Expanded Tele-Health Platform for Android

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Technical Report No. UCB/EECS-2015-90
http://www.eecs.berkeley.edu/Pubs/TechRpts/2015/EECS-2015-90.html

May 14, 2015

Acknowledgement

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MASTER OF ENGINEERING - SPRING 2015

EECS

Robotics & Embedded Software

Expanded Tele-Health Platform for Android

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This **Masters Project Paper** fulfills the Master of Engineering degree requirement.

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Final Capstone Report

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May 10 2015

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Abstract

In 2013, of 26 billion dollars spent on patient readmissions in Medicare, an estimated 17 billion of this was generated by readmissions caused by avoidable factors. The most preventable of these factors - and arguably the most severe - are improper administration of therapy and medication. To combat this, we are developing a lean, smartphone-based telemedical system that not only provides personal health statistics to the patient, but relays this information to the doctor allowing for a more tailored approach to medicine. By leveraging the latest open source health monitoring algorithms and libraries, we have created a reliable, low-cost and easily implementable solution that has the potential to simultaneously improve patient care and dramatically reduce healthcare expenditure.

1. Introduction

In 2010, $17 billion dollars was spent on patient readmissions in Medicare. (Centers for Medicare & Medicaid Services: 2012). The most preventable readmission factors - and likely the most severe - are improper administration of therapy and medication. To combat this, we are developing a lean, smartphone-based telemedical system that not only provides personal health statistics to the patient, but relays this information to the doctor allowing for a more tailored approach to medicine. By leveraging the latest open source health monitoring algorithms and libraries, we have created a reliable, low-cost and easily implementable solution that has the potential to simultaneously improve patient care and dramatically reduce healthcare expenditure.

The team, advised by Dr. Ruzena Bajcsy and led by Ph.D. student Daniel Aranki, consisted of several members, including four Master of Engineering students (Phillip Azar, Adarsh Mani, Quan Peng, and Jochem van Gaalen) specializing in Robotics & Embedded Software concentration in the EECS department, and engineers Arjun Chopra, Priyanka Nigam, Sneha Sankavaram, Maya Reddy and Qiyin Wu.

The aim of this project is to develop and test a highly configurable, open-sourced Android powered framework that will enable doctors and hospitals to remotely monitor outpatients with chronic health conditions and determine their risk of re-admittance. This platform will transform the ubiquitous smartphone into the backbone of a tele monitoring system which uses various sensors to track different vital signs. These sensors can either be off-the-shelf products (e.g. temperature sensors) or sensors embedded in the smartphone itself (such as gyroscopes, accelerometers, cameras etc.). Once the data is extracted, the smartphone will be used to relay the information, in a fault-tolerant manner1, to servers where various diagnostic algorithms are run to calculate re-admittance risk factor and other recuperation metrics. Security and privacy procedures will be embedded into these data structures prior to storage.

[1] Fault-tolerance can be thought of as a personal guarantee to the user that the process will be handled despite the presence of faults such as unexpected power downs, disconnection etc.

The team’s specific contribution to this project is to develop:

Fault-tolerant communication between various off-the-shelf vital sign extractors and the smartphone via Bluetooth.

Novel vital sign extraction algorithms for heart rate and blood pressure using the smartphone’s camera to serve as a proof of concept to demonstrate the fault-tolerant communication and provide a simpler way to conduct health and vital monitoring.

Over the course of the academic year, an application in Android was built and tested through laboratory validation of individual components, and a pilot study conducted near the end of the project which combined these. The results of this work is outlined in this report, along with challenges faced and potential next steps for this project.

This project was also analyzed from a business perspective, with potential competitors highlighted, and a thorough analysis of the industry and market trends to aid in identifying potential business opportunities.

2. Market Trends Analysis

2.1.1 Motivation & Outline

This section of the paper is dedicated to analyzing the telehealth industry and deriving a potential business strategy for a startup centered about our capstone project. It begins by discussing the broad industry trends that show which direction would yield the best go-to-market results. Next, the importance of adopting a well-defined strategy in terms of maximizing business potential is highlighted. From analyzing the industry as a whole in terms of its value chain, the most optimal place within this market a business should occupy will be determined. This is done by identifying the full chain and finding the strongest link. This is followed by an analysis of Porter's Five Forces, which is used to understand strengths and weaknesses in the chosen position within the value chain. Knowing these strengths and weaknesses is a key factor in shaping the business plan. The conclusions drawn from these forces will be presented along with suggestions for ameliorating any weaknesses identified.

After extensive analysis using these models, the section of the market that was identified to be targeted is the "mediator" segment - a segment whose products would form the platform that will serve as common gateway for devices measuring vital signs to communicate with health analytics services and vice versa. The platform the team is developing will allow for a much easier facilitation of data between entities specializing in either the analysis or measurement of health data. It essentially abstracts away the communication layer of the entire telehealth chain into an easy to use, robust and secure service. The strategy adopted to conquer this segment is to pursue an open-source double licensing model wherein royalty will be collected at a pre-determined rate only when the service or code is used for commercial purposes. Personal use cases will be free of charge.

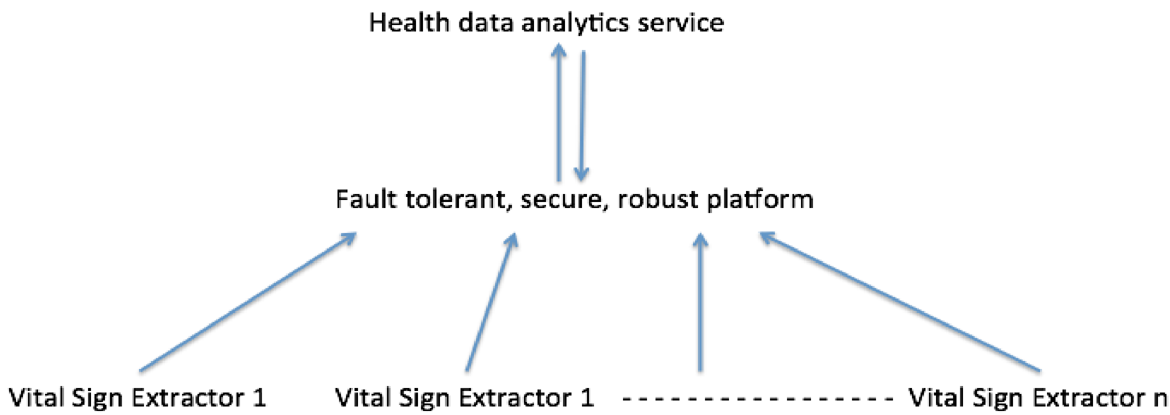

Figure 1: Telehealth Platform Hierarchy

We live in a highly interconnected world. Everything from common household appliances, such as refrigerators, to complex control systems, such as those found in vehicles are connected to information relaying services designed to expand their ordinary functionality. Our lives are becoming more and more dependent on being "connected," and as a result, many major social, technological, and economic trends in the last decade have been fueled by connectivity. Among these trends is the push for telehealth, which since the 1990s, has been a principal force in providing healthcare to underserved communities. (Miller 2007: 133-141) By leveraging major social trends towards connected privacy, availability, and transparency, it is possible to flesh out a telehealth strategy that addresses key impacts and vantage points associated with what will be collectively known as the "connectivity trends." These connectivity trends are driven by a new, socially aware consumer that can greatly influence a product's adoption rate and popularity.

To provide context for these consumers, it is important to examine contemporary cases of social awareness with respect to connectivity. In recent years, the online health industry has been abuzz with issues of privacy, data storage, and patient protection. So much so, in fact, that entire companies have been spawned out of the necessity for these core three attributes (e.g. Veeva Systems.) Chief among these concerns is that of patient protection. Where as many medical devices remain "analog" with respect to connectivity (i.e. no internet/wireless access,) manufacturers are pushing to create connected equivalents of these products. With this comes the potential for new features, but also the introduction of many risks. In a more extreme (and relevant) example, data from an insulin pump that now communicates via Bluetooth low energy may find itself in the hands of third party advertisers. (Hall & McGraw 2014: 216-221) While this data is protected under the Health Insurance Portability and Accountability Act (HIPAA) passed in 1996, it is very likely that the patient will be unaware of what is occurring, since they are often surrounded by Bluetooth enabled devices with internet access. This creates a very real, and potentially dangerous situation: data can be intercepted and collected from medical devices, which can then be used for almost any purpose. And in effect, what you find is similar in many ways with the motivation behind the Digital Millennium Copyright Act (DMCA,) in which illegally obtained data is so abundant that liability is no longer held against companies who store that data.

From a strategy perspective, the contemporary social awareness of patient privacy, data storage, and protection significantly detracts from attempts at commercialization. The FDA Center for Devices and Radiological Health (CDRH) is the major regulatory arm that governs the development, implementation, and evaluation of products with telehealth features. Since the FDA is a member of the federal government, policymakers, who in turn are influenced by those who they represent (and in many cases, special interest groups,) have the ability to directly impact the regulation of telehealth systems. Negative social acknowledgement can therefore directly harm the commercialization of a new telehealth product by influencing the implementation of stricter regulation. So the question remains, how can telehealth products hope to compete against an increasingly aware consumer base?

It is not feasible to simply promote ignorance of a very real and tangible problem: the digital age has long since begun, and next to nothing is primarily stored physically. If you cannot simply “wish” the knowledge away, then the next best thing is to approach the problem with the contrapositive: education. And this kind of education, one that targets the socially aware consumers (and in this case, patients,) is not strictly limited to the benefits of a product. In fact, it is critical to convey both sides of the technology. Net neutrality is one modern example where conveying only the benefits of a technology is more subversive than it is helpful. Major internet service providers attempted to only convey the benefits of discarding net neutrality in an attempt to mask its true purpose as a means for generating additional revenue. This had the effect of creating a nearly unanimous voice against the proposition. In conveying both the benefits and downsides to telehealth, we can best leverage the trend of social awareness in connected health care, and in turn, create a more positive public image.

The importance of influencing the socially aware consumer cannot be understated: coordinating a strategy of education rather than marketing can mean the difference between revolutionizing and downplaying the entire telehealth industry. With the advent of free online educational resources, it is simply not good enough to assume that a market segment will be ignorant about a product or feature. A good strategy will leverage this education and in some ways seek to exploit it, feeding a growing demand for high tech while at the same time appealing to the scientific side of a market segment. There are, however, many more sides to this "good" strategy that cannot be addressed by analyzing the consumer alone.

