تصميم عداد الارتفاع البارومتري الرقمي

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الآيـــــة

قال تعـــــــالي:

﴿وَكَذَلِكَ أَنْزَلْنَاهُ قُرْآنًا عَرَبِيًّا وَصَرَّفْنَا فِيهِ مِنَ الْوَعِيدِ لَعَلَّهُمْ يَتَّقُونَ أَوْ يُحْدِثُ لَهُمْ ذِكْرًا (113) فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ وَلَا تَعْجَلْ بِالْقُرْآنِ مِنْ قَبْلِ أَنْ يُقْضَى إِلَيْكَ وَحْيُهُ وَقُلْ رَبِّ زِدْنِي عِلْمًا (114)﴾

" صدق الله العظيم"

سورة طه – الآيتان ﴿ 113 – 114﴾

DEDICATION

To *whose I owe to them every features of success that I ever had in my life.* ***To*** *whose strive continuously for my smile and my satisfaction, encouraged me all the way, support me under all condition and have been the source of my strength throughout this program.*

To my family

To *Who I was missed in the facing of difficulties since I was young.* ***To*** *who gave his life for me and taught me the meaning of patience and sincerity in the work for success. It may be a long road that I will cross to meet you again but it is the will of Allah.*

To my Father

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Firstly, *foremost all the thanks and the praise be to ALLAH the most gracious the most merciful, who created this complex world in details and diversity. all the praise be to ALLAH who gave me the health, the strength and the power to wind up this work.*

Also, I am heartily thankful to my supervisor Dr. Moutaman Mirghani and my colleagues in ISRA whose encourage me, provided me valuable suggestions, recommend actions, technical information, alight of guidance and other unconditional support without any expectation of personal gain during the completion of this work, I had a great honor to belong to them.

Lastly *my thankful to engineering staff of aeronautical engineering department in Sudan University of science and technology whose encouraged me and provided me all possible facilities to complete this program.*

ABSTRACT

Altimeter is altitude measurement system that is used to determine the altitude of a flying vehicle and provide the aircraft pilots, navigators and other aerospace users the altitude information either in analog or digital readout. This information is a very important parameter for all aerospace users during flight in order to achieve safe and efficient flight operation. using an accurate and precise system for altitude measurement is essential, Therefore, design of a new digital altimeter is significant and much needed for this reason. The main objective of the thesis is to design and implement of low cost digital barometric altimeter. The design stages of this model have been carried out by enhancing conventional barometric altimeter system through diagnosing of measurement errors, expresses of these errors in mathematical derivations, compensate these deviations using a suitable algorithm, reduce mechanical parts and then simulate the conceptual model using proteus program. The simulated model has been implemented as prototype and then tested to show the sea level altitude in digital read out, good results have been achieved and compared to standard atmosphere model tables for more demonstration. In addition to that, new concept for altitude alert system has been carefully considered to alert the pilot when reaching a maximum cruising altitude.

مستخلص

العداد البارومتري هو نظام لقياس الارتفاعات وتستخدم لتحديد ارتفاع الطيران وتزويد الطيارين والملاحين وغيرهم من مستخدمي الفضاء الجوي بمعلومات الارتفاع أثناء الرحلة مستخدماً القراءة التناظرية أو الرقمية. وتعد هذه المعلومة مهمة جداً لجميع مستخدمي الفضاء أثناء الطيران من أجل تحقيق عملية طيران آمنة وفعالة حيث من الضروري استخدام نظام دقيق لقياس الارتفاع ، وعليه لا بد من تصميم مقياس ارتفاع رقمي دقيق ضروري ومطلوب بشدة لهذا السبب. الهدف الاساسي لهذا المقترح البحثي هو تصميم واختبار نموذج لعداد الارتفاع البارومتري الرقمي بأقل التكاليف. تم تنفيذ مراحل تصميم واختبار هذا النموذج بتحسين نظام مقياس الارتفاع التقليدي من خلال تشخيص أخطاء القياس التي يتعرض لها النظام ، وضع هذه الأخطاء في صورة اشتقاقات رياضية ، تعويض هذه الأخطاء باستخدام خوارزميات تصحيح وبتقليل الأجزاء الميكانيكية للنظام القديم ، من ثم تجري محاكاة التصميم التخيلي باستخدام برنامج بروتوس. تم تنفيذ التصميم التخيلي كنموذج اولي تم اختباره لإظهار ارتفاع مستوي سطح البحر في قراءة رقمية وتم الحصول علي نتائج جيدة مقارنة بقيم جدول نموذج الغلاف الجوي القياسي. بالإضافة إلى ذلك ، تمت إضافة مفهوم نظام الإنذار لتنبيه الطيارين بالارتفاع أثناء الطيران.

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LIST OF ABBREVIATIONS

VSI	Vertical Speed Indicator
TBI	Turn - Bank Indicator
MSL	Mean Sea Level
ATC	Air Traffic Control
FAA	Federal Aviation Authority
AGL	Above Ground Level
ISA	International Standard Atmosphere
LCD	Liquid Crystal Display
LED	Light Emitting Diode
RCT	Red Cathode Tube
WWⅡ	Second World War
BAS	Bonfire Airway System
NASA	National Aeronautics and Space Administration
ICAO	International Civil Aviation Organization
IATA	International Air Transport Association
GPS	Global Positioning System
IFR	Instrument Flight Rule
NACA	National Advisory Committee for Aeronautics
Amp	Amplifier
LPF	Low Pass Filter
µc	Microcontroller
IDE	Integrated Development Environment
PCB	Printed Circuit Board
DC	Direct Current
EMC	Electro- Magnetic Compatibility
EEPROM	Electrical Erasable Programmable Read Only Memory

RAM	Random Access Memory
PWM	Pulse Width Modulation
PC	Personal Computer
HAB	High Altitude Balloon

LIST OF SYMBOLS

G	Gravity acceleration
H	Actual altitude
$H_\circ$	ISA Altitude
ΔH	Total Altitude drift
ΔH_{P_H}	Altitude drift due to nonstandard pressure
ΔH_{P_o}	Altitude drift due to nonstandard sea level pressure
ΔH_{T_o}	Altitude drift due to nonstandard sea level temperature
ΔH_α	Altitude drift due to nonstandard temperature lap rate
P_0	Standard sea level pressure
P_H	Atmospheric pressure
P_{11Km}	Atmospheric pressure at 11 kilometers of altitude
ΔP_H	Pressure deviation from standard value
ΔP_o	Sea level pressure drift from standard value
R	Universal gas constant
T_0	Standard sea level temperature
ΔT_0	Sea level temperature deviation from standard value
α	Vertical temperature gradient
$\Delta\alpha$	Temperature lap rate drift
ρ_o	Atmospheric density

CHAPTER ONE: INTRODUCTION

1.1 Flight Instruments

The flight instruments are those instruments used to provide the aircraft pilot an information about the flight situation (flight parameters) such as altitude, speed, attitude and direction, to enable an airplane pilots and other aerospace users to operate within safe and efficient boundaries through providing the essential flight parameters in digital or analog read out, alert the pilot any improper flight condition may influence to aerodynamic and structural limitations of the aircraft and help aircraft pilots to avoid any expected midair collision between flying objects or between airplanes and other obstacles. Throughout the history of avionics science, a wide variety of flight instruments have been developed to inform flight crews with different flight parameters, today these instruments have become similar in most aircrafts and offered in two basic configurations (called T and 6 configuration) to provide all information's necessary for flight in an accurate, easily understood manner as shown on Appendix-A. These basic flight instruments are including Altimeter, Airspeed Indicator, Attitude Indicator, Vertical Speed Indicator, Turn - Bank Indicator and Heading Indicator [1].

The basic flight instruments are essential and mandatory for operating under instrument flight rule to provide a primary flight reference to the pilot to control the aircraft in all flight situations, particularly under poor visibility condition such as fly through clouds, snowstorm, thunderstorm, or other bad weather condition, whereas some parameter cannot estimate from visual reference outside the aircraft. The barometric altimeter is one of the most important of these basic instruments, used to provide the height of flying object above mean sea level [2].

1.2 Altitude Information

Altitude of the flying object is a vertical distance above some datum point used as reference [1]. Knowing of altitude of the flying vehicle in aerospace is very important parameter to the pilots during flight to achieve safe and efficient flight operation by keeping the vehicle above the obstacle’s peak, maintain a desired flying course to achieve maximum flight performance and flying at a prescribed altitude assigned by air traffic control (ATC) to maintain prescribed vertical separation minima along the airways to reduce the possibility of midair collision when the visibility is restricted. Therefore, the accurate altitude measurement system is mandatory from federal aviation regulation authority for either day or night operation [1], [2].

1.3 Altitude Reference Points

In the aviation field, there are two types of altitude called absolute altitude and relative altitude (altitude above ground level), both types of altitude have been defined based on the reference point that could use to measure it, these different kinds of attitudes are significantly useful for aerospace user and each one may use for specific reasons. The two common reference points that used to measure the altitude of the flying vehicles in aerospace are explained bellow.

1.3.1 Mean Sea Level (MSL)

The MSL is the altitude reference point where gravity acting on the atmosphere produces a pressure of 14.70 pound /in^2, this pressure supports a column of mercury in a barometer to a height of 29.92 inches. This reference point is very useful and applicable in the aviation field because of 80% of the earth's surface is water [3]. Due to variation of the gravitational pull at sea level and the earth itself is not perfectly round; the average value has been adjusted for this reference point to mean sea level [4]. therefore, the measured altitude from this point called absolute altitude.

1.3.2 Above Ground Level (AGL)

The AGL is an altitude reference point that represents the actual number of feet of the land mass above MSL. The altitude measured from this point called relative altitude, this elevation can be measured by precise instruments that are more accurate than the standard aircraft barometric altimeter such as a radar altimeter [4]. Due to a variety of terrain, the relative altitude is unreliable information to the pilots during the flight; however, it is useful when flying near the ground.

1.4 Digital Barometric Altimeter

The barometric altimeter in general is based on barometric method for altitude measurement which is the most common method used in the aviation field for altitude measurement. The principle of this method is based on the international standard atmosphere (ISA) model to determine the flying altitude by sensing the variation of atmospheric pressure with the height. This conversion of atmospheric pressure to equivalent altitude can be done using a sensitive pressure sensor (aneroid capsule) which deform proportionally to changes in the atmospheric pressure and consequently to the height of flying object, then the expansion and contraction of the capsules could be converted to display the equivalent flying altitude [5]. The digital barometric altimeter uses high sensitive pressure sensing element to achieve accurate degree of movement for given small change in atmospheric pressure, then transduces the response of the sensor into an electrical signal by using suitable pressure transducer, and then processing the electrical signal to calculate the corresponding flying altitude and provide the pilot an altitude information in digital read out using suitable digital display system such as LCD, LED, RCT.

1.5 Problem Statement

The barometric method for altitude measurement depends mainly on the (ISA) model of atmosphere, which is not so accurate under all conditions due to the deviation of the actual values of atmospheric parameters from this standard. Currently used altimeter systems are subject to other sources of errors (systematic and dynamic) during operation and causes drift on system read out. Due to complexity and integration of new technologies of aircraft avionics system, the altitude information should be in a digital form in order to suit these new integrated technologies.

1.6 Research Objectives

The aim of this thesis is design and implement of a precise digital barometric altimeter using low cost material.

1.7 Proposed Solutions

The proposed solutions are compensation of conventional altimeter errors by designing a new digital barometric altimeter to provide aircraft pilots, integrated aircraft sub-system and other aerospace user the actual altitude information in a digital read out.

1.8 Research Methodology

The research activities were carried out to achieve the main objective of the thesis within specified time schedule, starting from theoretical background about a barometric method for altitude measurement, analyze of conventional altimeter errors and introduce conceptual design of modern digital barometric altimeter, Then Simulate the design using computer program (proteus) and implement it as hard model(prototype). Finally, the designed system has been tested to verify the achieved results for more demonstration.

1.9 Thesis Layout

This thesis consists of six Chapters outlined as follows. The first Chapter consists of an introduction and general background about altitude measurement systems including overview of a digital barometric altimeter. Chapter Two contains literature review and related work covered on basic flight instruments. Chapter Three comprises diagnosis and analyze the error sources of barometric altimeter and developing sophisticated computer algorithms for errors compensation.

Chapter Four shows the design of a digital barometric altimeter in more details including conceptual design and simulation results achieved. And then hardware implementation including component selection, calibration, testing and prototype integration has been explained in Chapter Five. Chapter Six has been customized for conclusions regarding to the hardware implementation of final design and testing results, in addition to a few recommendations for future work.

CHAPTER TWO : LITERATU RE REVIEW

2.1 Aircraft Instrument Systems

The Second World War (WWII) was resulted in major growth in electronic equipment installed in aircraft and birth of avionics (aviation electronics) technology. Although the evolution of avionics technology has been a challenge throughout the aviation history, this transition leaded up to accurate measurement of flight parameters, share actual information's between aircraft sub-systems in real time and achieve safe and efficient operation of the aircraft.

Due to continues improvement of aircraft systems and increase of an information needed by the pilot to flying the aircraft and monitor the performance of its systems, a first coordinated group of aircraft instruments was seriously introduced in 1937 to provide the flight crew an information about the aircraft and its systems. Theses instrument has been classified based on their function in to flight instrument, navigation instrument and engine instrument [6].

2.2 Flight Navigation

In very early of the flying science there were no sophisticated flight instruments in the airplane to assist the pilot in navigation. One of the earliest attempts to aid pilots was "*Bonfire Airway System*" which would predetermine along a certain route to allow the pilot to fly from fire to fire across the country. With the advent of an airmail system and passenger travel, the need for a better navigation and guidance system became urgent and "light beacon system" was developed in 1927 to allow the Pilots to visually fly from one beacon to another to cover 10,000miles [6]. In 1929 the guidance system begun with radio beams between two points, such that the airplane was equipped with a receiver dialing in radio frequency, the pilot could navigate between these points of radio beams, the success of this system was resulted in the establishment of a low frequency airway system across the country. in June 1929, Jimmy Doolittle became the first pilot to take off, fly and land an airplane using instruments alone without seen a view outside of the cockpit, in 1937 the British Royal Air Force chose a set of six essential flight instruments which were remain the standard panel used for flying for the next 20 years [6], [7].

With daily progress and development of aircraft systems, the basic flight instrument system has been introduced and developed, including altitude measurement system, which was used to provide the height of the flying object above specific reference point such as sea level or terrain beneath. The most common ways to measure this vertical distance is rooted in the discoveries made by scientist's centuries ago, such that in seventeenth century the aerospace scientists proved that, the air in the atmosphere exert pressure on the things around us therefore led Evangelista Torricelli to inventing of barometer. In addition to that a Blaise Pascal was able to show the relationship exists between altitude and air pressure in the same century and concluded to that if altitude increases, air pressure decreases, the amount of this decrease is measurable and consistent for any given altitude change, therefore by measuring air pressure, altitude can be determined [7].

The problem of devising flight instrument systems for an accurate measurement of flight parameters (including altitude) has been a subject for many great research investigations' during the past 50 years, the greater part of this research has been performed by a variety of organizations in Britain, Germany, and United States such as National Aeronautics and Space Administration (NASA).

The studies of altitude measuring problems (vertical separation of aircraft) have been discussed in few last years ago by the International Civil Aviation Organization (ICAO) and International Air Transport Association

(IATA), they concluded to the current configuration of flight instrument. Due to applying computer science in aviation field today, the aircraft become a practical means of transportation, so a precise and accurate instrument is much required to sense and acquire data on a variety of aircraft systems during flight to enable the pilot to fly on predetermined course, maintain a safe distance above the ground and navigate on the aerial way system for safe and efficient flight operation [7].

