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Micro Electro Mechanical System (MEMS) based Pressure Sensor in Barometric Altimeter

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Abstract--- Barometer is a well-organized tool for determining atmospheric pressure. The altimeter is a tool which calculates the vertical distance in accordance with a reference level. The barometric altimeter, computes the altitude according to the atmospheric pressure. Accuracy and size are the major issues in altimetry. On the other hand the present day altimeters employing conventional pressure sensors consume more floor space and provide very less accuracy. To resolve this problem, in this paper implemented a Micro Electro Mechanical System (MEMS) based pressure sensor in the design of barometric altimeter. MEMS are a class of systems that shares the existence of micro machined parts having both electrical and mechanical components incorporated on a single chip. MEMS pressure sensor guarantees higher degree of accuracy and reliability. These MEMS based barometric altimeter system operates with high sensitivity in the pressure. A temperature sensor is interfaced with the system so as to implement the dynamic temperature profiling approach as an attempt to eliminate the temperature dependent errors prevailing in the present day standard temperature profiled altimeters. MEMS based Barometric Altimeter is implemented using the following two modules: Embedded Module and Simulation Module. Even though the size of the MEMS based Barometric Altimeter is reduced, it provides more accuracy.

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1. INTRODUCTION

ALTIMETER is an active tool which is used to calculate the altitude of an object over a predetermined level. The altimeter is an apparatus which determines vertical distance in accordance with a reference level. Louis Paul Cailletet was the French physicist who invented the altimeter and the high-pressure manometer. The conventional altimeter established in the majority of aircraft executes its work by calculating the air pressure from a stationary port. Air pressure reduces with the raise of altitude - about one millibar (0.03 inches of mercury) per 27 feet (8.23 m) closer to sea level. The altimeter is consistent to provide the pressure straightforwardly as altitudes, suitable to a mathematical model defined by the International Standard Atmosphere (ISA) [10].

Barometer is a well-organized tool for computing atmospheric pressure. It was invented in 1643 by the Italian scientist Evangelista Torricelli, who utilized a column of water in a tube 34 ft (10.4 m) long [14]. This difficult water column was almost immediately substituted by mercury, which is denser than water and requires a tube about 3 ft (0.9 m) length. The mercurial barometer contains a glass tube, sealed at one end and loaded with unadulterated mercury. After being heated to force out the air, it is overturned in a little cup of mercury called the cistern. The mercury in the tube goes under the surface to some amount, producing above it a vacuum (the Torricellian vacuum).

The barometer is an apparatus that can be utilized to determine the atmospheric pressure and is one of the most important apparatus in the science of meteorology. The accomplishment of barometer gives answer to a vital question of natural thinking at the time of its development: "Does the air have weight?" The air contains certain weight since the air is composed of molecules of nitrogen, oxygen, argon, water vapor, carbon dioxide and many other gases. These gases include some amount of mass and this is the reason why air is forced in the direction of the centre of the earth by the gravity. Since it is well-known, that the weight of the air approaching on every unit of surface area on the ground is called atmospheric pressure and this is the pressure computed by the barometer.

In 1928, German discoverer Paul Kollsman altered the world of aviation with the discovery of the world's first precise Barometric Altimeter also called the "Kollsman Window". The barometric altimeter, computes the altitude according to the atmospheric pressure, particularly, how the pressure and temperature of the air transforms with altitude, if the altitude is more, then the pressure is lesser and the lesser the temperature [6]. The normal pressure at sea level is 29.92 inches of mercury and the average temperature is 15° C or 59° F. If the pressure is not according to the normal pressure, the altimeter presents a barometer setting to modify to the

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non standard value. But, there is no potential for changing a non standard temperature.
The barometric altimeters perform its work by computing air pressure and comparing it to a particular altitude [12]. At elevated altitudes, air pressure reduces; at small altitudes, air pressure raises [21]. A barometric altimeter computes the air pressure identical to a meteorological barometer and then converts that measurement into an amount of altitude. A barometric altimeter has to be standardized for adjustments to local air pressure to achieve a good exact reading.
Accuracy and size are the major concern in altimetry [8] [16]. On the other hand the current day altimeters makes use of traditional pressure sensors which consumes more floor space and offers very poor accuracy. To resolve this issue, in this paper implemented a Micro Electro Mechanical System (MEMS) based pressure sensor in the design of barometric altimeter [17] [19].

