University of Cincinnati

Date: 7/10/2012

I, Radhika Balasubramanian, hereby submit this original work as part of the requirements for the degree of Master of Science in Electrical Engineering.

It is entitled:
PIC Microcontroller Based Smart Inhaler System for Asthma Patients

Student's name: Radhika Balasubramanian

This work and its defense approved by:

Committee chair: Fred Beyette, PhD
Committee member: Carla Purdy, PhD
Committee member: Philip Welsey, PhD
PIC Microcontroller Based Smart Inhaler System for Asthma Patients

A thesis submitted to the Graduate school of the University of Cincinnati in partial fulfillments of the requirements for the degree of

Master of Science in the School of Electronics and Computing Systems of the College of Engineering and Applied Science

July 2012

By

Radhika Balasubramanian

M.Eng (Electrical Engineering)

University of Utah, Utah, 2008

Thesis Advisor and Committee Chair: Dr. Fred R. Beyette Jr.
Abstract

The primary objective of this thesis is to develop a prototype of a smart inhaler system for use by asthma patients. Asthma is a chronic condition that mostly affects adolescents. It is a condition that requires continuous monitoring of the symptoms in order to provide an effective course of treatment. It also requires a strict adherence to medication prescribed by the physician. The smart inhaler system has been developed to provide frequent monitoring of the symptoms. Additionally the device provides a record of inhaler usage so that the physician can assess the patients level of adherence. Thus the physician is provided with usage information and patient status that is necessary to help the patients to better control the symptoms and lead a healthy normal life.

The key features of the system are the capability to perform spirometry tests, a user interface to obtain information from the patient regarding his/her condition and a record of the frequency with which the inhaler is used. Apart from this, an alarm is also provided so that the patient does not forget to take their medication. All the data is stored in non-volatile memory and can be retrieved by the physician at a later date so that they may be able to provide treatment based on the test data obtained over an interval of time rather than just one set of tests that are done during a regular checkup.

The smart inhaler system is comprised of a differential pressure sensor, a SD card memory and a PICDEM PIC 18 Explorer Demonstration Board that includes a PIC18F8722 microcontroller, a LCD Display, Push Buttons and a daughter board socket for the PICTail™ Daughter Board that includes the connection interface for a SD/MMC card.
This thesis details the design, implementation and testing of the prototype smart inhaler system.
Acknowledgements

I sincerely thank my advisor, Dr. Fred Beyette for giving me an opportunity to work on this exciting project and for all his encouragement and support during the course of my graduate studies. I consider myself very lucky to have had the opportunity to work under his guidance.

I am grateful to Doug and Jeff for all the technical support they have provided me during the course of my project. I have learned so many things from them in these two years. A special note of thanks to Dr. Heikenfeld for having let me use his lab for my experiments. I would also like to thank all the members of POCSDL for all their support and technical advice. I will always remember all the good times we have had together as lab mates and as friends.

I cannot even bear to think of a life in Cincinnati without my awesome friends Bharat, Venkat and Vignesh. I will never ever forget all the fun times we have had together. They will be part of every happy memory I have of my life in grad school. A special thanks to my dear friends Bindu and Madhu for always being there for me.

I would like to thank my parents and brother for always believing in me, sometimes even more than I did in myself.

I am grateful to God for making all these wonderful people a part my life and in helping me realize how lucky I am to have them.
Table of Contents

ABSTRACT ..........................................................................................................................i

BLANK PAGE ...................................................................................................................ii

ACKNOWLEDGEMENTS ..................................................................................................iv

TABLE OF CONTENTS ....................................................................................................v

LIST OF FIGURES ..........................................................................................................vii

LIST OF TABLES ..............................................................................................................x

1. Introduction
   1.1 Problem Statement ......................................................................................................1
   1.2 Objective ....................................................................................................................1
   1.3 Review of Previous Work ..........................................................................................3
   1.4 Thesis Outline ..........................................................................................................4

2. Design of the Smart Inhaler System
   2.1 Overview of working of the system ...........................................................................5
   2.2 Spirometry ................................................................................................................7
   2.3 Design Considerations ..............................................................................................9
3. Implementation Details of the Smart Inhaler system

3.1 PICDEM™ PIC18 Explorer Demonstration Board ............................................................13

3.2 PIC 18F8722 Microcontroller
  3.2.1 Features of the Microcontroller ..............................................................................17
  3.2.2 Programming the Microcontroller ..........................................................................36

3.3 Differential Pressure Sensor
  3.3.1 Operating Characteristics and Transfer Function ....................................................37

3.4 PICTail™ Daughter Board for SD/MMC cards .............................................................40

4. Test Results and Discussion

4.1 Experimental Set Up .....................................................................................................43
  4.2 Testing the different modes of the Smart Inhaler System .............................................45
  4.3 Results and Discussion ...............................................................................................49

5. Conclusion

5.1 Summary .......................................................................................................................59
  5.2 Suggestions for Future Work .......................................................................................60

REFERENCES ....................................................................................................................61
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Flow-Chart of the Smart Inhaler System</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Flow-Volume Loop</td>
<td>7</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Volume-Time Curve</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Block Diagram of the Smart Inhaler System</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Venturi Tube</td>
<td>10</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>PICDEM PIC18 Demonstration Board</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>List of components of the PICDEM PIC18 Explorer Demonstration Board</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Pin Diagram of PIC18F8722</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Generic I/O Port Operation</td>
<td>20</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Block Diagram of Timer1 module</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>T1CON Register</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.7</td>
<td>Block Diagram of the ADC module</td>
<td>25</td>
</tr>
<tr>
<td>Figure 3.8</td>
<td>ADCON0 Register</td>
<td>26</td>
</tr>
<tr>
<td>Figure 3.9</td>
<td>ADCON1 Register</td>
<td>27</td>
</tr>
<tr>
<td>Figure 3.10</td>
<td>ADCON2 Register</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.11</td>
<td>Block Diagram of the MSSP module (SPI)</td>
<td>30</td>
</tr>
<tr>
<td>Figure 3.12</td>
<td>SSPxSTAT Register</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3.13</td>
<td>SSPxCON1 Register</td>
<td>33</td>
</tr>
<tr>
<td>Figure 3.14</td>
<td>Master Slave Communication in the SPI mode</td>
<td>34</td>
</tr>
<tr>
<td>Figure 3.15</td>
<td>Clock Sources for PIC18F8722 Family of Devices</td>
<td>35</td>
</tr>
<tr>
<td>Figure 3.16</td>
<td>Operating Characteristics</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 3.17  Fully Integrated Pressure Sensor Chip ................................................................. 39
Figure 3.18  Output Voltages vs. Differential Pressure .............................................................. 39
Figure 3.19  Temperature Error Band ......................................................................................... 40
Figure 3.20  PICTail™ Daughter Board for SD/MMC cards ...................................................... 41
Figure 3.21  Jumper Positions and their associated features ...................................................... 41
Figure 4.1   Experimental Setup ............................................................................................... 43
Figure 4.2   Mouthpiece ............................................................................................................. 45
Figure 4.3   Message Displayed on the LCD to get users’ perception of their condition ............ 46
Figure 4.4   Spirometry Procedure ............................................................................................ 47
Figure 4.5   Output File in the Test Mode ................................................................................... 49
Figure 4.6   Flow-Volume Loop-Individual 1 ............................................................................. 50
Figure 4.7   Predicted values of the parameters for Individual 1 .............................................. 51
Figure 4.8   Flow-Volume Loop-Individual 2 ............................................................................. 52
Figure 4.9   Predicted values of the parameters for Individual 2 .............................................. 53
Figure 4.10  Irregularities in the Flow-Volume Loop due the use of long tubes ....................... 54
Figure 4.11  Flow-Volume Loop after the use of shortened tubes ........................................... 55
Figure 4.12  Output text file in the inhaler usage record mode ................................................... 56
Figure 4.13  LEDs blinking on the board acting as alarm to the patients to take their medication ....................................................................................................................... 57
List of Tables

Table 3.1 List of pins used in the Smart Inhaler System

19
Chapter 1

Introduction

This chapter presents a brief overview of the problem statement and the objective of the research work as well as a review of the background work and motivation behind the project. It also provides an outline of the thesis.

