Automated mobile systems for multi-dimensional well-being sensing and feedback

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Abstract
In recent years, we have seen a prolific rise of mobile and wearable sensing in healthcare and fitness. Although the data generated is incredibly useful, state-of-the-art feedback technologies are often limited to either providing an overall status or serving large volume of multi-dimensional sensor data with little processing. My research falls into filling this gap. I work on developing systems that use sensors to understand different dimensions of well being, and subsequently devise interventions through personalized and actionable suggestions. Using simple machine learning techniques, my systems automatically mine user behaviors that influence specific well-being dimensions. Then utilizing decision theory and behavioral psychology theory, my systems create personalized actionable suggestions that are related to existing user’s behaviors. In this proposal, I describe how I realize such automated systems for sensing and providing feedback.

Author Keywords
Health; Feedback; Mobile sensing; Behavior change;

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.
Introduction

In recent years, we have seen a momentous rise in application of mobile and wearable devices in personal healthcare. These mobile and wearable devices with sensors can track fine-grained details of a user’s physical activity, social interactions, and other important contexts of life. The number and variety of these sensors are also increasing over time, and in the process giving more details (e.g., heart rate, attention) of a user’s lifestyle\[1\][13]. Although these tracked data are incredibly useful, state-of-the-art technologies are often limited in processing and feeding this information back to the users. Current state-of-the-art techniques fall in one of two categories: (1) providing overall summary (e.g., total number of steps) statistics\[2\] (2) visualizing the whole data across multiple dimensions that create information overload\[1\] (Figure 2).

However, a closer look at the data can reveal interesting patterns of a user’s life that can be targeted for personalized intervention. For instance, Figure 1 shows places where a user stays stationary and a location where the user most frequently walks. An intelligent machine can easily quantify and target such behaviors to create personalized interventions. For instance, the system may suggest users to continue, change, or avoid the respective behaviors.

My research falls into filling this space. I work on developing systems that use sensor data to understand different dimensions of well-being, and intelligently create interventions through personalized and actionable suggestions. I accomplished this task in a highly interdisciplinary fashion. A typical workflow in my research constitutes the following. First, I apply machine-learning techniques to understand different human behaviors that are related to a well-being dimension. Then I efficiently implement these algorithms in mobile applications and deploy the applications across user studies. While users use these applications in their everyday life, the applications automatically understand user behaviors related to specific well-being. Subsequently my apps create suggestions with well-known decision-making algorithms. In order to increase the odds of following these suggestions, the decision-making algorithms utilize proven health intervention techniques from behavioral psychology (low-effort\[3\][4] and self-efficacy\[5\]) and heavily contextualize the suggestions to a user’s life. For instance, based on Figure 1(b), a suggestion could be “You walked 30 times near place X in last 14 days. Let us continue or increase the walking behavior”. Since the suggestions are already part of a users life, they easy and low-effort to follow.

![Figure 1](image1.png)

**Figure 1**: A specific user’s stationary (a) and most frequent walking behavior (b) over 14 days.

![Figure 2](image2.png)

**Figure 2**: Visualization of daily activity from Basis B1 tracker\[1\]. It is often hard to visually find patterns and devise actionable outcomes for a healthier life style.
Depressive symptoms of mental and physical interaction and physical activity

Table 1

<table>
<thead>
<tr>
<th>Sensor measures and correlation</th>
<th>Depressive symptoms</th>
<th>Mental health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall face-to-face interaction</td>
<td>$R = -0.73, p = 0.09$</td>
<td>$R = 0.82, p = 0.05$</td>
</tr>
<tr>
<td>Overall physical activity</td>
<td>$R = 0.88, p = 0.01$</td>
<td>$R = 0.82, p = 0.05$</td>
</tr>
</tbody>
</table>

Table 1: Overall face-to-face interaction and physical activity correlate highly with clinical measures of mental and physical well being.

In the following, I first describe research that I have already completed in my research. Then I will describe what I am planning to do next before the completion of my thesis defense. I will finish this proposal with my expectation from the doctoral colloquium and my biographical sketch.

