Printed Circuit Board Design of a Low Power, Lightweight and Compact 3D Structured Air Quality Monitoring System

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Abstract

This paper presents wireless integrated compact, lightweight and portable printed circuit board (PCB) device of air quality monitoring system (AQMS). The system is fabricated in double-sided three PCBs to observe real-time data of CO₂, CO, NO₂ and weather parameters. For the convenience of 3D stacking, the PCB design is built on three boards so that it consumes minimum area. The volume of the entire board is found 110 mm × 80 mm × 24 mm. Strategy of power reduction has been adopted in the design. To reduce power consumption, switching technique is applied to the electronic sensors. This technique is controlled by the use of demultiplexer device. This low power switching technique enhances the battery life of the AQMS structure has been enhanced. Experimental results show that with the chosen battery bank, average power is 1.0588992 Watt during runtime operation of the device. Thus, AQMS runs in safe mode for 33.75 hours continuously using a fully charged power bank. Electrostatic discharge (ESD) protection has been introduced in the PCB to prevent the circuit damage from high voltage during data transmission. The system is capable of being powered by natural resources such as the solar system, which is installed to charge lithium-ion battery. Moreover, the physical weight of the fabricated device is 172gm excluding the weight of the package.

1 Introduction

The level of air pollution in the world is increasing day by day to this extent which is affecting the natural cycle and disrupting quality of human life. Thus, monitoring of air quality plays an important role in identifying levels of air pollution [1]. Due to the rapid development of industrialization and urbanization processes in the world, environmental pollution has become a deep problem around the globe. Over the past few years, research into smart sensor networks [2], [3] has been carried out, and the possibilities of using sensor networks in air quality measurement methods are being studied. More than around fifty-five thousand people die per year from air pollution caused by vehicles [4]. Hence, some instruments are necessary to detect real-time air quality measurements to help people understand in detail about air quality levels. With the aim of minimal maintenance, this air quality monitoring instrument should be reliable, easy to use for both long-term and short-term deployments. A processor is designed for tracking out polluted air due to CO, NO₂, and SO₂ in [5]-[7]. The effects of greenhouse gases (CO, NO₂, and SO₂) are growing continuously. Therefore monitoring these effects also become an important goal of human life [8], [9]. As the effects of the greenhouse gases are increasing, the monitoring system should have the ability to find out the concentration of greenhouse gases [10]-[12]. The developed AQMS in this paper is useful due to its portability, compact size and it can be used in awareness of health impacts. AQMS is developed as a stand-alone system, which is expert in monitoring data from different locations such as indoor as well as outdoor environments. This monitoring system is well featured in research level accuracy.

The development of sensor nodes focuses on the structural elements of [13] and allows people to design environmental monitoring systems [14], [15]. The monitoring system consists of multiple sensors for gathering data and monitors air pollutants in real-time. Wireless sensor network (WSN) application is

necessary to satisfy the demand of achieving information of a system in real-time [16]. Wireless communication is designated for some solutions, like interfacing of sensors and other elements, data formation as a packet, processing and transmission of data through wireless channel, which are combined easily with extended nodes [17]. Another sensor network reported in [18], [19] is designed based on wireless communication for monitoring real-time data of toxic compounds in the atmosphere. The state of the art in different areas of research concept has been presented in [7] based on WSN. In most cases, research related projects can be seen on the basis of mathematical calculations, simulations and theoretical models, where accuracy is checked with lab tests. Proposed implementation of Internet of Things (IoT) vision, which illustrates the effects of the Internet of Things on industry and environment based wireless sensor network reported in [20], [21]. After gathering the valuable information from the study of Internet of Things, it is expected to incorporate Internet of Things in the extended version of this PCB design in future analysis. In [22], authors discussed the working principle of forecasting model of urban air quality monitoring system. The literature describes a variety of solutions that provide a limited design concept for the expanded formation of the system. But the solution of accuracy and achieving battery lifetime in the design is not measured. There are several studies available to evaluate circuit functionality [23], integration of all components, data collection process, cost of microcontroller board etc. Implementation of wireless based device to check health parameters are defined in [24]. So far, in the previous literatures there are no methods adopted for low power in the PCB based monitoring system. In this paper, hardware PCB design of AQMS is addressed. We have developed a strategy to decrease the power consumption of the monitoring system without hampering the normal operation of the system. The system consumes low power with portable capability which provides better solution from prior works. In the calculation of power budget by examining the power value of PCB device shows that the life of the battery has increased. Special effort is given during layout design to optimize the area by placing different components in suitable layers of the three PCB boards. However, in the layout design of PCB the positioning of the controller unit in proper way and the systematic explanations are addressed in this work. These results in a compact PCB design of AQMS. Other functional characteristics of the device are proposed in this work.

