Managing Children's Asthma with a Low Cost Web-Enabled Multifunctional Device

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Abstract. The essence of this paper is to present an innovative, viable, low cost, cloud based asthma management system solution, regarding children's asthma issues. The proposed device is a spirometric element that combines the functionality of several other devices that are so important for the daily life of asthma patients aged between 6 to 14. All the above are achieved using the latest technology in wireless and medical equipment that would make the device become irreplaceable to the end user.

Keywords: Asthma, Spirometer, Inhaler Detector, Wireless Module, Multifunctional.

1 Introduction

Asthma, is the most common reason patients visit pulmonologists in the US [1]. It is a chronic disease without permanent treatment. Patients with asthma have respiratory issues and they have to check their lungs status frequently. In a nutshell, it decreases the diameter of the lungs' airways and also produces a small amount of mucus that makes patients breath with difficulty. Dyspnea and coughing are the symptoms that follow patients through their entire life.

The daily medication for asthma consists of steroids in order to control the lungs' function [2]. This type of medication, includes the use of inhalers. The inhaler is a small form factor device that provides the user measured doses of the steroid which is placed into it. There is the blue colored inhaler, called reliever, for emergency asthma crisis and a red one called preventer, for daily use that improves and maintains the lungs' airways in good condition.

Moreover, there are some other devices that experts recommend for daily use. The spacer, peak flow meter and the spirometer:

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The Spacer is a device that works in conjunction with the inhaler in order to help patients breathe the steroids in low pressure. It helps people to breathe easier than using the inhaler directly into their mouth.

The Peak Flow Meter measures the maximum level of a forced expiratory. It is quite useful for doctors due to the fact that it indicates in which colored health zone the patient belongs to [3]. There are three zones: the green zone is the healthier zone that patient do his usual activities without problems, the yellow zone describes some small breathing issues and patient cannot complete all of his daily activities and the red zone for emergencies in which patients cannot breath very well and need to move to a hospital. Contrary to spirometers that doctors use to monitor lungs' condition, peak flow meter is a cheap spirometer that measures only the peak of the expiratory air flow rate parameter (PEF) but it's still useful.

The Spirometer is the most advanced method of monitoring lungs function. Experts use many kinds of spirometers depending on the situation. The most prevalent type of spirometer is the digital spirometer. It's an electronic spirometer without mechanical parts that measures several medical parameters such as PEF (Peak Expiratory Flow), FVC (Forced Vital Capacity), FEFx (Forced Expiratory Flow rate in x percentage), FEV (Forced Expiratory Volume in t timeslot), FIFx (Forced Inspiratory Flow in x percentage). It has a built-in LCD screen and a wireless communication technology so that you can see and transmit the values of those parameters. They are required by doctors' diagnosis and they help them to make sure about patients health.

Currently, the devices mentioned above, are quite complex and expensive, hence they are unattractive to the end user. The cost of modern commercial spirometers can be over nine hundred dollars. They have screens, buttons, weird design and ugly interfaces that patients are at least reluctant to use, and quite user unfriendly, so they need to read many manual pages in order to operate them correctly.

In this paper, we describe a new way to address this problem, developing a novel spirometric device that could look more elegant and ergonomic. The external design must be attractive in order to use it more frequently during the day. Asthma is a disease that can easily affect younger people than 15 years old because of the vulnerable immunogenic system. Henceforth, they need more daily health monitoring than older people. Also, the prevalence and severity of childhood asthma have increased substantially in recent years [5]. This is the reason why the proposed device is focused to be used by children between 6 and 14 years old. Nowadays, children's daily life includes many activities that require a lot of energy. The biggest concern about children from 6 to 14 years old is finding a way to motivate children to use all the above-mentioned equipment every time and how difficult is to carry around them complex devices. It is quite obvious that we should motivate young children with asthma to use all these devices more frequently than they do presently.