1.1 Characteristics of the Pressure Sensor

Sensitivity

The sensitivity is defined as the change in input parameter which is required to produce a standardized change in the output. In TO-8 sensors sensitivity is expressed in millivolt per bar. The sensitivity of one bar, absolute MEMS pressure sensor is 100mV/bar.

Dynamic Range

The dynamic range is the range of input values in which the sensor is supposed to operate. That is, the minimum and maximum values of input quantity which the sensor is designed to measure. The dynamic range of this sensor is 0-1 bar.

Hysteresis

Hysteresis is the belongings due to which the output of the transducer becomes capable of following the changes in the input regardless of the direction in which the change is made.

Resolution

It is the smallest increment of quantity being measure which be detected with certainty by a sensor. Resolution can be expressed either as a proportion of the reading (or the full-scale reading) or in absolute terms.

Accuracy

It is defined as the degree of closeness with which the instrument reading approaches the true value of the quantity to be measured. Again, the accuracy can be expressed either as a percentage of full scale or in absolute terms. Accuracy of the sensor used is $\pm 0.1\%$ full scale.

Offset

The drift in the value of sensor output even when the input variable is zero for an extended period of time is termed as the Zero drift or Offset.

Linearity

The linearity of the sensor is the ability to reproduce the input characteristics symmetrically and linearity; it indicates the straight line nature of the calibration curve. The static nonlinearity is often subject to environmental factors like temperature, vibration, acoustic noise level, and humidity.

2. RELATED WORKS

C.E. Lin, et al., [1] proposed electronic barometric altimeter in real time correction. The barometric altitude calculation by means of modern electronic sensors has considerable error because of atmospheric pressure deviation in accordance with the weather and time. Depending on the altimeter setting idea, the barometric altimeter is supposed to be accurate based on hourly QNH data to preserve accuracy. This paper presents an airborne altitude computation approach with the help of barometric measurement and actual time calibration through GPRS uplink. The proposed technique is convenient in finding the time variant error of the electronic barometric altimeter without human intervention. Once these corrections are completed, the static and dynamic accurateness of the electronic barometric altimeter can be much enhanced into less than 2% errors in real time. The proposed method is appropriate for ultra light aircrafts (ULA) or unmanned aerial vehicles (UAV).
Zichen Zhu, et al., [2] recommended a micro barometric altimeter with applications in altitude-holding flight control for MAVs. This paper explains the progress of the altimeter for Micro Aerial Vehicles (MAVs) and its implementation in altitude-holding flight. The possible tasks for MAVs comprises of military missions and marketable applications, for instance visual reconnaissance, communications relay, investigate and rescue and field research. For these tasks, the altitude control is essential. A micro barometric altimeter was implemented as an element of the control system to feature altitude hold. The 3-gram altimeter provides a greater resolution and accuracy. The low frequency noise produced by vibration of airframe is detected, so the Kalman filter is used. Many experiments carried out on numerous aerial vehicles with 680 mm span to test this altimeter and PD control law, the vehicle issuccessful in hovering automatically.
M. Tanigawa, et al., [3] suggested drift-free dynamic height sensor using MEMS IMU aided by MEMS pressure sensor. An economical, less-power, and little form factor solution to drift-prone, better resolution, vertical positioning by integrating MEMS accelerometers with MEMS barometric altimeter is established. In this method, an extremely reactive but drift-free characteristic of the MEMS accelerometers is become constant by barometric altimeter and high-reliability height tracking is obtained. Classic perpendicular human actions such as walking up or down a step can be tracked in real-time

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with this method. The height tracking performance of this method is tested with standard dataset and an error analysis is carried out.