1.1 Problem Statement

Asthma, a chronic health condition prevalent in children can be characterized by breathlessness, chest tightness and coughing. An asthma attack can be triggered by a variety of factors including environmental conditions, intense physical activity, humidity and dust. In the United States, as of February 2010, 7 million children (10%) were reported to be suffering from asthma. This condition is generally more prevalent among adolescents in the age group of 11-17. Due to the high prevalence of asthma in children and the difficulty involved in diagnosing the condition it becomes imperative to come up with technological solutions for continuous care and management of patients with this chronic disease.

1.2 Objective

The objective of this project is to develop a smart inhaler-a point of care device for use by asthma patients, which can perform multiple functions that enable a physician to monitor the patient’s condition and to provide continuous care. The different functionalities in a point of care device that are considered vital in caring for patients with asthma are discussed below.
Spirometry is a pulmonary function test that measures lung functions and can be used to generate pneumotachographs to assess conditions such as asthma, pulmonary fibrosis, cystic fibrosis and COPD. The most common parameters measured by spirometry are Forced Vital Capacity, Forced Expiratory Volume at discrete intervals of time, Forced Expiratory Flow and Maximum Voluntary Ventilation.

Spirometry is generally used to assess any ailment related to the proper functioning of the lungs and results are obtained as graphs called as spiromograms. There are typical values for the parameters, which can be obtained from the graph. If these standard parameters are not obtainable or if the expected trend of the graph is not followed, the patient is diagnosed to have either an obstructive lung disease or a restrictive lung disease. Asthma and COPD are examples of obstructive lung diseases. For patients having this condition, the flow volume loop, explained in detail in section 2.2 will have a concave shape and the value of FEV1 will be reduced from the expected norm. Spiromgrams can be a useful tool for physicians to assess the condition of the patient suffering from asthma. Therefore, there is an inevitable need for a point of care device for use by asthma patients that can be used to perform spirometry regularly.

Asthma is a condition that requires adherence to a strict medical regime in order to improve the quality of life by control of the symptoms. It is therefore necessary for the patients to take on the responsibility of self-management. Given the age group that is most affected by asthma, it also becomes necessary for the physicians to monitor the adherence level of the patients to the prescribed medication.

In order to help adolescents develop self-management to deal with the chronic health condition, it also becomes necessary for the physicians to gain more insight into the perception
of the condition from the patient. A user interface which allows for such an interaction also becomes an important feature to be incorporated into the point of care device.

The idea behind this work is to develop a point of care device which can ideally be integrated with an inhaler which is usually carried around by asthma patients with all of the above features. In addition, the device should also incorporate an alarm to remind the patients to take their medication and also a memory which stores all the test results, patients’ perception of their condition and the regularity with which the inhaler is used so that the physicians can later use these data to accurately assess the condition of the patient.

1.3 Review of Previous Work

Monitoring systems that have been developed for use by asthma patients include portable spirometers that have an embedded web based server\(^4\), a multisensory microsystem for diagnosis of pulmonary functions which integrates temperature, pressure, flow and RH sensors\(^5\).

Several prototypes of the spirometer have been developed. There are different methods of flow measurement such as turbine flowmeters, differential pressure flow meters, positive displacement flow meters, thermal mass flow meters\(^6\). Portable spirometers have been developed based on hot wire anemometry\(^7\), differential pressure measurement\(^6\) and positive displacement techniques\(^8\).

However the need for a complete hand-held system that can be carried by the patient at all times, that monitors the patients’ condition and stores information for use by the physician and provides a way of interacting with the patients has given impetus to the conception of this project.
1.4 Thesis Outline

This thesis is divided into five chapters.

Chapter 2 deals with the design of the system incorporating all the different features of the smart inhaler.

Chapter 3 deals with the development of the system, involving the interfacing of the different peripherals with microcontroller.

Chapter 4 discusses the results and the operation of the system in different modes.

Chapter 5 concludes the thesis and suggests future work.
Chapter 2

Design of the Smart Inhaler System

This chapter deals with the overview of the entire system and goes over the details of spirometry tests to enable the reader to better understand the utility of the prototype developed. The project essentially involves the design of a system that can be integrated with an inhaler, commonly used by asthma patients, which provides the following features.

1) It should be able to perform spirometry tests periodically.

2) It should be able to monitor the regularity of intake of the medication.

3) It should provide an alarm reminding the patient to take the medication.

4) It should be able to obtain information regarding the patient’s perception of his/her condition.

5) Finally, it should also store all of the above data for use by the physician.

2.1 Overview of working of the system

The system has been designed in such a way that there are essentially three modes of operation-standby, inhaler usage record mode and test modes. In the standby mode the microcontroller is in standby and does not perform any function. In the inhaler mode, the system essentially records when and how many times the inhaler is used by the patient, depending on an interrupt received from a button press. The time stamp from an RTCC module implemented using a timer is recorded in a text file in the SD card. The test mode essentially consists of two phases. In the first phase, the system receives input from the user regarding the patient’s
perception of his/her condition. In the second phase, the airflow sensor is activated and values are recorded to calculate vital respiratory parameters. Fig. 2.1 shows a flowchart of the system.

![Flow Chart of the Smart Inhaler System](image)

**Figure 2.1 Flow Chart of the Smart Inhaler System**
2.2 Spirometry

Spirometry is a pulmonary function test which is used to assess the lung condition of patients suffering from asthma. Several parameters can be measured using spirometry. The most commonly measured parameters in spirometry are:

Forced Vital Capacity (FVC)-The volume of air that is exhaled rapidly after complete inhalation

Peak Expiratory Flow (PEF)-The maximum flow of air obtained during maximum exhalation after complete inhalation

Forced Expiratory Volume (FEV)-This is the volume of air that is blown out at different time intervals of 0.5, 1, 2 and 3 seconds after maximum inhalation. FEV1 is the volume of air that is blown out in 1 second after full inspiration.

Forced Expiratory Flow-It is the flow of air coming out at discrete intervals usually measured at 25% and 75% of the Forced Vital Capacity.

Maximum Voluntary Ventilation- The maximum amount of air that can be breathed in and out within one minute.

![Figure 2.2 Flow Volume Loop](image)
Spirometry is done using a spirometer. The results of the spirometer are in the form of graphs called spirograms. The results can be depicted either as a flow volume loop as shown in Fig.2.2 or volume-time graph as shown in Fig.2.3. In patients with obstructive lung diseases like COPD and asthma the shape of the curve is concave and the volume of air expired in 1 second is lesser than that of a normal person. Depending on the shape of the curve, the type of lung disease can be determined from the spirogram.

The most basic maneuver in spirometry is the measurement of the Forced Vital Capacity. The maneuver involves the patient to take in a deep breath and blow out air as hard and for as long as possible, preferably for a period of 6 seconds. During the test, nose clips are generally used to prevent the air from escaping through the nostrils. The success of the maneuver is highly dependent on the patient cooperation and is usually repeated several times to ensure reproducibility.
2.3 Design Considerations

Fig. 2.4 shows the block diagram of the system incorporating all of the above features. The block diagram identifies the hardware components that will be required to realize the smart inhaler system.

![Block Diagram of the Smart Inhaler System](image)

**Figure 2.4 Block Diagram of the Smart Inhaler system**

The explanation following the block diagram details the exact components that were chosen and the reasons for choosing them.

It can clearly be seen that at the heart of the system lies a microcontroller. For the implementation of the above system, the PICDEM PIC18 explorer demonstration board from Microchip has been used. Apart from the explorer board, the other components used are the PICTail daughter board for SD/MMC cards also from Microchip and the differential sensor MPX5010 from Freescale.
The explorer board consists of the microcontroller 18F8722 at its core which is programmed to work in three modes of operation—standby, inhaler and test modes. The reason for choosing the PIC 18F8722 microcontroller is because its feature such as the MSSP module, 10 bit ADC module, Timers and Interrupts. The PICDEM PIC18 Explorer demonstration board also contains an LCD and push button for user interface, which are extensively used in this project.

The differential pressure sensor has been chosen as the sensing module in the project because the differential pressures measured can be used to determine the flow rates. The flow rates obtained can then be integrated to obtain the volumes. The differential pressure sensor used works in the range from 0 to 10 KPa. The expected maximum flow rates are in the range of 10-12 liters/second. With the set up used for the project, this flow rate translates to about 6KPa, which falls within the range of the chosen differential pressure sensor.