2.2.1 Strategy: What it is and why it is required

Strategy is both the art and science involved in the formulation and evaluation of key-decisions that will give an entity an edge over its competitors, attain a sustainable advantage and help achieve its long-term objectives. Delineating a strategy also helps the organization formalize objectives, and hence give it concrete direction. It helps one decide how to position a product and what decisions to make to maximize growth and profitability, as it is just as important when trying to enter a saturated market as it is when trying to enter a nascent one. It is just as useful when trying to consolidate one's lead in a market as when one is trying to establish it.

The telehealth industry is still relatively nascent, but is rapidly expanding. Industry revenue was projected to grow $320.2 million in the five years leading to 2014, including revenue growth of 23.1% in 2014. From 2014 through 2019, the industry stands to reap the benefits of demographic, structural and legal factors. These include a growing aging population, advances in telecommunication and wearable technology, and statutes like the Affordable Care Act. As a result, industry revenue is expected to increase at an annualized 49.7% to $2.4 billion in the five years to 2019 (Morea 2014:9).

Although the top two companies, GlobalMed and InTouch Technologies, occupy 22% of the market share (Morea, 2014), the industry itself is rapidly expanding, and thus there is ample opportunity for this technology to enter the market and seize a sizable share.

However, given that the project is a potential spin off from an academic endeavor, and doesn't have (at least presently) the financial clout or business savviness of companies already in the market, adopting the right strategy becomes crucial to conquer and succeed in this market. Where the team temporarily lacks in business authority, it excels in technical skill and prowess. While it is acknowledged that this will have to change in the future, the team believes it can use this technical superiority to get a foothold in market.

2.3.1 The Strategy

As mentioned in the previous section, the team plans to leverage its technical prowess to its advantage. This involves building a robust easy to use, easy to integrate platform, and then treading the open-source route. In the current market, existing solutions are mostly "walled-gardens" with players providing proprietary solutions to all fields in telehealth (vital-sign extraction, collection, logging, analysis and result distribution). However, with the impending explosion of the internet of things, several third-party developers of medical hardware used for constantly monitoring vital sign data are expected (Lars 2014). The number of connected devices is expected to reach 50 billion mark by 2020 (Swan 2012). This data emphasizes a need for an open platform to handle the software/communication part of the system. It is this opportunity that the strategy is designed to seize.

2.4.1 Industry Value Chain Analysis

The first requirement one must consider when creating a new business is how it should be positioned within the industry. For example, there are many levels involved in delivering medical devices to hospitals. A company wanting to produce a device must first buy supplies, and then usually contract out the labor to a manufacturer. Once the devices have been manufactured, the company will sell these medical devices to a distributor who carries the device in a catalog. Hospitals partnered with these resellers will then purchase these devices, process them, and finally hand them over to doctors who will use them as a part of the care they provide.

We can see that the value chain is long, and in many cases, not quite linear. Various market forces also make the chain asymmetric in that the value that is realized in each part of the chain is not evenly distributed. Many markets often have a particularly ‘fat’, or highly profitable part of the chain while the other sections fight for the leftovers. An example of this can be seen in the technology industry. In delivering cell phones to consumers, Apple, the company that designs and markets its products, clearly makes the most money, even though there are many other businesses involved in the value chain such as the phone manufacturers (e.g. Foxconn), distributors (e.g. FedEx) and carriers (e.g. AT&T). Unlike the consumer technology industry which arguably has started to reach maturation, telehealth is still a fledgling industry, which is still being shaped by early startups, new government regulations and many new technological innovations. Despite this, the telehealth industry value chain is no different in that the ‘fat’ part of the chain can clearly be identified.

From the IBISWorld report on telehealth, the industry value chain is shaped with several ‘demand’ players such as data processing and hosting services, hospitals, physical therapists and health & welfare funds to name a few (Morea 2014:14) . On the other side of the chain, there are several ‘supply’ players providing infrastructure within which telehealth services can operate. These include businesses such as mobile carriers, software publishers and hardware manufacturers.

Because of the wide variety of players in the industry, both supplying and pulling technologies to and from telehealth services, a simplified linear model was developed to illustrate the supply chain. This is shown below in Figure 2.

Figure 2: Industry Value Chain

From here, we see that the chain is longer than one might expect in that there are several intermediate steps involved with getting a device into a hospital. It is important to note that this value chain is a simplification of the actual chain, which is not linear and has many more steps involved within each major stop in the chain presented.

Due to the established nature of similar industries requiring the same suppliers and hardware manufacturers as the medical devices industry, suppliers and hardware manufacturers are well developed and highly competitive (Kahn 2015:24). Thus, the fat part of the value chain is located with the medical device designers. A good example of the power of this part of the chain are medical devices like Medtronic and Siemens AG - companies whose revenues exceed $17 billion USD, which is where we would like to position a potential startup. It is important to note however that there remain several large pitfalls in which a business situated as a device designer could become wildly unprofitable. Many of these have to do with regulatory approvals (Morea 2014:21) such as meeting FDA requirements (Medina, Kremer & Wysk 2012). However, once met, these businesses will be well situated within the chain. The team's particular business would circumvent many of these pitfalls by taking on the 'mediator' role within the medical devices industry. As alluded to earlier, this would allow participating medical devices companies to safely gather data from patients and provide additional services derived from this.

By identifying the best location within the industry chain, we can now analyze which parties in the medical industry would have interests driving the adoption of new medical devices. These parties would be ideal candidates to which a startup business could offer services. Performing this analysis also has the added benefit of being able to predict the demand of the industry, which is a function of the size and strength of desire of its customers.

2.5.1 Potential Stakeholders

By its very nature, there are a plethora of potential stakeholders with key interests in the success of this platform. First, insurance companies would have an interest in the rise of tele-health monitoring systems, as having the ability to better assess the risk of patients could drastically change the way that insurance is calculated. From this, it follows that insurance payers and patients would see substantial benefits in the way that medicine is applied in that increased information about the patient will allow for more accurate diagnoses and more targeted treatments. This will ultimately help in lengthening and improving the quality of life.

Furthermore, the ability to take measurements of a patient's vital signs opens the door for alternative options to physically visiting the doctor – a practice continued for centuries. This is an enormous market currently valued at approximately $1.151 billion USD and growing at approximately 2.2% yearly (IBISWorld Report: Number of Physician Visits 2014:1) which presents a huge financial opportunity for the telehealth medicine. While certainly not a complete substitute, the telemedicine industry could replace large swathes of routine checkups and minor cases. This could serve as a boon not only for businesses looking to save on costs associated with granting time off to see a doctor but also for understaffed hospitals to relieve labor-related costs.

Governments and regulatory bodies such as the World Health Organization (WHO) would benefit from enhanced data collection in order to present new legislation or seek out cost cutting opportunities in relation to providing health care, and to help model and eventually mitigate the effects of contagious new diseases. With recent legislative moves seeking to expand health coverage in the US such as the Affordable Care Act, an increasing amount of financial support will flow into the telehealth industry contributing to the estimated 49.7% growth in industry revenue (Morea 2014:5) as a reaction to making care affordable to a wider swath of the population.

From this analysis, we can see that there are many large and powerful stakeholders with keen interests to either increase profits, or reduce costs with the aid of telehealth technology. This further validates the team's judgment in the Porter's power of buyer's analysis. With so many parties interested, and relatively weak internal industry rivalry, starting a business in this sector of the industry should have the highest chance of success.

Now that the stakeholders have been identified, it is crucial to understand the role that the team's technology would play in commercial applications. Investors in a startup are investing primarily in the technology, and the team, so without a clear vision of how the technology will function, it would become impossible to market it correctly or draw up a business model.

2.6.1 Relation between Technology and Commercial Product

The ability to monitor vital sign information in real time has direct applications to commercial technology. The team aims at providing a common platform to developers with some sample vital sign extraction methods embedded with the idea that other companies build on top of this platform. This platform will enable developers to work on producing technology more focused on data extraction and/or analysis without having to spend inordinate effort establishing fault tolerant protocols, server security, and data privacy. The idea here is to position the platform similarly to how the Android operating system is marketed. Android is an open-source cellular operating platform that comes with several basic functionalities, but is meant as a platform where third-party developers can extend its functionality.

Different vital sign extraction techniques are analogous to new apps developed specifically for this platform. Revenue would be collected from licensing agreements between device makers seeking to utilize the platform for profitable ventures. Such a strategy would have a benefit of rapid growth due to its flexibility, but could have the potential downside of being slow to grow revenue. In all likelihood, due to the nature of the technology industry to rapidly grow in new sectors, this would be the best approach as opposed to a strategy that would involve keeping the platform closed and competing rather than collaborating with medical devices and technology companies.

With a defined position within the value chain, and an idea of how the technology in this capstone project will interact with the final product, we can now analyze the remainder of Porter's Five Forces to assess potential threats in the industry.

2.7.1. Porter's Five Forces

In his seminal article in the Harvard Business Review, Michael E. Porter outlines five major factors that should influence the approach one should espouse to be successful (Porter 2008). These are:

1. Bargaining power of buyers

2. Bargaining power of suppliers

3. Threat of new entrants

4. Threat of substitutes

5. Rivalry amongst existing competitors

Each of these forces will be analyzed in detail in how they pertain to our chosen industry in the following sections.

2.7.2 Bargaining power of Suppliers

The bargaining power of suppliers refers to the ability of business providing materials, data, IP etc. to a business further down the chain to ask for increased compensation or to switch to supplying a direct competitor. Due to the fact that this platform is largely based off the heavily subsidized, and highly competitive mobile phone market, the suppliers in this regard have little power to demand higher prices were the telemedicine industry to grow and increase their demand. Furthermore, the ubiquity of Android-based phones (International Data Corporation 2014) in the consumer market further weakens dependence on suppliers as our platform does not require a proprietary phones. Rather, a patient can just use a personal phone to use the monitoring platform.

2.7.3 Bargaining power of Buyers

The bargaining power of buyers refers to the ability of customers of the business to demand extra features, lower prices, or switch to a competitor. Due to the suggested licensing strategy of this product, the buyers in this case would be device manufacturers and potentially research laboratories and regulatory bodies looking to do research on the aggregate dataset of patient data. It is without doubt that the sale or licensing of data would come with some sort of public resistance, but if done in an identity sensitive way (and this is already ingrained into the platform itself from its inception) this could open the door to many licensing opportunities. Since there are few alternatives to this system, the power of buyers to simply switch to another platform would be weak.