Qiang Zhou et al., [4] recommended a novel barometric altimeter system for vehicular testing of SINS. An innovative barometric altimeter arrangement for the application of vehicular examination of SINS has been planned and implemented. The barometric altimeter arrangement has been planned to provide altitude and speed details of the vehicle. The most important component of the barometric altimeter arrangement is the pitot tube, the gas circuit, huge-accurate sensors, one PXI acquisition computer and user program. The entire arrangement and the gas circuit are provided. A realistic dynamic calibration has been taken to balance the altitude value calculated by the barometric altimeter method. Numerous testing have been executed to estimate the effectiveness of the barometric altimeter method. The observation shows that this method is very compact. The altitude and speed details of the vehicle can be calculated in real time. Therefore, it is appropriate for the vehicular dynamic testing atmosphere.

R. Govindan, et al., [5] proposed an altimeter-derived ocean wave period using genetic algorithm. It is recognized that wave period can be expected from altimeter measurements of wave height, wind speed, radar backscatter cross section, etc., by means of empirical association [7] [15]. Recently, the data adaptive method of neural networks has been utilized to obtain wave period from altimeter data, and it has been revealed that the approach emerges to be better compared to the empirical techniques. An additional commanding data adaptive technique of genetic algorithm has been discussed more in recent times in oceanographic investigations. Even though mainly used for forecasting time series, the approach can be tuned to discover a relationship among input and output variables [9]. In the current work, this approach has been used to get estimates of wave period from altimeter-observed parameters, and the effectiveness of the approach has been found to be reasonably acceptable [13]. It has been also established that the beginning of wave age shows the way to noteworthy development of the accuracy of the estimate.

3. Micro Electro Mechanical Systems

Micro Electro Mechanical Systems (MEMS) are little integrated apparatus or arrangement that integrates electrical and mechanical elements. They vary in size from the sub micrometer altitude to the millimeter altitude and there can be several numbers, from a small number to millions, in a specific system. MEMS broaden the fabrication approaches developed for the integrated circuit industry to include mechanical elements for instance beams, gears, diaphragms and springs to devices [18].

These devices can sense, manage and trigger the mechanical processes on the micro scale, and perform independently or in arrays to produce effects on the macro scale. The micro fabrication machinery facilitates fabrication of huge arrays of apparatuses, which independently carry out simple tasks, but in combination can carry out complicated functions.

The major applications MEMS device comprises of fluid pumps, inkjet-printer, cartridges, micro-engines, locks, inertial sensors, micro-transmissions, micro-mirrors, micro actuators, optical scanners, miniature robots, accelerometers, transducers and chemical, pressure and flow sensors. Latest applications are budding as the existing application is applied to the miniaturization and combination of traditional devices.

MEMS approach can be put into practice using a number of different materials and modern techniques; the preference of which will depend on the device being produced and the market area in which it has to operate [20].

Materials for MEMS manufacturing: Silicon, Polymers, Metals.

4. MEMS Basic Processes

Deposition Processes

One of the essential building blocks in MEMS processing is the capability of depositing thin films of material with a thickness somewhere between a few nanometers to about 100 micrometers.

Patterning

Patterning in MEMS is defined as the process of transportation of a pattern into a material.

Lithography

Lithography in MEMS circumstance is characteristically the transfer of a pattern into a photosensitive substance by careful exposure to a radiation source for example light [18]. A photosensitive material is a material that undergoes a certain alteration in its physical properties when shown to a radiation source. If a photosensitive material is partially shown to radiation, the pattern of the radiation on the substance is moved to the material exposed, since the property varies between the exposed and unexposed areas.

This exposed area can then be detached or conditioned by offering a mask for the underlying substrate. Photolithography is characteristically used with metal or some other thin film deposition, wet and dry etching.

Etching Processes

There are two fundamental kinds of etching practices: wet and dry etching. In the wet etching, the substance is liquefied when dipped in a chemical solution. In the dry etching, the substance is sputtered or suspended by using reactive ions or a vapor phase etchant methods.