2 Motivation

The main objective of this study is to develop a telemedicine system which can manage asthma data for patients in childhood without the need of frequent visits at health care centers. This system includes the development of a multi-functional spirometric device that can solve the problem of daily patient's monitoring. This study is about developing a novel device that could replace all current medication and monitoring devices with one single device being an essential part of a remote medical monitoring service. This device should combine a spirometer with peak flow meter and spacer because we should motivate children to be more responsible with their medication, while having fun playing with it at the same time.

A key feature that could motivate and train children about asthma and their lungs' function is the cooperation of the spirometer with devices as a smartphone or a tablet giving opportunities to mobile software developers to build game applications in order to motivate children to learn more about their health status. Finally, this device must be a relatively low cost product in order to succeed in our task. It is quite important, to make as affordable as we can, so it can be useful and attractive for parents who have children with asthma.

3 The Proposed Model

Using the proposed system, we can easily monitor patients through the Internet as a cloud based service. This system comprises of two devices and an internet service (Fig.1). The basic device is the spirometer that collects patient's measurements and data. The second device is a smart handheld device that plays a dual role in our model.

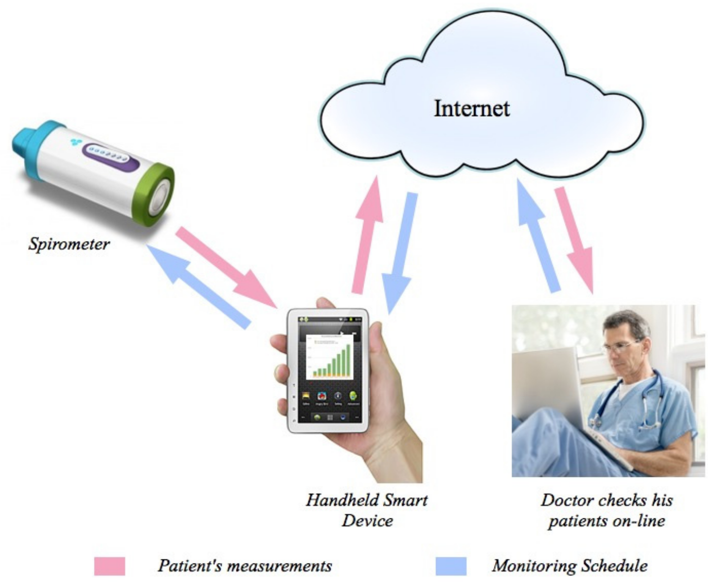

Fig. 1. This model can be the structure of an asthma telemedicine system with a cloud telemedicine service

The basic reason that we use a smart handheld is that spirometer can gain access to the internet through it via a Bluetooth wireless connection. Furthermore, an application is installed on the handheld with a simple to use interface. It contributes to manage the saved data in spirometer's memory and send them to doctor's monitoring system via a cellular or Wi-Fi connection. The app has the ability to display the current measurements and draw a real-time air flow graph when the child blows across the spirometer.

The Concept Works in a Quite Simple Manner

The child uses the spirometer during the whole day according to a predefined monitoring schedule.

When the device finds any previous paired smart device bluetooth enabled, it automatically establishes a connection. Then it launches a specific app showing the daily results and uploads them to a specific server which can only be accessed by the doctor. After that, patient's medical file is updated with new measurements.

Consecutively, the doctor can study his patient's health improvement and suggest a new monitoring schedule for the next days. So, he can upload a new schedule data to the spirometer via his information system. A sound alert will notify user that he must do a spirometric measurement or time to breathe the preventer steroid. Consequently, it's an interactive model, in which there is an interactive communication between spirometer and doctor.

We focus on developing a multi-functional spirometer as part of that telemedicine system with some concrete and discrete characteristics:

- *Elegant and simple design*
- *Reliable measurement ability*
- *Wireless connectivity with smart devices and computers*
- *Rechargeable*
- *Small and comfortable size and weight*
- *Easy to use UI (user experience)*
- *Visual and audio indications*
- *Invisible function to the user*
- *low cost (up to 250$)*

All these characteristics are our goals and guidelines in designing a useful medical device for monitoring asthma patients. We should implement an efficient architecture and set out specific technical features to reach the initial goals.