The differential pressure sensor quantifies flow based on Venturi Effect. Bernoulli’s principle states that for an inviscid flow, with decrease in pressure there is an increase in velocity.
of the fluid. The continuity equation indicates that for an incompressible fluid the reduction in diameter will result in an increase in flow speed. The Venturi effect combines these two effects to determine the flow rate of a fluid. Venturi effect is essentially the reduction in pressure that takes place as the fluid flows through a constriction in the pipe as shown in Fig.2.5.

The pressure drop at the constriction is given by Bernoulli’s equation

\[ p_1 - p_2 = \frac{\rho}{2} (v_2^2 - v_1^2) \]

The Venturi tube can be used to measure the volumetric flow rate (Q) and is given by

Since

\[ Q = v_1 A_1 = v_2 A_2 \]

then

\[ Q = \sqrt{\frac{2 \Delta p}{\rho}} \left[ \frac{A_2}{1 - \left(\frac{A_2}{A_1}\right)^2} \right] \]

where, \( p_1 \) and \( p_2 \) are the pressures in different sections of the Venturi tube

\( A_1 \) and \( A_2 \) are the cross sectional areas of the two sections

\( v_1 \) and \( v_2 \) are the velocities of the fluid in the two sections of the tube

\( \rho \) is the density of the fluid

This project requires the use of a memory module that can store a high volume of data. All the parameters are recorded for use, later. Therefore, a PICTail™ daughter board for
SD/MMC card has been used to interface a 2 GB SD card with the PICDEM PIC18 Demonstration board.

The LCD module is provided on the demonstration board itself. The user interface is accomplished with the help of push button on the demonstration board. These buttons can be used to acquire input from the user.

Chapter 3 discusses the hardware components and the implementation of the system in detail.
Chapter 3

Implementation Details of the Smart Inhaler System

3.1 PICDEM™ PIC18 Explorer Demonstration Board

The microcontroller used for the implementation of the smart inhaler system is the PIC18F8722 microcontroller from Microchip. PICDEM™ PIC 18 demonstration board from Microchip provides a platform for evaluation of 18FXXXX family devices\(^\text{11}\). It comes with a PIC 18F8722 mounted on it. The reason for choosing this demonstration board is that apart from the mounted microcontroller it has several features as shown in Fig. 3.1\(^\text{11}\).
PIC18F8722 microcontroller – The sample, primary microcontroller mounted on the board.
2. Male header pins for connecting Plug-In Modules (PIMs). A PIM enables an alternate PIC18 device to be connected to the board, as the primary microcontroller.
3. In-Circuit Debugger (ICD) connector.
5. 10 kΩ potentiometer for analog inputs.
6. Push button switch – For external Reset.
7. USB connector – For RS-232 communication.
8. PIC18LF2450 microcontroller – For converting RS-232 communication to USB protocol for attachment of a host PC.
9. 12 MHz crystal – For the PIC18LF2450 microcontroller.
10. RS-232 DB9 socket and associated hardware – For direct connection to an RS-232 interface.
11. Jumper J13 for routing RS-232 communication through either the USB port or the RS-232 socket.
12. Jumper J4 – For selecting between programming the main PIC® device or the PIC18LF2450, used for USB to RS-232 communication.
13. Switch S4 – For designating the main microcontroller as either the board-mounted PIC18F8722 or a PIM-mounted microcontroller.
14. LED – For power-on indication.
15. JP1 – For disconnecting the eight display LEDs.
16. Eight LEDs.
17. 32.768 kHz crystal – For Timer1 clock operation.
18. Two push button switches – For external stimulus.
19. Analog temperature sensor, MPC9701A.
20. 25LC256 SPI EEPROM.
21. JP2 – To enable/disable EEPROM.
22. JP3 – To enable/disable LCD.
23. 10 MHz crystal – For the main microcontroller.
24. PICtail™ daughter board connector socket.
25. SPI I/O expander – For LCD display, MCP23S17.
26. Prototype area – For user hardware.
27. LCD display.
28. J2 three-pin, male header – For selecting between a voltage of 3.3V or 5V.
29. J14 four-pin, male header – For use with a PIM, if required, to connect 3.3V or 5V, VIn and ICE MCLR.

Figure 3.2 List of components of the PICDEM PIC18 Explorer Demonstration Board

The labels of the demonstration board have been described in Fig. 3.2. The features
incorporated on the demonstration board are used for developing general-purpose applications. The main features on the board that are used in this project are highlighted. Each of the highlighted features is described briefly below:

1. PIC18F8722-This is the main microcontroller, which is programmed to perform all the functions of the smart inhaler system, switching between the different modes of operation, interfacing with the differential pressure sensor and the SD card and providing a user interface. A more detailed description of the microcontroller is given in the following section.

2. Six Pin PICKit2 Connector-It is used to connect the demonstration board to the computer running MPLAB IDE. It is through this connector that the microcontroller is programmed to perform the required operation.

3. Push Button Switch for External Reset-When this button is pressed the microcontroller is reset.

4. Jumper (J4)-As described in the figure above, it is used to select between the main PIC device and PIC18LF2450.

5. Switch (S4)-This is used to switch between the board-mounted microcontroller 18F8722 and the PIM mounted microcontroller.

6. LED-This LED indicates that the demonstration board has been powered up.

7. Eight LEDs-The LEDs are connected to a port on the microcontroller and can be used in any application. In this particular project it is used as an alarm system.

8. 32.768 KHz crystal for Timer1 Operation-Timer1 can be used as a real time clock. For this purpose, a 32.768 KHz crystal has been provided. This has been used extensively in the project for obtaining a timestamp on the readings and for the alarm.
9. Two Push buttons-The push buttons on the demonstration board are used to create interrupts to switch between the different modes of operation and for the purpose of user interface creation.

10. 10 MHz crystal for main microcontroller-This provides the clock source for the microcontroller

11. PICTail daughter board connector socket-This socket is where the PICTail daughter board for SD/MMC card is connected so that the microcontroller can interface with the SD card in order to record the values during the experiment.

12. SPI I/O Expander – For LCD Display, MCP23S17 provides a general-purpose parallel expansion I/O for SPI applications. The microcontroller communicates with LCD display provided on the demonstration board using SPI.

13. LCD Display-The LCD Display provided is used to obtain information from the users by displaying a question regarding their perception of their health condition when they are about to take the test.

3.2 PIC 18F8722 Microcontroller

The microcontroller is used to control all of the operations that are required to implement all the functionality of the smart inhaler system. The software is developed in MPLAB IDE and is downloaded onto the program memory of the microcontroller using the PICKit2 programmer. The code developed is used by the microcontroller to control and activate all the hardware peripherals that interface with it.
3.2.1 Features of the Microcontroller

PIC18F87222 is a 80 pin 1MBit enhanced flash microcontroller with 10 bit A/D. The following are the key features of the microcontroller:

- Two Master Synchronous Serial modules supporting SPI\textsuperscript{TM} and I\textsuperscript{2}C\textsuperscript{TM} master and slave modes
- 10 bit A/D converter module with auto acquisition capabilities
- Four external programmable interrupts
- Four input change interrupts
- C compiler optimized architecture
- Priority levels for interrupts
- Two 8-bit timers and three 16-bit timers
- 128 Kbyte Flash Program Memory
- 1024 bytes of EEPROM and 3936 bytes of SRAM
- Address Capability of upto 2Mbytes

There are about 70 I/O pins divided into 9 ports A,B,C,D,E,F,H,I and J. Each of these ports is bidirectional and 8 bits wide except port G that is 6 bits wide. If a particular pin is connected to a peripheral device on the board and the peripheral is enabled then the pin may not be used as a general purpose I/O.

The pin diagram and a brief description of the pins that are used are given below. The other features described in detail are the Timers, Interrupts, A/D converter module, MSSP module and the oscillator modes of the microcontroller as these are the most commonly used features in the system developed.
Figure 3.3 Pin Diagram of PIC 18F8722

Fig. 3.3 shows the pin diagram of 18F8722 microcontroller, which has 70 I/O pins.
Table 3.1 lists only the pins that were used in the smart inhaler system developed.