Wet Etching

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This is the easiest etching method. All it needs is a bottle with a liquid solution that will liquefy the substance in question. But, there are difficulties because generally a mask is preferred to selectively etch the substance. One should be required to discover a mask that will not liquefy or at least etches very slower than the substance to be patterned. Then, certain single crystal substances, for instance silicon, show anisotropic etching in some chemicals. Anisotropic etching in contradiction of isotropic etching says that different etches rates in dissimilar directions in the substance. The typical example of this is the $< 111 >$ crystal plane sidewalls that come into view when etching a hole in a $< 100 >$ silicon wafer in a chemical for instance potassium hydroxide (KOH). The effect is a pyramid shaped hole rather than a hole with rounded sidewalls with an isotropic etchant.

Electrochemical Etching

Electrochemical etching (ECE) for dopant-selective elimination of silicon is a general technique to automate and to selectively manage etching. A dynamic p-n diode junction is necessary, and either kind of dopant can be the etch-resistant ("etch-stop") substance. Boron is the familiar etch-stop dopant. With the integration of wet anisotropic etching as explained, ECE has been used effectively for controlling silicon diaphragm thickness in commercial piezo-resistive silicon pressure sensors. Areas which are selectively can be produced either by implantation, diffusion, or epitaxial deposition of silicon.

Dry Etching

Xenon difluoride (XeF2) is a dry vapor phase isotropic etch for silicon initially used for MEMS in 1995 at University of California, Los Angeles.[4][5] it is chiefly used for releasing metal and dielectric structures by undercutting silicon, XeF2 has the improvement of a stiction-free release not like wet etchants. Its etch selectivity to silicon is extremely high, permitting it to work with photoresist, SiO2, silicon nitride, and several metals for masking. Its reaction to silicon is "plasmaless", is entirely chemical and impulsive and is frequently operated in pulsed mode. Models of the etching action are obtainable, [6], and university laboratories and numerous commercial tools provide solutions using this technique.

HF Etching

Hydrofluoric acid is generally used as an aqueous etchant for silicon dioxide (SiO_2, also known as BOX for SOI), usually in 49% in rigorous form, 5:1, 10:1 or 20:1 Buffered Oxide Etchant (BOE) or Buffered HF (BHF). They were primarily used in medieval period for glass etching. It was also utilized in IC fabrication for sampling the gate oxide before the arrival of RIE as a substitution.

Hydrofluoric acid is regarded as one of the more hazardous acids in the hygienic room. It enters into the skin upon get in a touch on it and it diffuses directly to the bone.

Reactive Ion Etching

In reactive ion etching (RIE), the substrate is positioned within a reactor where numerous gases are established. Plasma is struck in the gas combination with the help of an RF power source, rupturing the gas molecules into ions. The ions are speeded up towards, and react with, the exterior face of the substance being etched, producing an additional gaseous substance. This is recognized as the chemical step of reactive ion etching. There is also a physical step which is related in nature to the sputtering deposition procedure. If the ions posses elevated adequate energy, they can blow atoms out of the substance to be etched without any chemical reaction. It is extremely difficult operation to build up dry etch processes that stabilize chemical and physical etching, as there are numerous parameters to alter. By altering the balance it is achievable to pressure the anisotropy of the etching, because the chemical step is isotropic and the physical step is extremely anisotropic the mixture can form sidewalls that have shapes from rounded to vertical. RIE can be deep and its name would be Deep RIE or DRIE Deep reactive ion etching (DRIE)

Deep Reactive Ion Etching

A special subclass of RIE which maintains to develop quickly in reputation is deep RIE (DRIE). In this method, etch depths of hundreds of micrometers can be achieved with approximately all vertical sidewalls. The most important method is the basis on the so-called "Bosch process", named after the German company Robert Bosch which filed the unique copyright, where two dissimilar gas compositions are alternated in the reactor. At present there are two dissimilarities of the DRIE. The primary variation comprises of three different steps (the Bosch Process as utilized in the UNAXIS tool) while the second dissimilarity only comprises of two steps ASE used in the STS tool. In the initial Variation, the etch cycle is as follows: (a0 SF6 isotropic etch; (b) C4F8 passivation; (iv) SF6 anisotropic etch for ground cleaning. In the next variation, steps (a) and (c) are integrated.