The contribution of this work is structured as follows:

- i. To develop a compact and power consumed AQMS in double-sided PCB having six layers 3D structure. The concept of ESD protection is used to save the circuit from damage.
- ii. The area is miniaturized by dividing the complete design into three different parts. Each functional part is designed into each PCB and then stacked three PCBs together to create a compact six-PCB layered design.
- iii. The major concern is to minimize power. So, a switching logic is implemented in sampling the sensor output for reduction of total power. A demultiplexer circuit is placed at the bottom layer of PCB to switch the sensors regularly with a fixed time interval. In the device sensors are switched multiple times by enabling the select lines of the demultiplexer and make the device energy-efficient. Therefore, power dissipation is minimized during the collection and processing of data.

- iv. The average power is measured during power budget calculation of the PCB. From the result it can be said that the battery life of the device has increased. Hence, the system can be well operated without any failure activities.
- v. The wireless communication is developed through the zigbee module. Hence, it is possible to capture real-time data in a place where internet service is not available. Moreover, zigbee has the capacity of consuming less energy compared to Wi-Fi.
- vi. The real-time data collected from PCB are compared with the data gathered from breadboard design of AQMS and results have matched.
- vii. After completing the whole work and fabricated the design in the form of PCB, weight of the device is measured of 172gm. This value achieves the result of being lightweight of the device.

The top board of the PCB is assigned for sensors. Sensors collect data from the environment without any obstruction. The local display LCD (liquid crystal display) is mounted on the top layer of the PCB, ensuring that users can visualize the output and accurately measure air quality. In the middle PCB there is a microcontroller, two voltage regulators for 5V power supply and one voltage regulator for powering 3.3V are present. Regulators have been used to maintain a correct supply of power to the PCB. The middle board has a higher chance of good air circulation than the lower board. As a result, microcontroller does not get damaged from overheat. In the bottom board switching technique and wireless communication is done. For connection between each board, header pins are used.

The rest of the paper is planned as follows. Section 2 presents the schematic design of AQMS architecture. Section 3 describes the board level design of AQMS in PCB form. Section 4 highlight the layout and routing process adopted for making PCB. The layout and routing process are done when board level schematic design is successfully achieved. This section also describes about the computer aided design (CAD) method for double-sided PCB. Section 5 represents layout design of AQMS and inside this section, PCB layout of top board, middle board and bottom board are presented. Power budget is calculated by measuring value of current and voltage, and the satisfactory battery life is presented in Section 6. At last, the paper is concluded in Section 7.

2 Schematic Design Of Aqms Architecture And Operation

The architectural design of wireless network based AQMS is shown in Fig. 1. The idea of wireless sensor station means that nodes without the ability to physically sense will be able to process the data received and communicate wirelessly.

Low power-hungry analog sensors are selected in the operation of data collection which are integrated to microcontroller unit. Arduino Uno ATmega328P IC (integrated circuit), an AVR microcontroller comprises of a flash memory of 32KB is used in the design. AVR microcontroller is used for processing the internal operations of the device. Arduino Uno helps to measure sensing data of CO₂, CO, NO₂, temperature and humidity from atmosphere and determine the status of the environmental quality in real-time. The circuit is designed in such a way that all sensor values can be displayed on LCD and it can provide a constant

feedback to the user. The circuit is powered through rechargeable lithium-ion battery. Individual sensors are tested initially by integrating with the microcontroller unit for proper working conditions. Including all sensors, the circuit consists of demultiplexer and zigbee wireless network. The entire data is transmitted serially using zigbee wireless technology when the sensors are in active mode. Zigbee network communication is based on IEEE802.15.4 standard. A demultiplexer 74HC238 is an IC chip that contains one data input line and eight data output lines. The select lines are used as inputs to control the outputs of demultiplexer connected with sensors. The microcontroller IC is centrally connected to all components. A standard supply voltage of 5V compatible with microcontroller board is used in the design. This supply voltage is given to all parts of the system where in zigbee is supplied by 3.3V. To detect the presence of CO₂ in the air MH-Z14 sensor is used. The use of non-dispersive infrared sensor reduces power dissipation. This is a spectroscopic approach which is suitable for gas concentration measurement. The selected CO₂ sensor detects data in ppm (parts per million) range. Based on the significant aspect of the design, MiCS-4514 has been chosen for determining CO and NO₂ gas in atmosphere. It is a kind of dual sensor and can sense both gases simultaneously. If individual sensors are selected for both gases, the total power consumption would be even higher. MiCS-4514 is defined as a resistive sensor with the voltage ranges operated between 4.9 to 5.1 volts. Pre-heating input is given to the MiCS-4514 sensor for initializing. Heating voltage is equivalent to supply voltage. LM35 and HIH-4030 sensors are chosen for temperature and relative humidity measurement to minimize power in the device. LM35 is a 'three pin plated through hole (PTH) sensor' which is fabricated in board. The three pins of LM35 sensor is configured with supply voltage, output and ground. The power consumption of LM35 is observed to be approximately 1.8mW. Particularly, the device is customized within a specific structure for monitoring air pollution at indoors and outdoors. Zigbee transmits data within a range of 30 meters for indoor and 100 meters for outdoor without any interruption.