2.7.4 Threat of New Entrants

New entrants bring with them fresh ideas and a tenacity ideas to gain a share of the market from existing players. Ease of entrance, characterized by barriers to entry, will encourage more new comers especially if the industry is nascent and has potential for being lucrative. This precisely characterizes the telehealth market. We live in a connected world and with the Internet of Things verging on explosion, telehealth is one of the many industries that will receive a significant boost in market size (Lars, 2014.)

In such a scenario, it is anticipated that many players will prop up to get a piece of the pie. It is, therefore, of utmost importance to increase the barriers to entry to dissuade potential entrants. The team has done this by increasing barriers to entry in the following ways:

1. As the team is building a platform that will be leveraged by third-party manufacturers of health monitoring devices, the platform has to be robust, complete and easily joinable. Developing a solution that offers all three features requires a lot of developmental effort and time, which in turn raises the barrier of entry.

2. Once adopted, it'll be very difficult for our customers/partners to switch to a new platform.

3. The open source model works in the team's favor. Open source provides for collaboration and cooperation as opposed to competition. As the platform gains more adoption, a larger community would organically grow, further fuelling adoption.

By raising the barrier to entry for new entrants, the team has ensured a sustainable "economic moat" can be built.

2.7.5 Rivalry

Rivalry is greatest in an industry if competitors are roughly of equal size, industry growth is slow or if exit barriers are high (Porter, 2008). It can become particularly entrenched if the rivals are competing on price. Size and financial might of the competitors play a major role in determining who comes out victorious in market share wars. The current major players in the telehealth market are GlobalMed and InTouch Technologies who together own 22% of the market (Morea 2014:25). However, the industry itself is rapidly growing and hence there is abundant opportunity for entry.

In the telehealth industry, the basis of competition is primarily based on product quality, which is determined by factors like product functionality, features, speed and ease of use. Other media of competition include breadth of services, marketing, customer services and training offered to clients. (Morea 2014:24)

Given this, the biggest threat for the team comes from the threat of rivals. Being a potential startup spun off from an academic endeavor, the team is definitely at a disadvantage in terms of the amount of money that can be spent on marketing and customer service.

However, the open-source strategy being adopted will help us overcome this hurdle. The team aims at revolutionizing the telehealth industry the way Linux revolutionized the mainframe operating system industry or the Android revolutionized smartphone operating system industry. By providing a free to use platform that can be leveraged by third party developers, the growth of a community of support and innovation is encouraged. This will be particularly successful because:

1. The proliferation of cheaper hardware and sensors is spurring the growth of independent original equipment manufacturers who can use the team's platform to build a complete solution.

2. With cheaper networking solutions and the growth of internet of things, several startups are developing devices each with their own proprietary communication protocols. Currently, there isn't a single platform that would allow these disparate devices to talk to each other. This reduces interoperability, which can stall growth of the industry a whole (Ghosh et al., 2011). As adoption increases, the open source platform the team is developing has the potential to allow for greater interoperability, thus further spurring the industry growth.

3. Existing companies have their proprietary platforms which can be licensed by third party developers at a hefty fee. By providing an open source solution, the team can win over more developers, thus gaining market share.

2.7.6 Threat of Substitutes

A substitute product is one that that offers similar benefits to customers of a company from other industries. The threat of substitutes describes the possibility that substitutes can replace the company's products. If the company is faced with a high-level threat of substitutes, it loses the control over the price that it can set to sell to customers, since customers can easily switch to its substitutes if the price is set too high. Therefore, it is important to analyze the threat of substitutes given it can affect profitability of the company and the industry. In this section, we will discuss the problem our technology tries to solve, what substitutes there are that solve the same problem, and what the level of threat the substitutes pose on our technology.

Health care is by far one of the most expensive industries in the United States. Readmissions lead to a huge hospital costs. According to Agency for Healthcare Research and Quality, there were 3.3 million readmissions in the United States, which cost hospitals about $41.3 billion USDs (Heins et al 2014). By developing a system that can reduce trips to the hospital, helping people get in touch with their own health, and mediate the link between patient and physician, we can cut down the waste in health care. Specifically, the problem that our technology tires to solve is to reduce hospital readmissions by reporting patients' vital signs (including heart rate, blood pressure, energy expenditure and body temperature) to physicians, who will in return give patients' health advice remotely to keep healthy.

Except our technology, traditional medical devices and modern technologies may achieve the same purpose and become our substitutes. Traditional medical devices are single functional devices such as thermometer, sphygmomanometer, EE monitors and etc. Patients can use those devices to record their vital signs by themselves and remotely consult physicians for feedback with recorded data.

Traditional medical devices have advantage on price over our product. They are relatively cheaper to Bluetooth-enabled medical devices required by our technology, which may lead patients to adopt traditional medical devices instead of our technology. Another weak point of commercializing our technology is switching cost. Since our technology is open-source, we should obey open source philosophy, which states that open-source software should be freely used, changed and shared (Open Source Initiative 2015:1). As a result, there is no reason to charge termination fees to patients when they decide switching to substitutes. However, our technology differentiates from these substitutes in three aspects which can stick patients to our product:

1. Instant data transmission.

Our technology helps patients to transfer health data to physicians. If the patients use traditional medical devices to monitor their vital signs, they have to record the data and call or email physicians for advice. This procedure is both time consuming and boring. The patients may give up tracking their health conditions after several trials. With our technology, the health data gathered by Bluetooth-enabled devices will transmit to smartphones immediately and then transfer to physicians by cellular network. The instant health data transmission saves time for patients and physicians.

2. Easy access to health data.

Our technology provides convenience for patients to check their vital signs record. Traditional medical devices are separate. To check vital signs history, patients need to check on individual devices. Our technology is based on smartphone. All measured vital signs will store on the phone. As a result, patients can check their health data anywhere anytime with their phone.

3. Expandable functionalities.

Our technology is expendable because we built an open-source platform for telemedicine. Developers can write more applications using our platform. Therefore, in the future, our technology has potential to provide more useful functionalities as well as benefits to patients and physicians by the contributions of third-party developers.

In addition to traditional medical devices, modern technologies could also pose a threat to the platform we are developing. Following are two existing modern technologies serve as substitutes of our product.

1. Motorola - Moto 360™

Motorola has recently released a smartwatch called the Moto 360™. Other than being an accessory to a smartphone, it can give basic biomedical data such as skin temperature, heart rate and energy expenditure. This platform could be developed further to come closer to the product we envision, but this would require substantial modifications to the current product.

2. Microsoft – Kinect

Microsoft's Kinect system has cameras which can be used to detect heart rate, energy expenditure and even mood by sensing the changes in flood flow in the face (Zhang 2012:4-10). Microsoft is currently focused on integrating the Kinect system with its Xbox One gaming console. However, this does not stop third-party developers from using this system to provide in-house medical diagnostics such as respiratory surface motion tracking (Alnowami et al 2012), 4D thermal imaging system (Skala 2011 et al:407-416), and otoneurological examinations (Dolinay et al 2014).

With considerations about price, switching cost, and differentiators with respect to traditional medical devices and discussion about modern technologies, the threat of substitutes of our product is moderate.

2.8.1 Major Conclusions

In this report, it was concluded that the best part of the industry for a startup centered about the technology being developed in our capstone is as a mediator between medical device companies and data services. This is the fat part of the chain. A Porter's Five Forces analysis was also conducted, and it was determined that with small tweaks to the planned dual-licensing strategy, all of the forces can be reduced to weak or moderate in strength. It is important to note however that this favorable analysis in no way guarantees success. As will be discussed in papers to come, the largest hurdles lie not within the placement of the startup, but with issues like avoiding IP prosecution, gaining the necessary industry approvals, and building up a reputation for being protective about sensitive health information. These issues are not easy, and some will be addressed specifically in future papers.

3. Intellectual Property Strategy

3.1.1 Introduction.

This section of the report is dedicated to explaining the strategy the team would like to adopt with respect to intellectual property. While the final goal is to create an open source product, the strategy is to attempt to patent the system architecture in order to safeguard the platform against patent trolls. We will first provide a brief outline of the technology, and then dive into the strategic reasoning behind patenting this particular part of the project in terms the competitive and strategic advantages it would give the team. We will then talk about what the risks of not patenting are and how these hurdles can be overcome.

3.2.1 The Aspect: System Architecture

Being the platform that forms the intermediary between data collection and analysis mandates robustness, fault tolerance and ease of use. For widespread adoption, not only is it necessary to be first to market, it is also necessary to provide an easy to integrate solution. The application programming interfaces that would be provided should be seamless enough for people in the adjoining industries to build upon. The product's system architecture caters to all these requirements. We believe the innovation that went into meeting the constraints imposed by the requirements puts the team in good stead to warrant a patentable system architecture. This architecture allows for an instant state recall, clever storage and persistent reconnection as broad means to implement fault tolerance and robustness - aspects that are quite novel and developed from needs specific to handling sensitive health data.

3.3.1 Problems with Software Patents

Software patents are notoriously difficult to obtain due to the difficulty involved in proving the novelty and obviousness of them, unless they are extremely specific. Common problems include

1. Deeming software is math, and math is not patentable.(Jones, 2009)

2. Software programs being different than electromechanical devices because they are designed solely in terms of their function. While the inventor of a typical electromechanical device must design new

physical features to qualify for a patent, a software developer need only design new functions to create a working embodiment of the program.(Plotkin, 2002)

3. Computers are deemed to be the "designers" and “builders” of the structure of executable software. Software developers do not “design” the executable software's physical structure, but merely provide the functional terms.(Plotkin, 2002)

4. The large number of micro-niches in software and relative few examiners mean patent examiners seldom have sufficient know how to recognize if the technology disclosed is innovative or novel enough.(Bessen, Meurer, 2008)

For the reasons stated above, it may not be possible for a small team of engineers to mount a serious patent application. In order to overcome this, we plan on leveraging U.C. Berkeley’s Office of transfer office, the Office of Technology Transfer, to help design and formulate a strong application to provide the best chance of being awarded a patent.