2.3 Flying Altitudes

There are various kinds of flying altitude defined based on which atmospheric parameter is used to determine it and the reference point used to measure the altitude. These different kinds of altitudes are significantly useful for aerospace user and each one may use for specific reasons. So, the aircraft Pilots and other aerospace users are usually concerned however with five types of altitudes as defined below.

a. Absolute altitude: - is the vertical distance of the flying object above the terrain level.

b. Pressure altitude: -is the altitude measured from calibrated altimeter referenced to the standard atmosphere level (29.92" of Hg), the pressure altitude is used for computer solutions in flight plan calculations to determine density altitude, true altitude, true airspeed …etc. [8].

c. Density altitude: Its pressure altitude corrected for nonstandard temperature variations of the standard atmospheric model. The density altitude is the most important altitudes for the aerospace user because of it is directly related to aircraft and its engine performance particularly in takeoff and climb situation [8].

d. True altitude: It’s the actual number of feet of flying object above MSL

e. Indicated altitude: its uncorrected reading of a barometric altimeter

2.4 Altitude Measuring Methods

There are different techniques used in aerospace field to determine the altitude of the flying object as explained below. The barometric and radio methods are two methods commonly used in the aviation field; therefor this research focuses on enhancement of the barometric approach for altitude measurement.

2.4.1 Acoustic method for altitude measurement

The principle of this method depends on the transmission of sound waves down to a reference surface and measure the time that will take to receive the echo of this signal and then calculate the altitude of the flying object. In 1931, the first sonic altimeter for aircraft has been tested by united states army air group, and point out that its more reliable and accurate than the altimeter system based on air pressure [5].

2.4.2 Acceleration method for altitude measurement

This method mainly depends on the measurement of vertical acceleration of the flying vehicle and then integrates it twice to obtain the height of the flying object.

2.4.3 Radio method for altitude measurement

The principle of this method is based on sending of radio signal to the ground or other reference surface and processes the timed information will take to receive the signal, then calculate the distance between the reflecting surface and the aircraft as shown on Figure 2.1. The radio altimeter is commonly used in most present aircrafts and essential for a safe landing to provide the pilot with actual altitude information of the aircraft above landing area (runway). Also, the radar altimeter is used as a component of terrain avoidance warning systems and allows the aircraft pilot to fly in very low altitude over the terrain head [5].

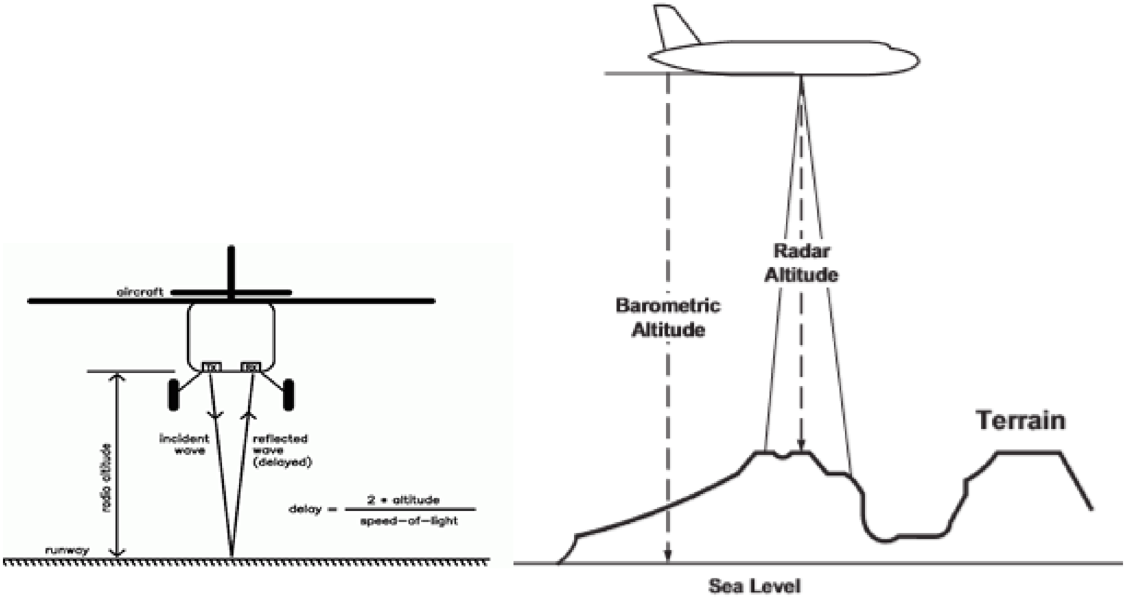


Figure 0.1: Principle of the radio method for altitude measurement [5]

2.4.4 Barometric method for altitude measurement:

This is the most common method used in aviation for aircraft altitude measurement. The principle of this method is based on the international standard atmosphere (ISA) model to determine the flying altitude by sensing the variation of atmospheric pressure with the height and translate this variation to flying altitude. This translation can be done using a sensitive pressure sensor which deform proportionally to changes in the atmospheric pressure and consequently to the height of flying objects. Therefore, the expansion and contraction of the capsules could be converted through a dedicated mechanism to display the equivalent flying altitude in digital or analog read out.

2.4.5 GPS method for altitude measurement

The global positioning system (GPS) can be used to estimate the vertical and horizontal location of any flying vehicles at any time. Whereas the space segments of the GPS systems (satellite) generate a unique pseudo random code containing the transmission time and satellite position, the

GPS receiver (user segment) measure the time differences between the transmission and reception of the coded message and then multiply it by the speed of light to determines the distances (pseudo-range) between the GPS receivers and its satellites, and consequently calculates the position of the user in term of latitude, longitude and height.

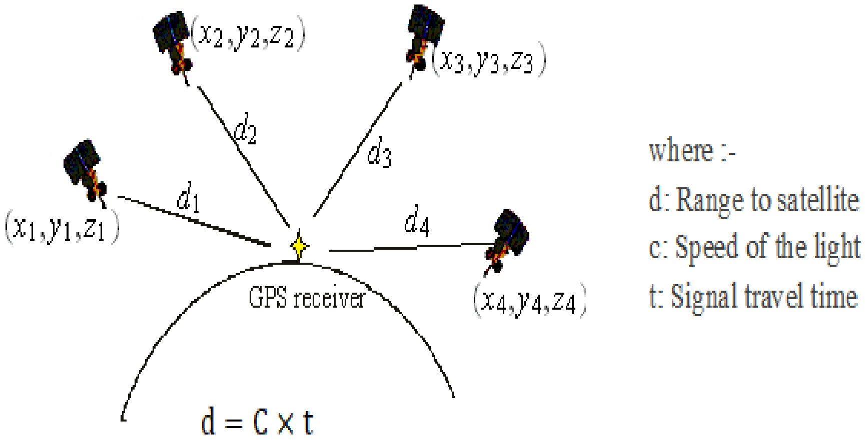


Figure 0.2: Using GPS satellite for altitude measurement [3]

Pseudo-ranges from four satellites or more are required to obtain the horizontal and vertical position of the user as shown on Figure 2.2 The GPS height is expressed relative to the WGS 84 reference (ellipsoid model of the Earth), and then converted into geo potential height, which adjusts the MSL height to compensate the gravity variation with latitude and elevation [6]. From methodological point of view, the determination of height with help of GPS is more complicated compared to the other methods. The altitude information estimated by GPS is not accurate enough to supersede the pressure altimeter without using some method of augmentation, such that in most conditions ten meters or less of vertical accuracy is obtainable using the GPS system [6]. This uncertainty of the GPS system is resulting from many factors effect on the GPS system itself such as, satellite errors (orbits, clock bias), signal propagation errors, receiver associated errors, and signal multipath and diffraction errors.

2.5 Introduction to barometric altimeters

The barometric altimeter is kind of altitude measurement system that based on barometric method for altitude measurement. There are different types of barometric altimeters were introduced, constructed and used to measure and provide the altitude of flying vehicles in digital or analog read out. The barometric altimeter systems in general consist of Pressure sensing element, Transmission (translation) mechanisms and altitude Indicating part. The most common barometric altimeters were used in aviation field for altitude determinations are explained in the next following sub-section.

2.5.1 Drum-type altimeter

Its old conventional altimeter system, that use a stack of bellow to drive the drum and pointer through complex transmission mechanism (gear) to indicate the altitude information to the pilot in analogue display [8]. The main inherent problems of this type the torque required to drive the drum and pointer mechanism, in addition to other problems will result from using of mechanical parts (friction, vibration…etc.).

2.5.2 Servo altimeter (sensitive altimeter)

It’s dual barometric scale altimeter type that use a stack of evacuated, corrugated bronze aneroid capsules to obtain very accurate pressure measurement and provides more power to drive the mechanical linkage [8]. This type of altimeter has adjustable barometric scale allowing the pilot to set the reference pressure to identify which reference point will use for measure the altitude through visible small window. this altimeter uses continually rotating drum as shown on Figure 2.3 to measures and transmit the absolute pressure and displays it in analogue read out. The sensitive altimeter shown the altitude information in three-digit format behind the pointers which will use as transponder code for altitude reporting.

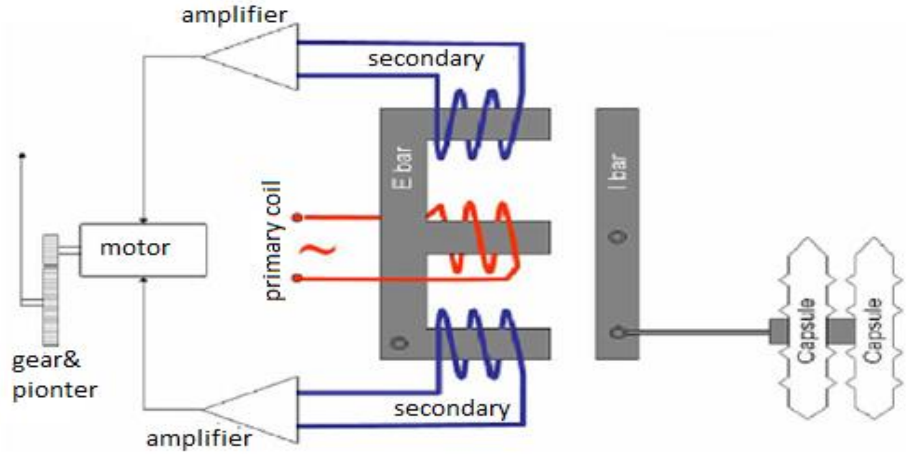


Figure 0.3: Servo - assisted altimeter [8]

2.5.3 Encoding altimeter

Its servo type altimeter with additional capability for sending accurate digitalized output to the transponder, this accurate altitude is essential for air traffic control to orderly flow the high density of traffic. the mechanism of the system as shown on Figure 2.4, use servo to drive a dedicated glass disc etched transponder and opaque sector, light source shines through the disc onto photoelectric cells which convert the disc movement into code signal for transponder through extra low-torque pick off to provide high degree of accuracy with very low torque requirement.

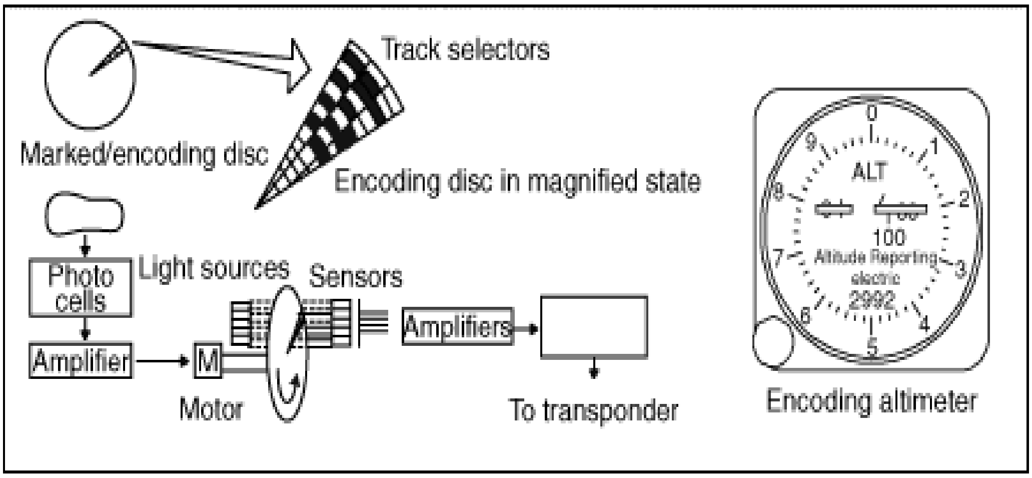


Figure 0.4: Encoding altimeter mechanism [8]

The sensitive encoding altimeter output is accurate enough under Standard day conditions of ISA model, where it has been accepted for IFR flight by federal aviation administration and currently uses in aircraft. this accuracy and reliability of encoding altimeter was result to adequate enhancement in integration of ATC transponder system for automatic altitude reporting and leaded to safe and efficient use of aerospace.

2.6 Earth Atmospheric Parameters

The environment surrounding the earth's surface has been divided by Physicists into the five regions, troposphere, stratosphere, mesosphere, thermosphere and Exosphere based on certain intrinsic features such as the vertical distribution of some parameters due to rotation of the earth itself and variation of gravitational pull to the air particles according to Newton’s law of universal gravitation [9]. Airplanes and all other flying objects fly on the earth's atmosphere, therefore knowing the nature and properties of atmospheric parameters (such as air pressure, temperature, viscosity and air density) are essential in aircraft design, performance testing, instrument calibration, and other important aeronautical and aerospace science applications [9], [10].

2.7 International Standard Atmospheric (ISA) model

The International Standard Atmosphere (ISA) is the standard model for the variation of earth's atmosphere parameters with altitude; this model has been established to provide the aerospace user a reference of values for these parameters at different altitudes, in addition to some relations to how those values were derived with altitude using numerical integration methods. The first model of the earth atmosphere was developed in 1920 in both United States and Europe with slight differences mostly in the upper layers of the atmosphere, with the progress of aeronautics and aerospace science the international standard atmosphere (ISA) model has been introduced and adapted by National Advisory Committee for Aeronautics and accepted by the international civil aviation organization in 1952 with continuously update, intended for scientific use for aircraft performance calculations as well as facilitating the development and calibration of aircraft flight instruments. The ISA model divides the atmosphere into layers, assuming that the atmospheric parameters at sea level will remain constant, wherein the air pressure is 1013.25 Pa; the temperature is 15° C, air density is1.225kg /m^3 and also assume the gravity acceleration is constant whereas the temperature is linearly function with altitude by -6.5 $^{\circ}$C/km throughout the troposphere [11].

2.7.1 Variation of atmospheric parameters vs Altitude

Remote sensing of the atmosphere with satellites began in the early 1960s and remains extremely important for measuring properties of the different layers of the atmosphere. Based on the main assumptions of the National Advisory Committee for Aeronautics (NACA) of hydrostatic equilibrium of the atmospheric condition at sea level, perfect gas, gravity independent, and constant temperature lapse rate on the troposphere layer, the variation of earth atmospheric parameters with altitude has been detected, tabulated and used to generate standard relation to calculate the altitude of flying objects at any height below 11km (troposphere). The static air pressure of the atmosphere decreases linearly with altitude at troposphere layer as shown on Figure 2.5, while the distribution of the atmospheric temperature has a more complicated profile with altitude, and may remain relatively constant in the region of 11 km to 20 km and then will change (increase or decrease) with altitude according to the properties of the region as shown on Figure 2.7. Consequently, other relations could be used to calculate the flying altitude above 11km where the temperature distribution affected by other natural phenomena.

The density of the earth atmosphere also varies with altitude as shown on Figure 2.6, where strongly affected by atmospheric dynamics, solar flux, and distribution of gravity pull and rate of atmospheric temperature change with height. The density as atmospheric parameter is very important factor for understanding the structure of the atmosphere and aerospace studies, whereas it is a major factor for spacecraft modeling, flight performance testing, and space object (satellite) lifetime calculation by predicting the atmospheric drag of the orbit.