**Completed research**

One of my early works [6] explored the use of multi-modal sensing to understand mental and physical well-being states. Accelerometer, barometric pressure and privacy-sensitive audio [7] data were continuously collected from 8 elderly patients. We found that the amount of face-to-face social interactions positively correlated with overall mental health and inversely correlated with depressive symptoms. Overall activity levels (walking, running, stationary etc.) were also found to correlate significantly with standard medical surveys to measure level of physical activity. Table 1 shows a summary of the results found.

Given this success of using multi-modal sensing in understanding physical and mental well-being, I co-built the BeWell [8] system that can sense and provide feedback on multiple dimensions of well-being. BeWell provides feedback on overall physical activity, socialization level and sleep in an animated live wallpaper of an android phone (Figure 3). This live wallpaper portrays an aquarium where fish in the aquarium move more if the users perform more physical activity. More fish are present if the socialization level is high. The aquarium is brighter with more light, if the user gets enough sleep. A pilot study with BeWell demonstrated that users using BeWell slept better, socialized more and performed higher amount of physical activity.

One of the shortcomings of the BeWell system is its use of overall statistics that makes little use of a user's common behaviors and lifestyle information contained in the sensor data. As an alternative, I built a system called MyBehavior that provides personalized actionable feedback by suggesting specific existing user behaviors to continue, change, or avoid. These user behaviors are automatically learned using unsupervised clustering of users dietary and physical activity tracked overtime. During suggestion making MyBehavior uses a multi-armed bandit, which is a sequential decision making algorithm. It maximizes chances of reaching a calorie loss goal. The system can also balance this caloric goal with the user’s personal preferences by using pareto-frontier algorithm. In two formative pilot trails, users reported MyBehavior suggestions to closely relate to their lives and were low-effort to implement. Preliminary evidence indicates that MyBehavior users were more active and made healthier food choices. To our knowledge, MyBehavior is the first mobile system to combine sensing and decision theoretic principles to automatically generate personalized and low-effort suggestions for health. Figure 4 shows a set of suggestions generated by the MyBehavior system.

In addition to generating personalized suggestions, I worked on sensing stress, an important component of our mental and physical well being. I co-developed a system called StressSense [9] that sense stressful episodes from an individual's speech. StressSense fits in my overall goal of understanding multi-dimensional well-being, since it is unlikely for individuals to change an existing behavior or relapse during stressful time [10]. Also, excessive stress can cause mental health problems such as depression.

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Finally supporting multi-dimensional well being with multi-modal sensing is a challenging problem at a systems level. For example, same audio, location or accelerometer data are used in recording sleep [11], regular activity (e.g., watching TV, dancing) or voice recognition [6]. Furthermore with sleep status inferred, it is possible to perform more energy efficient sensing by reducing the rate of activity recognition. Thus different sensing and inferences performed inside a device are highly interdependent on each other and needs to share data. Ad-hoc implementation of such interdependence can create complex interconnection and data flow in the code. This complexity can make realistic mobile systems hard to scale with new capabilities and to reuse individual. In order to tackle this interdependency, I built a sensing and inference toolkit called SAINT where any sensing and inference module can share their data (figure 5) over a unified bus. The unified bus eliminates the complexity and interdependency in data sharing. The bus is implemented in an energy efficient manner with fast circular buffers and inters process communication. A paper on SAINT is in submission and the project will be open sourced once the paper is accepted.

**Proposed work**

In my future work, I plan to do a long-term study with MyBehavior. The primary goal will be to quantitatively demonstrate that MyBehavior users adopt healthier lifestyles in the long run without novelty effect. I plan to run this study for at least 9 weeks with a one-week baseline period. Users total level of physical activity and food choices will be used as objective measures to show quantitative difference with the control. Also, there will be open-ended formative components consisting of post-hoc statistical analysis and qualitative inquiries. Different combinations of user demographics (age, gender, motivation and stress level) and outside influencers (weather, holidays etc.) will be analyzed using post-hoc tests. Qualitative interviews will be conducted and daily diaries will be maintained across the study period in order to triangulate quantitative findings and devise limitations and future works of MyBehavior.

