Designing Engaging Camera Based Mobile Games for Implicit Heart Rate Monitoring

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Abstract
Heart rate monitoring is widely used in clinical care, fitness training, and stress management. However, tracking individuals' heart rate faces two major challenges, namely *equipment availability* and *user motivation*. In this paper, we present a novel technique, LivePulse Games (LPG), to measure users' heart rate in real time by having them play casual games on unmodified mobile phones. With LPG, heart rate is calculated by detecting changes in transparency of users' fingertips via a mobile device's built-in camera. More importantly, LPG integrate users' camera lens covering actions as an essential control mechanism for game play, and detect heart rate *implicitly* from *intermittent* lens covering actions. We explore the design space and trade-offs of LPG through three rounds of interactive design and report the preliminary results from a 12-subject user study.

Author Keywords
Heart rate; mobile phone; game design; serious game; ECG.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces.

Figure 1. Real-time heart rate measurement via LivePulse Games (top: City Defender, bottom: Gold Miner).

Introduction

Heart rate is one of the most important vital signs for measuring human health [3]. In comparison to men with 50 or lower bpm (beats per minute) resting heart rates (RHR), 81 - 90 bpm RHR increases the mortality rate by 100% and over 90 bpm RHR increases the risk by around 200% [3]. Heart rate has also been used in fitness training and competitive sports for managing work-out intensity, balancing physical exertion [4], and predicting cognitive workload [9], in contexts such as computer user interfaces, traffic control, and intelligent tutoring etc. Therefore, efficient measuring and recording of heart rate can be of great significance in scenarios involving physical health, mental activities or a combination of both.

Unfortunately, most heart rate measurement methods are either time-consuming or require special measuring equipment that may not be available to a wide audience. For example, manual pulse counting with fingers may be tedious, and inaccurate. More precise methods for determining heart rate include Electrocardiograph (ECG) [4, 5, 6, 7] and pulse oximeters. However, such dedicated heart rate monitoring devices share at least three disadvantages. First, the costs of these devices could prevent wide adoption in everyday life; Second, it is not convenient to carry and use the devices "on the go"; Lastly, existing methods provide little immediate benefits or *motivation* to users and thus may be tedious to track heart rate in a longitudinal setting.

To overcome the limitations of existing techniques, we have developed LivePulse Games (LPG, figure 1) to measure users' heart rates in real time by having them play serious games on unmodified mobile phones. LPG calculate heart rates by detecting the transparency change of fingertips via the built-in camera (i.e. Photoplethysmography). More importantly, our method integrates users' camera lens covering actions as essential parts of the game play so as to detect heart rate *implicitly* from *intermittent* lens covering actions. With the increasing popularization of smartphones, LPG have the potential to measure heart rate anytime, anywhere, in a natural and enjoyable way.

Related Work

The most widely adopted approaches for detecting heart rate are based on Electrocardiography (ECG or EKG, usually in the form factor of chest band, wrist band, or watch) and pulse oximetry. A state-of-the-art device, the Berkeley Tricorder [5] by Naima and Canny, is capable of measuring a subject's ECG, EMG, respiration, and motion via a 2 by 2 inch Bluetooth device. Despite the steady drop on manufacturing costs[1] for such devices, they are still not readily available for most users in an everyday setting.

LivePulse Games rely on photoplethysmography to detect heart rates. Although the fundamental mechanism of photoplethysmography through mobile phones has been explored by both commercial applications (e.g. Instant Heart Rate [2], and Cardiograph) and researchers [1] in the past, all existing methods require users to cover and hold the mobile phone camera lens intentionally and steadily for an extended amount of time before receiving heart rate estimates. While these systems eliminated the equipment availability challenge, none of them

[1] Depending on the brand, form factor, and communication interface supported, a heart rate monitoring watch (e.g. Omron HR-100CN, MIO Alpha, or Basis) costs from US$30 to US$200 as of Dec 2013.

