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Pulmonary Disease Management System with Distributed Wearable Sensors

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***Abstract*---A pulmonary disease management system with on-body and near-body sensors is introduced in this presentation. The system is wearable for continuous ambulatory monitoring. Distributed sensor data is transferred through a wireless body area network (BAN) to a central controller for real time analysis. Physiological and environmental parameters are monitored and analyzed using prevailing clinical guidelines for self-management of environmentally-linked pulmonary ailments. The system provides patients with reminders, warnings, and instructions to reduce emergency room and physician visits, and improve clinical outcomes.**

I. Introduction

Chronic pulmonary diseases, such as asthma, often require a regular schedule of treatment and on-going reassessment for the duration of a patient's life. That is, these diseases are managed. Disease management is defined as managing a patient with a known diagnosis with the intention of providing patient education and monitoring to prevent symptom flare ups and acute episodes of the disease [1]. There is growing evidence of the advantages of disease management systems including quality of life improvements and healthcare cost reductions [2], [3]. Most disease management systems are focused on diseases such as Asthma/COPD, cardiovascular disease, diabetes, and cancer [4].

Recent technological advances in sensors and low-power wireless networks have enabled low-cost, miniaturized, light weight and intelligent solutions for non-invasive ambulatory monitoring [5]–[7]. In this study, the use of acoustic sensors for monitoring of lung function is introduced. Similar technology in quiet environments has been well studied [8]; however, ambulatory application has not been reported. The two major challenges are (1) to adapt sensor designs to minimize the impact of background noise and patient activity level, and (2) to develop a "light-weight", efficient algorithm implementable in an embedded system such as PDA.

Patients with pulmonary diseases are often sensitive to environmental factors. For example, significant increase of prevalence of pulmonary symptoms, bronchitis or pulmonary infection has been found in association with particulate pollution [9]. Therefore, near-body environmental monitoring adds critical value to pulmonary disease management. Integration of environmental monitoring with traditional pulmonary disease management procedures is a key novelty of this study. The resulting system not only allows patients to be warned of known environmental irritants, but also makes it possible to identify previously unknown environmental factors impacting the individual patient's pulmonary disease.

II. System Overview

The pulmonary disease management system defined in our study consists of distributed physiological and environmental sensors for continuous ambulatory monitoring. The data collected by on-body and near-body sensors are transferred to a personal digital device such as a PDA or cell phone through a multi-hop wireless BAN. Using the sensor data, the system monitors disease related physiological parameters and personal environments, while providing real time disease specific expert analysis of disease status and providing early warnings to the user.

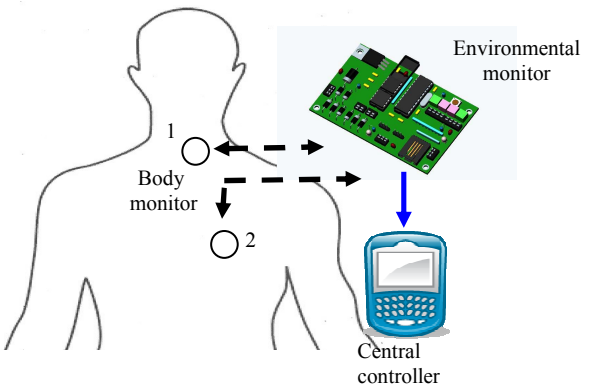

Fig. 1. System overview

As shown in Fig. 1, the pulmonary disease management system involves three major components:

1. Body monitor - On body monitor uses an acoustic sensor to acquire body sounds. Depending on the application, the system could have one or more body monitor.

2. Environment monitor - Waist-worn multi-sensor platform includes optical sensor for airborne particle monitoring, temperature and humidity sensors, accelerometer, and SpO_2 module.
3. Central controller - It may be a PDA or cell phone which provides the user interface (UI) and disease-specific rules-based expert system, and signal processing module. HP iPaq 2795 was selected as central controller for this system.

The system is designed for very low power consumption (e.g. 3 mW for body monitor which yields 40 hours battery life) and light weight (e.g. 1 g for body monitor) such that the user is comfortable to continuously wear.