3.4.1 The Strategy

Applying for a patent is best in this case as it would protect the business from the threat of patent trolls and also would set a legal basis by which the business can protect its work. Forgoing patents could spawn copycat businesses that would patent this architecture, and could ultimately lead to the business being coerced into paying licensing fees for technology it originally developed. Applying for the patent protects the product irrespective of the outcome of the application for two reasons:

1. Approval of the patent will ensure that other competitors do not develop similar technologies, and thus raise barriers to entry. While it is true that the business may ultimately pursue an open-source strategy to encourage an organic growth of a strong third party community (which in itself raises barrier to entry), being awarded the patent ensures that the economic moat the team aims at building is deeper and wider.

2. Failure to get approval of the patent reassures the business that the same technology likely will not be awarded to a patent troll, giving peace of mind.

It is true that established competitors are much larger and financially capable than a startup this capstone group can produce, but the playing field can be leveled by leveraging the resources of the university to apply for a patent. This will both ease the financial burden, and cast a much larger enforcement net over the patent then could be done alone.

3.5.1 Risks of Not Patenting

If the backend architecture of the platform is not patented during the development phase, the team would leave itself open to the threat of having the architecture stolen and patented by another entity. As a consequence, the team could lose revenues from licensing, or even have to pay for technology the team invented in the first place. This could happen if some other group invented similar back-end architecture and patents it before the group's project is finished and released as an open source software. In addition, due to the highly collaborative nature of these projects, there is a risk that external developers would file a patent for the technology themselves. This would distract the team with crippling legal proceedings rather than focusing on further innovations.

Because of the risks of not patenting, it is advisable that patentable parts of the project are quickly pursued. To achieve this, an internal search utilizing university resources such as the Office of Technology Licensing (OTL) must be conducted to discover any prior art that may stand in the way of granting a patent. Legal experts should be then involved as quickly as possible to explore the potential patentability of the system architecture. Upon a thorough literature review by these experts, their advice will be taken and put into action.

In the case that it is found that a patent would be unlikely to be granted, the group would focus on making the platform open source as soon as possible in order to reduce the risk of infringement of patent rights. This establishes a record of prior art which can be used as a legal defense against patent trolls. A dual-licensing model will then be adopted to produce revenue. With dual-licensing, clients can use the technology under the condition that they redistribute their technologies as open source as well. If these entities wish to commercialize technologies utilizing this technology however, they will be required to pay a licensing fee on a per-use basis.

In conclusion, patenting the backend architecture provides a shield from legal problems and enables safe cooperation with external developers to speed up the development of the platform. In the unfortunate case that the patent is not granted, the only way to reduce legal risk is to release the platform as quickly as possible to establish prior art against potential litigation.

4. Individual Technical Contribution

Our project aims to develop and test an open-source, highly configurable Android platform allowing doctors to monitor and determine risk of re-admittance for heart-attack patients released from the hospital. The platform uses various sensors such as accelerometers, gyroscopes and cameras already onboard most smartphones to relay vital sign data (such as heart rate, blood pressure, temperature and caloric expenditure) to both patients and to their assigned healthcare professionals in a secure and fault-free manner.

Specifically, our group contributed to the development and testing of novel vital sign extraction algorithms for heart rate and blood pressure using the previously developed fault-tolerant framework. The group will also expand the communication functionality of the application by implementing a fault-tolerant Bluetooth framework to help interface with currently available medical devices such as blood pressure monitors.

My technical contribution to this project was the development of an algorithm that could provide estimation of heart rate in real-time on an Android phone. In this paper, I will walk you through literature of various heartrate estimation methods at first. Then I will describe the heartrate estimation algorithm in more details in methodology section. After that, I will show you results of the algorithm and reflections of whole development process.

4.1 Literature Review

Heart rate is an important vital sign, which can help monitor fitness levels and find emerging health problems. For example, previous research shows there is a statistically positive relationship between high heart rate and high arterial stiffness (Cunha et al 1997: 1423 - 1430). In addition, an irregular pulse may indicate heart diseases such as a blocked artery and myocardial infarction (Buchman 2002). As a result, heart rate becomes one of the vital signs the team aims to collect for health condition inference.

There are many ways to measure heart rate. The oldest method to measure the heart rate is manual method, which describes the way to measure heart rate by placing index and middle fingers together on the opposite wrist or on either side of the neck and counting the number of beats in a minute. This manual method relies on tactile sensation (sensing the heart beat) and an optical sensor (checking time) of the subject. This method is not very accurate because people can make mistakes in sensing the heart beat while checking the time. Therefore, heart rate monitors were developed to get more accurate measurements. Figure 3 shows two typical examples of heart rate monitors.

The first monitor consists of two elements: a chest strap and a wrist receiver. The second monitor has a finger strap rather than a chest strap. Both monitors utilize the sensor on the strap in order to detect small vibrations caused by the heart beat and calculate the heart rate based on interval between consecutive heart beats.

Figure 3 Left image shows a chest-strap heart rate monitor. Right image shows a finger-strap heart rate monitor

Although these heart rate monitors are more accurate and stable than the traditional method, they are not perfect. Both monitors are somewhat invasive instruments – they have to contact the human body to get measurements, along with the following disadvantages:

1. It takes time for people to put on these monitors. They have to spend time to carefully put on those monitors.

2. It makes people feel uncomfortable. The chest strap may cause breathing difficulty, and the finger strap may obstruct the blood circulation in the finger.

To avoid these disadvantages, we need a non-invasive technology, which can measure people's heart rate without contacting their body.

There is a published paper about noninvasive technique to measure heart rate (Poh et al 2011: 7 - 11). They described a method to measure heart rate by using a webcam to capture a video of the subjects' face. The reason why this approach works is that when the heart pumps, more blood goes into capillaries around the face, which leads to subtle changes in red, green and blue (RGB) values of the video stream. By utilizing signal processing algorithm over the video stream, the corresponding heart rate signal can be extracted. The result section in their paper shows that the method can achieve stable and high accuracy as compared to a FDA-approved finger blood volume pulse (BVP) sensor and chest belt respiration sensor.

The algorithm in the paper by Poh et al is an offline algorithm that is suitable for implemention on a computer with high computation power and large amount of memory. Since our goal is to use a smartphone to extract the heartrate, all computation would be done on a phone with less computation power and smaller memory. In order to run the algorithm on the phone, we have to reduce the memory consumption. In addition, Poh et al don't include an important part of the algorithm – a customized peak detection algorithm in their paper, which forces us to modify the algorithm further to make it functional.

My contribution to this project was to implement and modify Poh et al's method on an Android phone using the phone's camera. Specifically, I developed a heartrate calculation pipeline in both MATLAB and Android. The MATLAB pipeline is an offline pipeline which takes a video as input and outputs a heartrate estimate. The Android pipeline is an online pipeline which estimates heartrate with the camera preview streaming in real time. In the following section, I will describe those two pipelines in more detail.

4.2 Methodology

4.2.1 MATLAB pipeline

Figure 4 shows the structure of the MATLAB pipeline. The structure is nearly identical to that described in Poh et all. The MATLAB pipeline consists of two components: i) offline video processor and ii) heartrate calculation. It takes a video of face as input. The offline video processor component calculates average RGB values of the face region in each video frame and stores the value in a list. Once the offline video processor component processes and stores the average RBG values of all video frames in the list, the heartrate calculation component analyzes the list of average RGB values to estimate the heartrate.

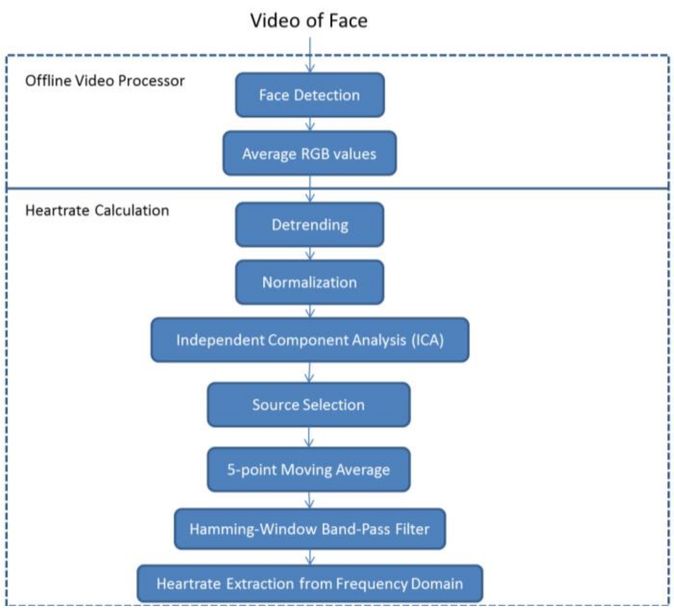

Figure 4 MATLAB pipeline framework

Next, I will briefly discuss the individual steps in the pipeline.

Face Detection

At the beginning of the project, we utilized a deprecated library javacv to both load the video and perform the face detection. Javacv works well for short video clips with clean background, but it performed poorly when the background was noisy. As a result, we decided to discard the javacv library and to utilize the face-detection library of MATLAB Computer Vision System which provided more accurate results than the javacv library. Thus far, we have not noticed any face-detection failures while using the libraries. Figure 5 shows an example of the result of MATLAB face detection.

Figure 5 Left image shows the original image with face. Right image shows the detected face from original image.

Average RGB values

After performing the face-detection in MATLAB, we extract the face region of each frame and average all RGB values over that region to get average RGB signals over time of the video. After all frames are processed, we construct three average signals over three channels – R channel, G channel, B channel – by combining average RGB values of all frames in chronological order. Figure 6 shows an example of the average RGB signals in time and frequency domain.