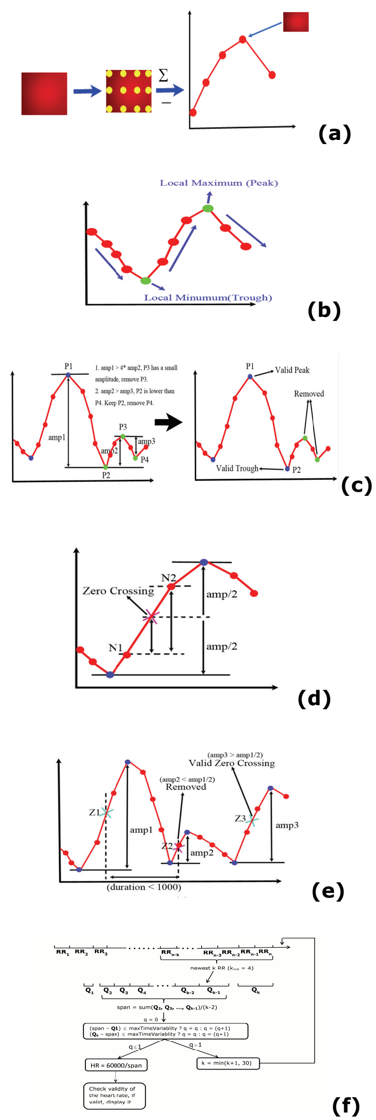

Figure 2. Major steps of the LivePulse algorithm.

attempted to address the human motivation challenges involved. In contrast, LPG explore the feasibility of extracting heart rates from *implicit*, *intermittent* lens covering actions in the middle of mobile game plays, and design engaging mobile games that balance measurement speed, accuracy and entertainment value.

It's also possible to calculate heart rate by recording and analyzing thermal changes, color changes [8], and involuntary motion of human faces in video. However, such approaches are more sensitive to environmental illumination changes and the component analysis (PCA or ICA [8]) techniques used also require users to stay still for an extended amount of time (e.g. 60+ second). Still, facial video analysis from a mobile device's front camera could be an interesting future direction to explore with LPG.

Heart rate has also been used by researchers in fitness training, and balancing exertion [4] in games. TripleBeat by Oliveira et al [7] is a mobile fitness training application that uses an ECG instrumented chestband to encourage runners to better achieve a predefined exercise goal. Nenonen et al. [6] allowed users to control parameters of video games (e.g. speed, slop of the road) by adjusting their heart rate. Instead of using heart rates to control in-game parameters, *LPG use games to motivate users and heart rates are measured as a side effect*.

LivePulse Algorithm

There are two main challenges in designing LivePulse Games. The first task is to formulate an algorithm that can detect human heart rate reliably and efficiently on unmodified mobile phones. This task could eliminate the need for specialized heart rate monitoring equipment. The second task consists of designing a game that integrates the slightly "bizarre" requirement in photoplethysmography (i.e. covering the camera lens with fingertip and holding it steadily) naturally into mobile game play. The second task addresses the motivational challenges in heart rate monitoring, converting heart rate measurement from a dull routine into a fun and engaging activity.

LPG rely on the built-in camera of mobile phones to estimate heart rates. The underlining theory is: in every cardiac circle, the heart pumps blood to the capillary vessels of a human body, including fingertips. The arrival of fresh blood changes the transparency of fingertips. Such transparency changes correlate directly with heart beats, and can be detected by the built-in camera when a user covers the lens of the camera with her fingertip.

Although camera based heart rate detection algorithms have been reported previously [1], their algorithms were not optimized for extracting heart rates from *intermittent* covering actions in game play. For commercial products such as Instant Heart Rate [2], and Cardiograph, their algorithms were not disclosed and the actual performances of their applications (e.g. speed, accuracy) were never reported. As a result, we implemented our own algorithm that could meet the speed, accuracy and robustness requirement of this project.

Instead of using component analysis and then transforming signals to the frequency domain [8], our LivePulse algorithm extracts heart rate information directly from the temporal domain. We made this

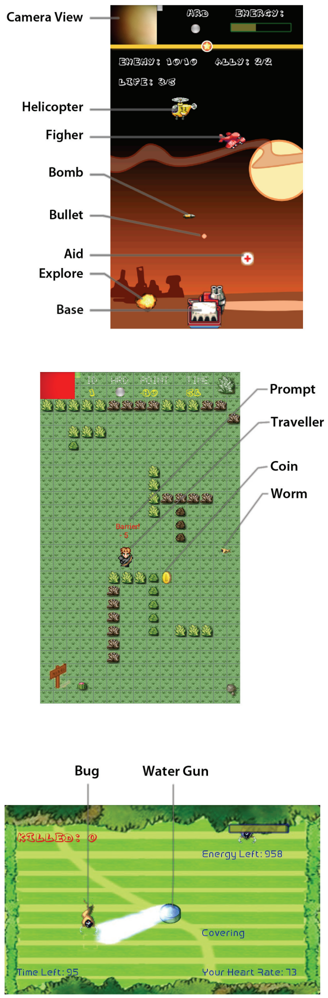

Figure 3. Screenshots of the three games: City Defender (top), Gold Miner (middle), and Bug Defender (bottom).

decision for two major reasons: 1) Given the intermittent nature of our envisioned usage scenario, we do not assume that consistent, uninterrupted signals will arrive for an extended amount of time, which is necessary for transformations such as PCA/ICA; 2) We expect the LivePulse algorithm could run efficiently on mobile devices in real-time and leave enough CPU power to handle the graphics and multimedia effects during game plays. Matrix factorization operations and frequency domain transformations are still expensive on mobile devices.