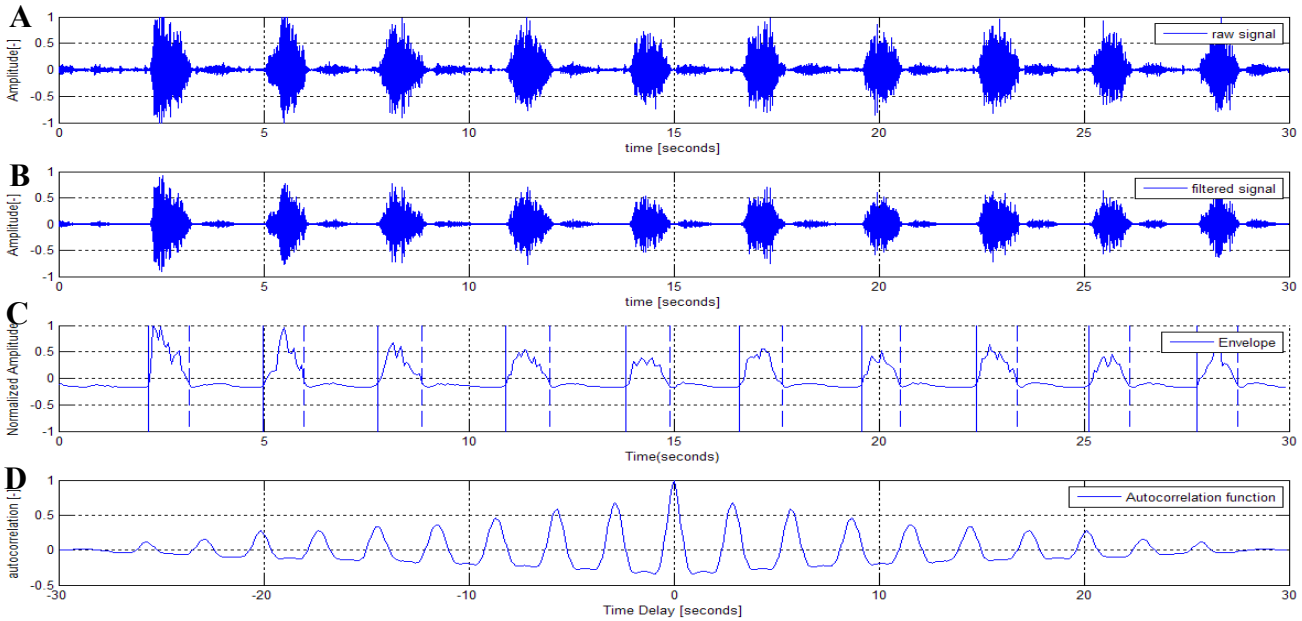

Fig. 2. Acoustic signal processing A: raw signal acquired from normal subject's tracheal location B: Signal after 300-600 Hz band pass filter C: envelope detection with start points for inspiration (solid lines) and start points of expiration (dashed lines) D: autocorrelation function

III. System Components

A. Acoustic sensing and signal processing

A piezo-ceramic microphone (BL-21785, Knowles Inc. Itasca, IL) is used with a cylindrical air chamber (r=1.2cm, h=0.6cm). The data acquisition module has a dynamic gain control algorithm to continuously evaluate the signal and adjust the gain to ensure the tracheal sound not too small or saturated because of the effects of background noise and activity level change. The signal is 3.2 KHz for sampling frequency and 16 bits per sample.

Fig 2 shows the process for lung sound signal analysis. A 5th order Butterworth band pass filter (300-600 Hz) is applied to the raw signal (Fig. 2A) which is acquired at a normal subject's tracheal location to isolate the lung sound signal (Fig. 2B) for other body sounds and background noises. Then the lung sound signal is further smoothed to detect the envelope of slow change periodical component by taking the standard deviation of every 50 sample points; the envelope is shown as Fig. 2C. Auto correlation (Fig. 2D) is performed on the detected envelope to determine the respiration rate (corresponding to the distance between central peak and 2nd peak as in Fig. 2D). From the detected envelope, the start points of each inspiration and expiration phases is determined in order to compute the time duration ratio of inspiration to expiration which is an important indicator for asthma status assessment. In Fig. 2C, the start points of inspiration are marked as solid lines and the start points of expiration are marked as dashed lines.

Similar processing is also applied to calculate heart rate, of course with the appropriate band-pass filter (20-120 Hz) for isolating heart sound from other body sounds and background noises.

B. Environmental monitor

The environment monitor consists of temperature and humidity sensors as well as an optical sensor for airborne particle detection, including particle type analysis (based on size information), and particle density information. Besides environmental sensors, an accelerometer is used to measure the patient's activity level, contextual data for patient status analysis. Finally, an SPO_2 sensor measures the blood oxygen saturation (a key indicator of advanced pulmonary symptoms) and pulse rate.