<table>
<thead>
<tr>
<th>Pin Name</th>
<th>Function</th>
<th>I/O</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA1/AN1</td>
<td>AN1</td>
<td>I</td>
<td>Analog Input from the sensor module</td>
</tr>
<tr>
<td>RA2/AN2</td>
<td>RA2</td>
<td>O</td>
<td>Chip select signal for LCD</td>
</tr>
<tr>
<td>RA4/T0CK1</td>
<td>RA4</td>
<td>O</td>
<td>Write Protect signal for the SD card</td>
</tr>
<tr>
<td>RB0/INT0/FLT0</td>
<td>INT0</td>
<td>I</td>
<td>External interrupt connected to switch S0</td>
</tr>
<tr>
<td>RB2/INT2</td>
<td>INT2</td>
<td>I</td>
<td>External interrupt connected to switch S1</td>
</tr>
<tr>
<td>RB3/INT3/ECCP2/P2A</td>
<td>RB3</td>
<td>I</td>
<td>Card Detect signal from the SD card</td>
</tr>
<tr>
<td>RB4/KBIO</td>
<td>RB4</td>
<td>O</td>
<td>Chip Select signal for the SD card</td>
</tr>
<tr>
<td>RC0/T1OSC0</td>
<td>T1OSCO</td>
<td>O</td>
<td>Timer1 Oscillator output. Enabled when Timer1 oscillator is enabled.</td>
</tr>
<tr>
<td>RC1/T1OSCI</td>
<td>T1OSCI</td>
<td>I</td>
<td>Timer1 Oscillator Input. Enabled when Timer1 is enabled.</td>
</tr>
<tr>
<td>RC3/SCK1/SCL1</td>
<td>SCK1</td>
<td>O</td>
<td>Clock for SPI module connected to SD card and LCD</td>
</tr>
<tr>
<td>RC4/SDI1/SDA1</td>
<td>SDI1</td>
<td>I</td>
<td>Data input of the SPI module connected to SD card</td>
</tr>
<tr>
<td>RC5/SDO1</td>
<td>SDO1</td>
<td>O</td>
<td>Data output of the SPI module connected to the SD card and LCD</td>
</tr>
<tr>
<td>RD0-RD7</td>
<td>RD0-RD7</td>
<td>O</td>
<td>Connected to the LEDs on the board</td>
</tr>
</tbody>
</table>

Table 3.1 List of pins used in the Smart Inhaler System
I/O Ports

There are up to 9 ports that are available. Figure 3.4\textsuperscript{12} shows the generic I/O port operation. There are essentially three registers involved-TRIS, LAT and PORT

![Figure 3.4 Generic I/O Port Operation\textsuperscript{12}](image)

**Figure 3.4 Generic I/O Port Operation\textsuperscript{12}**

TRIS Register-This sets the direction of the data. Setting this register to ‘0’ will make the corresponding pin an output.

LAT Register-This is the output latch. Writing to a pin essentially writes to the port latch.

PORT Register-This register is used to read the level on the corresponding pin.
**Interrupts**

PIC microcontroller 18F8722 has multiple interrupt sources and an interrupt priority feature. The high priority interrupt vector is at 0008h and the low priority interrupt is at 0018h. There are ten registers involved in the operation of interrupts.

- PIR1, PIR2, PIR3
- PIE1, PIE2, PIE3
- RCON, INTCON, INTCON2, INTCON3
- IPR1, IPR2, IPR3

There are three bits to control the interrupt operation.

- The flag bit to indicate whether an interrupt has occurred or not.
- The enable bit which causes the transfer of program control form the main program to the interrupt service routine when the flag bit is set.
- The Priority bit which indicates whether it has high priority or a low priority interrupt.

The interrupt priority feature can be turned on by setting a bit in the RCON register and all the interrupts are enabled in the INTCON register. When the interrupt flag bit is set, based on the priority, the program control will transfer to either of the addresses. When several interrupts have the same priority then the source of the interrupt is determined by polling the interrupt flag bits. When responding to an interrupt, the global enable bit is cleared in software so as to avoid further interrupt, the return is address is pushed onto a stack and the program control is transferred to the interrupt vector address. After executing the Interrupt Service Routine, the
interrupt flag bit corresponding to the source that caused the interrupt is cleared and global interrupts are enabled once again.

The different registers that are used to control the interrupt operation are set based on our requirements. For the system designed, interrupts are generated in three cases-

- Overflow of TIMER1 causes an interrupt. This is used as the real time clock in the system. TIMER1 is initialized in such a way that an overflow occurs every second resulting in an increment of the seconds register. When the seconds register reaches 60, the minutes register is incremented and so on.
- The button press of RB0 causes an interrupt. In the smart inhaler system, this causes the transition from the standby mode to the test mode.
- The press of push button RA5 causes an interrupt resulting in the system changing from the standby mode to the inhaler usage record mode.

RA5 has been connected to the external interrupt pin INT2/RB2. The priority of the external interrupts is determined from the interrupt priority bit except for RB0/INT0, which is always high priority. In this project, all the external interrupts have been grouped under high priority and the interrupt from the timer is classified as low priority.

**Timer**

Timer1 has been extensively used in this project for providing an alarm as well as a timestamp for the values recorded in the test mode and a timestamp for the button press in the inhaler usage record mode. Timer1 has the following features

- It can be used as a 16 bit timer or a counter
• Readable and writable 8 bit registers TMR1H and TRMR0L
• The clock source can be either the internal oscillator of Timer1 or the device clock.
• Interrupt gets generated on overflow of the registers

The block diagram of timer 1 is shown in Fig.3.512.

![Figure 3.5 Block Diagram of Timer 1](image)

Timer1 has an on chip crystal oscillator circuit between T1OSCI and T1OSCO. The oscillator is a low power circuit rated for 32 KHz crystals. The TMR1 register pair increments every clock cycle and goes from 0000 to FFFF after which an overflow occurs. This overflow can be used to generate an interrupt. With a 32.678 KHz clock the overflow occurs every 2 seconds. In order to cause an overflow at an interval of one second the register pair is preloaded and incremented. The timer is controlled by the T1CON register, which is shown in Fig. 3.612.

Timer1 can be operated either as a counter or as a timer. The operating mode of timer1 depends on clock select bit in the T1CON1 register. It can be programmed to increment every instruction cycle or every rising edge of the Timer1 oscillator.
The A/D module in the microcontroller has 16 channels and converts an analog signal into a 10-bit digital value. There are five main registers for the operation of the A/D module:

- **ADRESL**: Low byte of the result is stored in this register.
- **ADRESH**: High byte of the result is stored in this register.
- **ADCON0**: This register controls the operation of the A/D module.
- **ADCON1**: This register configures the functions of the port pins.
- ADCON2: This register configures the clock for the A/D module and sets the acquisition time.

The block diagram of the A/D converter module is shown below.

![Block Diagram of ADC Module](image)

**Figure 3.7 Block Diagram of ADC Module**

The ADCON0 register is used to choose the ADC channel, enable the ADC module and start the conversion process. Fig. 3.8 shows the ADCON0 register.
Fig. 3.8 shows the ADCON0 register. This control register is used to choose the channel for A/D conversion. In the project, channel 1 (AN1) was used. This register is used to check the status of the conversion process and to enable the A/D converter module.