Starting to explain the functionality of the spirometer, we have to describe the basic architecture.

4 Architecture

The architecture of this spirometer should include some very remarkable features in order to achieve our requirements:

Features:

1. ***Reliable Airflow sensor***
2. ***LED indication** for current airflow levels*
3. ***Sound alerts***
4. ***Inhaler detection***
5. ***GPS** for acquiring location data and geolocation*
6. ***RTC** for acquiring the time of an event*
7. ***EEPROM Memory bank** for saving monitoring schedule and measurement event data.*

Our project's target group is ages between 6 to 14 years old and it's impossible to carry around with them devices as a smartphone. Thus, we don't use the already smart devices' embedded stuff; we have to implement geolocation features, real time clock and a memory module into the device for better monitoring. The basic implementation architecture is illustrated in Fig. 2.

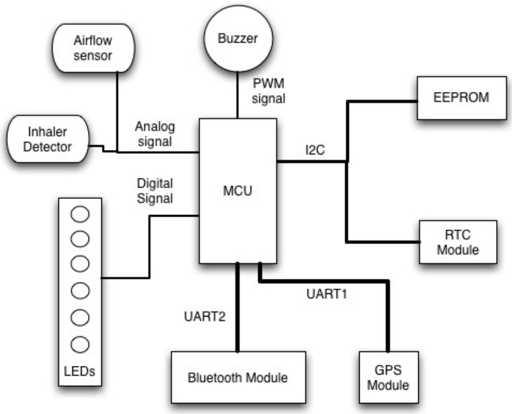

Fig. 2. This scheme constitutes the whole architecture which shows how all the basic electronic components communicate with central microcontroller

EEPROM memory and Real-Time-Circuit are connected with a microcontroller by an I2C synchronous serial interface. The Bluetooth and GPS module communicates through asynchronous UART protocol. An airflow sensor and a color sensor (thus the inhaler detector) are attached to analog inputs of the microprocessor in order to have better control at sampling procedure. The LED array and the buzzer are used as optical indication and sound notification respectively. They constitute the unique mechanism that children get feedback from the device in a simple way.

When the device is on, the microcontroller can be triggered by two ways. The one way is that users' blows, an air flow sensor detects elemental amount of air stream, then air flow samples are being saved in the memory IC as well as the time and date data. Then, the microcontroller asks for location determination from the GPS module and saves its data at the same memory IC. The second scenario is about the detection of a mounted inhaler. When the color sensor detects the existence of a blue or red color, microcontroller asks for location and time information again. The detection of each colored inhaler can be done as the plugged inhaler on the front of the spirometer reflects a unique color direct to the sensor's sensitive point. Then, the microcontroller saves a specific color value for each inhaler to the created event file.

Spirotube

Beyond the implementation part of the electronics, we need to design carefully an airway that airflow sensor will take the pressure samples when someone blows into the device. This procedure is very essential as the spirotube is the main hardware part that delivers two different samples of the inserted air flow to the airflow sensor. We can estimate the velocity of the air in liters/second via the output voltage of the airflow sensor and the following equation:

$$F_A = F_{FS}\left(\frac{Vo}{Vs} - 0.5\right), \tag{1}$$

F_A = Flow applied across the device, F_{FS} = Full scale flow specified for the device,

V_O = Output voltage of the device, V_S = Supply voltage measured at the device.

Moreover, the spirotube is the contact between the user's mouth and the airflow sensor (Fig.3). It is designed with precision so as to achieve 150 Pa/L/sec airway resistance per 14 litters per second air velocity. That is the requirement of the ATS(American Thoracic Society) in standardization of spirometry.