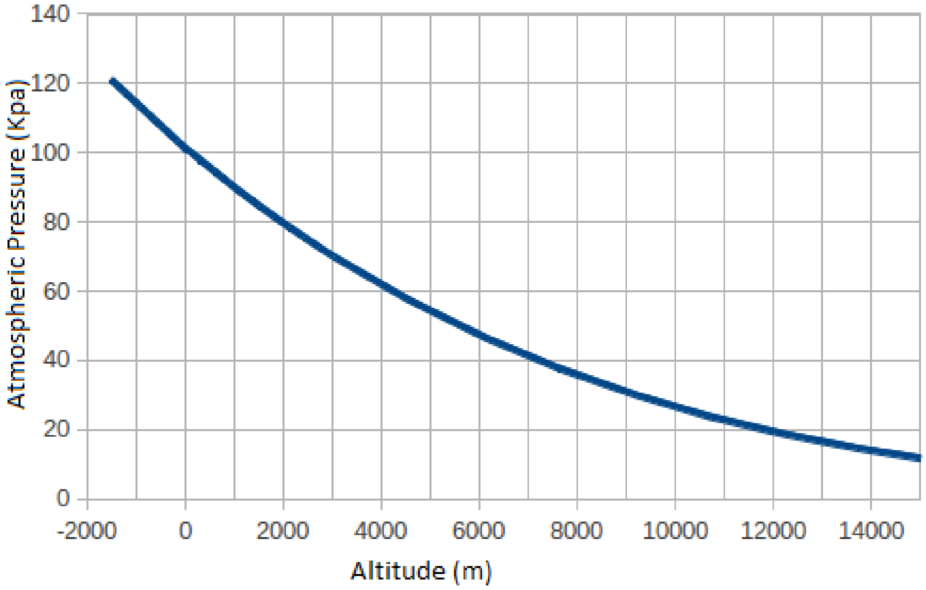


Figure 0.5: Variation of atmospheric pressure with altitude [11]

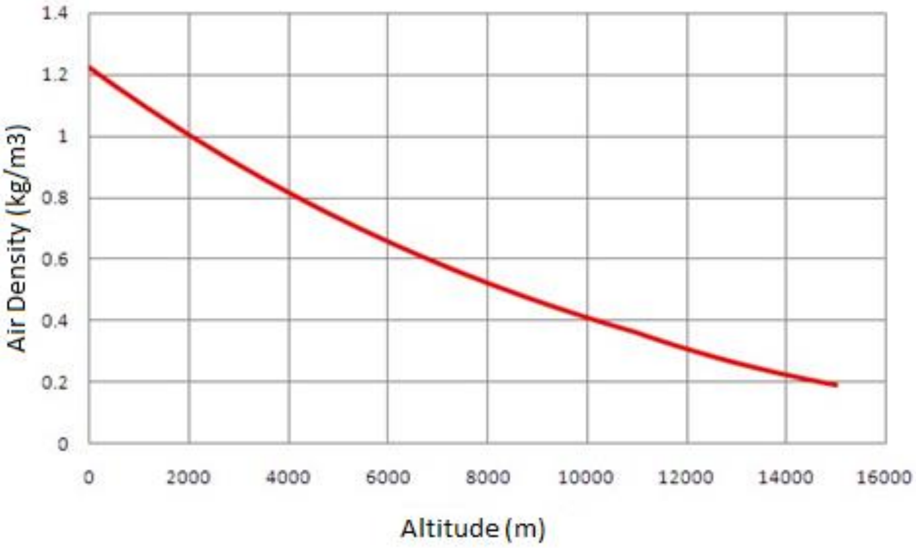


Figure 2.6: Variation of atmospheric density with altitude [10]

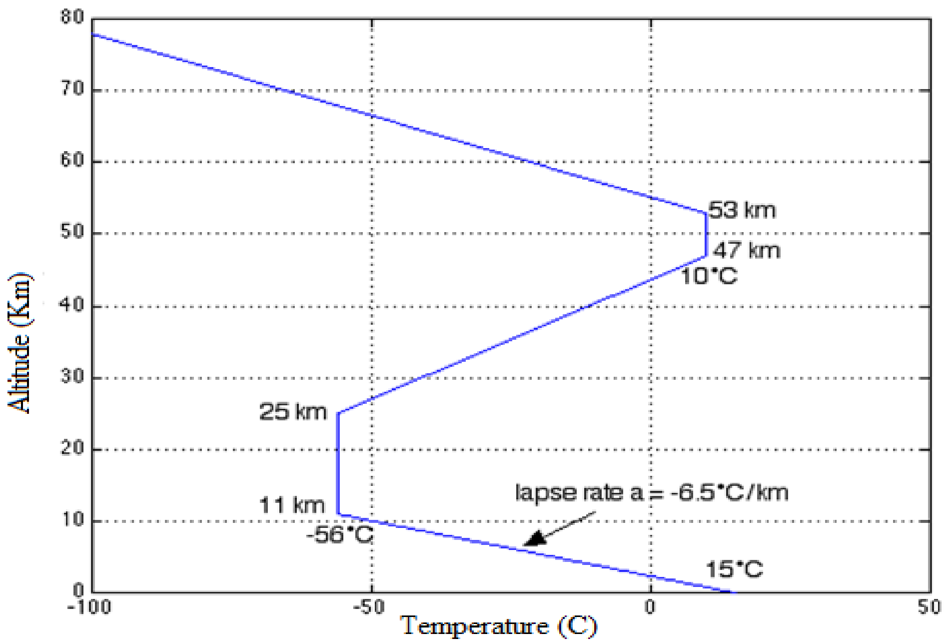


Figure 0.7: Distribution of earth atmospheric temperature [11]

2.7.2 Non-standard pressure and temperature

The barometric altimeter measures altitude based on international standard atmosphere model, which was based on many assumptions as mentioned in section 2.6, therefore the indicated altitude by the barometric altimeter is correct only if the atmospheric condition under ISA standard. For any deviation of these parameters from their standard values the actual flying altitude will be differ from indicated altitude and the flight could be hazardous, thus most used altimeter today allows a barometer setting to adjust to the nonstandard value of ISA atmosphere for resulted errors compensation [11].

CHAPTER THREE : DIAGNOSE AND ANALYSIS OF BAROMETRIC ALTIMETER ERRORS

3.1 Basic Elements of the measurement systems

The measurement systems in general consist of several functional elements to measure, convert and describe the physical variables in quantitatively. These essential parts of the instrument system as shown on Figure 3.1 are include transducing element that sense and convert the physical variable to an analogous form to be handled, data acquisition unit to apply and processes the output of the transducer and data presentation or display part to represent the measured variable to user's in quantitative form

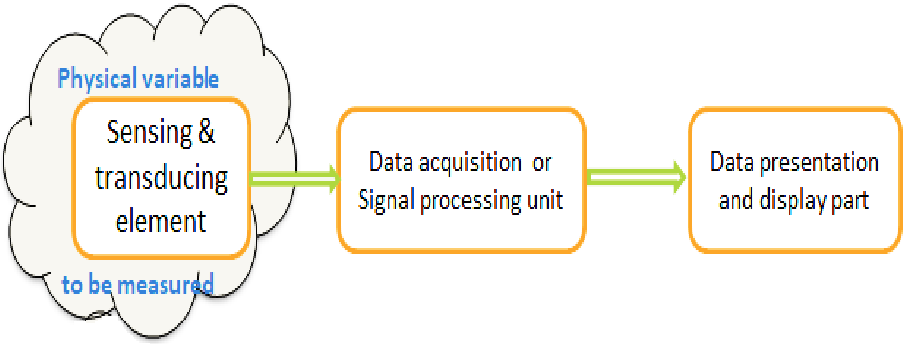


Figure 3.1: Elements of the instrument system

3.2 Instrument Errors

The error of the instrument is a deviation of the measurement system output from its standard reference value [12]. This deviation may result from many reasons related to the instrument itself or a surrounding environment. However the performance and accuracy of the measurement system is very important parameter for instrument designers and venders to be ensure they provide the users the actual information about a measured physical variable, thus a systematic approach for equipment design or optimization of existing instruments is necessary and much needed to identify all sources of these errors, estimate of their magnitude and introduce suitable way for compensation to mitigate this deviation of the instrument output from true value. In instrumentation science the errors of the instrument reading classified in to three categories as gross errors, systematic errors and random errors based on the sources of those errors will arise. The main errors of barometric altimeter may cause due to limitation of the mechanical components, atmospheric variations and blockages within the pressure sensing element itself.

3.3 Overview of Barometric Altimeter Elements

3.3.1 Pressure sensing element (aneroid capsule)

The Capsule is a metallic pressure sensing element (air breathers) used for barometric altimeter, which was formed by joining corrugated elastic metal discs together, evacuating and sealing them to produce a linear motion from its expansion and contraction under the effect of a pressure difference across the element. Beryllium copper alloy and Phosphor-bronze alloy are two common materials that have been used in manufacturing aneroid capsules because of their stiffness, high strength, light weight and their dimensional stability over a wide temperature range. In addition to that these alloys have other important properties (such as fatigue and Corrosion resistance, overheating Prevention and elastic properties) that made it to be widely used in defense and aerospace industries as pressure sensitive device for high speed aircraft, missile, and space vehicle. The deflection curve of pressure sensing element of the barometric altimeters as shown on Figure 3.2 is broadly affected by relative thickness of the capsule and total concentrated force (tension) acting on it. The expansion and contraction of the sensor can be expressed mathematically as explained in Equation 3.1

$$X = f\,(P, T, D, E, \mu \text{ and } \frac{t}{D}) \qquad (3.1)$$

Whereas: -

T: total concentrated force (tension) acting on the capsule

P: uniform pressure

D: designated linear dimension

E: young’s modulus

µ: shear modulus

t: capsule thickness

$(\frac{t}{D})$: relative thickness

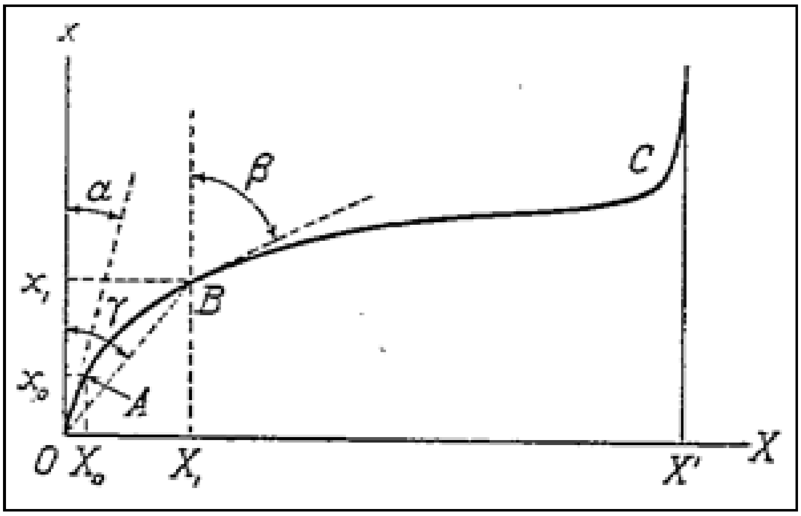


Figure 3.2: Deflection Curve of the aneroid capsule [12]

3.3.2 Altitude Indicating Part

The conventional barometric altimeter uses mechanical mechanism or servo driven mechanism to translate the deformation of the aneroid capsule to equivalent altitude. This expansion and contraction of the capsule is proportional to the changes in static pressure and consequently to the altitude of the flying vehicle. This translated altitude information will be indicated and represented in readable form to the pilot in analog or digital read out according to which type of barometric altimeter that use.

3.4 Barometric altimeter errors

The barometric altimeter system subject to many sources of errors during operation, such that can be broadly classified to systemic, methodical and dynamical errors based on the sources of these errors will arise. Those errors have been carefully considered, diagnosed and compensated in this design to provide the actual altitude information to the pilots and other integrated systems during flight.

3.4.1 Systematic errors

The systematic errors of the barometric altimeter are those errors caused by system itself, which results from manufacturing discrepancies, hysteresis, friction, inertia of the moving parts and change of elasticity modulus of the pressure measuring element[12]. These errors can be partially compensated by inserting bimetallic mechanical parts in the instrument mechanism and accomplishing a laboratory calibration for altimeter system.

3.4.1.1 Elastic Recovery and Hysteresis Errors

These errors work up due to delay in the pressure sensing element (aneroid) to response the changes in atmospheric pressure in various altitude. This delay will lead to lagging in the pointer movement for change in altitude. The degree of elasticity “stiffness” of beryllium copper alloy makes the aneroid capsule to deform within proportional limit, in specific point of deformation the physical properties of the alloy may change, and the elastic properties of the material will change accordingly. this change will prevent the aneroid to regain its initial dimension (normal shape) after deformation for any given atmospheric pressure and resulting to errors on the system as shown on Figure 3.3 and Figure3.4.

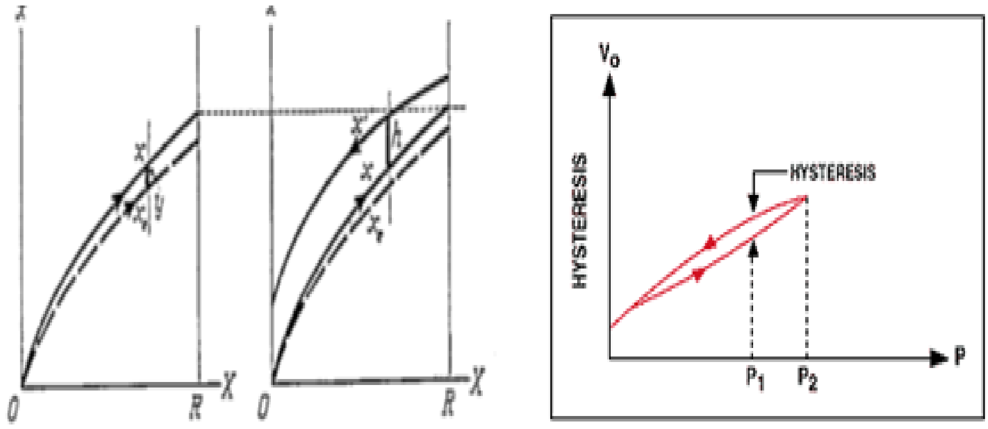


Figure 3.3: Elastic recovery and hysteresis errors of capsule [12]

3.4.1.2 Friction error

friction of moving mechanical parts (bearing, rods, sectors, gears…etc.) of the analogue instruments system will result to reading error and generates irregular jumpy motion of the pointer.

3.4.1.3 Temperature Error

The variation of the surrounding temperature has direct impact to linearity, offset and sensitivity of the pressure sensor. The aneroid capsule may subject to various degrees of temperatures depending on the operational altitude, so this variation of environmental temperature will result in change of sensor properties and may lead to error in sensor readout. The output of the sensor is function in the sensitivity of the aneroid capsule and its offset as shown on Figure3.4. Whereas the pressure sensor may be modeled as illustrated in Equation (3.2).

$$V_o = K_0 + K_1 P \tag{3.2}$$

Whereas: -

K_0: offset voltage

K_1: Sensitivity of the sensor

V_o : Output of the sensor

P: operational pressure

Also, the Pressure sensing element cannot produce the same output with consecutive apply of same pressure value during operation when a pressure sensing element property have been changed as shown on Figure3.5.