<p>| Bit 7-6 | Unimplemented: Read as ‘0’ |</p>
<table>
<thead>
<tr>
<th>Bit 5-2</th>
<th>CHS3:CHS0: Analog Channel Select bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>Channel 0 (AN0)</td>
</tr>
<tr>
<td>0001</td>
<td>Channel 1 (AN1)</td>
</tr>
<tr>
<td>0010</td>
<td>Channel 2 (AN2)</td>
</tr>
<tr>
<td>0011</td>
<td>Channel 3 (AN3)</td>
</tr>
<tr>
<td>0100</td>
<td>Channel 4 (AN4)</td>
</tr>
<tr>
<td>0101</td>
<td>Channel 5 (AN5)</td>
</tr>
<tr>
<td>0110</td>
<td>Channel 6 (AN6)</td>
</tr>
<tr>
<td>0111</td>
<td>Channel 7 (AN7)</td>
</tr>
<tr>
<td>1000</td>
<td>Channel 8 (AN8)</td>
</tr>
<tr>
<td>1001</td>
<td>Channel 9 (AN9)</td>
</tr>
<tr>
<td>1010</td>
<td>Channel 10 (AN10)</td>
</tr>
<tr>
<td>1011</td>
<td>Channel 11 (AN11)</td>
</tr>
<tr>
<td>1100</td>
<td>Channel 12 (AN12)</td>
</tr>
<tr>
<td>1101</td>
<td>Channel 13 (AN13)</td>
</tr>
<tr>
<td>1110</td>
<td>Channel 14 (AN14)</td>
</tr>
<tr>
<td>1111</td>
<td>Channel 15 (AN15)</td>
</tr>
</tbody>
</table>

**Note 1:** These channels are not implemented on 64-pin devices.

<table>
<thead>
<tr>
<th>Bit 1</th>
<th>GO/DONE: A/D Conversion Status bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A/D conversion in progress</td>
</tr>
<tr>
<td>0</td>
<td>A/D Idle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bit 0</th>
<th>ADON: A/D On bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A/D converter module is enabled</td>
</tr>
<tr>
<td>0</td>
<td>A/D converter module is disabled</td>
</tr>
</tbody>
</table>

**Legend:**
- **R** = Readable bit
- **W** = Writable bit
- **U** = Unimplemented bit, read as ‘0’
- **n** = Value at POR
- ‘1’ = Bit is set
- ‘0’ = Bit is cleared
- **x** = Bit is unknown

---

**Figure 3.8 ADCON0 Register**

---

Fig. 3.8 shows the ADCON0 register. This control register is used to choose the channel for A/D conversion. In the project, channel 1 (AN1) was used. This register is used to check the status of the conversion process and to enable the A/D converter module.
ADCON1 register is used to set the reference voltage and to configure the ports as analog or digital. Figure 3.9\textsuperscript{12} shows the ADCON1 register.

![Figure 3.9 ADCON1 register](image-url)

\textsuperscript{12}Figure 3.9 ADCON1 register\textsuperscript{12}
The acquisition time of the A/D converter module, the conversion clock frequency and the justification of the result is set in the control register ADCON2

In the smart inhaler system, the A/D converter module is used in the test mode. The differential pressure that is measured across the two ports of the sensor is converted to a digital value using the A/D converter module. The output voltage signal obtained from the differential pressure sensor varies between 0 and 5V. Since the A/D converter module converts an analog signal to a ten bit digital value, each value corresponds to an incremental step of 0.005V.

The following steps are done to perform an A/D conversion
• Configure the A/D pins and choose the reference voltage—The ADCON1 register is set so that all the pins are digital except RA1 and RA0. The reference voltage is chosen to use the device’s supply voltages.

• Select the A/D channel—Channel 1 that corresponds to the input at pin RA1 is selected. The output of the differential pressure sensor is connected to pin RA1.

• Select the conversion clock and the required acquisition time—For accurate operation, the conversion clock should be as small as possible but greater than the minimum period $T_{AD}$ specified. The conversion clock is chosen to be $F_{osc}/32$. The acquisition time is chosen to be $20T_{AD}$.

• Start the conversion. Poll the bit to GO/DONE bit to see if the conversion is complete.

• Read the A/D result register—ADRESH:ADRESL. The result is right justified so ADRESL hold 8 bits of the result and ADRESH holds the remaining two bits.

**MSSP Module**

The MSSP module is a serial interface unit that is used to establish serial communication between the microcontroller and peripheral devices. It can operate in two modes:

- SPI™ mode
- I²C™ mode
  - Full Master Mode
  - Slave Mode(with general address call)
In this project the MSSP module has been used extensively in the SPI mode to communicate with the peripheral devices such as the LCD and the PICTail Daughter Board for SD/MMC cards.

The SPI mode allows synchronous transmission and reception of 8 bits of data. Fig.3.11 shows the block diagram of the MSSP module in the SPI mode. The MSSP module can support all four modes of SPI and three pins are essentially used for communication:

- Serial Data In (SDIx)-Pin RC5 or RD4 can be configured as SDI
- Serial Data Out(SDOx)-Pin RC4 or RD5 can be configured as SDO
- Serial Clock (SCKx)-Pin RC3 or RD6 can be configured as SCK.

There are three control register associated with the MSSP module-the status register, SSPxSTAT and the control registers SSPxCON1 and SSPxCON2. These control registers are set

![Figure 3.11 Block Diagram of MSSP Module (SPI)\textsuperscript{12}](image)
based on whether the MSSP module is used as in the \( \text{I}^2\text{C} \) mode or the SPI mode. The registers that are used with the SPI mode are SSPxSTAT, SSPxCON1, SSPxBUF and SSPxSR. The first two are the status and control registers respectively.

The microcontroller essentially has two MSSP modules so depending on which one is being used, the corresponding value is used in place of ‘x’ in the names of the registers SSPxBUF, SSPxSR, and SSPxSTAT and SSPxCON1. These two modules work independently. Several peripherals can be connected to the same module provided the chip select line is different for each. The SSPxCON1 is readable and writable whereas the lower 6 bits of SSPxSTAT are read-only. The SSPxBUF and SSPxSR creates a double buffered receiver. During transmission, the data is sent to both of these registers. The SSPxSR register is used to shift data in and out.

In this project, the microcontroller is configured as a master that communicates with two peripherals, the daughter board for SD card and the LCD module. This is achieved by using different pins as the Chip Select (CS) signal for the two peripherals. The SPI mode is chosen to work as a master at a frequency of \( F_{\text{osc}}/64 \). In the master mode, the data is transmitted/received as soon as the SSPxBUF is written into. For the pins to behave as serial input and output the direction bit must be set for some of them. The SPI automatically sets the direction for the SDI pin but for SDO and SCK the direction must be set using the TRIS register corresponding to those pins.

The control registers SSPxSTAT and SSPxCON1 in the SPI mode are shown in Fig.3.12\(^\text{12}\) and Fig.3.13\(^\text{12}\) respectively.
This register is monitored to determine the status of the SSPxBUF register during transmission.
This register is used to select the mode of operation, clock frequency and configure the port pins.
The communication in the SPI mode is depicted in Fig. 3.14

**Oscillators**

Fig.3.15\(^1\) shows the clock sources for the PIC18F8722 family of devices. There are essentially three clock sources

- Primary Oscillator
- Secondary Oscillator
- Internal Oscillator Block

Primary oscillators include the external clock, external RC modes, the internal oscillator and external clock modes. The secondary oscillators are oscillators that are not connected to the OSC pins. The timer1 oscillator is an example of a secondary oscillator. The internal oscillator block in addition to being a primary oscillator is also power managed clock source.
PIC 18F8722 can be configured to run in one of ten different oscillator modes. These modes are as follows:

- LP- Low Power Oscillator
- XT-Crystal/Resonator
- HS-High Speed Crystal/Resonator
- HSPLL-High Speed Crystal/Resonator with PLL enabled
- RC-External resistor/capacitor with $F_{osc}/4$ output on RA6
- RCIO-External resistor/capacitor with I/O on RA6
- INTIO1-Internal Oscillator with $F_{osc}/4$ output on RA6 and I/O on RA7
- INTIO2-Internal Oscillator with I/O on RA6 and RA7
- EC-External Clock with $F_{osc}/4$ output
• ECIO-External clock with I/O on RA6

The HS, LP, HS and HSPLL mode require a crystal to establish oscillation. In this project the INTIO2 mode has been used. In the INTIO1 and INTIO2 modes, the clock for the device is derived from an internal oscillator block. The difference between the two mode arises depending on whether one or two of the external oscillator pins can be used for digital I/O. The output of the internal oscillator is an 8 MHz clock signal which can be directly used to drive the device. It is also used to drive a postscaler, which can be used to provide a range of frequencies from 31 KHz to 4MHz.

3.2.2 Programming the Microcontroller

In order to program the microcontroller the following are the requirements:

• Source Code-A source code in C that describes the operations that the microcontroller needs to perform in order to interface with the peripherals and implement all the functionalities of the system. MPLAB® IDE tool includes a debugger for working with Microchip hardware tools.

