Heart and Sole: Shoe-based heart rate monitoring

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1 INTRODUCTION

Continuous heart rate monitoring is useful in a variety of areas from sports to medicine. Heart rate monitoring during exercise can be used to monitor training intensity and avoid inefficient training routines or injury. Changes in heart rate over time can aid in the diagnosis of Parkinson's Disease and Multiple Systems Atrophy[5], predict cardiovascular risk in people who appear not to have heart disease[2], and diagnose Postural Tachycardia Syndrome[3], among other uses.

Many wearable and ambient sensors have been proposed to provide continuous heart rate monitoring, but so far none of them combine completely unobtrusive ambient sensing with location flexibility. Wearable bracelets, T-shirts and similar devices must fit snugly against the body to reduce motion artifacts, and they require interaction with the user, who must remember to put on a dedicated sensor that may be uncomfortable or inconvenient to wear. Another method of heart rate monitoring involves adding sensors to the environment, such as a bed frame[1]. This method has the advantage that the user does not have to do extra tasks, but it is location-specific and activity-specific: one has to be in bed.

Our goal is to create a heart rate monitor that is generally applicable to any location or activities while requiring no interaction with the user. By incorporating sensors into shoes that the user would wear in everyday life, we can create a sensor that follows the user around but also remains ambient in the environment. The sensors sit pressed against the foot as part of the tongue of the shoe, which, unlike a T-shirt, is already designed to fit snugly against the body. Unlike clothing, people often wear the same shoes every day, which works well for long-term monitoring. Our research challenge with this method is to pick up a weak signal in a noisy environment where the sensors are often in motion. We address this challenge from two directions, both amplifying the signal and identifying low motion points where we can more easily extract the signal.

We present *Heart and Sole*, a shoe-based system that can track a subject's pulse through their feet. We propose a method to extract the weak signal of the pulse using a pressure sensor with amplification and a method to discard noisy motion data by applying a noise threshold that identifies high motion.

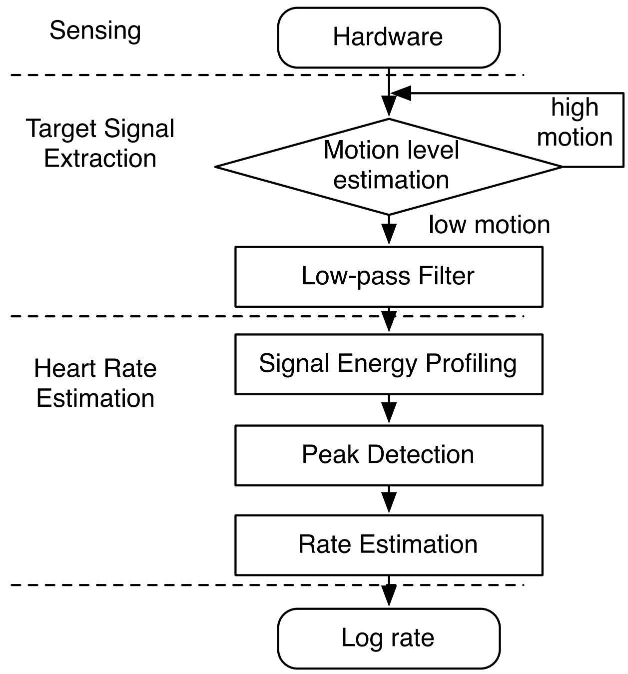

Figure 1: System Design

2 SYSTEM DESIGN

Heart and Sole consists of three modules as shown in Figure 1: the sensing module, the target signal extraction module, and the heart rate estimation module.