3 Printed Circuit Board Design

Equipping the PCB design means that creating electrical connection between different components instead of wires. Normally, PCB is an electronic device where conductive paths such as point-to-point wire communications are printed with thin lines of copper material. The advantage of designing PCB helps in various investigation and performance analysis [25]. Design fabricated on PCB helps to avoid problems like noise, distortion, inferior contact etc. It supports the circuit of having off the shelf electronic components, surface mount devices, socket components laminated with copper traces. For miniaturization of the design, double-sided with 'plated through hole' (PTH) concept came into effect. Through-hole technology presents those holes that can fit perfectly inside the boards. With the help of PTH a conductive path is formed from one side of the board to other. In order to maintain high quality and reliability, thickness of the multilayer PCB boards is chosen wisely. There are various steps involved in the design of printed circuit board. The initial work is to design the schematic level diagram of the circuit (already discussed in Section 2) which will be fabricated and assembled on the board after layout design. Care must be taken when connecting to the board. The schematic diagram defines a process and secures electrical connections by checking functionality of the system. The whole process of PCB is done

with due diligence so that the constructed device can successfully monitor the polluting gas levels accurately.

4 Layout And Routing Process

Layout and routing process are carried out precisely to make the device compact, small sized and reliable. Routing is done in a well-fashioned manner for proper orientation from both sides. Once the height and width of the board are established based on available space, the succeeding step is to make layout of the schematic design, built with interconnect wiring of components. In layout, first placing of components is made and then point-to-point communications are started. The relationship among the components must be compatible, according to design approach in terms of electromagnetic interaction like capacitive and inductive effect. The process of such rearrangement of components is required for more clear design. In this work, the components need to be placed and rotated while working on minimizing the length and crossing of airwires. Airwires represent a number of lines connections between components. In the PCB layout, crossovers should be avoided to prevent unwanted garbage. If not possible then jumpers must be used. If it is seen that in double-sided board crossovers cannot be avoided, a diagram must be drawn roughly for each board and finally the locations of the components need to be made accurately in the layout design. The design goal is to place all the components in such a way that the interconnect length is minimized. The design displays connections which are replicated as a copper material in the manufacturing level of the board. The ground plane of PCB is identified by making the outline on four corners. The creation of ground plane indicates a large area in a polygon shaped. It is attached to the circuit's ground point which is a terminal of the power supply. The ground plane functions as the return path for current from various components.

4.1 Computer Aided Layout Design Method of Two-Sided (Two-Layer) PCB

The schematic and layout steps of PCB are developed with the help of a CAD tool, Autodesk Eagle. CAD tool is used in this work to create three-dimensional (3D) model of PCB. This makes a technical design and layout of all components through the analysis of assembling to manufacturing process. In case of schematic, all components are identified by name and connections are shown. If pads need to be placed they are numbered consecutively in the schematic view. The list of components include manufacturer's part number, voltage rating, dimension etc. along with its name. Mechanical features include size, shape, mounting holes etc. The net class determines the thickness of the wire for power supply, ground connection and intermediate net connection. In schematic design, electrical rule check (ERC) is carried out for physical verification. It is observed whether there is any possibility of generating excess heat due to incorrect placement of the components. Secure electrical and logical functionality are accomplished with the help of ERC checking. In layout, the board list shows X-Y co-ordinate system. All the components are manually placed within the allotted coordinates using the positioning method. After completing the

placement process, in the next step auto-routing is undertaken where some operations are performed such as:

- Interconnections between the components are well balanced according to length.
- Routing is concatenated with the shortest distance.
- All existing barriers are sorted out.
- ViA is used for connecting metal layers. The numbers of ViA holes are minimized and placed in feasible sections of routing from one side to another side of the board.