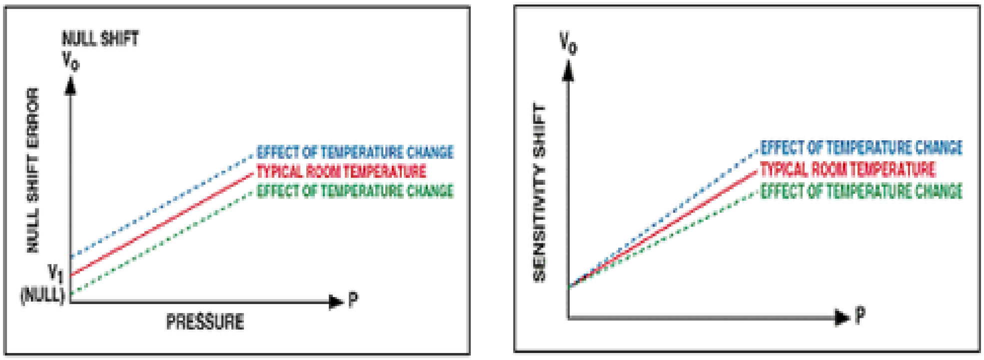


Figure 3.4: Temperature effect on the sensitivity and offset of the sensor (capsule) [12]

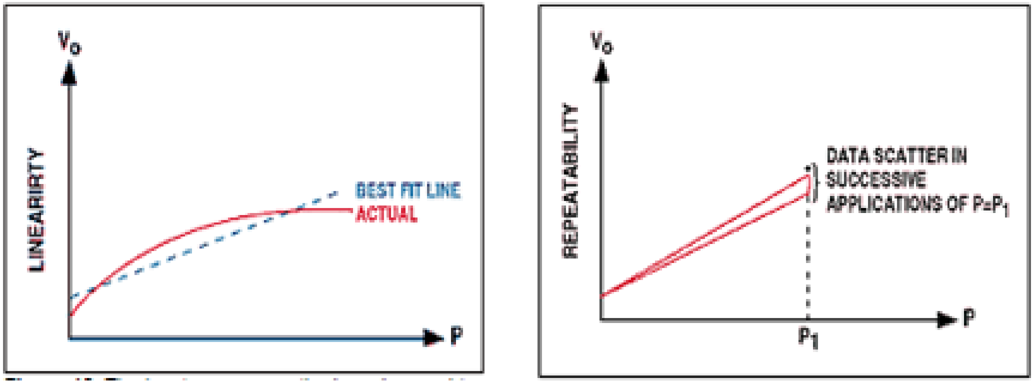


Figure 3.5: Temperature effect on the linearity and precision of the sensor [12]

3.4.2 Dynamic errors of barometric altimeter

The dynamic errors of barometric altimeter are generated due a difference in local static pressure and free stream (air) pressure due to movement of flying object in static atmosphere, which results in flow disturbance around the Pitot probe as shown in Figure 3.6. This error must be considered from a design stage, and can be minimized through aerodynamically shaping of the probe and locating of the Pitot static probe in minimum disturbance point along aircraft as shown on Figure 3.7.

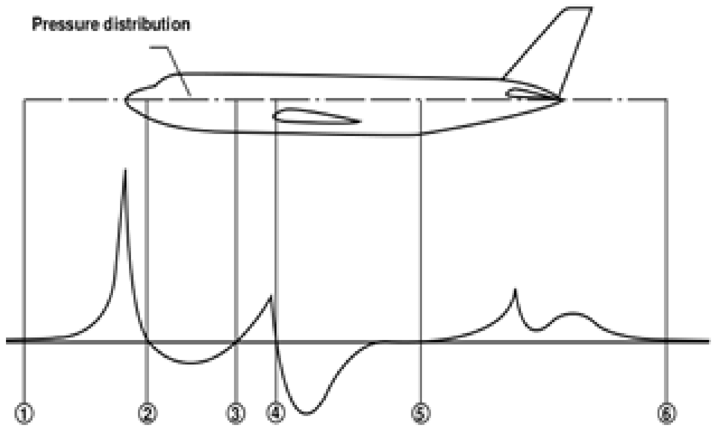


Figure 3.6: Pressure disturbance along the aircraft [13]

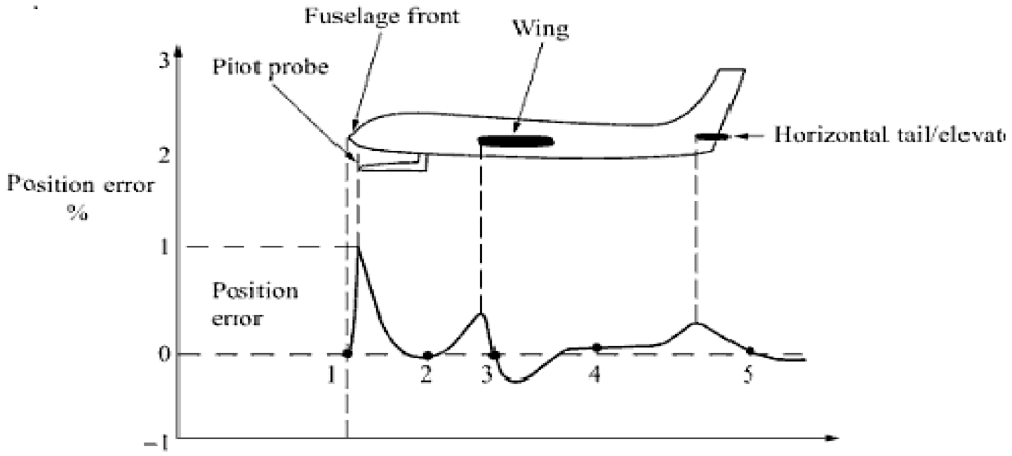


Figure 3.7: Optimum position of Pitot static along the aircraft [13]

3.4.3 Methodical errors of barometric altimeter

The major source of barometric altimeter errors is the method used for measuring the vehicle altitude itself. Such that mainly depend on ISA model of earth which assume and define a standard distribution of most atmospheric parameter on sea level and over wide range of altitude for all condition. So any deviation of the actual atmospheric parameters (such as pressure, temperature and temperature lab rate) values will results to error in altimeter read out. In this research most methodical errors of the barometric altimeter has been quantified and estimated using Taylor’s series relations for correction purpose as expressed in equation 3.4.and then the estimated values shall be compensated directly in the processor to correct any deviation of the measurement system due to this drift and measure the actual value of altitude, as explained in equation 3.3.In addition to that, the barometric altimeters must be calibrated on the basis of the standard atmosphere to mitigate this kind of errors[12].

$$H = (H_o + \Delta H) \tag{3.3}$$

$$\Delta H = \sum_1^\infty \left(\frac{\delta^i H}{\delta {T_o}^i} . \frac{{\Delta T_o}^i}{i!} + \frac{\delta^i H}{\delta \alpha^i} . \frac{\Delta \alpha^i}{i!} + \frac{\delta^i H}{\delta {P^i}_H} . \frac{{\Delta p_h}^i}{i!} + \frac{\delta^i H}{\delta {P^i}_o} . \frac{\Delta {P^i}_o}{i!}\right) \tag{3.4}$$

3.4.3.1 Temperature drifts from ISA values

Deviation of absolute temperature from ISA value will affect the air density and therefore the pressure of atmosphere and then altitude of flying vehicle. (i.e. if an aircraft flies into a region where the temperature is lower than what it should be under the ISA, the altimeter will read higher, if the temperature is higher than the standard for that altitude, the altimeter will under-read and result to error). To quantify the absolute temperature errors, ΔH_{T_o} and ΔH_α which are produced from the deviation of the atmospheric parameters at sea level (temperature, and vertical temperature gradient) from their standard ISA values; the following expressions have been used.

$$\Delta H_{T_o} = -\frac{\Delta T_o}{T_o} H \tag{3.5}$$

$$\Delta H_\alpha = -\frac{T_o}{\alpha^2}\left[1 + \left(1 + \frac{\alpha}{T_o} H\right)\left(Ln\left(1 + \frac{\alpha}{T_o} H\right) - 1\right)\right]\Delta\alpha \tag{3.6}$$

The distribution of absolute and relative methodical errors of altitude ΔH_{T_o} and $\frac{\Delta H_{T_o}}{H}$ that resulted from the drift of T_o from its standard value is shown on figure3.9. As well as a same distribution of methodical errors of altitude due to deviation of temperature lab rate α form its standard ISA values have been showed experimentally as illustrated on Figure3.10. In Figure3.9 the altitude errors produced from drift of ambient temperature

ΔH_{T_0} has zero value at sea level (where the actual values of atmospheric parameters are known from meteorological information and Can be inserted manually) and rise with altitude linearly, while the absolute altitude error produced from drift of temperature lab rate ΔH_{α} is also zero at sea level but rise exponentially with the altitude as shown on Figure3.10.

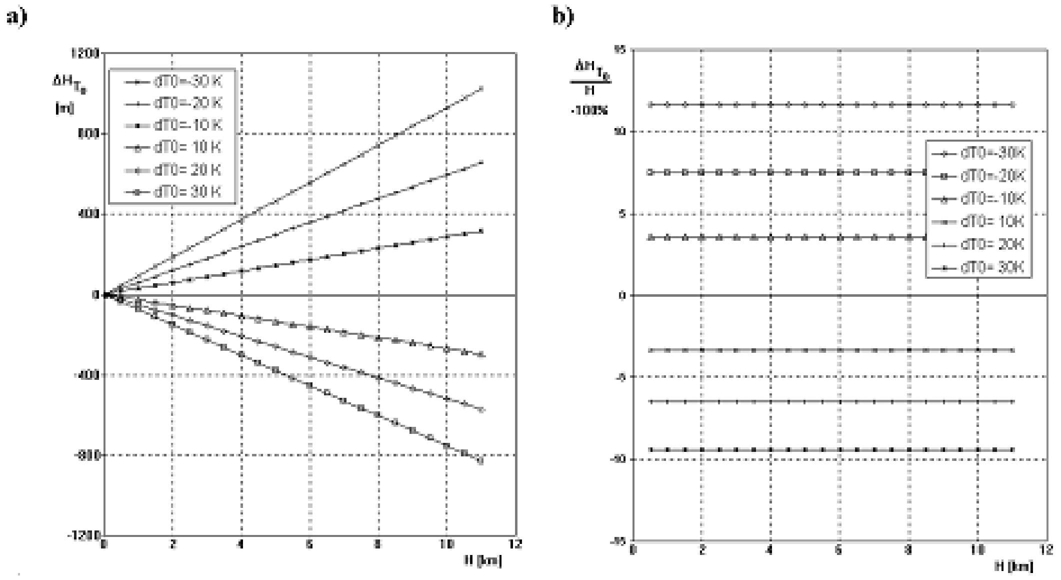


Figure 3.8: absolute and relative altitude error due to deviation of SL temperature from standard value [12]

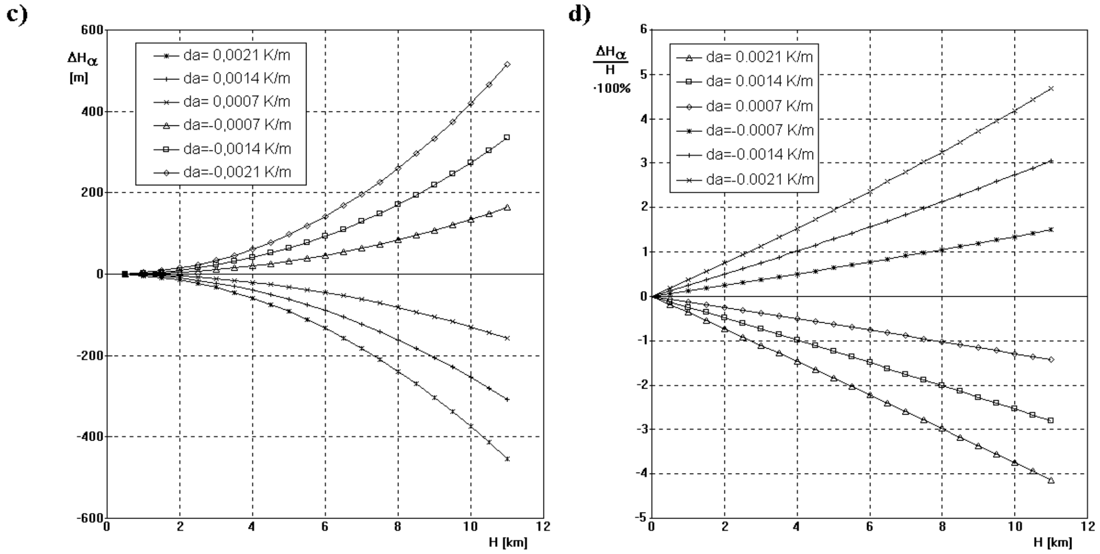


Figure 3.9: absolute and relative altitude error due to drift of temperature lap rate from standard value [12]

3.4.3.2 Atmospheric pressure drifts from ISA values

To quantify the absolute pressure altitude errors, ΔH_{P_H} and ΔH_{P_o} which are produced from the deviation of the atmospheric pressure at sea level P_o and the deviation of atmospheric pressure at any prescribed altitudes P_H from their expected standard ISA values, the following expressions have been used.

$$\Delta H_{P_H} = \left| g.\rho_o \left(1+\frac{\alpha}{T_o}H\right)^{-\left(1+\frac{g}{R\alpha}\right)} \right|^{-1} \Delta P_H \qquad (3.7)$$

$$\Delta H_{P_o} = -\frac{R}{g}.(T_o+\alpha H).\frac{\Delta P_o}{P_o} \qquad (3.8)$$

The distribution of absolute and relative methodical errors ($\Delta H_{P_o}, \Delta H_{P_H}$, $\frac{\Delta H_{P_o}}{H}$ and $\frac{\Delta H_{P_h}}{H}$) that will results from drift of atmospheric pressure from its standard values have been experimentally illustrated as shown in Figure 3.11and Figure 3.12, such that the absolute altitude errors ΔH_{P_H} and ΔH_{P_o} have non-zero value at zero altitude (sea level), and the ΔH_{P_H} rise exponentially with altitude while the ΔH_{P_o} drop with altitude.

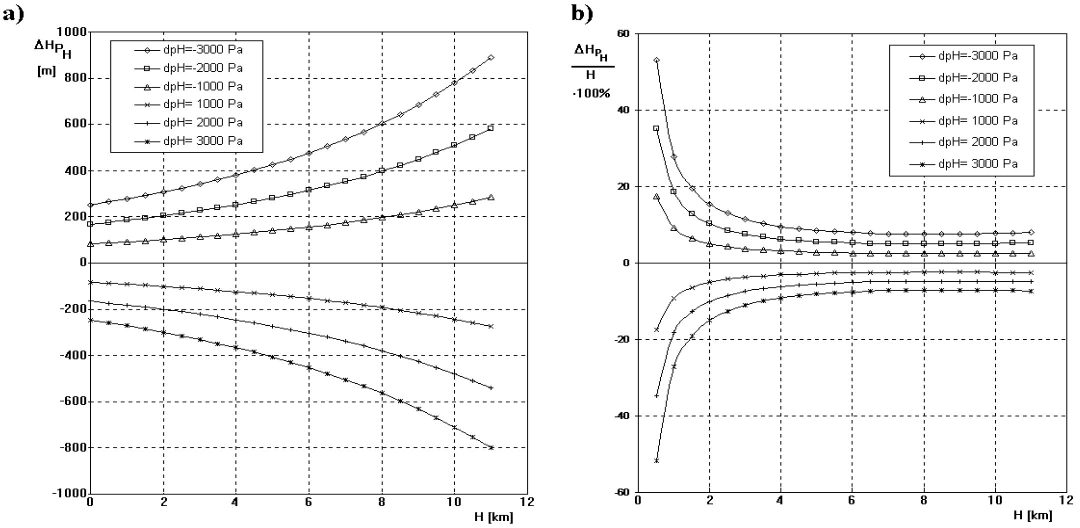


Figure 3.10: Absolute and relative altitude error due to pressure drift from standard value [12]

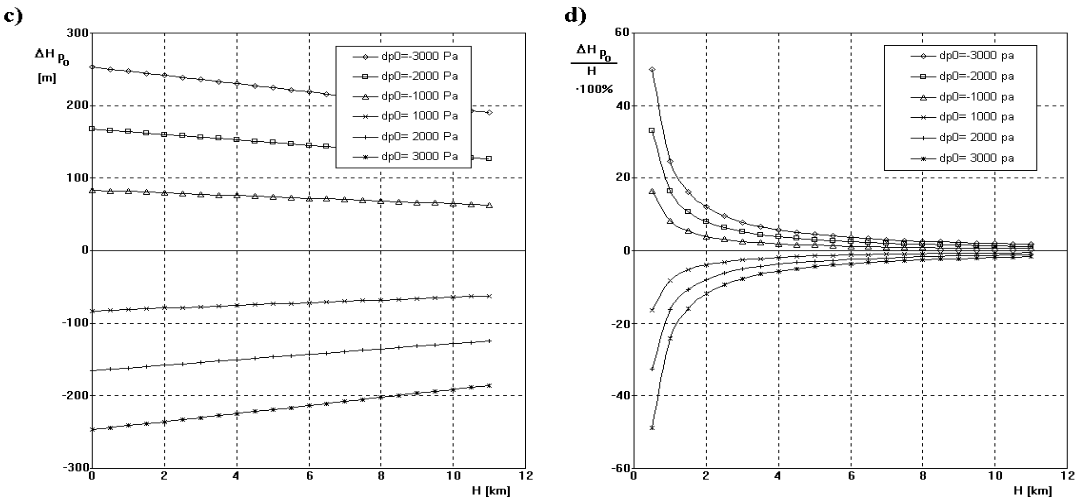


Figure 3.11: Absolute and relative altitude error due SL pressure drift from standard value [12]

CHAPTER FOUR: DESIGN OF BAROMETRIC DIGITAL ALTIMETER

4.1 Conceptual design of a barometric digital altimeter

The digital barometric altimeter is similar to a conventional(mechanical) barometric altimeter in its function and its principle of operation, whereas both of them measure the vehicle altitude by detecting the changes in atmospheric pressure, but the digital barometric altimeter uses high sensitive pressure sensing element to achieve accurate degree of movement for given small change in atmospheric pressure, and then transduce the response of the sensor (expansion & contraction) into an electrical signal using suitable pressure transducer, and then process this electrical signal using sophisticated calibration equation to calculate the corresponding vehicle altitude and provide this altitude information in digital readout , by using suitable digital display.