2.1 Background

The dorsalis pedis artery runs down the top of the foot, lateral to the first metatarsil bone. This artery lies over the muscles but is partially covered by connective and lymphatic tissue. It is close enough to the skin to be used by medical professionals to take pulse

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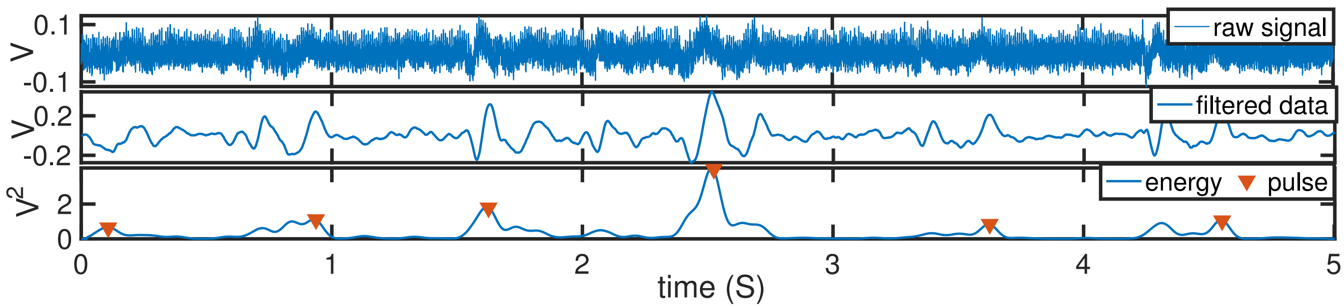

Figure 2: A raw signal contrasted with its low-pass filtered signal and windowed energy feature.

readings. We use pressure sensors to feel the movement of this artery, allowing it to work over a sock, unlike a pulse oximeter. However, even when a subject is sitting still there are also small pressure changes caused by motion of nearby joints and muscles. This motion noise is increased when the person is standing, as they shift to keep their balance, and vastly increased when a person moves around, which causes pressure changes of the foot moving against the shoe. On average, people spend over half their waking hours sitting[4], so we just collect periods of low-motion data, discarding high motion periods.

2.2 Sensing

The sensing module consists of a pressure sensor connected to an amplifier deployed in the tongue of a sneaker. The dorsalis pedis artery can be felt a few centimeters in front of the ankle. The tongue of athletic shoes is designed to put pressure on the top of the foot there, and keep the shoe from sliding around and chafing its wearer. This allows the tongue to hold the sensor effectively against the artery and feel the slight pressure changes caused by the pulse. The shoe only needs to be tied tight enough that it is resting against the skin. A too-tight shoe can reduce blood flow in the foot, but as long as there is some circulation there will be movement in the artery. The top graph in figure 2 shows the raw signal captured by a pressure sensor placed on the top of the foot of someone sitting down. It is possible to see the small peaks which correspond to the subject's pulse; however, further signal processing is necessary to extract heart rate, as explained in Sections 2.3 and 2.4.

2.3 Target Signal Extraction

The target signal extraction module breaks the signal into parts and applies a noise threshold to extract data with less movement. Jia et. al. show that most motion and ambient noise occurs at over 10 hz, so we use a low-pass filter with a 9hz cutoff to separate that from heartbeat signals[1]. We choose a second order Butterworth filter, which has a flat passband and gradual roll off because we don't need a steep cut off for adequate noise reduction. The middle graph in figure 2 shows the filtered signal output.

2.4 Heart Rate Estimation

The heart rate estimation module then profiles the windowed signal energy, smooths the result, and uses a peak detection algorithm to find the distance between each pulse as shown in Figure 2. Using the windowed signal energy smooths the data, getting rid of more noise, and emphasizes the peaks. Next, we apply a sliding average smoothing algorithm. The motion of the pulse shows two close-together peaks per heartbeat. Applying this two-stage smoothing process combines the two peaks into one, emphasizing their location and giving us more consistent results. The bottom graph in figure 2 illustrates the smoothed energy feature and its peaks, which correspond closely to where the true pulses are. A rolling list of the distances between peaks is used to provide an estimated heart rate.

3 DEMO

We showcase a real-time performance of our system by demoing a shoe with a connected sensor. A computer program will display a graph showing the detected pulse on the raw signal, and an updating heart rate metric. A pulse oximeter on the finger will provide ground truth data. During the demo, we ask a demonstrator wear their own shoes equipped with our system and present a set of real-world scenarios (sitting, standing, etc.) to show the robustness and flexibility of our system.

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