The optical sensor measures the scattered light from airborne dust particles at 100 Hz sampling frequency. Small particles and larger particles have different pattern for the scattering light signal. The dust particle analysis is

shown as Fig. 3.

Fig. 3A and 3B is a comparison of collected scattering light signal between small particles (incense smoke 200~300nm) and large particles (Arizona dust, 10~20μm). Fig. 3C and 3D shows the signal passing a 20 Hz high pass filter (HPF). Average value for every 20 points in Fig. 3A and 3B is plotted as Fig. 3E corresponding to dust particle density information. Standard deviation of every 20 points was calculated to differentiate large and small particles as shown in Fig. 3F. With this analysis, particle size information could be determined. If the type of the dust particle is included in the patient's known disease triggers is detected, an alarm to the patient will be sent to notify the patient to take appropriate precautions (e.g., medication, or simply leaving the current environment).

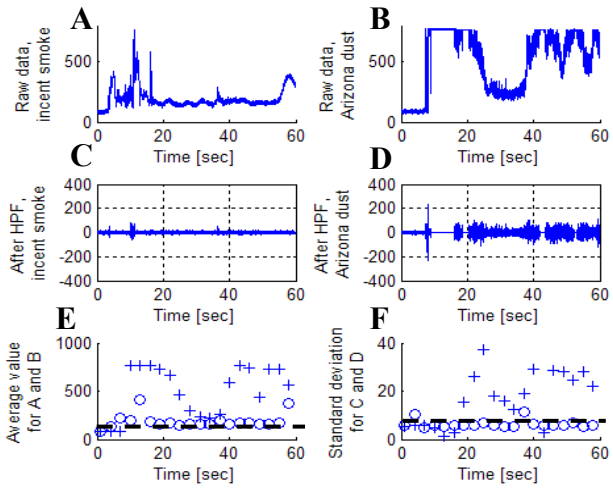

Fig. 3 Dust particle detection and identification
A. Scattering light signal with incense smoke
B. Scattering light signal with Arizona dust
C and D: signal of A and B after a 20 Hz HPF
E. Average value of every 20 points for A and B to detect of dust particles presenting, black dash line: threshold between presenting and no presenting (Circle: incense smoke, plus: Arizona dust)
F. Standard deviation of every 20 points for C and D to determine dust particle size information, dash line, threshold between large particles and small particles (Circle: incense smoke, plus: Arizona dust)

C. *Wireless BAN*

To achieve ambulatory monitoring, raw and derived data are sent to the central controller through a multi-hop BAN, as shown in Fig. 4. The link between the environmental monitor and central controller is Bluetooth (BT), which is commonly available for most personal digital devices. The environmental monitor also hosts a low power radio (LPR) link for communication with the various physiological monitors. The LPR network has high data load, with small size and limited weight battery. The environmental monitor aggregates and relays data from its low power network to the central controller via the BT link. This design opts to locate the multiple radio "hub" on the environmental monitor, rather than on the central controller.

The network also supports remote server access for transferring data to a web server for clinician's review and analysis. A caregiver message can also be sent to the server if the patient presses the button on the environmental monitor (for example, patient is experiencing symptoms and needs help).

A proprietary application level control protocol has been designed for the network. In different transition mode, the wireless network can send unprocessed raw data (up to 100 bits/sec) for PDA analysis; it can also only send derived data which is processed on the body monitor and environment monitor. Key features include, network configuration, status checking, power management, data transfer and caregiver notification [10].