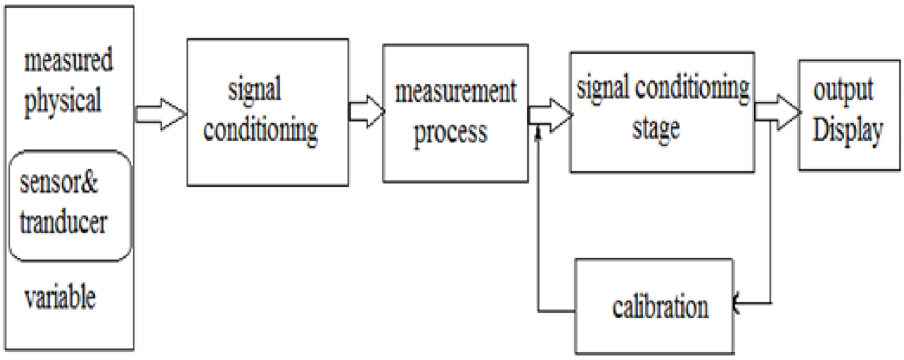


Figure 4.1: General block diagram of measurement process

In general, the measurement process of any physical quantity will be carried out in many stages as illustrated in Figurer4.1, starting from Sensing and transducing stage, Signal conditioning stage, Measurement process stage, output control stage and display the measured variable to show the readings. The conceptual design of the digital barometric altimeter has been carefully introduced as shown in Figure 4.2 including all design stages as defined bellow.

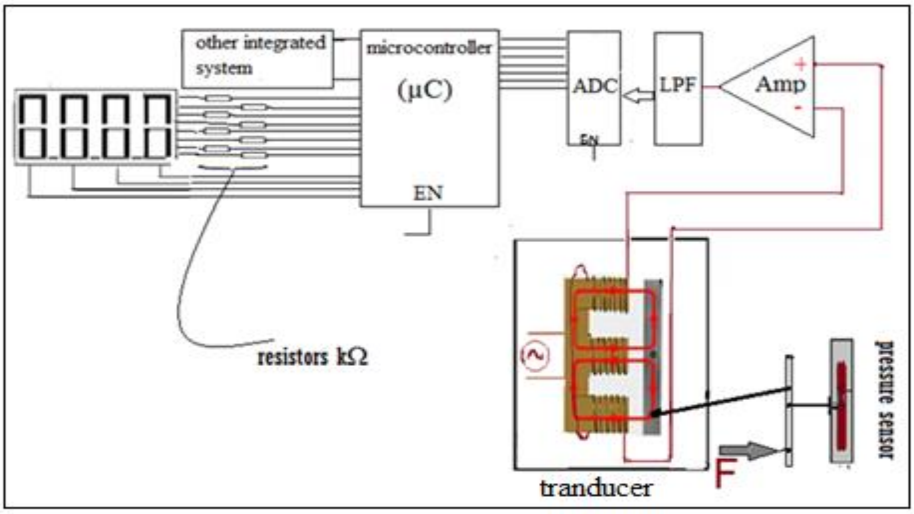


Figure 4.2: Conceptual design of a digital barometric altimeter

a) Sensing and transducing stage

Aneroid capsule may be used as pressure sensing element in this design and the EI bare transducer also used to transduce the net deformation of the capsule to electrical signal, this electromagnetic transducer depends on movement of the I bar from its equilibrium position and subsequently to deformation of capsule element. such that when I bar moves from its equilibrium position the air gaps between the two bars become unequal, resulting in flux change at the limbs, and then the induced voltages will change accordingly as shown in figure 4.3 b and figure 4.3 C. for the neutral position of the I bar as shown on Figure 4.3 a where the air gaps at each end are equal, the magnetic flux is equally induced, equal and opposite voltage will generated in the outer limbs, therefore the output signal will be zero and the display shall indicate to SL altitude . LM53 and MPX415 temperature and pressure sensor has been used in state of aneroid capsules for simulation purpose.

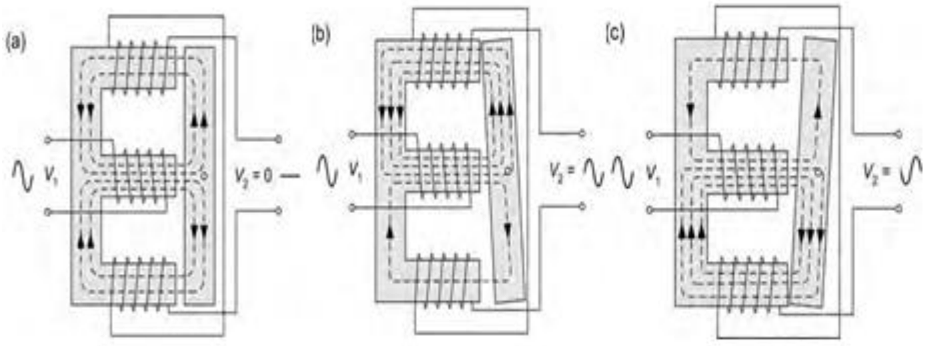


Figure 4.3: EI bars operation principle [14]

b) Signal conditioning stage

The output of the transducer will be amplified, filtered, adjusted, and converted to digital signal as shown in Figure 4.4 in order to suit the processing stage. The quality of signal conditioning circuit output is key factor for performance accuracy of this design, so a proper signal conditioning circuits are much needed and has been carefully consider for this reason.

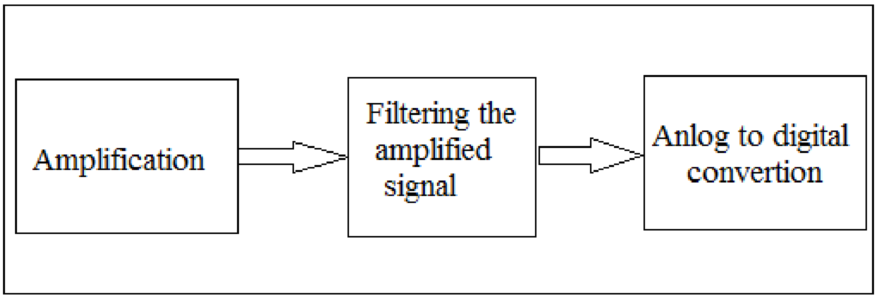


Figure 4.4: Signal conditioning stages

c) Altitude Measurement

The Uno board has been used in this model as processing unit to receive sensor data, convert it to corresponding digital signal and apply it to the dynamics of the measurement system to translate it to pressure variation and then to equivalent altitude according to calibration equations of barometric altimeter for standard atmosphere of troposphere and the Stratosphere that introduced by ISA.therefore the standard relation generated by ISA model has been used to calculate the altitude of flying objects at any height below 11km (troposphere) as illustrated in equation (4.1).

$$H = -\frac{T_0}{\alpha}\left[1-\left(\frac{P_H}{P_0}\right)^{-\frac{R*\alpha}{g}}\right] \qquad (4.1)$$

Also, because of complicated atmospheric temperature profile shown on figure 3.4 which will vary with altitude until 11km and remain constant between 11 km and 20 km, and then changed with altitude rapidly, the Laplace relation must be used to calculate the flying altitude above 11km as explained below.

$$H = 11{,}000 - \frac{R}{g} \times T_{11}\,\mathrm{Ln}\left(\frac{P_H}{P_{11Km}}\right) \qquad (4.2)$$

d) Altitude Display stage

The computed altitude information was conditioned again and displayed using Liquid crystal display to provide the user an accurate and precise altitude information in digital format for system performance monitoring.

4.2 Altitude calculation and errors compensation algorithm

The Arduino Uno processor has been used in this design and programmed to calculate the height of flying vehicle according to the flow chart described in figure 4.5. in addition to that the concept of the altitude alerting system has been carefully added to altimeter system to alert the pilot (voice / text) when the aircraft reaches a pre-selected altitude. Also as shown in processing flow chart, the program has been written in Arduino Integrated Development Environment (IDE) to detect the input of the capsule, translate it to equivalent pressure value and apply it in calibration equations (4.1) or equation(4.2) to calculate the corresponding flying altitude, and then call a dedicated subroutine to compensate all generated errors to provide the actual altitude information in Liquid Crystal Display in digital format.

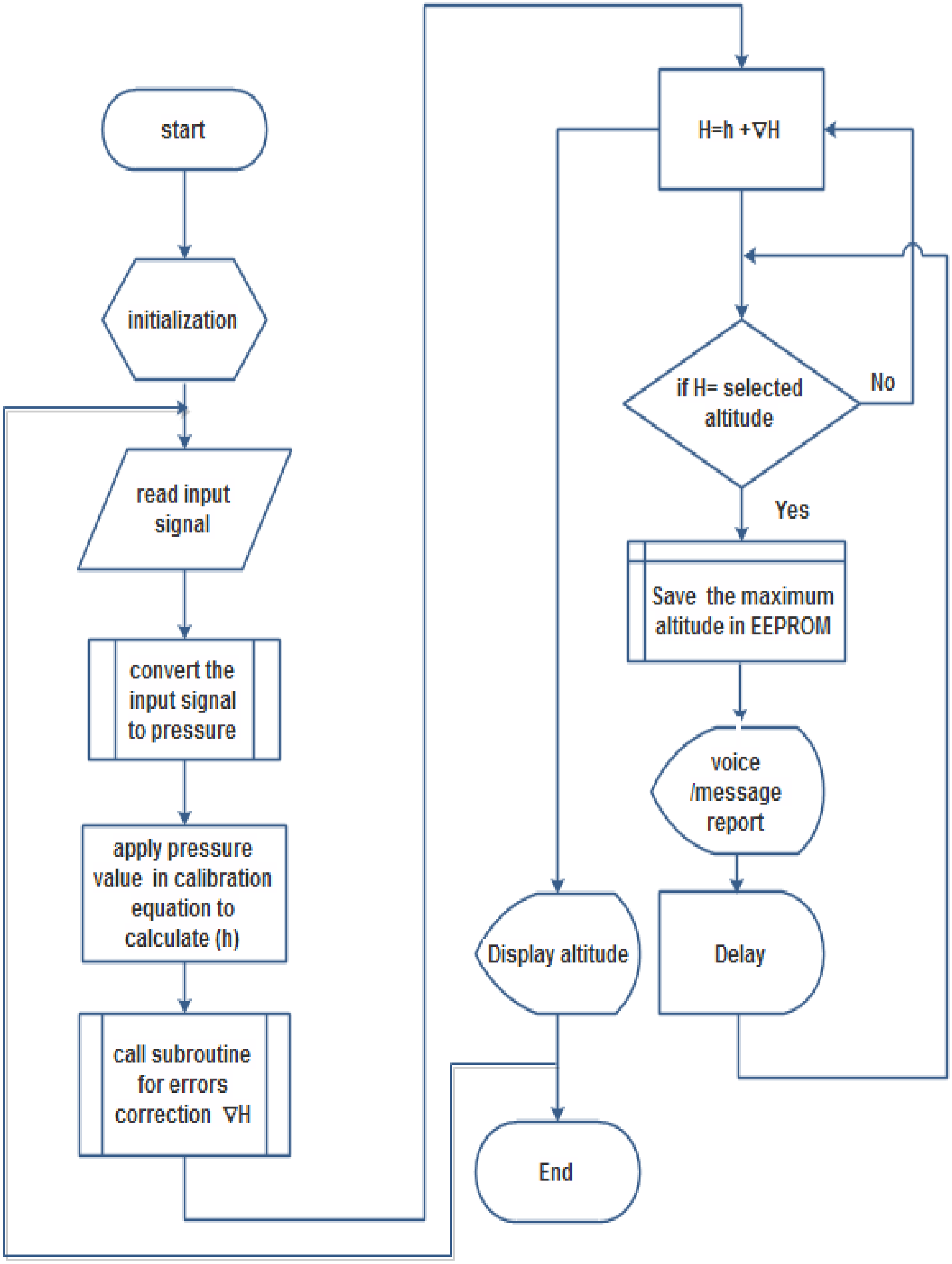


Figure 4.5: Program flow chart

4.3 Design Simulation Results

The performance and capability of the designed digital barometric altimeter system has been predicted by modelling the design using proteus7.7 program. After running the simulation, good results have been achieved, as shown on figures 4.6 & figures 4.7.

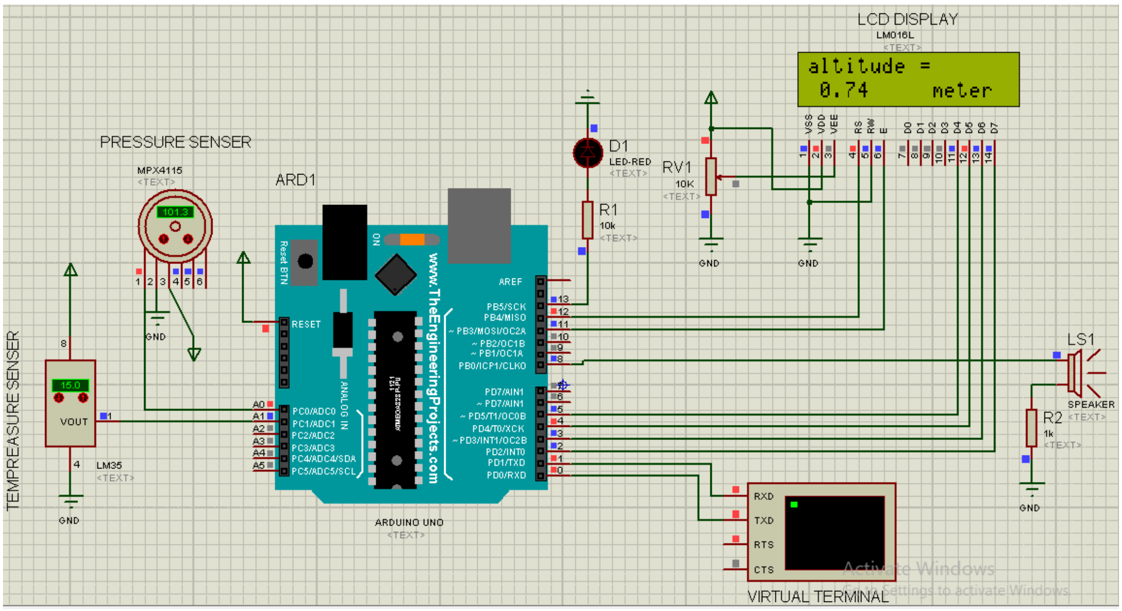


Figure 4.6: Digital barometric altimeter model simulation for sea level altitude

The simulation was carried out and run two times to measure the sea level attitude and 2km flying altitude. And then the achieved results have been compared with international standard atmosphere calculations as in ISA table shown in appendix-C. Such that, the atmospheric parameters (pressure and temperature) was sensed using MPX4115 and LM15 sensors and 0.74 meter reading of altitude has been indicated in LCD for sea level altitude as shown on figure 4.6 as well as 1992.3 meter(1.9923 km) reading has been obtained for 2km altitude (ISA value) as shown on Figure 4.7. In addition to that, all detected and compensated errors during the measurement process due to deviation of atmosphere from standard values has been detected and indicated in virtual terminal for more explanation and analysis as shown in figure 4.8 and Figure 4.9.