• Assembler/Compiler-Source code must be compiled to generate a HEX file that can then be transferred to the microcontroller. MPLAB® IDE includes a MPLAB® C18 compiler which is a C compiler for PIC18 microcontrollers.

• Programmer-Once the HEX code is ready, it can be use to program the microcontroller. This is achieved by the use of MPLAB® In-Circuit Debugger (ICD) 2 or PICKit™ starter kit.
3.3 Differential Pressure Sensor

The differential pressure sensor used, MPX5010 is a temperature compensated, signal conditioned, calibrated pressure transducer from Freescale. The following features of the pressure transducer make it suitable for use in the smart inhaler system

- The range of pressure that can be measured is from 0 to 10 KPa
- It is suited for microcontroller/microprocessor application
- Since all of the signal conditioning is done on-chip the output of the pressure transducer can be directly connected to the A/D input of the microcontroller
- It is available in different packaging styles such as through hole and surface mount configurations
- It has been compensated over a wide range of temperature from -40ºC to 125ºC
- It provides a high-level analog voltage corresponding to the pressure applied. Since the range of the output voltage varies between 0V and 5V it can be directly interfaced with the microcontroller without the need for any amplifying circuitry
- It is available in differential and gauge configurations. For the purpose of this project, the differential configuration of the sensor was used.

3.3.1 Operating Characteristics and Transfer Function

The operating characteristics of any sensor specify parameters such as response time, warm up time, supply voltage, offset accuracy and sensitivity.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage$^{(1)}$</td>
<td>$V_B$</td>
<td>4.75</td>
<td>5.0</td>
<td>5.25</td>
<td>Vdc</td>
</tr>
<tr>
<td>Supply Current</td>
<td>$I_S$</td>
<td>—</td>
<td>5.0</td>
<td>10</td>
<td>mA/μA</td>
</tr>
<tr>
<td>Minimum Pressure Offset$^{(2)}$</td>
<td></td>
<td>0</td>
<td>0.2</td>
<td>0.425</td>
<td>Vdc</td>
</tr>
<tr>
<td>$V_{off}$ (0 to 85°C) @ $V_B$ = 5.0 Volts</td>
<td></td>
<td>4.475</td>
<td>4.7</td>
<td>4.925</td>
<td>Vdc</td>
</tr>
<tr>
<td>Full Scale Output$^{(3)}$</td>
<td></td>
<td>4.275</td>
<td>4.5</td>
<td>4.725</td>
<td>Vdc</td>
</tr>
<tr>
<td>$V_{FSS}$ (0 to 85°C) @ $V_B$ = 5.0 Volts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy$^{(3)}$</td>
<td></td>
<td>—</td>
<td>—</td>
<td>±5.0</td>
<td>%$V_{FSS}$</td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td>450</td>
<td>4.413</td>
<td></td>
<td>mV/mm mV/mm H₂O</td>
</tr>
<tr>
<td>Response Time$^{(6)}$</td>
<td>$t_R$</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>ms</td>
</tr>
<tr>
<td>Output Source Current at Full Scale Output</td>
<td>$I_{O+}$</td>
<td>—</td>
<td>0.1</td>
<td>—</td>
<td>mA/μA</td>
</tr>
<tr>
<td>Warm-Up Time$^{(7)}$</td>
<td>—</td>
<td>20</td>
<td>—</td>
<td>—</td>
<td>ms</td>
</tr>
<tr>
<td>Offset Stability$^{(8)}$</td>
<td>—</td>
<td>±0.5</td>
<td>—</td>
<td>±5%</td>
<td>%$V_{FSS}$</td>
</tr>
</tbody>
</table>

1. Device is ratiometric within this specified excitation range.
2. Offset ($V_{off}$) is defined as the output voltage at the minimum rated pressure.
3. Full Scale Output ($V_{FSS}$) is defined as the output voltage at the maximum or full rated pressure.
4. Full Scale Span ($V_{FSS}$) is defined as the algebraic difference between the output voltage at the full rated pressure and the output voltage at the minimum rated pressure.
5. Accuracy (error budget) consists of the following:
   - Linearity: Output deviation from a straight line relationship with pressure over the specified pressure range.
   - Pressure Hysteresis: Output deviation at any pressure within the specified range, when this pressure is cycled to and from the minimum or maximum operating temperature points, with zero differential pressure applied.
   - Pressure Hysteresis/Output deviation at any pressure within the specified range, when this pressure is cycled to and from the minimum or maximum rated pressure, at 25°C.
   - TcSpan: Output deviation over the temperature range of 0°C to 85°C, relative to 25°C.
   - ToffSet: Output deviation with minimum rated pressure applied, over the temperature range of 0°C to 85°C, relative to 25°C.
   - Variation from Nominal: The variation from nominal values, for Offset or Full Scale Span, as a percent of $V_{FSS}$, at 25°C.
6. Response Time is defined as the time for the incremental change in the output to go from 10% to 90% of its final value when subjected to a specified step change in pressure.
7. Warm-Up Time is defined as the time required for the product to meet the specified output voltage after the Pressure has been stabilized.
8. Offset Stability is the product's output deviation when subjected to 1000 hours of Pulsed Pressure, Temperature Cycling with Bias Test.

**Figure 3.16 Operating Characteristics$^{13}$**

The operating characteristics of the pressure sensor are shown in Fig. 3.16$^{13}$.

The performance over a wide range of temperature is achieved because of integration of the shear-stress strain gauge, temperature compensation and signal conditioning circuitry on a single chip. Fig. 3.17$^{13}$ shows the block diagram of the fully integrated pressure sensor chip. The sensor used in the project is unibody and the connections to the different pins are shown below. A supply voltage of 5V has been used as recommended in the data sheet.
Fig. 3.17 Fully Integrated Pressure Sensor Chip\textsuperscript{13}

Fig. 3.18\textsuperscript{13} shows the output voltage obtained for different pressure values over a range of temperature.

From the figure, it can be seen that the transfer function is given by,

\[ V_{out} = V_s \times (0.09 \times P + 0.04) \pm (Pressure \ error \times Temp \ Factor \times 0.09 \times V_s) \]

where \( V_s = 5 \pm 0.25V_{dc} \)

Figure 3.18 Output Voltages vs. Differential Pressure\textsuperscript{13}
Fig. 3.19 Temperature Error Band\textsuperscript{13}

Fig.3.19\textsuperscript{13} shows the band of temperature over which the multiplication factor has to be taken into account. It can be seen that the response is linear from -40\(^\circ\)C to 0\(^\circ\)C and between 85 and 125\(^\circ\)C.

3.4 PICTail\textsuperscript{TM} Daughter Board for SD\textsuperscript{TM} and MMC Cards

The PICTail\textsuperscript{TM} Daughter board for SD and MMC cards is an expansion board compatible with the PIDEM PIC18 Demonstration Board that is used for evaluating, reading and writing data on SD and MMC cards\textsuperscript{14}. There are several features that make the use of the PICTail daughter board favorable for use in this project. In the test mode, given the large volume of data that needs to stored and retrieved, an SD card has to be interfaced with the system. This interface is made possible because of this expansion board. A Sandisk 2GB SD card is used to collect all the data. Fig. 3.20\textsuperscript{14} shows the PICTail\textsuperscript{TM} daughter board.
The PICTail™ Daughter Board is compatible with a wide range of SD cards and can be operated over a range of voltages from 3.3 V to 5 V. Seven jumper locations are available on the board. This jumper position and the associated feature are given in Fig.3.21.