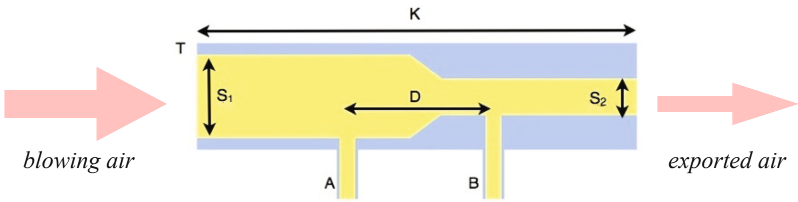

Fig. 3. Splinted view of the spirotube. In designing stage, we decided to make an asymmetric structure of the tube, building two different holes so as to increase the pressure drop across the fitting A and B. As we can see the S_1 diameter is bigger than the S_2 so as the pressure at the point A is enough increased than at the point B.

After real airflow tests [2], we have estimated that the suitable drop is 3/8" from the large S_1 diameter to the smaller S_2. This diameter drop is so crucial that the airflow sensor can clearly distinguish the pressure difference across the fittings without ambient interference.

Block Diagram

We should describe the full functionality of the ideal spirometer in the following block diagram (Fig. 4):

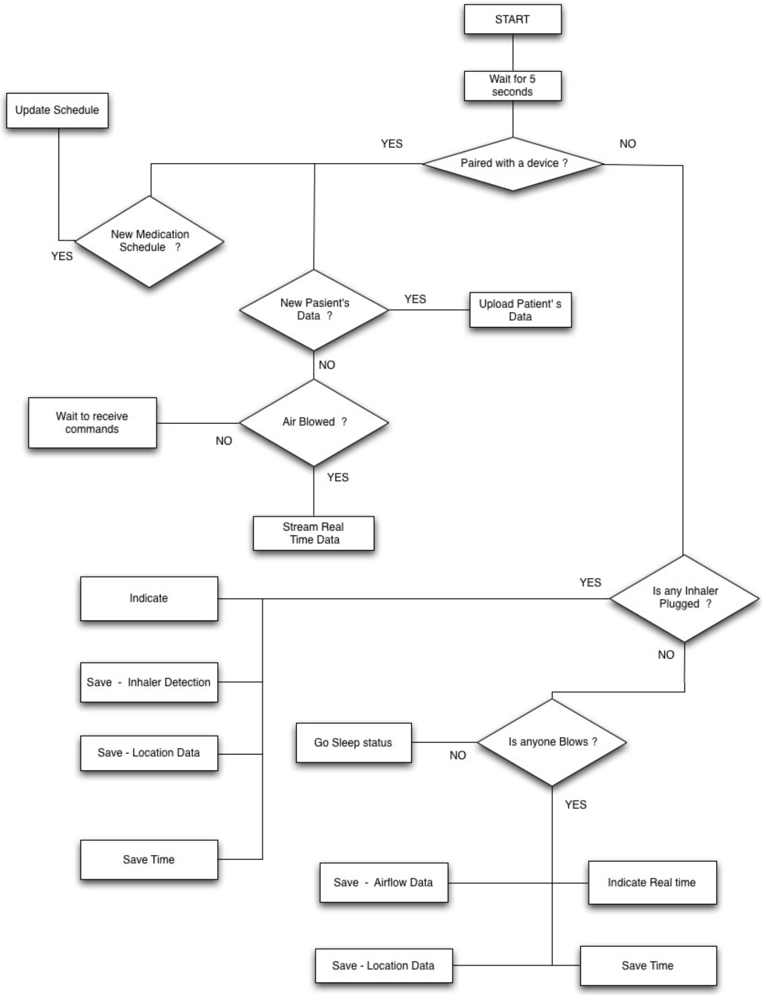

Fig. 4. Logic data flow diagram of the proposed spirometric device

When the spirometer is turned on, there an interval waiting time that device loads its program and the Bluetooth module searches for previously paired Bluetooth devices to establish a wireless connection. Actually, the first time that you will try to set up the spirometer, you need to engage a pairing process which takes no more than 5 seconds. In case of a successful connection with a smartphone for example, the spirometer can be updated with new medication or monitoring schedule by a specific application. If it's in use without wireless connection, data as a detected inhaler or air flowed, location and time would be saved in the built-in memory. All these data will be synced with doctor's files by a smart device internet connection.