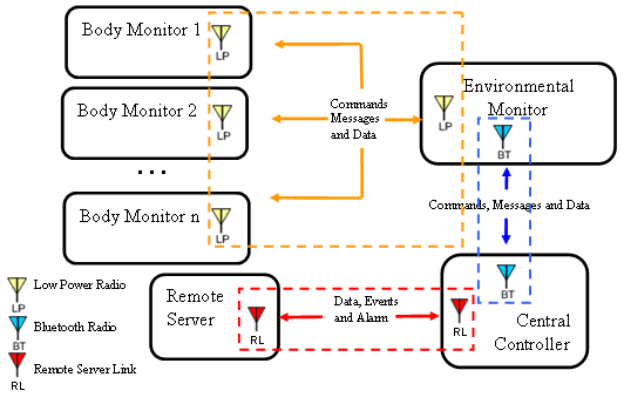

Fig. 4. Multi-hop body area network

D. *Expert system*

The expert system estimates a patient's level of pulmonary disease exacerbation by "scoring" current and recent patient information from several perspectives:
1. Physiological perspective: based on value and trends of physiological parameters extracted from collected signal, including heart rate, respiration rate, Ti/Te, pulse rate and blood oxygen saturation
2. Environmental perspective: based on presence of airborne particles, humidity and temperature
3. Self reported symptoms perspective: patient's daily self-reported symptoms based on clinician-provided self-management plan and patient's self reported prescription medication usage relative to scheduled dosages and usage guidelines
4. Overall patient status: summary view across the four detailed perspectives

The expert system additionally provides "confidence indices" for the scoring of each perspective on the patient's asthma status. The confidence index indicates the availability of patient data as input to the scoring process. This is important because the flexibility of the disease management platform allows users to monitor and enter all data at their convenience, thus some status scores

might represent less that the maximum number of indicators for a given assessment calculation.

IV. Results

Fig. 5 shows continuous parameters for all the physiological and environmental parameters. All the parameter is fed to the expert system to real time estimate the patient's disease status score.

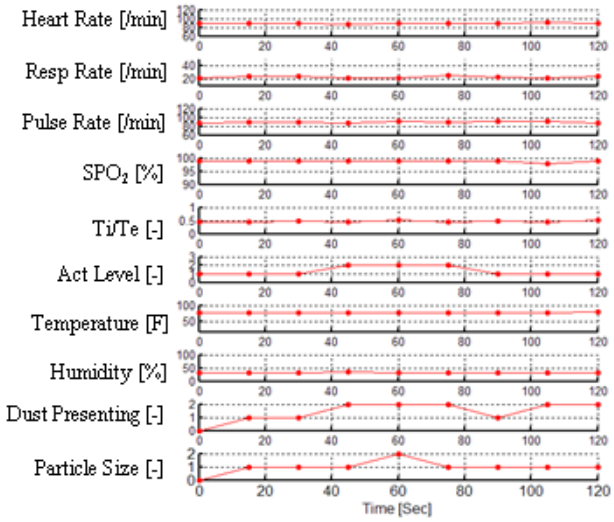

Fig. 5. Physiological and environmental parameters in continuous monitoring, dust presenting, 0: no dust, 1: low level, 2: high level; Particle size, 0: none or unknown, 1: small particle, 2: large particle

Fig. 6 shows the main page of the user interface on the central controller. The user interface provides a simplified, color-coded display of pulmonary disease status with confidence indices (Green: normal, Yellow: mild warning, Red: severe warning). Reminders and instructions are also provided corresponding with each warning.

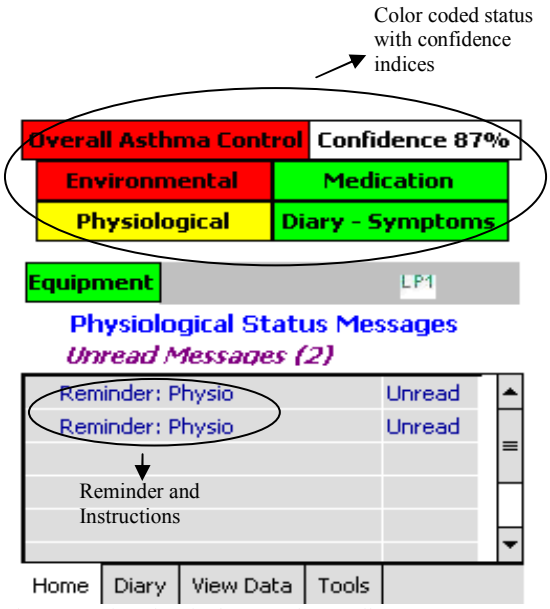

Fig. 6. User interface in the central controller

V. Conclusion

A pulmonary disease management system with distributed wearable sensors is presented for real-time, continuous, ambulatory monitoring during the patient's activities of daily living. The system provides early warnings of escalating symptoms of disease exacerbation, thereby reducing the likelihood of severe symptoms (e.g., an asthma attack and saving the cost of emergency room visits.

This system provides (1) a significant extension of current manual, non-continuous self care processes (such as keeping a paper symptom diary), and (2) a pulmonary parameter collection/analysis system to enhance the clinician's ability to identify environmental triggers, as well as medication effectiveness for an individual patient.

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