Both variations work correspondingly. The C4F8 produces a polymer on the surface of the substrate, and the second gas composition (SF6 and O_2) etches the substrate. The polymer is immediately sputtered away by the physical fraction of the etching, other than that only on the horizontal surfaces and not the sidewalls. As the polymer only dissolves very gradually in the chemical part of the etching, it builds up on the sidewalls and guards them from etching. From the observation, etching aspect ratios of 50 to 1 can be attained. The process can straightforwardly be utilized to etch entirely through a silicon substrate, and etch rates are 3– 6 times superior than wet etching.

5. MEMS Based Pressure Sensor

Inspite of the presence of so many altitude-measuring

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technologies there are certain problems that continue to prevail due to the characteristics of the pressure sensing element. At ultra low pressure values measurement becomes increasingly difficult due to decreased accuracy of the absolute pressure sensing element. Sensors that depend on thermal conductivity or ionized gas for measurement respond differently to different gases, and hence they need to be calibrated against dry air. At the same time conventional pressure sensors are bulky in size hence they occupy more floor space.

The solution to above problems is to use an integrated control circuit along with miniaturized absolute pressure sensor. The simplest unit that would integrate the electronic control circuit and the high performance mechanical sensor is the MEMS based pressure sensor.

The use of MEMS technology has created a breakthrough in the design of sensors. Extremely small silicon capacitive absolute pressure sensor can now be realized by utilizing the MEMS technology. This new break through has created possibilities to design extremely robust capacitive pressure sensing elements with low current consumption and excellent performance.

The complete sensor component is only 6mm in diameter and 1.7mm high. This device is capable of detecting the smallest barometric pressure change, which enables extremely accurate weather forecasting and altitude measurements. The supply voltage ranges from (3-5) V and current consumption of (0.5-50) µA make it easy to integrate into products like sport watches and other equipments.

6. MEMS Altimetry

1.1. Design Criterion

1. The barometric altimeter system needs a pressure sensor that must have a pressure range of 64kPa to 105 kPa.
2. There are three different kinds of pressure measurements: gauge, absolute and differential. As the most important objective is to calculate alterations in ambient pressure, hence there is requirement for a known pressure reference. As a result, the pressure sensor must be able to measuring absolute pressure.
3. Since there can be huge temperature transform from one elevation to another, the sensor for the design should be reference calibrated and temperature balanced.
4. Therefore a 1-bar, compensated, MEMS based absolute pressure sensor would be the best choice that would design the design criterion.

1.2. Working

A real time working model of a MEMS based barometric altimeter was created as per the design is . After the design and selection of an appropriate pressure sensing element and amplification circuit an embedded circuitry was developed in order to interface the system with the real time environment. Investigating the memory space required and the resolution of the ADC unit 8051 was chosen to be the MCU for the reference design. A sophisticated Human Machine Interface (HMI) was also created by using mode selection switches as the input device and a LCD unit as the output device.

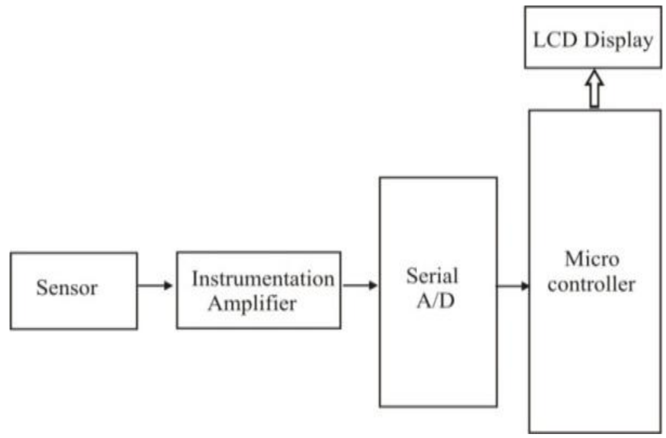

Fig-1: General Block Diagram of Barometric Altimeter

Pressure and temperature are the two physical quantities that are necessary to calculate the value of altitude from the reference plane (Mean Sea Level).The value of atmospheric pressure prevailing in the environment is sensed by the pressure sensors whereas the ambient temperature is sensed by using an appropriate temperature sensor.