5 Developing a Prototype

The chameleon prototype constitutes a simple combination of the basic materials and electronics building a simple digital spirometer. It includes only the most significant parts: airflow sensor, inhaler detector, LED indications, sound buzzer, bluetooth module and the power supplying circuits. A spirotube is built into the plastic enclosure (Fig.5).

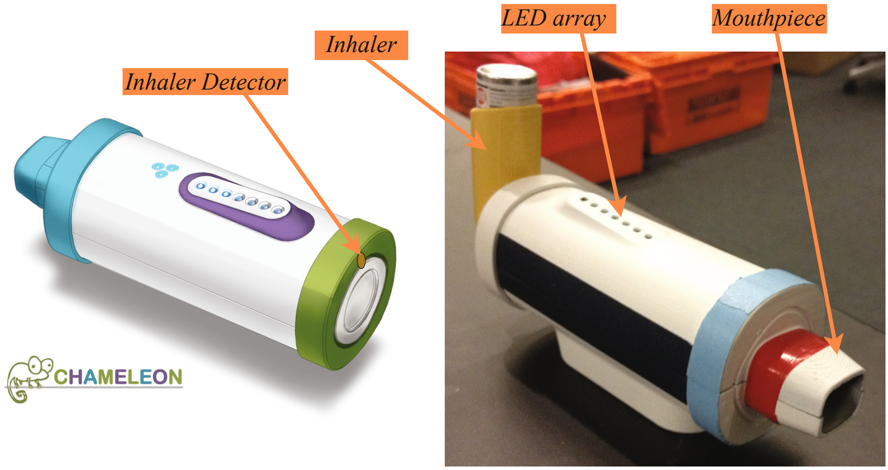

Fig. 5. Chameleon, the first extremely low cost spirometer prototype. In the left picture is showed the 3D rendered model and the one at right photo is pictured the real 3D printed construction. It's made by Asthma Management team with a cost of about 120$ during a two weeks innovation event in MIT Media Lab. *(27/01/2012)*

AirFlow Sensor

As an airflow sensor we have selected a differential pressure sensor that contains two different MEMS(MicroElectoMechanical Systems) based pressure sensor made by Honeywell. It operates comparing to different air samples and an internal circuit estimates the pressure difference between them and it exports an analog signal. There are three pins: the first is the analog voltage output and the other two of them for supplying purposes. We selected Honeywell Zephyr series the 3.3 Volt analog version in order to control the sampling rate via a central microcontroller.

It's the most expensive part of our implementation because of its high accuracy reaching at ±2.5%. It fits the ATS spirometry requirements being capable ranging air flow between 0 to 14 litters per second. Also, there is no need for calibration procedure and its low power consumption allows portable application use such as a spirometer. Concluding, there is no need to have any special requirements regarding extreme heat - which can be found in several African countries.

Breathing Tests Applied and Monitored

This Honeywell sensor is already pre-calibrated by the manufacturer. However we confirmed its operating condition via our digital oscillator performing some real-time blowing tests (Fig.6).

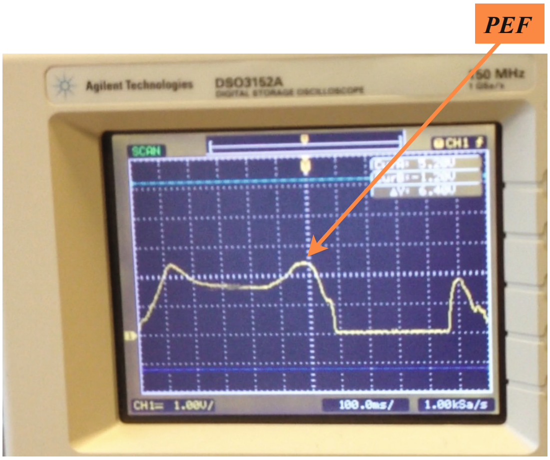

Fig. 6. Easily recognized PEF factor reaches 3.35 volts, the upper bound of the output voltage as we expected

Inhaler Sensor

The essential information when an inhaler is mounted on the spirometer is the color of the inhaler. So, we need a RGB color sensor as the Hamamatsu C9303 like the one we have used in our prototype. The C9303 is an analog RGB color sensor which is capable of distinguishing color differences between a vast variety of colors.