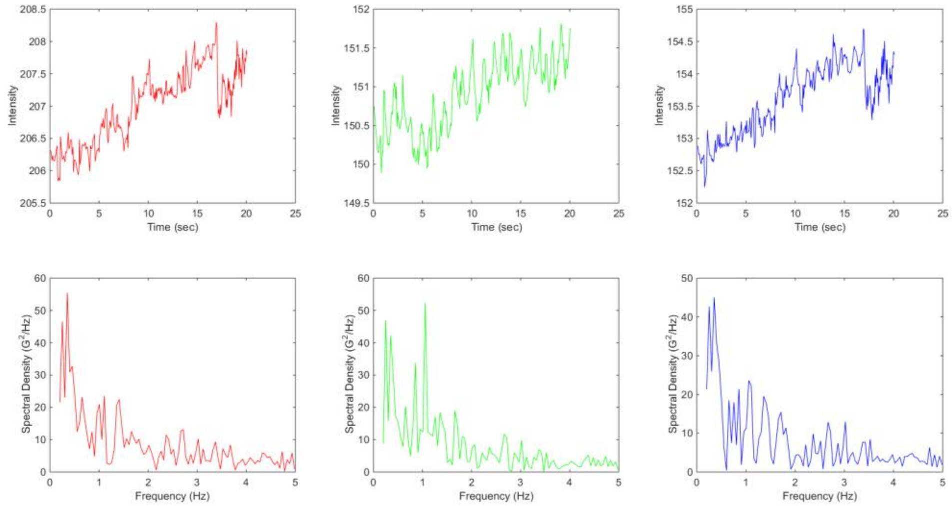

Figure 6 Top charts are average RGB signals in time domain. Bottom charts are corresponding average RGB signals in frequency domain

Detrending

Detrending is the process of removing trends from a non-stationary signal to make it stationary. Non-stationary components such as linear or more complex trends in a signals can produce distortion in time and frequency domain analysis. In order to remove non-stationary components in the average R, G, B signals, we applied a detrending algorithm to those signals based on a smoothness priors approach (Tarvainen et all 2002: 172-5). This algorithm removes general trends with small frequencies caused by camera movement during the video recording. Figure 7 shows an example of processed signals after detrending.

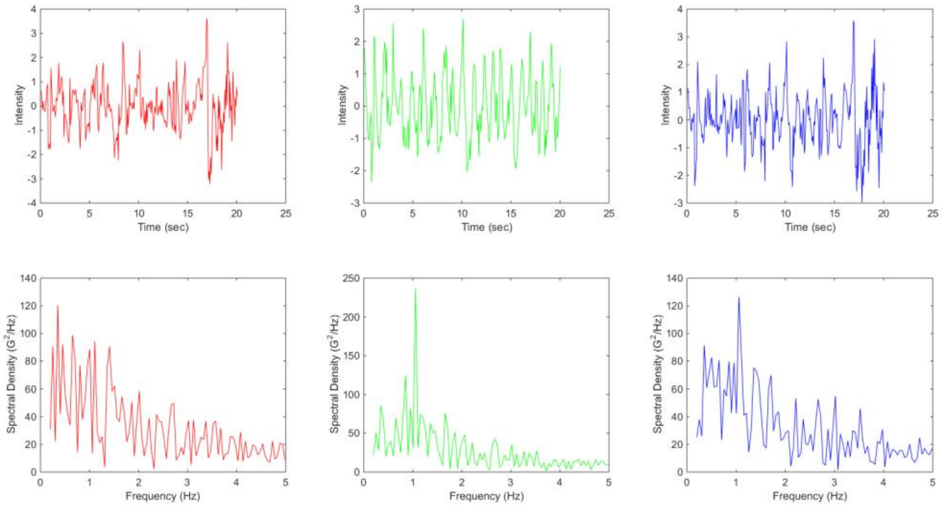

Figure 7 Top charts are detrended average RGB signals in time domain. Bottom charts are corresponding detrended average RGB signals in frequency domain

NOTE: The smoothness-prior detrending algorithm is a memory intensive algorithm which involves large-size matrix operations. It is not feasible for implementation on a phone. Therefore, we removed this step in Android pipeline.

Normalization

We normalized the detrended average RGB signals to ensure those signals have similar dynamic ranges. The normalization was done with the following formula:

$$y_i'(t) = \frac{y_i(t) - \mu_i}{\sigma_i}$$

For each i = 1, 2, 3 where μ_i and σ_i are the mean and standard deviation of $y_i(t)$ respectively. Figure 8 shows an example of the processed signals after normalization.

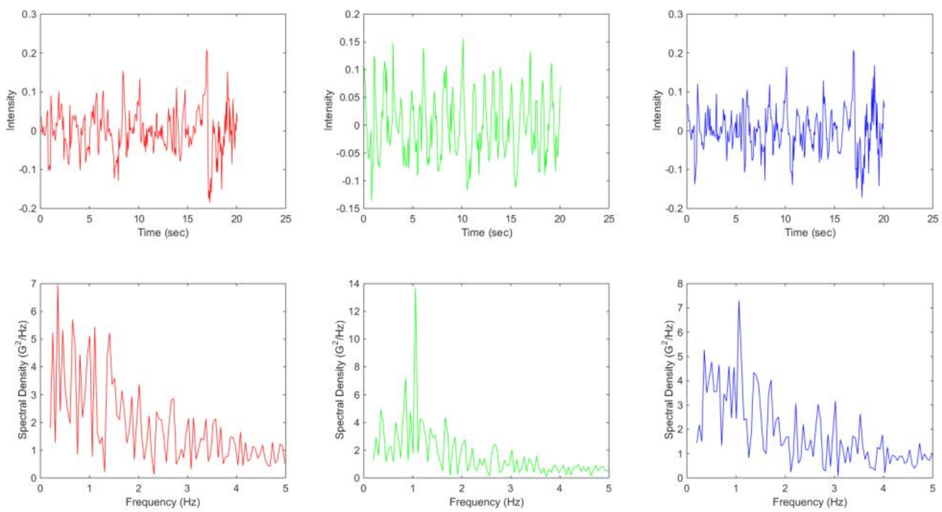

Figure 8 Top charts are normalized signals in time domain. Bottom charts are corresponding normalized signals in frequency domain

Independent Component Analysis (ICA)

Detrending can filter out general trends from the raw signals as described by Tarvainen et al, but it is not designed to remove the dependence between average RGB signals. We hypothesize R, G and B signals are combination of three sources: i) heart rate signal; ii) stationary color of the face; and iii) noise. ICA is a computational method for separating multivariate signals into independent and additive sources. We utilized ICA to extract three sources from RGB signals. Figure 9 shows an example of the source signals extracted by ICA.

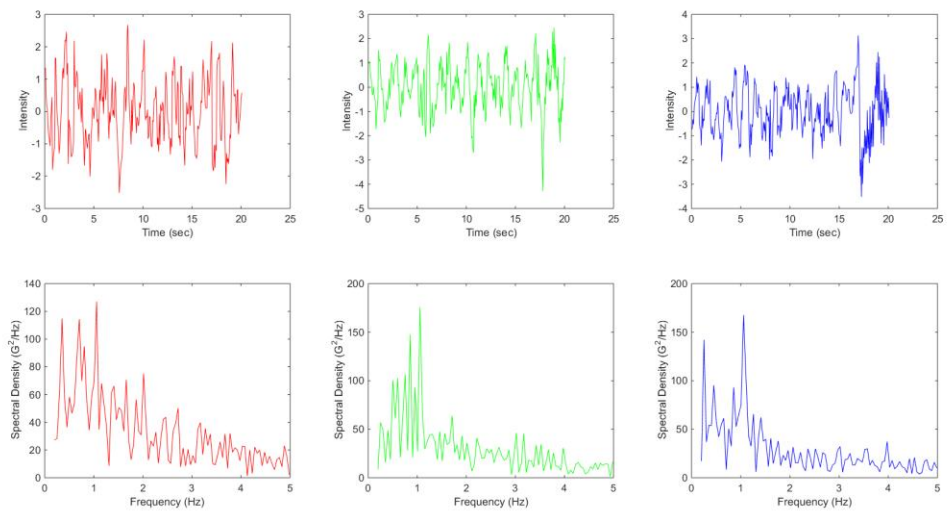

Figure 9 Top charts are source signals in time domain. Bottom charts are corresponding source signals in frequency domain.

Source Selection

ICA outputs three independent and additive sources. We need to select one of them to perform further analysis. In Poh et al’s approach, they select the source with highest peak of spectral density in frequency domain. We didn’t follow their approach. Instead, we select the signal with the highest peak/area ratio in frequency domain. Specifically, we decided to look into frequency range from 0.7 Hz to 4 Hz (corresponding to heartrate 42 bpm ~ 240 bpm) because we believe normal people’s resting heartrate would not exceed this range. Then we find the peak and sum up spectral density (area) in this range for each source. With the peaks and areas, peak/area ratios are calculated for three sources and we select the source with highest peak/area ratio. Figure 10 shows the selected signal from three sources in figure 9.

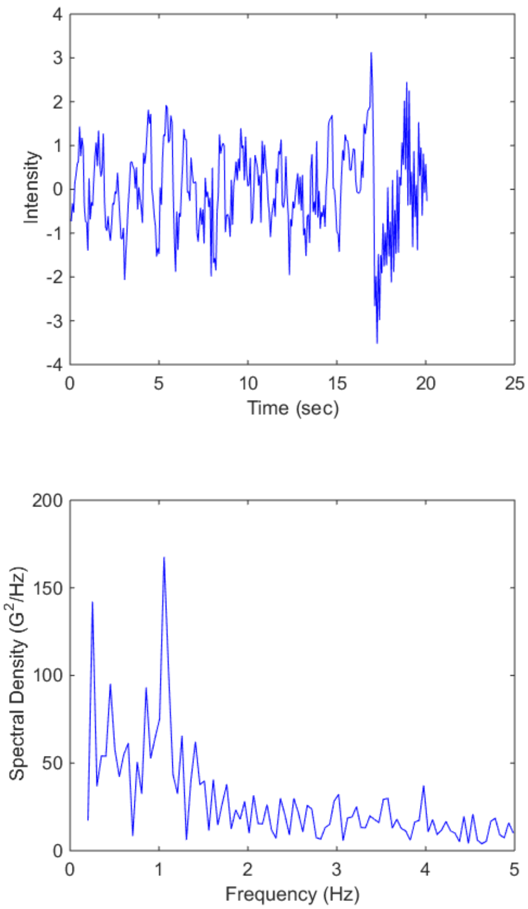

Figure 10 Top chart is selected source signal in time domain. Bottom chart is corresponding selected source signal in frequency domain.

5-point Moving Averaging

From figure 10, we can see that selected source signal is not smooth. To smooth out the signal, we utilized a five-point moving average filter, which smooth signals by averaging every 5 successive points. Figure 11 shows an example of the smoothed signal after 5-Point Moving Averaging.