The analog signals from these sensors are fed into the inbuilt ADC of the microcontroller. The digital values thus obtained are processed according to the mathematical model which correlates the values of pressure with altitude. Hence from the known values of pressure and temperature the values of unknown variable, 'Altitude' can be found out.

As an attempt for effective data utilization the values of sensed temperature and pressure are also displayed in the LCD along with the calculated value of altitude. A sophisticated Human Machine Interface (HMI) is created by using three mode selection switches which enables the user to use the equipment in three different operating modes.

1.3. Implementation Modules

The working model of the MEMS based altimeter comprises of two modules:

- Simulation Module
- Embedded Module

1.3.1. Simulation Module

The MEMS based altimetry is designed to operate in the pressure range of 64kPa to 105kPa.Inorder to verify the operating characteristics of the altimeter a low pressure zone is created by means of employing a Simulation chamber [11].

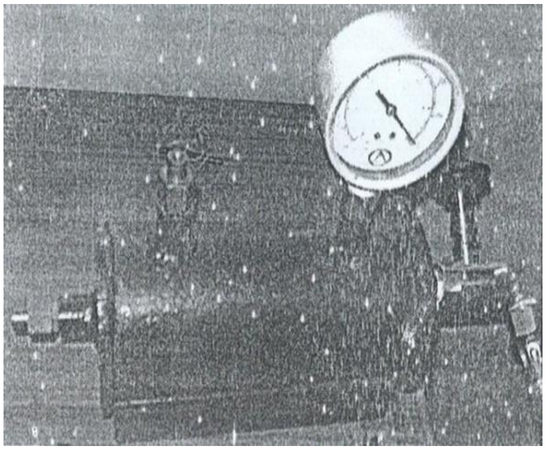

Fig-2: Simulation Module

The simulation chamber is constructed using mild steel sheets. Provisions are made for the accommodation of the MEMS sensor, vacuum gauge and an exhaust valve. A low pressure region is created by sucking out air from the sealed chamber using a vacuum pump. The low pressure region thus formed is maintained by closing the needle valve.

1.3.2. Embedded Module

The embedded module comprises of the electronic components required for the sensing and processing of the two physical quantities i.e., temperature and pressure.

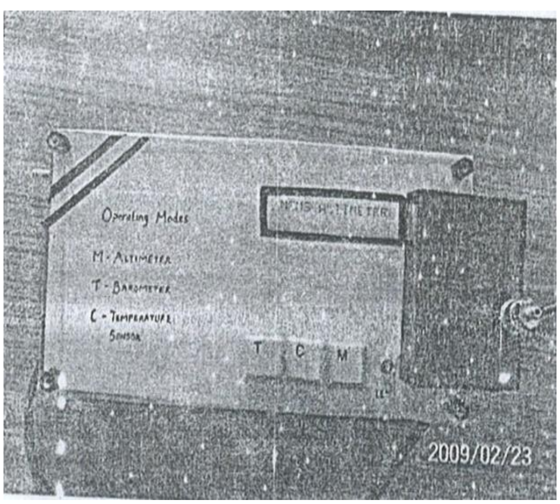

Fig-3: Embedded Module

1.4. Modes of Operation

The reference design of the MEMS based altimetry is mainly concerned towards the accurate measurement of altitude. In the process of determining the altitude two of the physical parameters i.e. pressure and temperature are processed. Therefore as an attempt of effective data utilization, these values of atmospheric pressure and ambient temperature are displayed.

In order to display the real time values a HMI is created using press button switches which makes the system to operate in three different modes.

In mode one the system operates as an altimeter and it provides the altitude values in meters. In mode two the system operates in barometric mode and it provides the value of atmospheric pressure in terms of torr. Whereas in mode three the system is designed to operate as a temperature sensor and it display the ambient temperature in degree Celsius. The modes of operation are given in Table I.