Moreover, it is suitable for our prototype because of its operating voltage ranging between 2.7 and 5.5 volts. The only issue is that it requires 3 ADC channels from the main chip, one for each basic color. Its small dimensions provide us with more flexibility to eliminate the wasted internal space by the electronic components.

The 3 output pins drive to the ADC chip the corresponded values of voltage for each color assisted by the light of a small white LED bulb. Then, the main chip calculates which color has the inhaler combining the three different values of the output voltage.

Main Chip

The main microcontroller was the PIC16F877A that operates as an Analog-to-Digital converter for 10 bit per sample with 625KHz sampling frequency. We supply this IC via a 5 volts circuit and a crystal oscillator at 20MHz. It constitutes a low power consumption MCU (MicroController Unit) that could be powered by a 2 volts source at least. It consumes less than 0.6 mA at 4MHz and 3 Volts Vcc (Fig. 7).

It is configured to release 4 analog input channels, 3 for the color sensor and one for the airflow sensor. A serial UART channel set up at 115.2kbps speed so as to communicate with bluetooth wireless module. That Microchip MCU applies the central management of the whole product. It sensors data based on the block diagram's flow. MCU is the only component that determines when the data should be saved or sent to wireless module.

Moreover, the main chipset blinks the LED array indicating notification about new monitoring schedule or corresponding to percentage level of the current expirations into the spirotube. The sound buzzer is driven by PWM pulses that are generated by an internal comparator varying frequency and duty cycle.

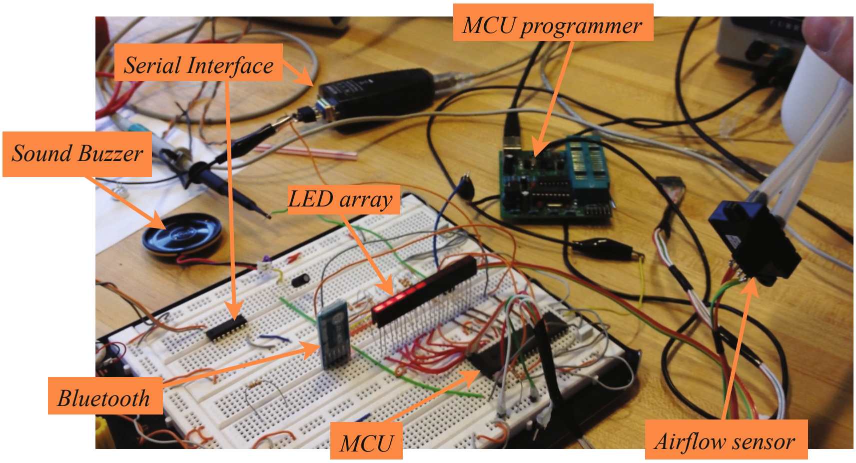

Fig. 7. All the electronic components pined on the breadboard . Testing the functionality of the whole circuit being the base of our final prototype.

Bluetooth Module

The first prototype was implemented via a CSR BC417 Bluetooth 2.1 EDR module. The converted air flow samples are delivered from the MCU to the module by a UART channel. After that, the data are transmitted wirelessly at 2.4GHz. Its power requirements are quite low. It operates at 3.3 volts and consumes 50mA at the maximum wireless transmit rate (2Mbps). Initially, we have set up for the HID Bluetooth profile for testing purposes and we achieved to send sensor's data to a terminal client computer application as it is revealed from the Fig. 8.