Routing ventures are used for placing conductors in X-direction on one side of the board. The Y-direction conductors are placed in opposite side. If any interconnection between components is not finished, it is displayed by dotted lines. After completing the routing process, we have to check the design following designated standards. Using design rule check (DRC) method, all errors have been identified in the figure and corrected by user intervention. When the layout design has been completed, it is processed for generating Gerber data. We must take some certain actions for making error free manufacturing (fabrication and assembling) of the printed circuit board.

5 Pcb Layout Results Of Aqms

The hardware boards of PCB follows the rules that are the sum of the combined knowledge referred by the CAD system. The users through the analysis of accuracy achieve the experience in the system. The area is minimized by considering three boards without using a single board for the overall system. A condition-based program is installed in the microcontroller circuit. The program is recorded in the microcontroller unit of the monitoring device to control the operation. The controller takes some decisions to analyze data. This analysis relies on information received from user's measured pollution levels and the information, obtained from meteorological parameters that affect weather conditions. The PCB device of AQMS is focused by calculating net weight of 172gm having three boards stacked together. Lightweight of the device makes it more compatible for handling and it is easily portable. The details of board layout design are presented in the following sections.

5.1 Layout of Top Board

In order to achieve a double-sided PCB, following steps have been executed in the design. For satisfactory relationship among three boards, header pins are placed according to the process of the design. All sensors and display device is assembled at the top level of the board. The bottom layer is planned for connection with the next board. Traces and ground planes have been drawn on both sides of the board. Figure 2 illustrates the first board of PCB in 3D stacked design of AQMS. Auto-routing is done as discussed in Section 4 and the design is further miniaturized. Two metal layers are used in routing to avoid short connections in design.

The width of the routing net depends on the flow of current through the copper wire to supply voltage. The width of the supply voltage is set for 5V, 3.3V, and ground net and internal net as per the designer's expectation. In case of 5V supply, traces are placed with spacing of 1.5 mm. Similarly, for 3.3V spaces are given as 1.3 mm and for ground spacing of 1 mm is placed. A 10K potentiometer is placed to control the brightness of LCD. The number of ViA indicated by round shape, as shown in the Fig. 2, is added for joining the two metal layers and to dissipate heat. Finally, the ground plane has been drawn in a rectangular shape and DRC is performed to remove all the defects. To make the ground plane in Eagle, the first task is to run the polygon command. The ground plane is built for two layers. The ground plane is mandatory covering majority of the board to prevent the crosstalk between adjacent circuit traces. The area of the board is maintained 100 mm × 80 mm.

5.2 Layout of Middle Board

Figure 3 shows the layout of the middle board. This board is also double-sided. All the components are attached on the front side.

ATmega328P 8-bit AVR microcontroller is dedicated in this design of embedded system to execute applications for air quality monitoring. Regulating circuits are used of SMD components LM1117MP-5.0 and LM1117MP-3.3 maintaining supply in the design. The design consists of multiple sensors, IC chips and plated through hole (PTH) materials. 16MHz frequency of crystal oscillator is mounted to provide a clock speed. A reset switch is introduced in the board, it clears all previous errors and initialize a new one. All the resistors, capacitors and other components are integrated as per design rules to make the device optimized. After auto-routing, the region is optimized to 89 mm × 75 mm. The width of the trace associated to the USB port is set by 1.7 mm because of the large current passes through it. The surface current that generates on metal surface is a big intervention that appears in PCBs. It is therefore important to suppress interfered noise, so that it is not propagated to rest of the circuit. The width of other traces is set as previous design. Finally, the ground plane and DRC steps are followed.

5.3 Layout of Bottom Board

Figure 4 presents the PCB layout of bottom board. Here, the size of the board is compressed to 110 mm × 80mm. In the design a USB port has been attached and power is given from the battery source through it. This power flows throughout the design of AQMS. Hence, two ESD suppressors are mounted in this PCB to protect the internal circuitry and are suited for high speed applications. ESD suppressor helps the device being safe from overvoltage of continuous supply.