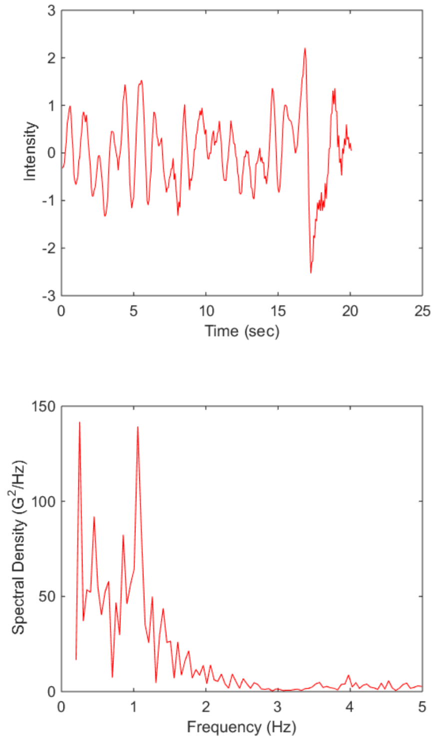

Figure 11 Top chart is smoothed signal in time domain. Bottom chart is corresponding smoothed signal in frequency domain.

Hamming-Window Band-Pass Filter

From Figure 11, we still cannot detect the heartbeat pattern. Poh et al had to continue to process the smoothed signal. The normal resting heart rate of an adult ranges from 60–100 bpm. Considering extreme cases, we follow Poh et al in utilizing 128-point Hamming-Window Bandpass filter with a band from 0.7 to 4 Hz (corresponding to 42 to 240 beats per minute) to filter signals. Figure 12 shows an example of the bandpassed signals after Hamming-Window Bandpass filter.

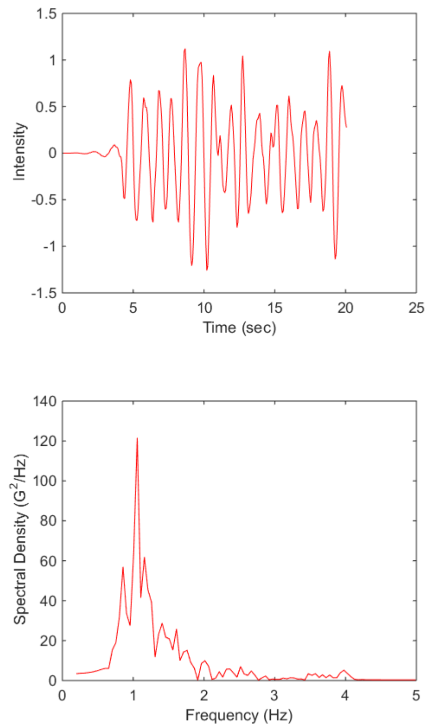

Figure 12 Top chart is bandpassed signal in time domain. Bottom chart is corresponding bandpassed signal in frequency domain.

Heartrate Extraction from Frequency Domain

The last component in the MATLAB pipeline is Heartrate Extraction from the Frequency Domain. To calculate the heart rate, we detect the peaks in the frequency domain of the processed signals after applying the Hamming-Window Band-Pass filter. Then we estimate the heartrate according to the formula:

$$Heart\ Rate = \ Highest\ peak\ frequency * 60$$

4.2.2 Android Pipeline

Android pipeline is an online pipeline built upon Android libraries. The online pipeline can process video frames and produce heartrate estimate in real time. Figure 13 shows the structure of the Android pipeline. The Android pipeline consists of three components:

1. Camera Preview

2. Online Video Processor

3. Heartrate Calculation

The camera preview component generates previews of what the camera sensor is recording. The online video processor component is a callback of Camera Preview. Specifically, every time a preview frame is generated by Camera Preview, Android operating system invokes the Online Video Processor to process the preview frame to generate an average RGB value for the frame and store it in a list for average RGB signals. Once the size of the list is big enough to calculate heartrate precisely, heartrate calculation is invoked to analyze the average RGB signals to extract heartrate information.

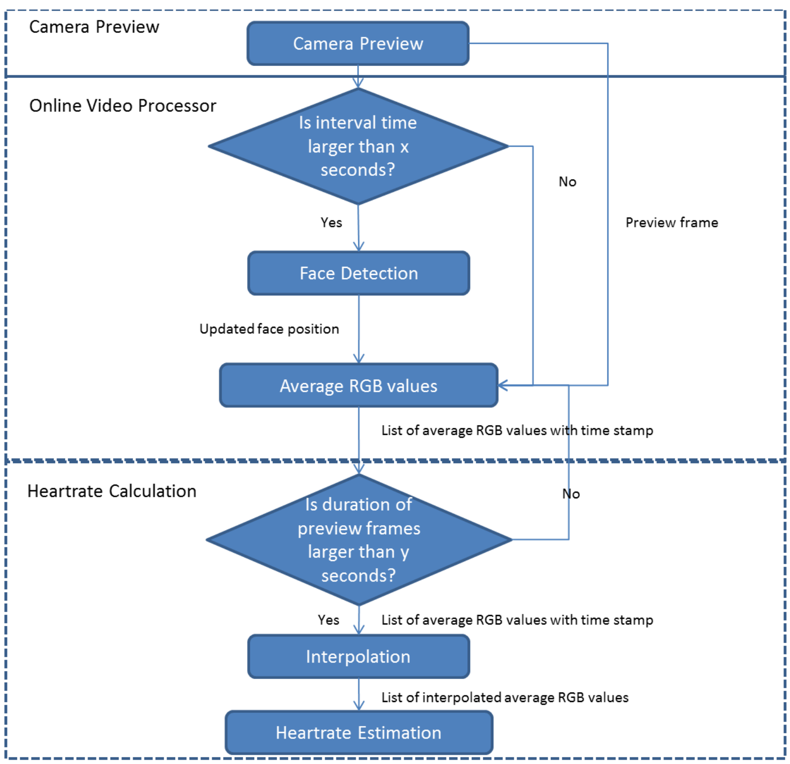

Figure 13 The Android pipeline framework

Next I will discuss each step of the Android pipeline in detail.

Camera Preview

Initially, we tried to record the video to the SD card and then process the video. However, it took about 20 minutes to process a 30-second video at 30 frames per second (fps) due to slow read times from the SD card. In order to speedup processing time, we decided to utilize camera preview. Camera preview is a feature of the digital camera which enables us to preview framing and other exposure details before taking the photograph or recording the video. In preview mode, nothing is recorded. In addition, every time a preview frame is generated, a callback method is invoked allowing us to process the preview frame in the callback method in a number of ways.

Face-Detection Trigger

In certain conditions, the face-detection trigger invokes face-detection algorithm over a preview frame to happen. Users of the Android pipeline library can define the condition. By default, face-detection trigger invokes this process every other second. We added face-detection trigger into the Android pipeline due to the tradeoff between processing framerate and the interval between two consequent face detections. Since it takes time to perform face-detection on a preview frame, the shorter the interval is, the lower the processing framerate is. The framerate also depends on computation power of the phone. As a result, we decided to pass the responsibility of finding the desired face-detection interval to the users of the Android pipeline library.

Face-Detection

Face-detection detects the face region of a preview frame after it is invoked by face-detection trigger. Before next face-detection is triggered, the detected face region will be used for subsequent preview frames to perform further processing. Therefore, we assume that subjects face would not move a lot during two consecutive face detections.

Average RGB Values

With face region of a frame, we calculate average RGB pixel values over that region of the frame. Then we add the average RGB pixel values with current timestamp attached to a list. Due to the scheduling of tasks on the phone, the callback method of the preview frames is not invoked at regular intervals. Since the underlying assumption of heartrate estimation (the last step of the Android pipeline) is that the average RGB pixel values in the list are sampled regularly, the list could not be used as-is. We have to further process the list in order to satisfy the assumption. That is why we attach timestamp to each data point in the list.

Heartrate Calculation Trigger

Heartrate calculation trigger invokes steps interpolation and heartrate estimation with certain condition. The default condition is the difference between the timestamp of first data point in the list and the timestamp of the last data point in the list is larger than 23 seconds. Users of the Android pipeline library can increase the time difference condition to get more reliable result.

Interpolation

As I discussed in average RGB values step, the assumption of heartrate estimation is that the average RGB pixel values in the list have same time interval. In order to assure the assumption, we utilize spline interpolator to interpolate data points in the list at 30Hz sampling frequency.

Heartrate Estimation

The heartrate estimation step can estimate the heartrate with the list of interpolated data points. Figure 14 shows the structure of heartrate estimation step, which looks similar with heartrate calculation component of MATLAB pipeline. The only difference is that it doesn't have detrending step. The reason why I didn't include detrending into the heartrate estimation step is that detrending requires huge-size matrix multiplication (Tarvainen et all : 2002). The size of matrix depends on the size of average RGB signals (around 900x900 for 30 seconds average RGB signals with 30 framerate). There is maximum limit amount of Random Access Memory (RAM) an Android app is permitted to use and 900x900 matrix far exceeds the RAM limit.

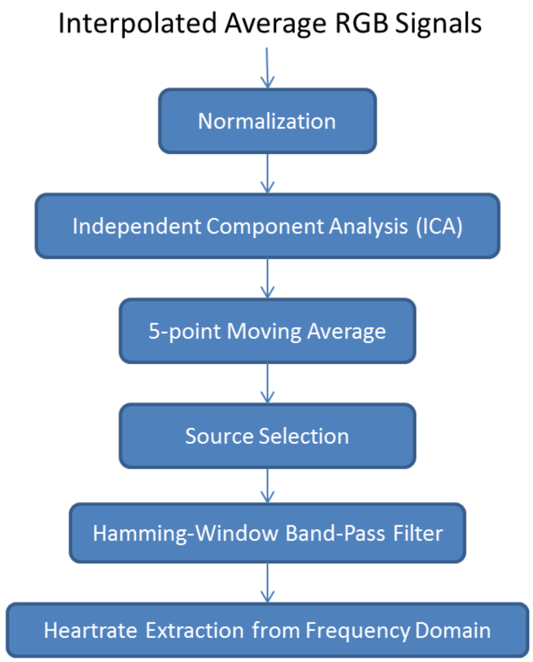

Figure 14 structure of heartrate estimation step

4.3 Results

4.3.1 MATLAB Pipeline Results

I performed 12 experiments to test MATLAB pipeline. An FDA-approved blood pressure monitor -- Omron blood pressure monitor was utilized in those experiments. I treated the heartrate measured by Omron blood pressure monitor as ground truth. In order to see if MATLAB pipeline adapts to people with high heartrate, I exercised before some experiments in order to attain high heartrate. In each experiment, I attached the Omron monitor to my left arm and placed phone's front camera stably in front of my face. Then I used Omron monitor to measure my heartrate and recorded video of my face at the same time. Each measurement lasted about 30 seconds. I observed that it takes time for phone's camera to adapt to the light condition and focus on the face. In order to check if the adaptation affects the heartrate calculation, I ran the MATLAB pipeline over those videos without trimming from the beginning to compute heartrate. Then I ran the MATLAB pipeline over those videos again with 3 seconds trimming from the beginning to compute heartrate. Figure 15 and Figure 16 show the result of MATLAB pipeline with and without trimming compared with Omron monitor.