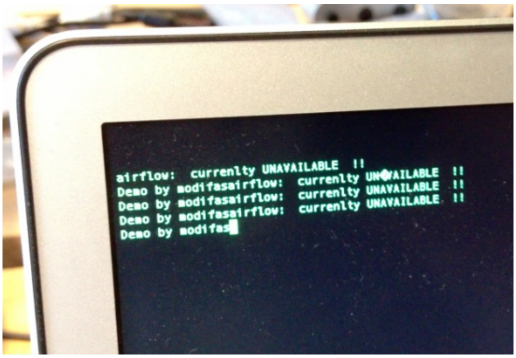

Fig. 8. Data wirelessly transmitted to terminal client of our computer by the first chameleon prototype via when it was turned on and paired

The second prototype is called BLESpiro. It is essentially a stripped down simple spirometer using Bluetooth 4.0 implemented via BLE profile. That is a significant improvement of the chameleon prototype decreasing the power consumption. It is the latest technology module that contributes in personal area networking and consumes current under 27mA. As a result of that it can eliminates the need for power be supplied by one 1/2AA type battery for approximately 24 hours.

The Bluegiga BLE112 bluetooth module is the most essential component on which the BLESpiro is based (Fig 9). The BLE112 module manages to replace multiple components as the microcontroller unit, ADC unit, supplying circuits and the wireless communication module in one single device. It utilizes the Texas Instrument CC2540 as integrated MCU chipset. Embedded 32 MHz and 32.678 kHz crystals are used for clock generation. The internal ADC is configured to 500KHz using resolution of 12bit per sample. BLE112 can approach the speed of 1Mbps for transmitting data over the air.

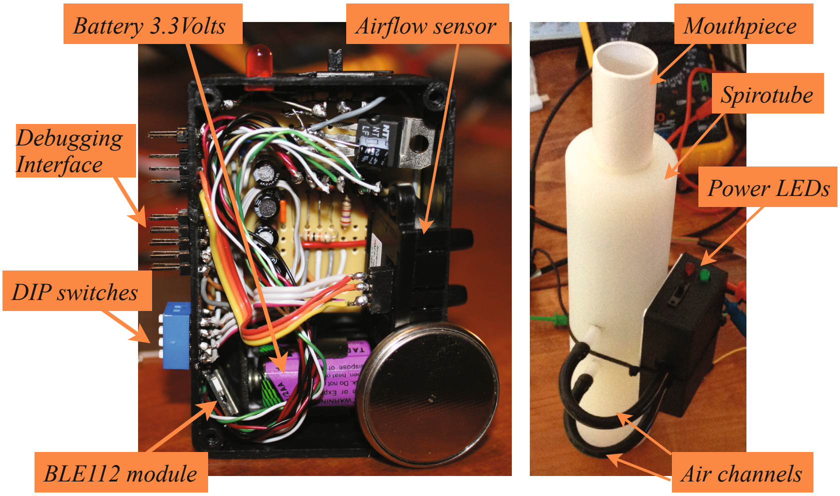

Fig. 9. The second prototype called BLESpiro, it based on a very simple structure. The small black box contains the airflow sensor, the BLE112 Bluetooth 4.0 module, our debugging PCB and a 1/2AA type 3.3V battery. This box is attached to the spirotube by two micro tubes 3mm. Also, a carton mouthpiece is showed on top of the tube. Black box enclosure is compared with a 3V coin cell battery.

6 Cost and Efficiency Ratio

A very important aspect of every new project that has aspirations in becoming the new standard is to make a quantitative research regarding the cost of the proposed system. It is quite obvious that we have managed to achieve the best performance possible, while using relatively low cost components and also keeping in mind the reliability of the system (Table I).

Table 1. The cost list of the real components that could be used for this project is shown below

Component description	Cost ($ USD)
Microcontroller (Microchip)	2-3
Airflow sensor (Honeywell)	70 - 90
Color sensor (Hamamatsu)	5
Bluetooth module (CSR)	8
Rechargeable Battery 3.7V	14-17
USB charging circuit	10
Electronic components	6-8
Spirotube made by Nylon/PVC	10-20
3D printed model	20-25
GPS module	26-27
EEPROM memory (Microchip)	1.5-3
RTC module	3.7-4
LEDs (9 pieces)	0.10
Piezo-electric Buzzer	1
PCB manufacturing	5-7
Total Cost	182.3 - 228.1

It is evident from the BOM's total cost, that the proposed device while keeping the price at a very low point, manages to implement more asthma devices in a single spirometric tool and all that at 230$. As a comparison, modern spirometers that are targeted to clinicians and experts are priced at around 1000$ and have only a fraction of our device's functionality.