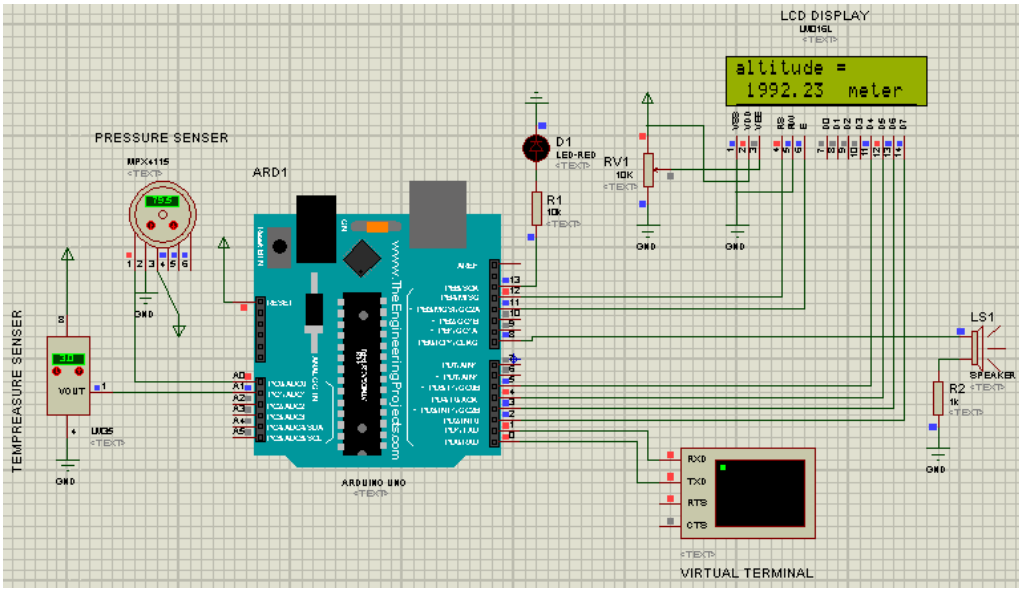
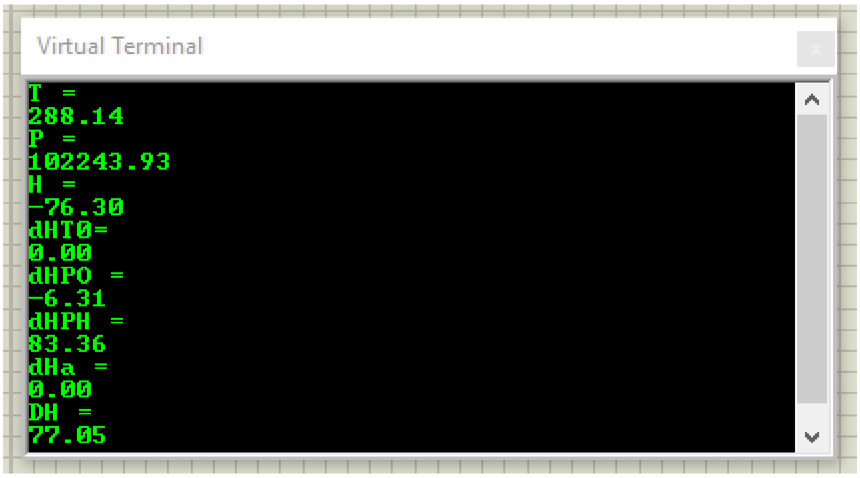
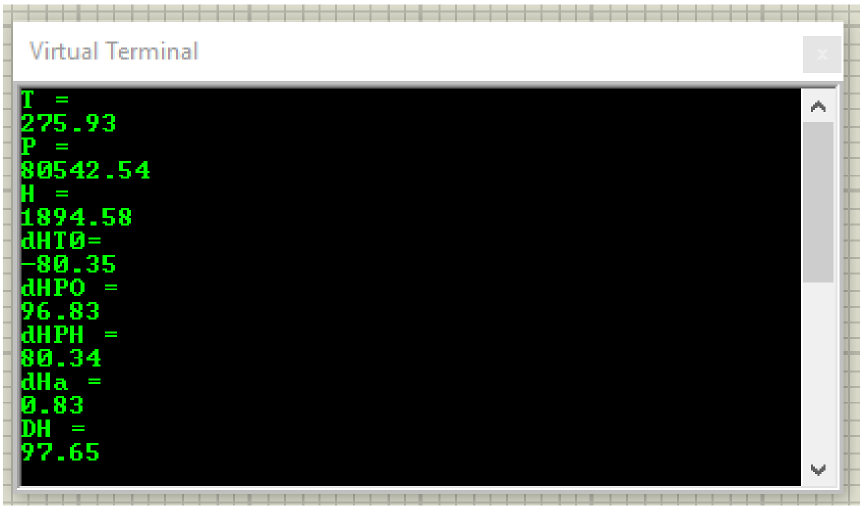


Figure 4.7: Digital barometric altimeter model simulation for 2km altitude



```
T =
288.14
P =
102243.93
H =
-76.30
dHT0=
0.00
dHPO =
-6.31
dHPH =
83.36
dHa =
0.00
DH =
77.05
```

Figure 4.8: Errors values generated at sea level



```
T =
275.93
P =
80542.54
H =
1894.58
dHT0=
-80.35
dHPO =
96.83
dHPH =
80.34
dHa =
0.83
DH =
97.65
```

Figure 4.9: Errors values generated at 2km altitude

Based on the simulation results shown in Figure 4.7,Figure 4.8 and Figure4.9, designed digital altimeter system is very sensitive to variation atmospheric parameters and strongly influenced by deviation of the atmospheric condition from standard values. Whereas the altitude errors generated due to drift of T_o and α are zero at sea level and -80.35 and 0.83 meters respectively at 1.992km altitude. Also the absolute methodical altitude errors on the system due drift of P_o , P_H has considerable values at zero altitude and then rabidly increased and decreased respectively at altitude of 1.992 km as shown on figure 4.7. Ttherefore according to achieved results from the simulation, the distribution of methodical altitude errors has been summarized on the table 4-1: -

Table 4-1: Methodical errors of designed barometric digital altimeter

ISA Altitude (m)	Generated altitude errors due to drift of atmospheric parameters (m)				Total Drift(m)	Indicated altitude (m)
	ΔH_{T_o}	$\Delta H\alpha$	ΔH_{P_o}	ΔH_{P_H}	ΔD	
Sea level	0.00	0.44	-6.31	83.36	0.74	**0. 74**
2000	-80.35	0.83	96.83	80.43	0.0077	**1992.23**

CHAPTER FIVE : IMPLEMENTATION ,RESULTS AND DISCUSION

5.1 Introduction

In this chapter, the digital altimeter prototype has been implemented as hard model, tested and the obtained results has been showed and evaluated in more detail way.

5.2 Implementation Methodology

The simulated model of the designed system has been implemented as hard model (prototype) using low cost electronics component and testing tool from local market for simplification reasons with fulfill of the design requirements. Whereas after selecting of model components the processing unit (Arduino Uno) has been programed and realized in testing board to investigate the performance of designed altitude measurement system in real environment. Furthermore, on chip integration of system components has been done in laboratory and then the obtained prototype has been tested and demonstrated and excellent results have been achieved.

5.3 System Hardware Specification

- The system is based on Arduino Uno processing unit to receive and process data
- The system consists of sensitive barometric pressure - temperature sensors to receive actual atmospheric parameters in various altitudes.
- The system uses memory card to store sensors data and altitude values during test.
- The system shall have reliable digital display in reading side to provide user the altitude information in digital readout.
- The system also may use GPS receiver to provide altitude information during the test phases for comparison purposes.

- The hardware model must be integrated on bridge board first and then gathered in one PCB with the possibility of putting the pressure sensors in minimum disturbance point on PCB according to the test plan.
- The system shall be adapted, configured and powered by external DC power source to supply the system during test phases.

5.4 System Software Requirements

The system software has been developed in integrated development environment of arduino board to achieve fllowing requirements.

- System software shall be able to initialize all sensors modules when it powered on.
- System software shall be able to read and convert the sensor output to convenient physical quantities and use it to estimate the corresponding altitude value.
- System software shall be able to predict, estimate and compensate all errors subject to the system and provide accurate altitude information in digital read out.
- The software also shall be able to monitor and compare the pre-selected altitude and alert (voice or message) to pilot when he reaches the desired flying altitude.
- System software shall be able to restart the system on request

5.5 Selection of Model Components

Although the components selection is a most critical activity in the design cycle of any electronic system, the hard components of this model has been fussily selected to combines high degree of accuracy, reliability and cost effectiveness through balancing between the technical and non-technical aspects and accordingly the selection process was carefully carried out as follow.

5.5.1 BMP180 barometric sensor

Its high precise digital pressure - temperature sensor used for aerospace applications because of its EMC robustness, high accuracy, linearity as well as its output stability. The BMP180 as shown on Figure 5.1 consists of a piezo-resistive sensor, an analog to digital converter and a control unit with EEPROM to compensate non-standard values of temperature, in addition to serial I2C interface for integration with a microcontroller.

Figure 5.1: BMP180 barometric pressure-temperature sensor [14]

i. General Specifications of BMP180

The electrical characteristics of BMP180 sensor was specified as shown in table5.1 which was carefully evaluated and considered for integrating and interfacing of the sensor with other components of the system.

ii. Typical Application of the BMP180

- Enhancement of GPS navigation (dead-reckoning, slope detection)
- Baro- altitude measurement
- Weather forecast
- Vertical velocity indication (rises/sinks speed)

Table 5-1: Specifications and limitation of BMP180

Specification	Value	Unit
Dimension	3.6 x 3.8 x 0.93	mm^3
Operating voltage	1.8 --- 3.6	V
Pressure range	300 --- 1100	hPa
Temperature range	-40 --- +85	˚c
Conversion time	4.5	mS
Pressure accuracy	± 0.12	hPa
Pressure Resolution	0.01	hPa
Temperature resolution	0.1	˚c
I2C data transfer rate	3.4	MHz

5.5.2 Arduino Uno

The Uno board has been used in this prototype as processing unit to receive sensor data, convert it to corresponding altitude, compensate all expected errors and provide accurate altitude values in a digital readout. This processor has been selected as shown on figure 5.2 to meet the design requirements such as low power consumption, low pin count, flash program memory, flexible programing environment and many other advantages. The Arduino UNO is microcontroller board based on the ATmega328 microcontroller with 32 Kb of flash memory for storing code, 2 Kb of RAM and 1 Kb of EEPROM [15].

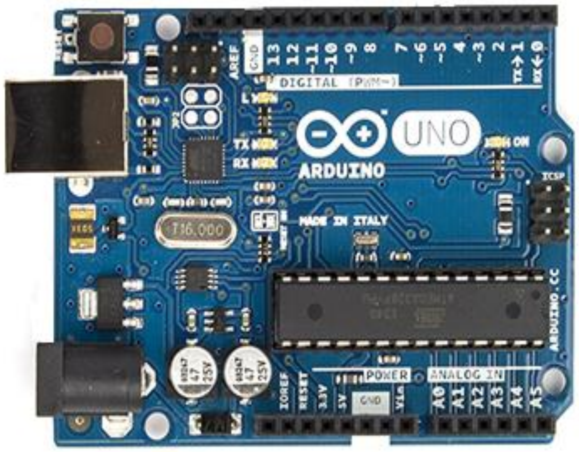


Figure 5.2: Arduino Uno processing unit

The used Uno board has 14 digital input/output pins, 6 can be used as PWM outputs, 6 analog inputs with 16 MHz crystal oscillator as shown in Appendix D and Appendix E. The UNO board can be powered using USB connection with electrical characteristic shown on table 5.2.

Table 5-2: General specification of Arduino Uno board

specifications	Value	unit
Operating Voltage	5	V
Input Voltage (recommended)	7-12	V
Digital I/O Pins	14	PIN
Analog Input Pins	6	PIN
DC Current per I/O Pin	40	mA
Flash Memory	32	KB
SRAM	2	KB
EEPROM	1	KB
Clock Speed	16	MHZ

5.5.3 LCD Display Unit

16×2 Liquid crystal display has been used in this design as monitor screen to show the altitude in digital format as shown on Figure5.3, this display unit was selected because of its low power consumption, reliability, cost effectiveness, and it can be used in a wide range of environments. The LCD will receive 8 bits' altitude data signal from Arduino microcontroller and then display it in digital format. The pins description of the LCD has been illustrated in table 5.3.

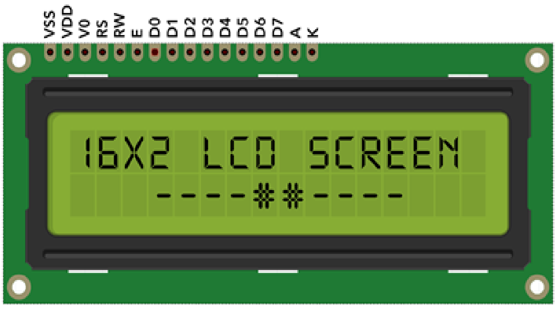


Figure 5.3: 16X2 LCD display unit

Table 5-3: LCD pins descriptions

no	Symbol	Function of Pin
1	V_{CC}	Ground
2	V_{DD}	+5v
3	V_0	Contrast
4	RS	Register
5	R/W	Read/Write
6	E	Enable
7	D_0	Data bus
8	D_1	Data bus
9	D_2	Data bus
10	D_3	Data bus
11	D_4	Data bus
12	D_5	Data bus
13	D_6	Data bus
14	D_7	Data bus
15	A	Anode (+5V)
16	K	Cathode (GND)

5.6 Components test and integration phases

The first phase of integration has been carried out by testing and checking the functionality and compatibility of individual prototype components, whereas the BMP180 barometric pressure sensor has been connected to Arduino board using testing bridge board as shown in Figure 5.4 and then calibrated to measure the actual parameters of the sea level atmosphere (temperature and pressure) such that the out pout of the sensor has been acquired and monitored through serial monitor of Arduino IDE on the PC screen, an accurate and precise results have been obtained compared to the actual condition of the testing room (32.10˚c of temperature and 96333 Pascal of surrounding air pressure). as shown in figure 5.5.