The microcontroller interfaces with SD card using the SPI mode. Apart from the four signals SCK, SDI, SDO and $\overline{CS}$ it will require two additional signals Card Detect (CD) and

<table>
<thead>
<tr>
<th>Jumper</th>
<th>Position</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP1</td>
<td>Pin 1-2</td>
<td>PIC18 Explorer Board enabled (SCK connected to RC3)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>PICDEM FS USB enabled (SCK connected to RB1)</td>
</tr>
<tr>
<td>JP2</td>
<td>Pin 1-2</td>
<td>PIC18 Explorer Board enabled (SDI connected to RC4)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>PICDEM FS USB enabled (SDI connected to RB0)</td>
</tr>
<tr>
<td>JP3</td>
<td>Pin 1-2</td>
<td>PIC18 Explorer Board enabled (SDO connected to RC5)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>PICDEM FS USB enabled (SDO connected to RC7)</td>
</tr>
<tr>
<td>JP4</td>
<td>Pin 1-2</td>
<td>No Connect (user can select an available port)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>Card Detect (CD) signal connected to RB4</td>
</tr>
<tr>
<td>JP5</td>
<td>Pin 1-2</td>
<td>No Connect (user can select an available port)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>Write-Protect (WD) signal connected to RA4</td>
</tr>
<tr>
<td>JP6</td>
<td>Pin 1-2</td>
<td>No Connect (user can select an available port)</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>Chip Select ($\overline{CS}$) signal connected to RB3</td>
</tr>
<tr>
<td>JP7</td>
<td>Pin 1-2</td>
<td>User can use RA5 as Shutdown (SHDN) signal for MCP1253</td>
</tr>
<tr>
<td></td>
<td>Pin 2-3</td>
<td>Shutdown disabled (connected to Vcc)</td>
</tr>
</tbody>
</table>

Figure 3.21 Jumper Positions and Associated Features
Write Protect (WD). The interface with the SD card is established by making use of the routines available in Microchip’s memory disk driver filesystem library\textsuperscript{15}. It supports both FAT16 and FAT32 filesystem.
Chapter 4

Test Results and Discussion

In order to test the working of the smart inhaler system the three different modes of the system have to be tested independently. For the working of the test mode and the inhaler record mode, it is necessary to establish an interface between the microcontroller and the peripherals—the SD card and the differential pressure sensor. In addition, it is necessary to test the ability of the system to switch between the three modes of operation.

4.1 Experimental Set Up

The experimental setup for the smart inhaler system is shown below.

![Experimental Setup](image-url)

Figure 4.1 Experimental Setup
It can be seen that the differential pressure sensor is connected across a mouthpiece. The mouthpiece is in effect a Venturi tube. Construction of the mouthpiece for the project was done in the machine shop. The mouthpiece is constructed in such a way that the diameter on one end is 1” and the opposite end is ½”. This difference in the cross sectional area causes the velocity of flow to increase as it moves through the constriction. The increase in velocity is measured as difference in pressure. This difference in pressure can be used to determine the volumetric flow rate \( Q \) given by

\[
Q = \sqrt{\frac{2\Delta p}{\rho}} \left[ \frac{A_2}{1 - \left(A_2/A_1\right)^2} \right]
\]

Where \( A_2 \) and \( A_1 \) are the cross sectional areas of the two sections of the tube.

\( \Delta p \) is the pressure differential.

\( \rho \) is the density of the fluid.

In this case, \( \rho \) is the density of air=1.225kg/m\(^3\).

\[
A_1 = \pi r_1^2
\]

\[
A_2 = \pi r_2^2
\]

Where \( r_1=1/2” \) and \( r_2=1/4” \) respectively.
Fig. 4.2 Mouthpiece (Venturi tube)

Fig. 4.2 shows the Venturi tube that was used as a mouthpiece in this project.

The two ends of the differential pressure sensor are attached to the tubes that come out of the two sides of the constriction. The voltage output obtained from the sensor is proportional to the differential pressure measured, which in turn can be used to determine the flow rate. Since the pressure at port, P1 should be greater than P2 the inhalation and exhalation should be done at opposite ends of the tube.

4.2 Testing the different modes of the Smart Inhaler System

In order to test the system it is imperative that the test for the different modes be carried out independently and also test the switching between the different modes. When the demonstration board is initially powered up the system is in standby mode and it stays in this mode until it receives an interrupt. In the standby mode, one of the LEDs (D0) glows. When push button S0 is pressed, it goes into the test mode. In the test mode, initially it displays a message on the LCD. The message asks the user for their perception of their condition. The figure below shows the message that is displayed on the LCD.
In response to this message, the user has to press one of the push buttons. ‘1’ in the message refers to push button S0 and ‘2’ in the message refers to push button S1. Depending on how the user feels at that moment, the appropriate button is pressed. The feedback given by the user is recorded on the SD card with a timestamp so that the physician can get an idea of the patient’s perception of their condition at that instant of time. Following this, the patient should take the spirometry test. The maneuver that the patient is expected to do is that they should take a deep breath and then exhale all of the air as rapidly and as hard as possible. The flow rates are recorded for a period of 7 to 8 seconds although the exhalation itself is not expected to be that
long. This is just done to ensure that the values are recorded even in case of disturbances while the procedure is carried out. It is necessary that the maneuver is carried out carefully and the procedure of spirometry is followed strictly, since patient cooperation greatly influences the quality of the result. The figure below shows the right way to carry out spirometry to ensure reproducible results.\textsuperscript{16}

It can be see that nose clips are generally used to prevent escape of air through the nostrils. The exhalation is not expected to last beyond 6 s. The output voltages are passed through the ADC and then further processed to obtain the differential pressure and the flow rates. The final flow rates are written onto the SD card. About 6 reading are taken in a span of 1 s and it has been assumed that the reading are equally spaced, meaning that a reading is obtained every 0.1667 s or every 167 ms. The flow rates recorded in the SD card is given to a tool like Excel or
Matlab to obtain volumes and a plot of flow vs. volume is created. The loop is analyzed to obtain values such as Forced Vital Capacity (FVC), Forced Expiratory Volume in 1 second (FEV1) and Peak Expiratory Flow (PEF).

After recording all the values, the system can be switched back to the standby mode by pressing the button S0 once again. Then, the button press of switch (S1) does the switch to the inhaler usage record mode. In the inhaler usage record mode, the interrupt created by the button press causes a timestamp to be written to a text file on the SD card. This time indicates the time the inhaler was used. After writing the timestamp in the SD card, it automatically exits out of the inhaler usage record mode to the standby mode waiting for further input from the user.

Apart from all this there is also a timer that works in the background. The timer is set in such a way that it creates an overflow every one second and causes an interrupt. There are register that keep track of the number of seconds and as the number of second exceeds 59 it is reset and the minutes register is incremented. Once the minutes register reaches 59 the hours register gets incremented and so on. Even when the microcontroller is in the sleep mode, the timer can be programmed to work if a super capacitor or a battery is provided. In the current system implemented, after every one minute the LEDs on the demonstration board blink thrice to alarm to the user that it is time to take their medication. This can however be reprogrammed to go off every few hours depending on the requirement. I had chosen a time interval as short as one minute to monitor the correct operation of the alarm in the system.
Results and Discussion

In the test mode, a typical text file that is obtained after the spirometry procedure looks as shown in Fig. 4.5. The value of 3.49 that is obtained for the flow rate is due to the offset value of the sensor ~0.18V. This is compensated for, while processing the data in Excel or Matlab and the final values for the flow rates are obtained.

![Figure 4.4 Output File in the Test Mode](image)
The flow rates that are obtained are integrated with respect to time to obtain the volumes and a plot of the flow vs. volume is created as shown in Fig.4.6.

The readings taken are for an Indian Female of 26 years of age. The parameters obtained are compared against those predicted\(^\text{17}\). The values obtained vary with ethnicity, age and sex. The values for FVC, PEF and FEV\textsubscript{1} for the experiment as obtained from the graph are shown below:

FVC= 3.4L

FEV\textsubscript{1}= 2.413 L

PEF= 6.8L/sec
It can be seen that the values obtained from the experiment are close to the predicted values. The predicted values of interest have been highlighted in red in Fig.4.7.

<table>
<thead>
<tr>
<th>Inputs were entered as:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
</tr>
<tr>
<td>Date of birth:</td>
</tr>
<tr>
<td>Current year:</td>
</tr>
<tr>
<td>Age:</td>
</tr>
<tr>
<td>Sex:</td>
</tr>
<tr>
<td>Ethnic origin:</td>
</tr>
<tr>
<td>Height:</td>
</tr>
<tr>
<td>Weight:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results predicted by ERS Quanjer 1993 references glossary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>FEV1</td>
</tr>
<tr>
<td>FVC</td>
</tr>
<tr>
<td>PEF</td>
</tr>
<tr>
<td>FEF2575</td>
</tr>
<tr>
<td>FEF25</td>
</tr>
<tr>
<td>FEF50</td>
</tr>
<tr>
<td>FEF75</td>
</tr>
<tr>
<td>RV</td>
</tr>
<tr>
<td>FRC</td>
</tr>
<tr>
<td>TLC</td>
</tr>
<tr>
<td>IV/C</td>
</tr>
<tr>
<td>RV/TLC</td>
</tr>
<tr>
<td>FRV/TLC</td>
</tr>
</tbody>
</table>

Figure 4.7 Predicted values of the parameters for Individual 117
The flow volume loop and the predicted values for an Indian male of 23 years are shown in Fig. 4.8. It can be seen that the expected parameters are different from those expected in the previous case.

