Zephyr Demo: Ubiquitous Accurate multi-Sensor Fusion-based Respiratory Rate Estimation Using Smartphones

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***Abstract*—This demo presents the *Zephyr* system for robust respiratory rate estimation that has been accepted in Infocom'16. Human respiratory rate is widely recognized as a vital measure of a patient's health and an indicator of several medical problems. However, it is usually ignored by medical practitioners due to limitations with available measurements techniques that are either visual counting by trained personnel or using invasive and/or devices limited to medical facilities. Contrarily, *Zephyr* leverages off-the-shelf smartphones to provide a non-invasive low-cost ubiquitous solution. The goal of this demo is to showcase *Zephyr* in action, where it takes the accelerometer and gyroscope measurements from a standard smartphone held on the user's chest to accurately track her respiration cycle and estimate her breathing rate in real-time. The demo also allows attendees to experiment with the different breathing signal extraction stages.**

I. Introduction

Respiratory rate is one of the important human vital signs. It captures the number of breaths a person takes within an amount of time (typically 60 seconds) while at rest. Abnormal respiratory rates and/or changes in respiratory rate are a broad indicator of major physiological instability and can be one of the earliest indicators of this instability. Hence, clinical guidelines emphasize the importance of measuring and documenting respiratory rate accurately for all hospital patients frequently. Yet, statistical studies show that measuring respiratory rate is commonly neglected by medical practitioners or even guessed [1]. Typically, this is due to limitations with available measurements techniques that are either performed through visual counting by trained personnel or using invasive and/or devices limited to medical facilities.

With the recent advances in wireless and mobile computing [3]–[8] along with the increasing desire for better healthcare, there have been a considerable attention from researchers to provide ubiquitous health sensing. Recently, researchers proposed monitoring breathing using special wireless devices [9], [10], earphones [11], or standard wireless signals [12]. While these approaches are non-invasive, they still require special devices to be installed in fixed positions and the performance of these systems degrades in typical noisy environments, e.g. clinical and home settings.

This demo presents *Zephyr*, a ubiquitous smartphone-based respiratory rate estimator. It leverages the energy-efficient

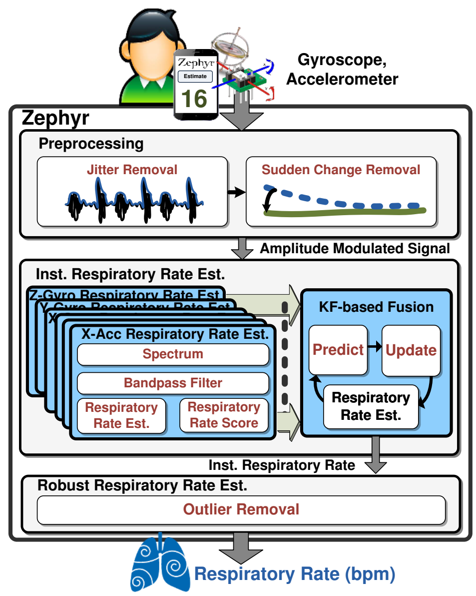

Fig. 1: The *Zephyr* system architecture [2].

inertial sensors, commonly available in commodity off-the-shelf smartphones, to provide a robust estimate of the user's respiratory rate. The basic idea *Zephyr* builds on is that the breathing process leads to expansion and contraction of the human lung, which in turn affects the different axes of the inertial sensors in a phone placed on the user's chest.

As compared to other systems, *Zephyr* ***has several advantages***: First, it is ubiquitous and resilient to ambient noise; users can use their phones to measure the breathing rate at anytime anywhere. Second, it is a low-cost alternative solution for the tiresome and subject-to-human-error visual counting method. Third, it is less intrusive when compared to typical measurement devices. Fourth, it has a remarkable and robust accuracy, especially in noisy environments, when compared to other audio or RF-based approaches [10], [11]. Finally, it can be used to continuously monitor the user's breathing rate through a chest strap (commonly used with fitness and heart-rate trackers).