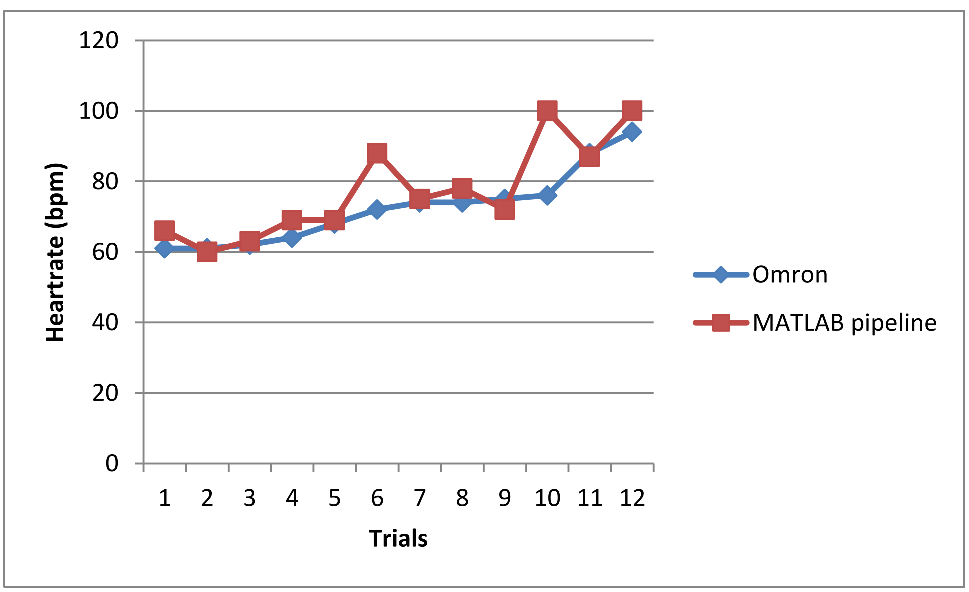

Figure 15 result of the Matlab pipeline without 3-second trimming

The root mean square error is 8.9 (assuming Omron monitor measurements are ground truth) for video without trimming from beginning.

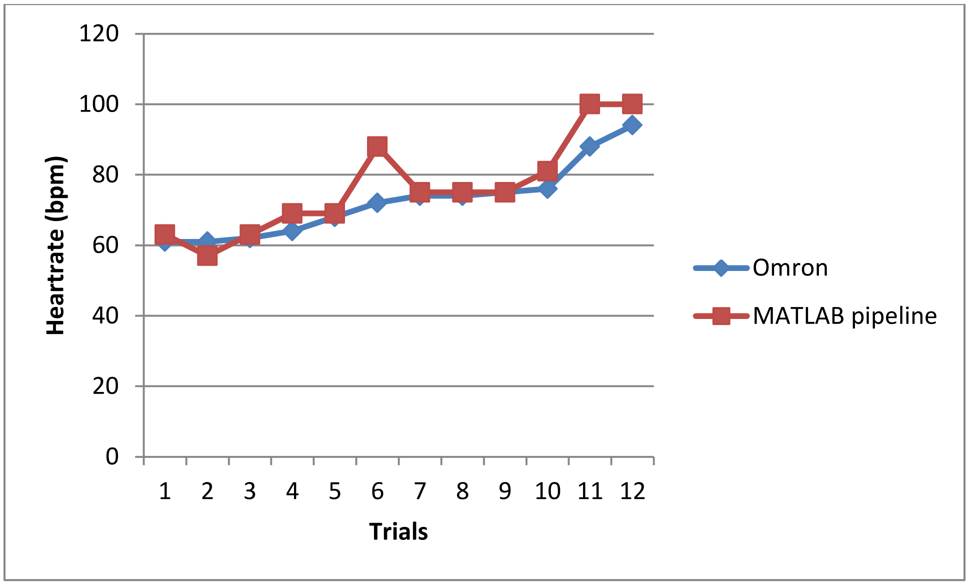

Figure 16 result of the Matlab pipeline with 3-second trimming

The root mean square error is 6.5 (assuming Omron monitor measurements are ground truth) for video with 3-second trimming from beginning.

The RMS of error of trimmed videos is less than that of untrimmed videos. Therefore, I conclude that adaptation of camera to the light condition and focus in the beginning of the video negatively affects the accuracy of MATLAB pipeline and it is advisable to trim 3 seconds at beginning of the video to get cleaner signals.

4.3.2 Android Pipeline Results

I performed 20 experiments to test Android pipeline. During the test, I attached the Omron monitor to my right arm and placed front camera of the Android phone stably in front of my face. Then I used Omron monitor to measure heartrate and started Android pipeline at the same time. Each test lasted about 30 seconds. Table 1 and figure 17 show the result of the experiments.

Omron reading V.S. Android pipeline estimate

Omron	Android pipeline estimate
64	64
59	62
61	60
57	65
61	63
83	84
73	49
70	69
67	69
94	61
83	83
78	78
75	74
71	73
91	44
82	85
76	44
71	73
75	76
69	70

Table 1 Result of Android pipeline experiments with outliers

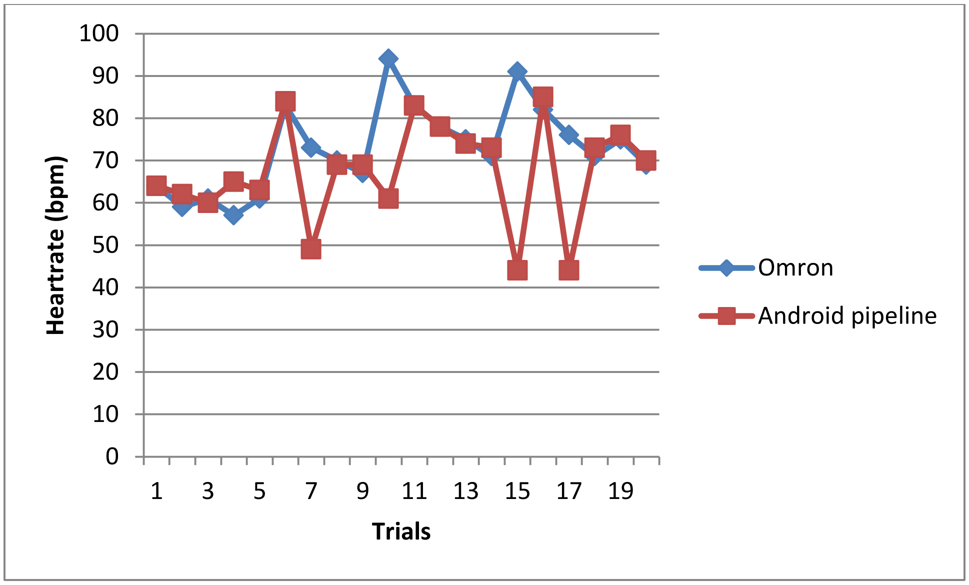

Figure 17 Result of Android pipeline experiments with outliers

Root Mean Square of Error: 15.8

From figure 17, we can see that most Android pipeline estimate agrees with Omron readings. But there are some outliers (Android pipeline estimate ranges from 40 to 50 bpm). We know this because the outliers are given as extreme lower bound of the band-pass filter. Table 2 and figure 18 show the result with outliers being removed.

Omron reading V.S. Android pipeline estimate without outliers

Omron	Android pipeline estimate
64	64
59	62
61	60
57	65
61	63
83	84

70	69
67	69
94	61
83	83
78	78
75	74
71	73
82	85
71	73
75	76
69	70

Table 2 Result of Android pipeline experiments without outliers

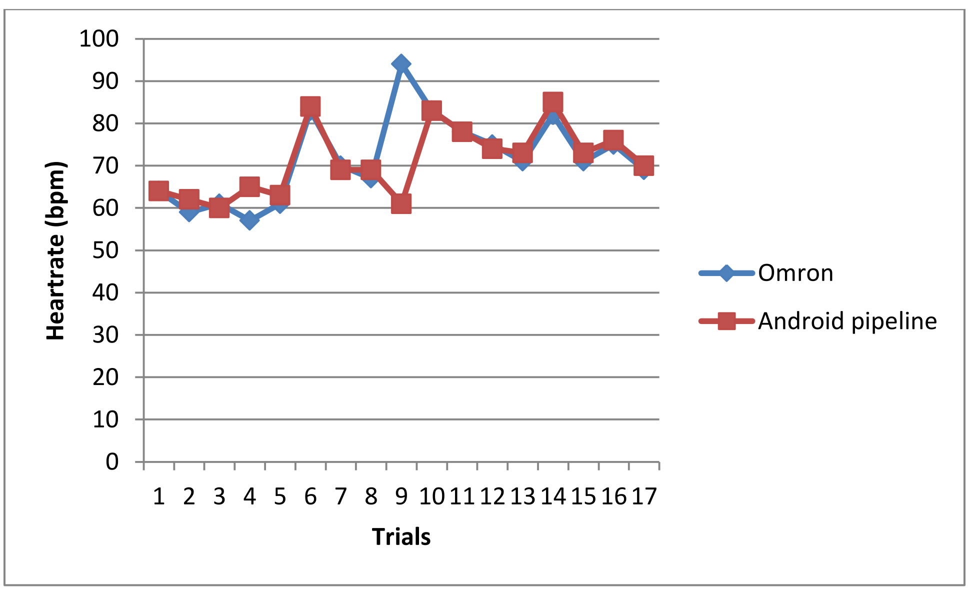

Figure 18 Result of Android pipeline experiments without outliers

Root Mean Square of Error: 8.3

The RMS drops from 15.8 to 8.3 after outliers were removed. We noticed that outliers occur when the corresponding Omron measurements are higher than 75. Human body is like a “capacitor”. If the heartrate is low, then the blood-flow change in the capillary of face is apparent when heart pumps. On the other hand, if the heartrate is high, then the blood-flow change in the capillary of face is not that evident. Therefore, the higher the heartrate, the weaker the heartrate signal is captured by phone’s camera. To improve performance of Android pipeline for people with high heartrate, increase in video frame resolution is required to capture weak heartrate signal. But this is not viable for the testing phone (if the testing phone is more powerful, we may increase the resolution) because of the tradeoff between resolution and fps. We set the video frame resolution to be 176x144 in order to keep fps larger than 10.