Ultimately, the mass production of our device will reduce the total cost even further, hence the cost efficiency ratio will be even larger. The key part of our project, which is the Honeywell airflow sensor will be a lot cheaper in large quantities. Although it is one of the most expensive in its category, it manages to outperform the competitors by quite a margin and also enable us to use cheaper components for the other functions, thus, keeping the cost at a bare minimum.

7 Conclusion

The main objective of this project is to build from the ground up a multifunctional spirometric device for children aged between 6 to 14, with a cost concern and an interest to spearhead above the current offers even from reputable and well established manufacturers.

Thus, in this study, we are presenting a really low cost spirometer, extremely useful and with a user interface that would attract young children aged 6 to 14 which was our main goal for this project. Not only we managed to do that, but we also chose and implemented materials that are relatively cheap but tested, robust and quite reliable, which is also another goal that we have set from the beginning. It would be without cause if we managed to use cheap materials in our BOM, but made the device unreliable, which would end up being another toy for the child. This is not the case though. The ease of use of the device is evident and also it being small and user friendly, so that it will motivate the users to continuously challenge themselves.

There are several matters that should be taken into perspective though. The project was more or less self-funded although the final results were remarkable. It attracted the first price of the MIT Health and Wellness Innovation 2012 award, and got the applaud of many academics and companies related to the medical instrument industry.

We managed to pull through a wide variety of issues and provided a reliable, cheap, easy to use, all around replacement tool for most of the asthma issues that a patient faces every day in his life.

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Appendix

Sample of the MCU Program Code

(Programming language Embedded C - MicroC compiler)

```
void main() {
  ADCON0 = 0b10000101; // configuration MCU - ADC - CLOCK
  ADCON1 = 0b10001000; // configuration MCU - PORTS
  TRISA = 0xFF; // configuration port directions
  TRISB =0; // configuration port directions
  TRISC = 0b10000000; // configuration port directions
  UART1_Init(115200); //Initialize UART module at 115200bps
  Delay_ms(100); // Wait for UART module to stabilize
  Sound_Init(&PORTC, 3); // set up the buzzer port
  while (1) {
rawdata = ADC_Read(0); //Get 10-bit results of AD conversion
voltage=(((rawdata)/1023.0)*5*1000); //Voltage is in mV
airflow=400*((voltage/3300)-0.5)/0.4 //conversion formula(1)
percentage = (voltage-2000)/5; // percentage flow value
                                // for LEDs array use
digit = percentage % 10u;
digit1 = mask1(digit);
digit = (char)(percentage / 10u) % 10u;
digit10 = mask1(digit);

// capture value for each color via the color sensor
voltageR=(((ADC_Read(1))/1023.0)*5*1000);
voltageG=(((ADC_Read(2))/1023.0)*5*1000);
voltageB=(((ADC_Read(3))/1023.0)*5*1000);
```

```
// check which inhaler is mounted and send data
if (voltageR=<1020) and (voltageG=<1020) and
(voltageB=>1500 and voltageB=<3345)) {
Inhaler=Blue;
PORTB.RB2=0;
PORTB.RB3=1;
UART1_Write(Inhaler);
}
else if (voltageR=<1020) and (voltageG=<1020) and
(voltageB=>1500 and voltageB=<3345)) {
Inhaler=Red;
PORTB.RB2=1;
PORTB.RB3=0;
UART1_Write(Inhaler); }
else { Inhaler=None; UART1_Write(Inhaler); }
GO_DONE_bit = 0 ;
UART1_Write(10);
UART1_Write(13);
UART1_Write_Text("you blow");
UART1_Write(airflow); // send airflow sensor data via
//UART-bluetooth module
UART1_Write_Text("SCCM");
PORTB=0b10000000;
}
```