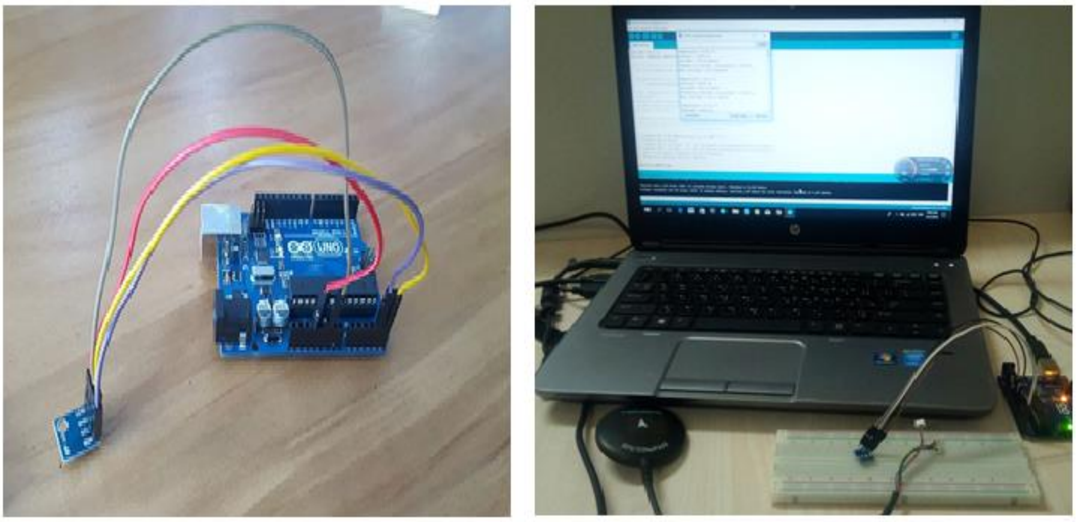
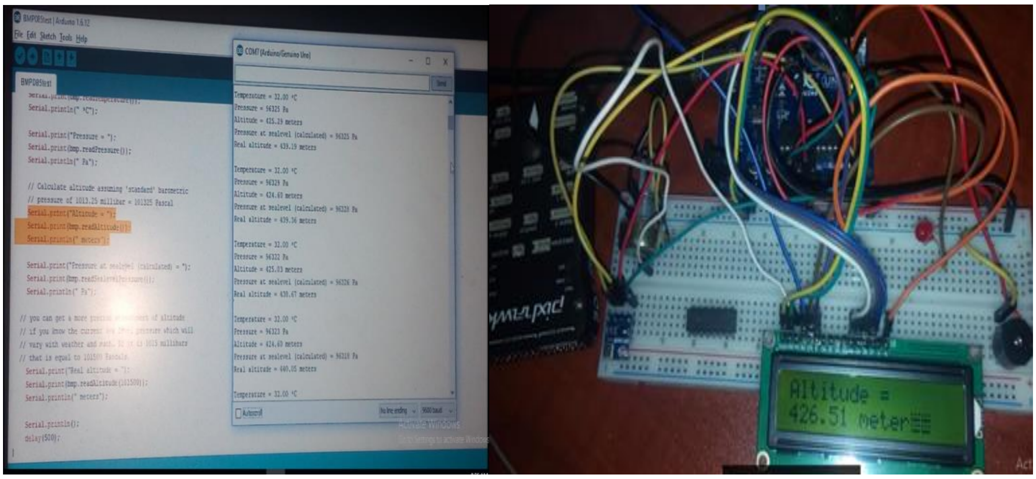


Figure 5.4: Bmp 180 sensor interface to Arduino

Also, the actual parameters of the atmosphere that sensed by Bmp180 at sea level has been displayed in digital format using 16×2 LCD as shown in figure 5.6 whereas the results were typically same to that monitored on PC using Arduino IED environment



```
  Serial.println(" *C");

  Serial.print("Pressure = ");
  Serial.print(bmp.readPressure());
  Serial.println(" Pa");

  // Calculate altitude assuming 'standard' barometric
  // pressure of 1013.25 millibar = 101325 Pascal
  Serial.print("Altitude = ");
  Serial.print(bmp.readAltitude());
  Serial.println(" meters");

  Serial.print("Pressure at sealevel (calculated) = ");
  Serial.print(bmp.readSealevelPressure());
  Serial.println(" Pa");

// you can get a more precise measurement of altitude
// if you know the current sea level pressure which will
// vary with weather and such. If it is 1015 millibars
// that is equal to 101500 Pascals.
  Serial.print("Real altitude = ");
  Serial.print(bmp.readAltitude(101500));
  Serial.println(" meters");

  Serial.println();
  delay(500);
```

```
Temperature = 32.00 *C
Pressure = 96325 Pa
Altitude = 425.29 meters
Pressure at sealevel (calculated) = 96325 Pa
Real altitude = 439.19 meters

Temperature = 32.00 *C
Pressure = 96329 Pa
Altitude = 424.93 meters
Pressure at sealevel (calculated) = 96328 Pa
Real altitude = 439.36 meters

Temperature = 32.00 *C
Pressure = 96322 Pa
Altitude = 425.03 meters
Pressure at sealevel (calculated) = 96326 Pa
Real altitude = 438.67 meters

Temperature = 32.00 *C
Pressure = 96323 Pa
Altitude = 424.60 meters
Pressure at sealevel (calculated) = 96318 Pa
Real altitude = 440.05 meters

Temperature = 32.00 *C
```

Figure 5.5: System component integration

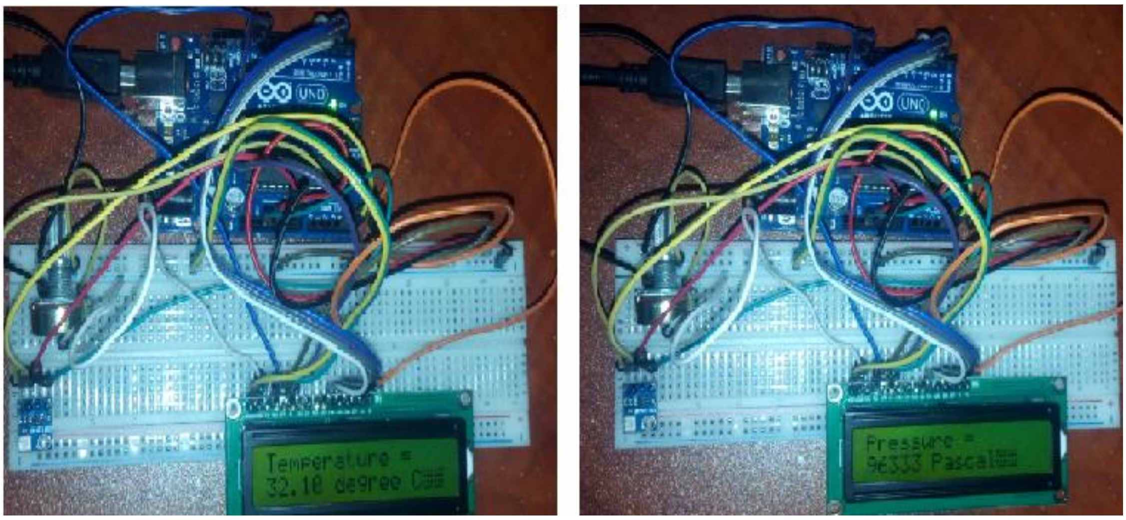


Figure 5.6: Bmp 180 test outputs on 16×2 LCD unit

5.7 Model integration

All components of the model including BMP180 sensor, Arduino Uno board, 16×2 LCD and altitude alerting devices (bazar and LED) has been carefully integrated in testing board and then the developed Arduino code for actual altitude measurement has been executed using Arduino IDE on PC and then load to Uno board .and then the prototype has been tested.

5.8 Results and Discussion

Based on the simulation results shown in chapter four , the designed altimeter system is very sensitive to variation of the sensors outputs and strongly influenced by deviation of the atmospheric condition from standard. the total drift of system is very high at sea level (0.74 meter) and decreased with height as shown in table 5.1 the altitude errors generated due to drift of T_o and α are zero at sea level and -80.35 and 0.83 meters respectively at 1.992km altitude . The absolute methodical errors of altitude due to drift of P_o and P_H are 6.31 and 83.36 at sea level and then rabidly increased and decreased respectively to 96.83 and 80.43 for 1.992 km.

Also based on the results obtained during prototype test and referance atomospheric parameteres provided by the international standard atmosher (ISA) table , the designed model is sensetive enogh to detect the actual atmosperic parometrers even under non standard condition and provide accurate altitude information in digital form as shown on figure 5.7 using dedicated subroutine to predict and compensate all inherent errors associated to the system during operation. Therefore, the actual result of altitude obtained during the test is variant few meters from standard ISA value as shown in table 5.2 due to variation of atmospheric condition from standard values.

Table 5-4: Actual atmospheric parameter sensed by the model

Test condition	**Sensed parameters**		
	P (pa)	T (° c)	actual altitude (m) calculation
Standard ISA values on SL	1013.25	15	426.51
Porotype out put	963.33	32.10	**440.58**

In addition to that, an altitude alerting algorithm has been carefully developed and considered on the design using simple buzzer and LED to alert the user for preselected altitude.

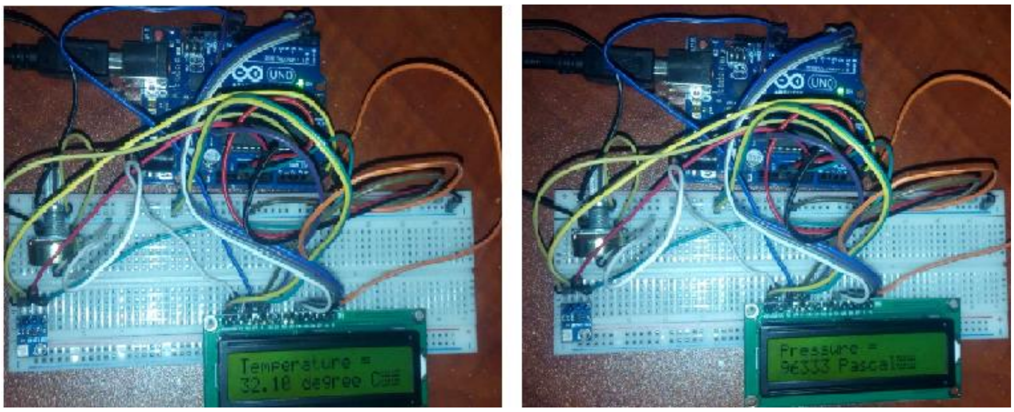


Figure 5.7: Actual sea level pressure and temperature sensed by digital altimeter

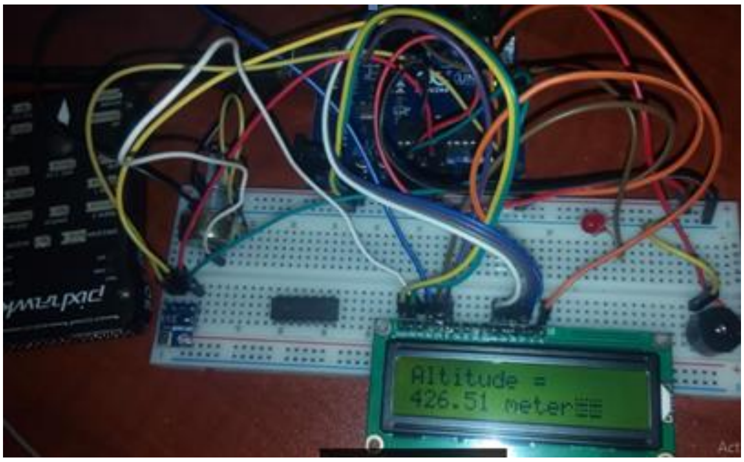


Figure 5.8: Corresponding sea level altitude reading before errors compensation

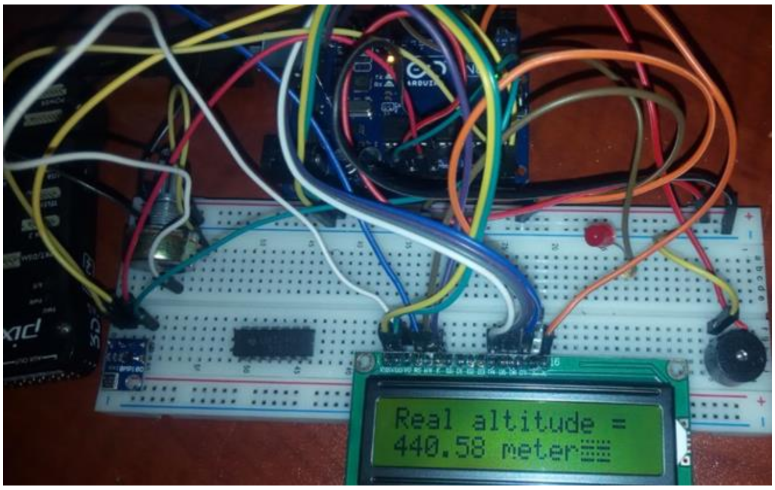


Figure 5.9: Actual sea level altitude reading after compensating errors

CHAPTER SIX : CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

After deep study and analysis of barometric method for altitude measurement, batter solution has been proposed by designing accurate and precise digital altitude measurement system. The conceptual design of this digital altimeter has been simulated for two level altitude (sea level and 2km) in a computer program to monitor the performance of the designed system using proteus software and Arduino IDE, good results have been obtained and altitude errors generated due to both test were showed and pointed that the total drift of the altitude is greater at sea level where is 0.74 meter and decreased to 0.0077 meters at 2km altitude.

In this thesis a simulated model has been implemented as prototype using BMP180 pressure sensing element and Arduino Uno board. The prototype was integrated to estimate a corresponding sea level altitude based on dedicated code developed on Arduino IDE environment, resendable result was achieved (440.58 meter) with few meters of variation in altitude from ISA value (426.51 meter) under that condition, the obtained altitude information was displayed in digital read out using 16×2 LCD and Altitude alerting device has been easily incorporated to the system.

The implemented model of digital altimeter is ready to be realized as final product in PCB, so as to determine the actual altitude of any flying vehicle under all conditions but more demonstration test is required in different environment to monitor the performance of the designed system.

6.2 Recommendations

According to preceding results obtained from real test of the digital barometric altimeter prototype, following points has been recommended for future works.

- The digital barometric altimeter porotype designed and implemented during this thesis was tested on bread board and does not released for use yet, therefore the model (prototype) should be realized in PCB as final product and introduced for use after final demonstration test.
- More investigation test may be required in different real environment condition using high altitude balloon (HAB) or any other sophisticated flying object to demonstrate performance and limitation of the designed altitude measurement system.

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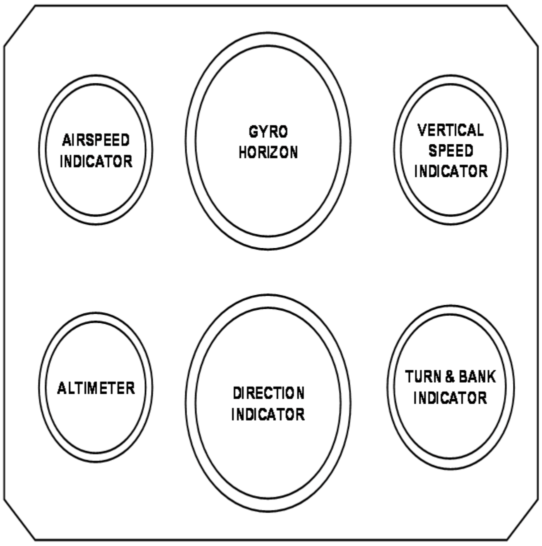
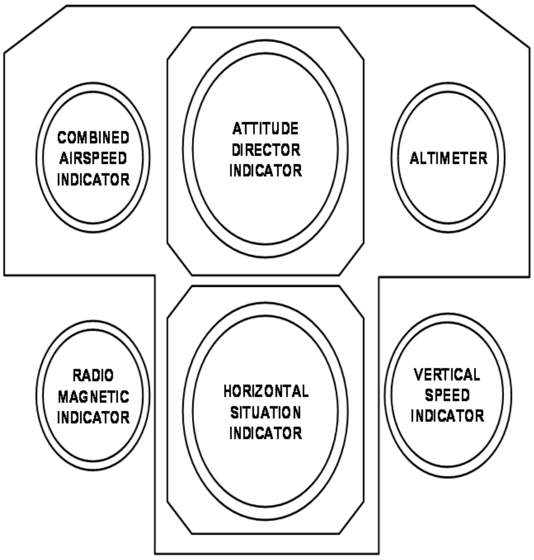
APPENDICES