Strategy of switching technique for low power AQMS is mapped on the bottom board. A demultiplexer IC is used in the bottom board to direct the ON / OFF condition of the power supply of the sensors to reduce the power consumption of the device. Sensor data from the AQMS device is transmitted wirelessly. The zigbee wireless module completes the process via zigbee shield in the PCB to establish the communication system. Successive steps are taken for completing the layout design. The complete flow diagram of PCB design methodology is given in Fig. 5 below:

Fabrication and assembling process of three boards (each board has two layers) has been done, which comprises of six layers with double-sided interconnections. The dimension of the overall board is 110 mm × 80 mm × 24 mm. The volume of the device indicates the compact size of the design. Complete device of AQMS is shown in Fig. 6. The front view and side view of air quality monitoring system is shown in Fig. 6a and Fig. 6b. The side view of PCB device gives a clear idea of 3D structure in stacking form. In the PCB design, surface mount device (SMD) components are assembled for high accuracy, area optimization and easy handling purposes.

The environmental pollutants are measured by PCB based AQMS. To see the correctness of the results, the results of the breadboard design of AQMS are compared with the results of the PCB design. In the design, off the shelf components are placed according to the schematic (Fig. 1) on the Vero board. The breadboard design of AQMS is shown in Fig. 7. It can be seen that the information of the pollutants received from fabricated PCB based AQMS match the real-time data of the pollutants observed in the breadboard design of AQMS. The accuracy is measured as $95\pm5\%$ and the system has the availability of local storage and display purposes.

6 Power Budget Calculation And Battery Life Estimation

A voltmeter and an ammeter are used to get voltage and flow of current value of the device. The arrangement of the device for calculating power budget is shown in Fig. 8 below.

From the above arrangement of the device, current values and voltage values are extracted to measure how much power is consumed during runtime operation using the given formula:

Power=current × voltage (1)

From equation (1), power is measured. To calculate the average current and average voltage, fifteen readings are taken at one minute interval per day. We have tested around 75 times consecutively for five days from 08.07.2019 to 12.07.2019 and come out with an average value of 0.2105A and 5.0304V for current and voltage respectively. Hence, the calculated average power is found to be 1.0588992 Watt. From this result it is clear that the device is designed for low power consumption. Thus, the PCB design of AQMS can be referred to as a low power device. Table 1 shows the information of both the value of voltage and current taken at one minute interval of one day.

Table 1 Calculated voltage and current for one day

Time (PM)	Voltage (V)	Current (A)
12:30	5.042	0.205
12:31	5.041	0.207
12:32	5.037	0.210
12:33	5.035	0.206
12:34	5.042	0.213
12:35	5.043	0.214
12:36	5.041	0.209
12:37	5.039	0.214
12:38	5.038	0.212
12:39	5.036	0.208
12:40	5.005	0.209
12:41	5.013	0.213
12:42	5.025	0.208
12:43	5.022	0.210
12:44	5.011	0.203

PM= Post Meridiem Time, V=Voltage, A=Ampere

The performance of the device achieves that the system is energy-efficient. Noticing the battery rating of 10,400 mAh, if it is fully charged then receives the capacity of 37.44 Watt-hour. Thus, if the average power consumption during the runtime operation of the PCB device is 1.0588992 Watt, then battery supplies uninterrupted power of $(37.44 / 1.0588992)$ 35.357 hours to the PCB circuit till the next recharge. Hence, it can be said that this device gets a power supply of 35.357 hours without disturbing any power failure. But practically, it has been observed that the battery can supply power continuously for 33.75 hours respectively. The reduction in reliable operation time of the AQMS is due to the power loss across some internal resistance of the battery and some resistance of connecting wire of USB cable. So, based on the average power quality the battery is needed recharging after every one and a half days. That means the result of power budget increases the life of battery because recharging is done in less days, which lasts the battery longer.

7 Conclusion

The 3D stacking PCB design of developed AQMS controlled by a processor unit is presented. Zigbee wireless network is used for taking the advantage of measuring real-time sensor data from the PCB

device placed at any situation. The electronic connections are performed in the layout in such a way that the components are closely connected to reduce the area of the device and air circulation between the layers may be well carried out. The power consumption is reduced by suitably switching the sensors of the AQMS. The result of low power consumption increases the life time of the battery. The similarity is observed between the sensor data results obtained from breadboard design of AQMS and PCB design of AQMS. The performance of the device gives an accurate indication of the polluted data measured in real-time. The use of 3D stacking arrangement solves the area complexity issues and device becomes compact. The measured weight of 172gm of the PCB device confirms its portability.

Declarations

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Figures

Figure 1

Structural design of AQMS

Figure 2

Layout of AQMS top board

Figure 3

Layout of AQMS middle board

Figure 5

Flowchart of double-sided PCB configuration

Figure 6

PCB of air quality monitoring system. a Front view, b Side view

Figure 7

Experimental design of AQMS

Figure 8

PCB of air quality monitoring system. a Front view, b Side view