From the flow volume loop obtained for Individual 2 it becomes obvious that the parameters are different for different individuals and greatly depends on age, sex, and ethnicity. The values obtained for the different parameters are shown in Fig. 4.9:

FEV1 = 4.1L

PEF = 10.35L/sec

FVC = 4.8L
The predicted values are not too different from those obtained from the experiment. There are also some values that are obtained in the inhalation process such as FIF (Forced Inspiratory Flow) but as mentioned earlier the most important maneuver especially for assessing conditions like asthma and COPD, is Forced Expiration. Parameters such as FEV1 and FVC are of utmost importance and a lower value of these parameters suggests an obstructive lung disease.
As mentioned earlier, spirometry is a procedure that is highly dependent on patient cooperation and on the set up used to perform the test. Even in the hospital, it is repeated several times to get reproducible results. When it is not done properly, it results in erroneous values as shown in Fig.4.10.

Figure 4.10 Irregularities in the Flow-Volume Loop due to the use of long tubes

The mouthpiece that is generally used in the procedure is very different from that used in our experiment. Also in the experiments performed, nose clips were not used. It was simply achieved by holding the nose with the hand. The results obtained had a glitch associated with them. In general, in order to determine the forced vital capacity the flow volume loop should follow a particular trend. The flow should initially rise sharply and the fall of the flow rate should take place rapidly. The problem that occurred either due to improper set up or due to improper procedure is that the flow rose rapidly and that was followed by a plateau region of
Figure 4.11 Flow Volume Loop after the use of shortened tubes

flow rates where it remained high for a while and then dropped sharply. When those data points were avoided and the graph was plotted, a clean flow volume loop was obtained.

It was thought that the reason for the plateau region in the flow rates might be the long tubes that connected the sensor ports to the Venturi tube/mouthpiece. The lengths of the tubes were shortened and the values were recorded again. Fig.4.11 shows the flow volume loop obtained after making the change to the setup.

It can be seen that the graph obtained, although not perfect is better than the one obtained with long tubes. Here the FVC obtained is about 4L, PEF of 6.03 L/sec and FEV1 of 3.40 L. While we were using long tubes we were getting a plateau region in the flow rate readings. It is probable that since the tubes connecting to the ports were long, it took time to obtain the exact
pressure differential between the two ports. The long tubes were essentially creating a vacuum resulting in high values of flow rates to be recorded for a long period of time.

| 24 May 2012 01:00:22 |
| 24 May 2012 01:00:50 |
| 24 May 2012 01:01:18 |
| 24 May 2012 01:01:26 |
| 24 May 2012 01:02:05 |
| 24 May 2012 01:02:41 |

**Figure 4.12 Output text file in the inhaler usage record mode**

In the inhaler usage record mode, the button press of push button (S1) is recorded in a text file in the SD card. When the system is in the standby mode, the button press of S1 causes an interrupt and results in the recording of the timestamp at that instant. The timer in the microcontroller is programmed to function as a real time clock. The output text file, which contains a record of the time instances when the push button was pressed, is shown in Fig.4.12. The idea behind this feature is that, the physicians can get an idea of when the patient is taking the medication and if they are adhering to the course of treatment prescribed to them. Collecting all this information along with periodic test results will help the physicians to develop a more personalized course of treatment tailored to the needs of the individual.
The system developed also has an alarm to remind the patients to take the medicine. The alarm is implemented by means of the LEDs on the demonstration board. The timer generates an interrupt whenever the timer register overflows. It is set so that the overflow occurs every second. This update seconds register and after 60 seconds, the minutes register and so on. At the moment, the alarm is set to go off every minute. However, it can be modified to go off at any interval prescribed by the physician for the intake of medication. Fig.4.13 shows the alarm implemented in the system. The LEDs blink thrice indicating that it is time for the patients to take the medication.
Therefore, it can be seen that all the modes of the system have been tested successfully. Button press of the two push buttons achieves the switching between the modes. On reset, the system is usually in the standby mode. Once button S1 is pressed, it enters the inhaler usage record mode, records the timestamp and exits out to the standby mode again. The switch between the test mode and the standby mode is slightly different. When switch S1 is pressed, it enters the test mode, obtains the input from the user again using the two push buttons and then it performs the spirometry test. After this is completed, the user needs to press S1 again to exit out of the test mode and go back to the standby mode of operation.
Chapter 5

Conclusion and Future Work

5.1 Summary

A prototype of a smart inhaler system for asthma patients has been designed and developed. The smart inhaler system has been developed with the intent of being used a point of care system that can be integrated with the inhaler. The smart inhaler system consists of three modes of operation-standby, inhaler usage record mode and test mode. All the features that were originally planned for the project have been successfully developed. The major components in the development of the system are the microcontroller, differential pressure sensor, Venturi tube/mouthpiece and the SD card. Given the small size of the components in use, it is possible to package the system in such a way that it can be integrated with the inhaler that is used by asthma patients.

The system comprises of a sensing module, a microcontroller, a user interface module and a memory module. The sensing module is accomplished with the help of a differential pressure sensor MPX5010 from Freescale. The microcontroller used in this project is PIC18F8722 part of the PICDEM PIC18 explorer demonstration board. The user interface module is made up of push buttons and LCD, both of which are available on the PICDEM PIC18 demonstration board. The memory module is achieved by the use PICtail Daughter for SD/MMC cards and an SD card of 2GB from SanDisk.

The system can be operated in three modes-standby, inhaler usage record and test mode. The standby mode is the default mode of operation. It is characterized by a single glowing LED
(D0). The inhaler usage record mode essentially records the timestamp of a button press in a text file on the SD card. The test mode obtains input from the user regarding their perception of their condition and performs spirometry test on the user. The physician can later retrieve the values recorded on the SD card from which the flow volume loop can be obtained, and important parameters can be determined.

5.2 Suggestions for Future Work

The current smart inhaler system prototype uses a differential pressure sensor that measures pressure in the range of 0 to 10 KPa. It has the constraint that the port P1 should always be at a higher value of pressure than P2. In the present set up the port, P1 is connected to the side of the Venturi tube, which is 1” in diameter, and port P2 is connected to the mouthpiece on the other side of the constriction. Exhalation from the P1 side will ensure that P1 is always higher than P2. However, in the case of inhalation, since the flow is in the opposite direction, P1 will become lesser than P2 and no reading will be obtained. Therefore, it becomes necessary to carry out the process of inhalation from the other end of the mouthpiece. This can be avoided if the pressure sensor used can measure both negative and positive ranges of pressure.

Another modification that can be made to the system is the improvement of the set up itself in order to improve the reproducibility of the system. It can be seen that the present set up is quite rudimentary and it requires further work to bring it to the level of the set up used in the hospital in order for this prototype to be developed into a product.

In the current system, after recording the flow rates, the volumes are obtained by performing integration of the flow rates over time using a tool like Excel or Matlab. It would be a good idea to come up with an algorithm so that all of the integration and calculation of the
parameters can be performed in the microcontroller itself and the user is finally able to read off the results directly from the display. DSP microcontrollers may be used to implement this functionality in the system.
References


9 http://en.wikipedia.org/wiki/Venturi_effect

10 http://en.wikipedia.org/wiki/Bernoulli's_principle


12 PIC 18F8722 Family Data Sheet, Microchip®, DS39646, 2008


14 PICTail Daughter Board for Sd/MMC cards Data Sheet, Microchip®, DS51583B

15 AN1045: Implementing file I/O function using Microchips Memory Disk Drive filesystem library, DS1045B, Microchip, 2008

16 http://www.childrenscolorado.org/wellness/info/parents/62883.aspx

17 http://www.dynamictmt.com/dataform3.html