Appendix A: basic flight instruments

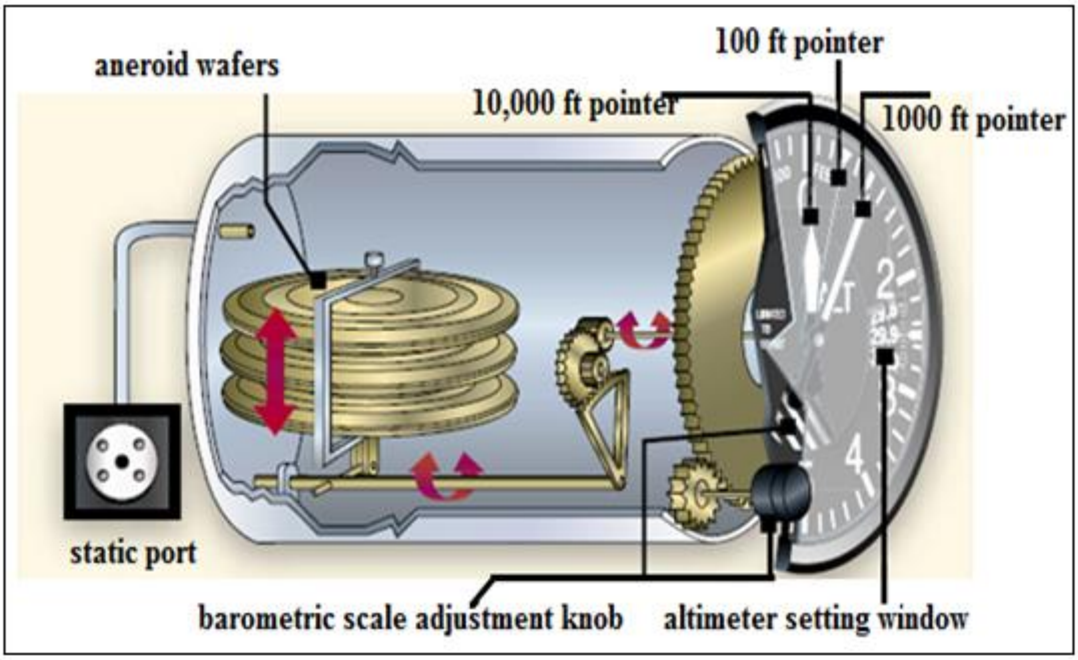


BASIC 6 GROUPING



BASIC T GROUPING

Appendix B: Conventional Barometric Altimeter



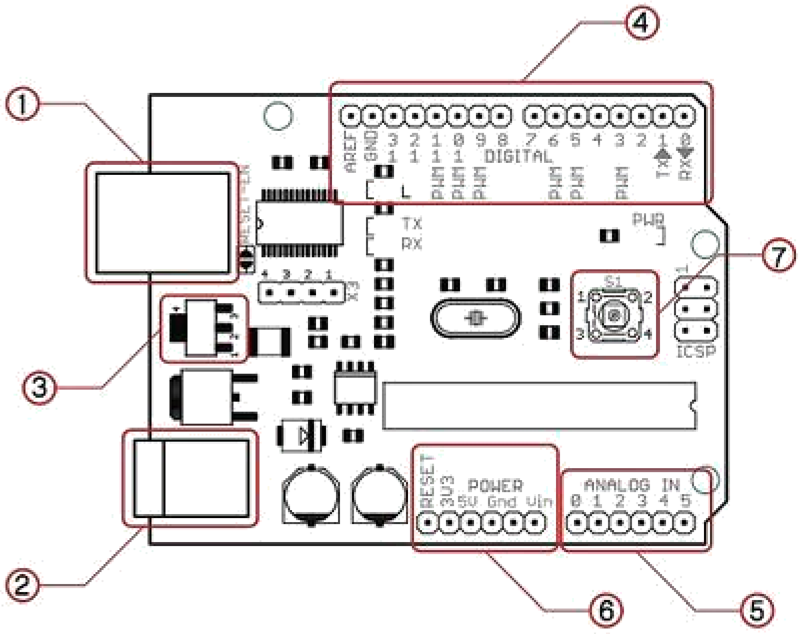
Appendix C: International Standard Atmosphere Model table

Elevation - z - (m)	Temperature - T - (K)	Pressure - p - (bar)	Relative Density - ρ/ρ_o -	Kinematic Viscosity - ν - x 10^{-5} (m^2/s)	Thermal Conductivity - k - x 10^{-2} (W/m K)	Speed of Sound - c - (m/s)
-2000	301.2	1.2778	1.2067	1.253	2.636	347.9
-1500	297.9	1.2070	1.1522	1.301	2.611	346.0
-1000	294.7	1.1393	1.0996	1.352	2.585	344.1
-500	291.4	1.0748	1.0489	1.405	2.560	342.2
0	288.15	1.01325	1.0000	1.461	2.534	340.3
500	284.9	0.9546	0.9529	1.520	2.509	338.4
1000	281.7	0.8988	0.9075	1.581	2.483	336.4
1500	278.4	0.8456	0.8638	1.646	2.457	334.5
2000	275.2	0.7950	0.8217	1.715	2.431	332.5
2500	271.9	0.7469	0.7812	1.787	2.405	330.6
3000	268.7	0.7012	0.7423	1.863	2.379	328.6
3500	265.4	0.6578	0.7048	1.943	2.353	326.6
4000	262.2	0.6166	0.6689	2.028	2.327	324.6
4500	258.9	0.5775	0.6343	2.117	2.301	322.6
5000	255.7	0.5405	0.6012	2.211	2.275	320.5
5500	252.4	0.5054	0.5694	2.311	2.248	318.5

6000	249.2	0.4722	0.5389	2.416	2.222	316.5
6500	245.9	0.4408	0.5096	2.528	2.195	314.4
7000	242.7	0.4111	0.4817	2.646	2.169	312.3
7500	239.5	0.3830	0.4549	2.771	2.142	310.2
8000	236.2	0.3565	0.4292	2.904	2.115	308.1
8500	233.0	0.3315	0.4047	3.046	2.088	306.0
9000	229.7	0.3080	0.3813	3.196	2.061	303.8
9500	226.5	0.2858	0.3589	3.355	2.034	301.7
10000	223.3	0.2650	0.3376	3.525	2.007	299.8
10500	220.0	0.2454	0.3172	3.706	1.980	297.4
11000	216.8	0.2270	0.2978	3.899	1.953	295.2
11500	216.7	0.2098	0.2755	4.213	1.952	295.1
12000	216.7	0.1940	0.2546	4.557	1.952	295.1
12500	216.7	0.1793	0.2354	4.930	1.952	295.1
13000	216.7	0.1658	0.2176	5.333	1.952	295.1
13500	216.7	0.1533	0.2012	5.768	1.952	295.1
14000	216.7	0.1417	0.1860	6.239	1.952	295.1
14500	216.7	0.1310	0.1720	6.749	1.952	295.1
15000	216.7	0.1211	0.1590	7.300	1.952	295.1
15500	216.7	0.1120	0.1470	7.895	1.952	295.1
16000	216.7	0.1035	0.1359	8.540	1.952	295.1

16500	216.7	0.09572	0.1256	9.237	1.952	295.1
17000	216.7	0.08850	0.1162	9.990	1.952	295.1
17500	216.7	0.08182	0.1074	10.805	1.952	295.1
18000	216.7	0.07565	0.09930	11.686	1.952	295.1
18500	216.7	0.06995	0.09182	12.639	1.952	295.1
19000	216.7	0.06467	0.08489	13.670	1.952	295.1
19500	216.7	0.05980	0.07850	14.784	1.952	295.1
20000	216.7	0.05529	0.07258	15.989	1.952	295.1
22000	218.6	0.04047	0.05266	22.201	1.968	296.4
24000	220.6	0.02972	0.03832	30.743	1.985	297.7
26000	222.5	0.02188	0.02797	42.439	2.001	299.1
28000	224.5	0.01616	0.02047	58.405	2.018	300.4
30000	226.5	0.01197	0.01503	80.134	2.034	301.7

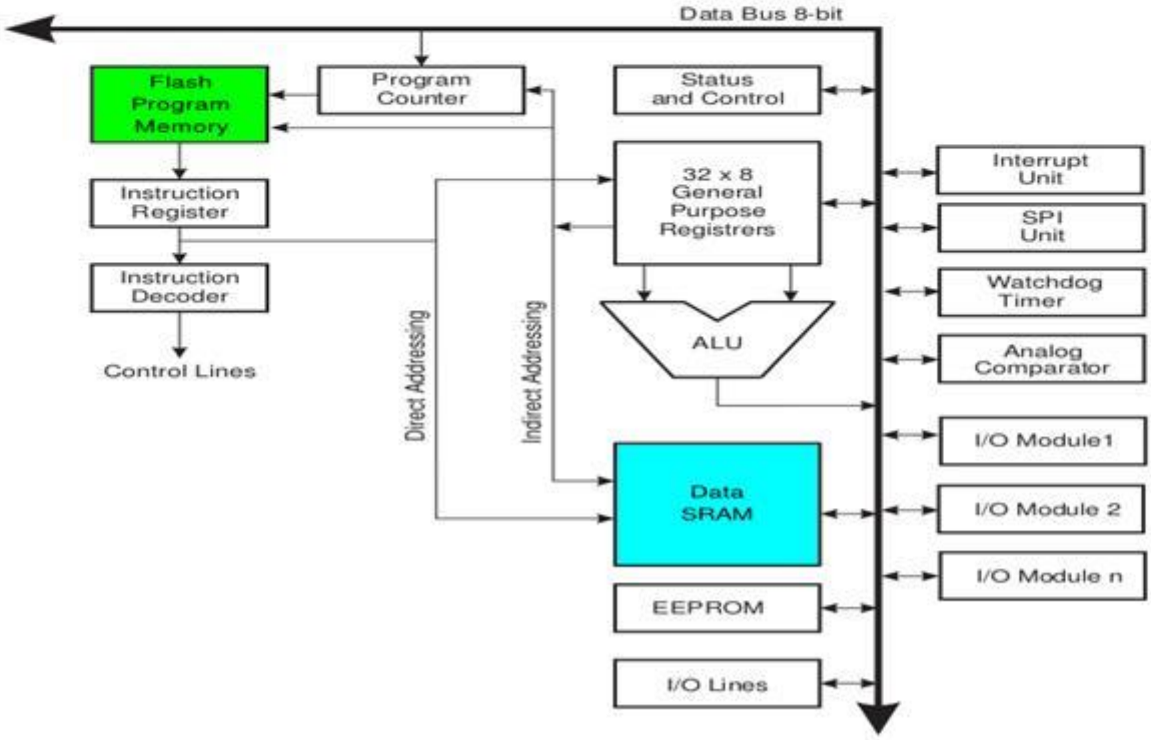
Appendix D: Arduino UNO pin schematic diagram



The most important parts on the Arduino board high lighted in red:

1: USB connector
2: Power connector
3: Automatic power switch
4: Digital pins
5: Analog pins
6: Power pins
7: Reset switch

Appendix E: Arduino Internal Architecture



Appendix F: Arduino program

Liquid Crystal Display testing code

```
/*
 LCD RS pin to digital pin 12                    // LCD interface to Arduino Uno
 LCD Enable pin to digital pin 11
 LCD D4 pin to digital pin 5
 LCD D5 pin to digital pin 4
 LCD D6 pin to digital pin 3
 LCD D7 pin to digital pin 2
 LCD R/W pin to ground
 LCD VSS pin to ground
 LCD VCC pin to 5V
 10K resistor:
 ends to +5V and ground
 wiper to LCD VO pin (pin 3) */
#include <LiquidCrystal.h>                 // include the library of LCD
#include <math.h>
LiquidCrystal.lcd (12, 11, 5, 4, 3, 2);   // set  and initialize the interfacing pins of LCD
void setup() {
       lcd.begin(16, 2);                        // set up the LCD's number of columns and rows:
       lcd.print("hello, world!");            // Print  test message to the LCD.
       }
void loop() {
      lcd.setCursor(0, 1);                    // set the cursor to column 0, line 1
      lcd.print(millis() / 1000);            // print the number of seconds since reset
     }
```

BMP180 Barometric Pressure & Temp Sensor testing code

```
#include < Wire .h >
#include <Adafruit_BMP180.h>
/*
- Connect VCC of the BMP180 sensor to 3.3V (NOT 5.0V!)
- Connect GND to Ground// Connect SCL to Analog pin 5
- Connect SDA to Analog pin 4
- EOC is not used, it signifies an end of conversion
- XCLR is a reset pin, also not used here
*/
```

```
void setup ()
{
   Serial.begin(9600);
   if (!bmp.begin()) {
   Serial.println("Could not find a valid BMP180 sensor, check wiring!");
   while (1) {}
   }
   }
void loop() {
   Serial.print("Temperature = ");
   Serial.print(bmp.read Temperature());
   Serial.println(" degree C");
   Serial.print("Pressure = ");
   Serial.print(bmp.readPressure());
   Serial.println(" Pa");
   delay (500);
}
```

Basic code for actual altitude calculation and error estimation

```
#include <LiquidCrystal.h>
#include <math.h>
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);                 // set the interfacing pins of LCD
int sensor1Pin =A0;                                    // arduino Pins that control relay
 int sensor2Pin =A1;
int LEDPin=13;
float  T,P;
float Altitude;
float Vout;
float S,N,H;
float dT0,dP0,dPH;
float dHT0;
float dHPO;
float dHPH;
float L,U,F,J,K,Z;
float dHa;
float DH;
const float T0 = 288.15;               // standard atmospheric temperature at sea level in (k )
const float P0 = 1013.24;               // standard atmospheric pressure at sea level in( Kpa)
const float a = - 0.0065;             // vertical temperature change rate in (° K/km)
const float R = 287.05287;            // universal gas constant in (m2/ (K x s2)
const float g = 9.80665;               // the gravity acceleration in (N/m2)
const float m = -433081.08;
const float row =1.225 ;              // atmospheric density
```

```
const int absolute ceiling =2000;
void setup ()
{
pinMode (sensor1Pin, INPUT);                 // configuring Pins A0, A1 as inputs
pinMode (sensor2Pin, INPUT);
pinMode(13, OUTPUT);                         // set led pin as output
lcd.begin(16, 2);                            // initialize 16× 2 LCD
lcd.print("hello, world!");
lcd.setCursor (2,0);                         // sets the cursor at row 0 column 1
lcd.print("altimeter ready");
Serial.begin (9600);
}
void loop ()
{
Vout = analogRead(A1);                       // read the voltage value from the sensor
Vout = (Vout*5.0)/1024.0;
T = Vout * 100;                              // sensed temperature in degree
P = analogRead(A0);                          // read the pressure value from the sensor
P = ((P/1024.0) +0.095)/0.009;
S = P/P0;
N= pow(S,m)-1;
H= (T0/a) *N;                                // equivalent altitude value

// Errors Estimation Subroutine
dT0 =T-T0;
dHT0 = - (dT0/T0)*H;                         // altitude error due drift of T0 from standard
dP0 = P-P0;
dHp0 = (R/g)* (T0 +a*H)*(dP0/P0);            // altitude error due drift of P0 from standard
L = H*(a/T0) +1;
U = - (1+ (g/(R*a)));
F = g*row*(pow (L, U));
dPH = PH-PH (ISA);
dHPH = pow (F,-1)*dPH ;                      // altitude error due drift of PH
J = (1+(a*H/T0));
K = pow(a,2);
Z = log(J);
dHa = -(T0/K)*(( 1+J )*(Z -1));        // altitude error due drift of alpha (a) from standard
DH  = dHT0 + dHPO + dHPH + dHa ;   // total altitude drift  of the system
```

```
// Errors Compensation Subroutine
Real Altitude = H+DH;                    // Real altitude read
lcd.clear();
lcd.setCursor (0, 0);                    // sets the cursor at row 0 column 0
Serial.print("Temperature = ");
Serial.print(T());
Serial.println(" degree C");

Serial.print("Pressure = ");
Serial.print(P());
Serial.println(" Pa");

Serial.print("Altitude = ");
Serial.print(H ());
Serial.println(" meters");

Serial.print("Real altitude = ");
Serial.print(Real Altitude ());
Serial.println(" meters");

Serial.println();
delay (500);


lcd.setCursor(0, 0);
lcd.print("Temperature = "),
lcd.setCursor(0, 1);
lcd.print(T ());
lcd.print(" degree C");
delay (2000);
lcd.clear();

lcd.print("Pressure = "),
lcd.setCursor(0, 1);
lcd.print(P());
lcd.print(" Pascal");
delay (2000);
lcd.clear();

lcd.print("Altitude = "),
lcd.setCursor(0, 1);
lcd.print(H());
lcd.print(" meter");
delay (2000);
lcd.clear();

lcd.print("Real altitude = "),
lcd.setCursor(0, 1);
```

```
lcd.print(Real Altitude ());
lcd.print(" meter");
   delay (2000);
   lcd.clear();
if (Altitude>= absoluteceiling)
 {
  digitalWrite(ledPin,HIGH);
  tone (8,50,20);
  lcd.setCursor (7, 1);
  lcd.print ("maxuimum crusing altitude");

  }
}
```