I also plan to extend my work on adaptive suggestions like MyBehavior for stress and sleep. Regarding stress, I will create an app called MySocialLife. MySocialLife will automatically mine face-to-face interactions to determine an ego network. Then MySocialLife will find which peers in the network are stress-inducing and which peers can provide social support. Social support is a big component of stress coping (Figure 6). Previous research has shown patients that underwent major surgery tend to live three times longer with social support compared to no social support [14]. MySocialLife will exploit privacy sensitive non-verbal features (pitch, speaking rate and speaker transition) and in phone processing to determine friends and stress inducers. Also, we expect that qualifying an individual’s social network with stress will have strong correlation with the power relations, a very important topic in social sciences. The suggestions components in MySocialLife will deploy an online adaptive algorithm that will encourage individuals to social conversations based on their stress level, location and prior history of conversations. During summer 2014, I plan to finish the system development of MySocialLife where I will build and implement models for friends and stress inducers. A deployment study will be conducted in Fall 2014 with MySocialLife’s suggestion component.
Regarding sleep, current research in ubiquitous computing is limited to sensing sleep from various context information. There is little to no work in Ubicomp that has explored the possibility of personalized actionable suggestions for sleep. However, it is harder to create actionable personalized suggestions similar to MyBehavior or MySocialLife for sleep. In MyBehavior, suggestions capitalize on user’s existing physical activity and dietary behavior to maximize chances of calorie loss. MySocialLife exploits social support to relieve from stressful situations.

However, what needs to be done to maximize good sleep isn’t very clear. Existing literature suggests that exposure to sunlight, caffeine, stress and alcohols can cause bad sleep [12]. But they don’t guide users on how to realize these suggestions by adapting to their lifestyle (for instance, “the user is working late in the office that causes lack of exposure to sunlight”). In order to see the feasibility of personalized sleep interventions, I will collect 6 months of data across different sensors in Fall 2014 and early Spring 2015. My initial hypothesis is that a simple bag-of-words model will separate out important user behavior that causes good and bad sleep.

**Related work**

Over the last few years, physical activity recognition has become a matured area of research. Lare et al. [15] provides an up-to-date review of this field. Sleep sensing has been explored by Chen et al.[11] using off-the-shelf mobile sensors. Wyatt [16] demonstrated the feasibility of using speech in modeling social networks.

Ubifit [2] provided feedback on physical activity as a background wallpaper of the phone. Lullaby [17] explores the possibility of visualization technique to monitor events during sleep time that may cause disrupted sleep.

My work uses the existing activity recognition and speech processing literature and largely re-engineers them for well-being sensing and intervention. My work on feedback falls between Ubifit and Lullaby. My systems generate suggestions that are more detailed than overall feedback like Ubifit, but they provide more

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**Figure 5**: The architecture of SAINT sensing and inference framework. SAINT provides a unified bus interface to share data across sensing and inference modules. Also client applications can connect with SAINT to receive SAINT’s sensing and inferred data.

**Figure 6**: MySocialLife application will automatically find peers that are stress inducing and provide social support. MySocialLife will provide personalized suggestions for social support during stressful conditions.

[Image: The architecture of SAINT sensing and inference framework. SAINT provides a unified bus interface to share data across sensing and inference modules. Also client applications can connect with SAINT to receive SAINT’s sensing and inferred data.]

[Image: MySocialLife application will automatically find peers that are stress inducing and provide social support. MySocialLife will provide personalized suggestions for social support during stressful conditions.]

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summarization than exploratory data visualization techniques deployed in Lullaby.

**Expectations from the Doctoral Colloquium**
I believe my research is taking a very novel approach in health intervention. My work deploys an interdisciplinary technique that combines computational tools with time-consuming system building and tedious user studies. Any input regarding prototyping software, designing pilot or longer-term user studies will vastly help my research.

**Biographical Sketch**
Mashfiqui Rabbi received his B. Sc. (Hons.) from Bangladesh University of Engineering and Technology in 2008. Since 2009, he is working with Prof. Dr. Tanzeem Choudhury. His research focuses on building mobile sensing systems for understanding and providing feedback for physical and mental well-being. He expects to finish his PhD by Summer 2015.

**References**