In our LivePulse algorithm, the camera is set in preview mode, capturing 144x176 pixel color images at a rate of 30 fps. We disable the automatic focus function and the automatic white balance function to avoid interference. We also turn the built-in flashlight on to improve performance in low illumination conditions.

When a finger covering action is detected (we used the *Static LensGesture* detection algorithm in [10]), our algorithm extracts heart rates via a 6-step, heuristic based process.

The LivePulse algorithm first converts each frame into one time-stamped heart beat sample point via equal distance sampling and the summation of 800 points on the Y (i.e. illumination) channel (Figure 2.a). The algorithm then detects all the local peaks and valleys in the converted temporal sequence signal (Figure 2.b). Heuristics are applied to eliminate small and noisy local minima/maxima points (Figure 2.c). Instead of estimating heart rates from two adjacent peaks/valleys directly, we found that it is more reliable to estimate and interpolate the time stamps of zero-crossing points between peaks and valleys and then derive heart rates from time stamp differences between two adjacent zero-crossing points (Figure 2.d, 2.e). To further improve the robustness of LivePulse, we save and sort the time intervals between adjacent zero-crossing points during the past five seconds. Real time heart rate is reported when at least 80% of the time-stamp distances are within a given error range (25%) (Figure 2.f).

From LivePulse to LivePulse Games

Two major concerns arise when designing LivePulse Games. First, what is the best trade-off in balancing the fun/engaging factor and the measurement accuracy during a game play? Second, what are the effective techniques to integrate lens covering actions required by LivePulse *naturally* into the games?

We clarify the first concern with a thought experiment. According to the working mechanism of LivePulse, the algorithm works best when a user covers the camera lens completely and steadily all the time. Following this trait, in one extreme situation, we could use the camera lens as a "*power switch*", i.e. the game continues when a user covers the camera lens, and pauses when the finger leaves the lens. Although heart rates can be measured with minimal interruptions, such scenario will lead to bad game playing experiences for two reasons: 1) the lens covering action is actually isolated from the actual in-game interactions; and 2) the finger covering action needed becomes an extra burden rather than an entertaining factor. As a result, users could feel bored and start to look for equivalent games that don't require lens covering.

In the other extreme situation, if the lens covering action is used as a high frequency input channel, e.g. directly controlling missile firing in a shoot-em-up video

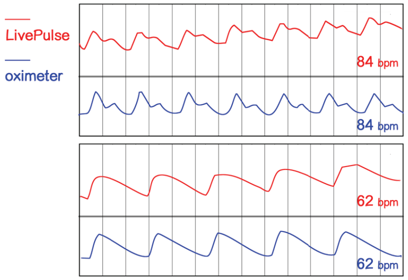

Figure 4. 14 seconds of sample heart beat signals from LivePulse (red) and oximeter (blue).

game, the game play could be engaging and satisfying, but the underlying algorithm may have trouble in getting reliable readings from brief and unstable finger touches.

In addition to the brute-force "*power switch*" metaphor, the lens covering gesture can serve as a "*trigger*" to activate an in-game event. In this scenario the camera lens is no different from a push button mounted on the back of the mobile phone. In this mode, the timing and frequency of covering are used for game control. The lens covering gesture can also be used as a "*clutch*" or a gas pedal. In this paradigm, covering the lens steadily will switch certain in-game object into a different mode (e.g. charging, accelerating etc). In the "*clutch*" mode, players use the timing and duration of covering as the primary control mechanism.

Through a total of three rounds of iterative design, we created three LivePulse Games, City Defender, Gold Miner, and Bug Defender to test pervasive, non-invasive heart rate monitoring on mobile phones.

The City Defender game (figure 3, top) allows users to protect a city by controlling a powerful, but slow anti-aircraft artillery. Users may fire bullets from artillery by tapping on the screen; users may also move the artillery left and right to collect rescue packages from allied helicopters. Each of these actions cost a certain amount of energy. The energy bar can be recharged gradually by covering the lens.

Gold Miner (Figure 3, middle) is similar to the classic snake game on Nokia mobile phone with some unique tweaks. In this game, the users move an explorer to collect randomly placed coins in the scene. The user moves the in-game explorer by tilting the phone in different directions (i.e. left, right, up, and down). The explorer has to avoid hitting bushes during movement. There are also poisonous worms in the game. Worm will start chasing and biting the explorer when the explorer moves. The only way to avoid being bitten by worms is to stop moving the explorer, which requires the users to release their fingers from the camera lens. Users need to wisely plan the timing and moving trajectory of the explorer in order to win.