TABLE I: MODES OF OPERATION

Operating Modes	Purpose
Altimeter	To display the value of altitude from the Mean Sea Level in meter. (Meters above M.S.L).
Barometer	To display the value of atmospheric pressure prevailing in the working environment in torr.
Temperature sensor	To display the value of ambient temperature in degree Celsius.

7. EXPERIMENTAL RESULTS

Barometric Altimeter uses MEMS based pressure sensor and it finds the altitude of an above the reference level based on the atmospheric pressure. The atmospheric pressure changes with the altitude. At different altitude there exists different atmospheric pressure and if the altitude increases, the atmospheric pressure will decrease. Hence the atmospheric pressure will decrease with the increase in the altitude.

The equation that was used for this reference design is exponential.

$$P = (P_0)e\hat{}[-(g/(RT)) \times (Z - Z_0)]$$

Where

P = pressure at an unknown altitude,
P_0= pressure at a known altitude,
e = a constant,
g = gravitational constant 9.8 (m/s^2),
R = dry air constant 287 J/(kg x K),
T = temperature at unknown elevation in Kelvin,
Z = unknown altitude in metres and

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Z_0= known altitude also in metres.

This equation originates from the hydrostatic equation:

$$dP = -\rho g dZ$$

The equation is in conjunction with the ideal gas law:

$$P = \rho RT$$

After some algebraic manipulation, plugging in constant values and converting meters to feet, the following equation was generated:

$$Z = Z_0 - (27887 \times ln\,(P/P_0))$$

Where

Z = unknown altitude in feet,

Z_0= known altitude also in feet,

P = known pressure at unknown altitude and

P_0 = known pressure at known altitude.

For this method to compute an altitude, Z, at a known pressure P, the user have to enter a known pressure, P_0, and its equivalent altitude, Z_0. To accommodate for changes in barometric circumstances, the known pressure and altitude data is required to be re-entered during each use to ensure accuracy.

The accuracy comparison of existing and MEMS based barometric altimeter is tabulated in Table II.

TABLE II: ACCURACY COMPARISON OF EXISTING AND MEMS BASED BAROMETRIC ALTIMETER

Barometer (mm Hg)	Atmospheric Pressure (PSI)		Altitude above Sea Level (Feet)	
	Existing Barometric Altimeter	MEMS Based Barometric Altimeter	Existing Barometric Altimeter	MEMS Based Barometric Altimeter
787.9	15.46	15.23	-1026	-1000
773.9	15.11	14.96	-523	-500
760.0	14.83	14.69	-7	0
746.3	14.57	14.43	483	500
738.0	14.35	14.16	923	1000
719.6	14.06	13.91	1429	1500
706.6	13.92	13.66	1923	2000
693.9	13.75	13.41	2323	2500
681.2	13.43	13.17	2912	3000
668.8	13.24	12.93	3400	3500
656.3	13.16	12.69	3865	4000
632.5	12.42	12.23	4265	5000
609.3	11.93	11.78	5210	6000
586.7	11.72	11.43	6597	7000
564.6	11.72	10.91	7551	8000
543.3	10.62	10.5	8254	9000
522.7	10.4	10.1	9232	10000
429	9.23	8.29	1483	15000

Table II shows that the proposed MEMS based barometric altimeter provides more accuracy in measuring the altimeter than the other existing approach.

8. CONCLUSION

The Altimeter, an incorporated barometer discovers its variety of application in the area of GPS system, weather stations & industrial systems. This paper illustrates the implementation of a MEMS pressure sensor in the design of a barometric altimeter which has significantly reduced the size and increased the accuracy of the barometric altimeter. Furthermore a temperature sensor is interfaced with the system with the intention of implementing the dynamic temperature profiling approach as an attempt to remove the temperature dependent errors prevailing in present day standard temperature profiled altimeters. Experiments result proves that the Micro Electro Mechanical System (MEMS) based pressure sensor in barometric altimeter provides more accuracy in measuring altitude than the existing Barometric Altimeter.

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