II. Zephyr Overview

The human respiration cycle consists of repeated inhalation and exhalation phases which involve an increase in the lungs' volume in the inhalation phase, followed by a decrease in the lungs' volume during the exhalation phase. This periodic lungs' volume change leads to periodic movement of the chest, which can be captured by the accelerometer and gyroscope measurements from a smartphone held on the user's chest. Note that the respiration cycle affects the measurements in the ***six*** sensors axes ($\{Acc_x, Acc_y, Acc_z, Gyro_x, Gyro_y, Gyro_z\}$); this is due to the tilt in the phone pose while measuring the respiration. This tilt is unavoidable due to the chest curved shape, the change of the chest cage size during the respiration process, and the imperfect non-straight human poses. *Zephyr* leverages this redundant information in the different sensors and axes to obtain robust respiratory rate estimation.

In this section, we provide an overview of the *Zephyr* system architecture (Figure 1) and how it extracts the respiratory rate from the noisy smartphone's sensors—***The system details and evaluation can be found in the full paper in the main Infocom 2016 proceedings [2]***.

A. Preprocessing

The goal of this module is to extract the user's breathing signal from the 3D acceleration and the 3D angular velocity. To do so, the Preprocessing module aims to remove (1) the high frequency jitters in the noisy inertial sensors measurements that disturb the breathing signal and (2) the large sudden changes in the sensor measurements due to users making sudden changes in their pose or moving the phone during the measurements.

The module applies the Jitter Removal and Sudden Change Removal sub-modules in succession on the raw inertial sensor measurements to mitigate these noises.

B. Instantaneous Respiratory Rate Estimation

The goal of this module is to estimate the user's respiratory rate using the preprocessed raw sensor signals. Due to the change of the chest volume during the respiration cycle, observing the spectrum of any *preprocessed single* inertial sensor measurements, e.g. the accelerometer x-axis, it should have its major frequency component nearby the actual user's respiratory rate. Therefore, the *Instantaneous Respiratory Rate Estimation* module starts by analyzing the frequency spectrum for the six inertial sensor measurements to extract their individual breathing rate estimates along with a quality score, for each stream, that indicates how likely its extracted rate represents the user's actual breathing rate. Then, these breathing rates are fused together while taking into account their relative quality using a Kalman Filter-based approach to estimate the instantaneous respiratory rate.

C. Robust Respiration Rate Estimation

The goal of this module is to provide a robust respiration rate estimate that is based on processing the instantaneous breathing rates. Such single robust reading can be required in some cases, e.g. to log the respiratory rate in the patient's health records.

The module applies an α-trimmed mean filter on the extracted consecutive instantaneous breathing rates to remove spurious estimates and provide a more robust one.

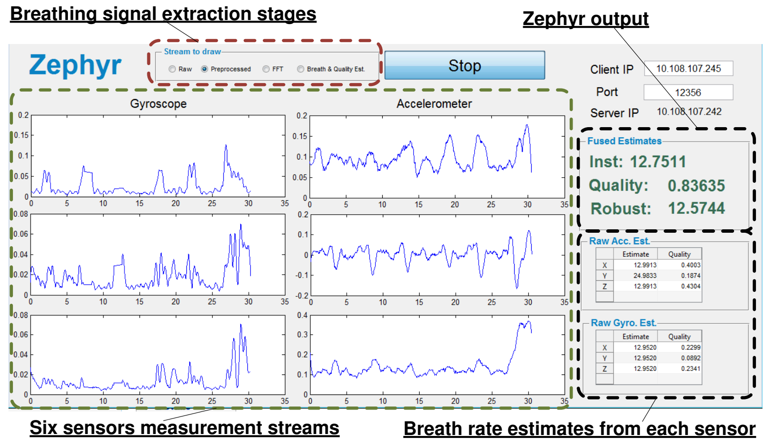

Fig. 2: The *Zephyr* demo server UI.

III. Demo Description

The *Zephyr* demo setup includes an Android-based smartphone client app and a laptop-based server. The android app is the core component of the demo; users place the phone on their chest to monitor their breathing in real-time. They can use the app to select which sensors to use in estimating the breathing rate. Also, they can play a metronome with a user-specified rate for testing the system. To visualize the streams, we developed a server application that displays the 3D accelerometer and the 3D gyroscope sensor measurements from the smartphone in real-time (Figure 2). Moreover, the server allows users to experiment with the different breathing rate extraction stages (visualize raw and preprocesed streams, power spectrum, and extracted breathing history); and compare the extracted breathing rate from the individual streams to the fused instantaneous breathing rate and the robust one.

To setup the demo, presenters will provide a smartphone and a laptop to run the mobile and server applications. Also, a table, a power outlet, and an internet connection are required.

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