Bug Defender (Figure 3, bottom) is a farming game where players aim to kill worms in their farms. The player charges a water gun by covering the lens. Tapping on the screen will aim the targets (worms in a garden) and fire the water gun. Worms can only be captured when the worm color matches the corresponding screen orientation, i.e. when red worms appear, the player needs to put the mobile phone in landscape mode and then shoot; when blue worms appear, the player needs to put the mobile phone to portrait mode.

Pilot User Study

We ran a 12-subject (3 female) pilot user study to test the accuracy and participants' subjective feedback towards LPG. The games ran on a Google Galaxy Nexus smartphone running Android 4.1. We used a CMS 50D pulse oximeter (FDA approved, medical grade. Error <= +/-2 bpm) as the "gold standard".

LPG were able to extract participant's heart rates successfully from all three sessions (idle, Gold Miner, City Defender) for all the 12 participants.

Overall, raw heart beat signals from LivePulse and the oximeter were highly consistent in both beat-to-beat interval and the actual wave shape (Figure 4).The Mean Error Rate (MER) of LivePulse in idle mode was 3.9%

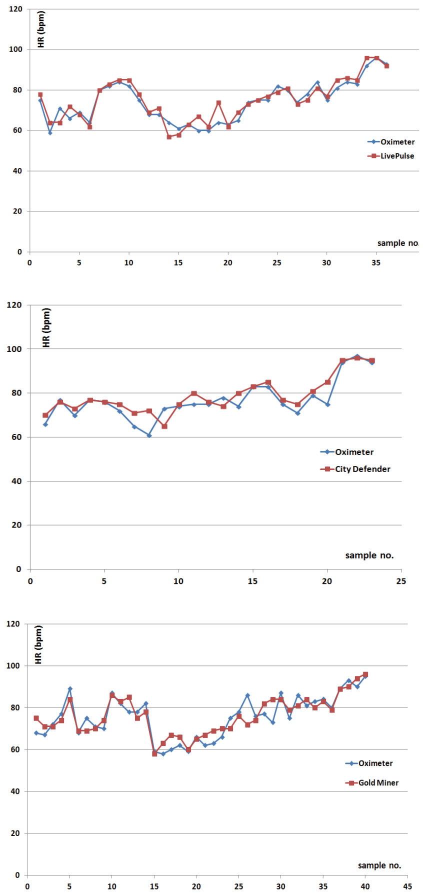

Figure 5. Heart rates (bpm) of 12 subjects (top:idle mode, middle: playing City Defender, bottom: playing Gold Miner) from LivePulse, LivePulse Games (red) and Oximeter (blue).

(-7 ~ +5 bpm, Figure 5, top), 4.6% (-8 ~ +11 bpm, Figure 5, middle) when playing City Defender, and 5.0% (-14 ~ + 11, Figure 5, bottom) when playing Gold Miner. Analysis of variance results showed that the heart rate readings from LivePulse (idle, City Defender, and Gold Miner) and the oximeter were not statically significant in all the three conditions: LivePulse (idle) vs. Oximeter($F(1, 11) = 1.64$, $p = 0.13$, n.s.), LivePulse (idle) vs. City Defender ($F(1, 11) = 0.83$, $p = 0.40$, n.s.), LivePulse (idle) vs. Gold Miner ($F(1, 11) = 0.23$, $p = 0.82$, n.s.).

Paradoxically, *we didn't observe a major difference in heart rates between the idle mode and two active game play sessions*. Among all three conditions tested, subjects' heart rates varied similarly from 56 bmp to 97 bpm. We believe this observation was caused by the causal style of LPG and the relative brief play sessions. It is possible that the users' heart rates may change significantly when playing more intensive games for an extended amount of time. It would be an interesting future work to predict the idle heart rate from heart rate measured in intensive game play sessions via machine learning should these kinds of differences occur.

The participants reported strongly favorable experiences with LivePulse Games. When asked how satisfied with the LPG overall, participants rated 4.25 on average (σ =0.60) using a five-point Likert scale. Participants gave an average rating of 4.17 (σ =0.80) on how "fun" LPG are. The average rating for "ease of learning" was 4.67 (σ =0.47).

Conclusions

In this paper, we present LivePulse Games (LPG), a novel technique to measure users' heart rate in real time by playing casual games on unmodified mobile phones. We demonstrated the feasibility of real-time, non-invasive heart rate monitoring by playing LivePulse Games on mobile phones.

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