To prove that increase in resolution can improve the performance by reducing the number of outliers, I conduct another experiment. In the experiment, I took 12 videos with Omron monitor attached to my left arm, and change the resolution of the videos to be 1280x720, 720x480, 320x240, and 240x180. Then I use MATLAB to extract average RGB signals from those four groups of videos. The intervals between average RGB values are identical because the videos are evenly sampled. However, the average RGB signals generated in Android pipeline are not evenly sampled. To simulate the average RGB signals of Android pipeline, we randomly took out some average RGB values in each second of average RGB signals, and then interpolate the average RGB signals to 30 fps. After that, we test those signals with the heartrate estimation step in figure 13. Figure 19, 20, 21, and 22 show the results of four groups of video with different resolutions.

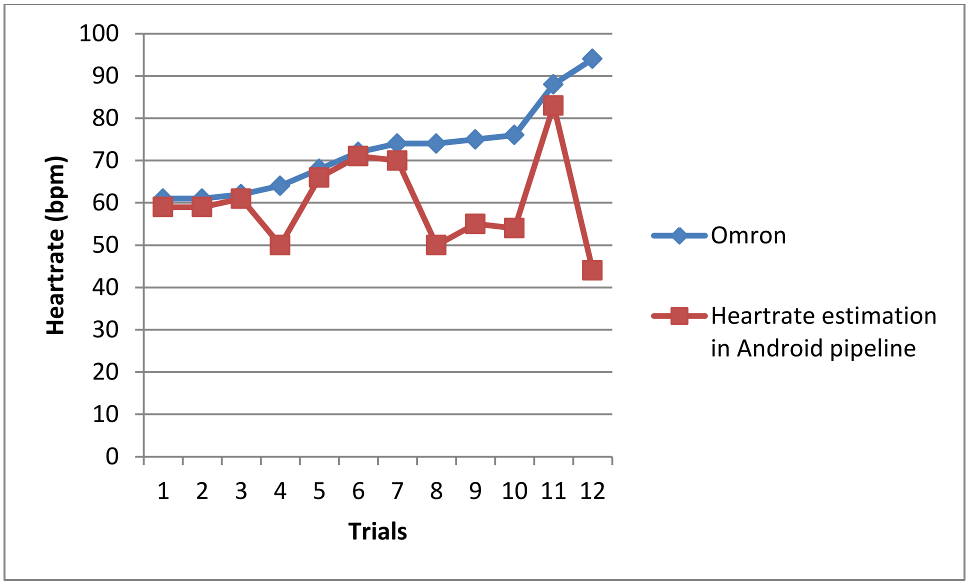

Figure 19 Android pipeline experiments over videos with 240x180 resolution

Error RMS of 240x180 videos is 18.7

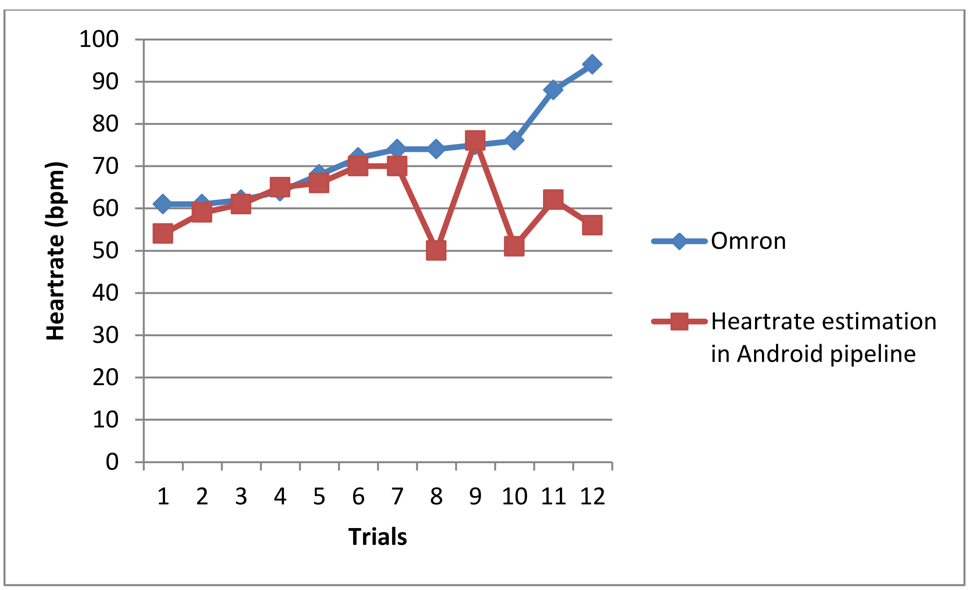

Figure 20 Android pipeline experiments over videos with 320x240 resolution

Error RMS of 320x240 videos is 16.8

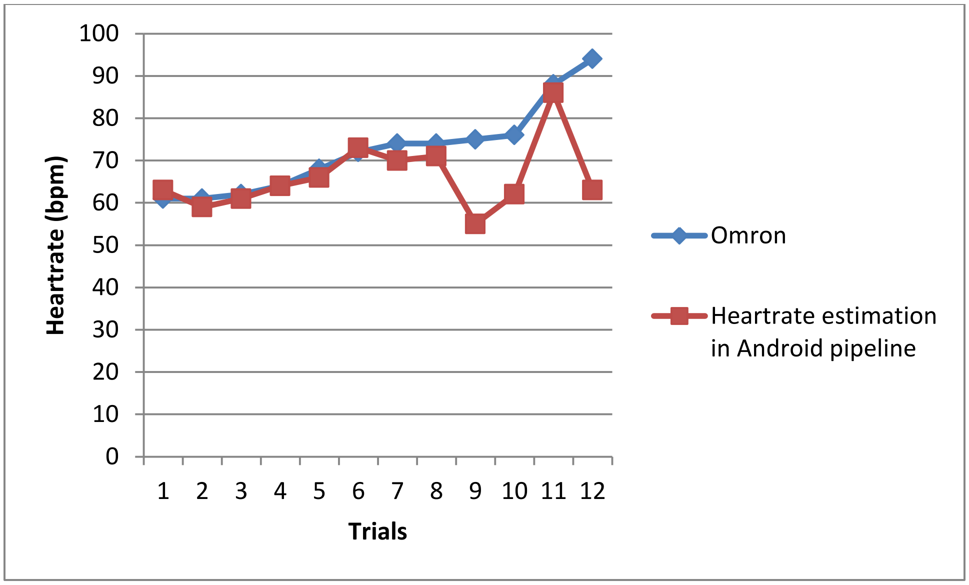

Figure 21 Android pipeline experiments over videos with 720x480 resolution

Error RMS of 720x480 videos is 11.5

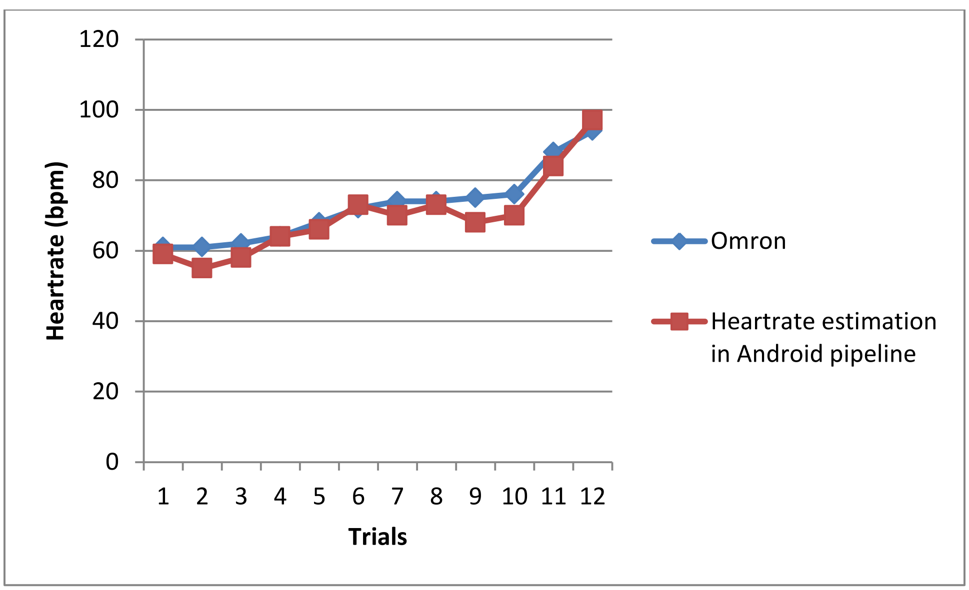

Figure 22 Android pipeline experiments over videos with 1280x720 resolution

Error RMS of 1280x720 videos is 3.9

The error RMS progressively decreases from 18.7 to 3.9 when the resolution increases from 240x180 to 1280x720. As a result, increase in the resolution of video frames improves the accuracy of heartrate estimate of Android pipeline.

Except resolution, other factors such as light condition, movement of face during the experiments might affect the performance of Android pipeline. Due to the time limit, we didn't perform experiments to explore the influence of those factors.

4.3.3 Pilot Study Analysis

We recruited 8 people to conduct a pilot study over the tele-monitoring android application. Before pilot study, each participant was required to fill out an acceptability questionnaire. Then they played with the application for two days. After that, they were asked to fill out the same acceptability questionnaire again. Figure 23 shows the responses of two questions in the questionnaire about heartrate estimation via face video. The figures on the left show the pre-study questionnaire responses while the figures on the right show the post-study questionnaire responses.

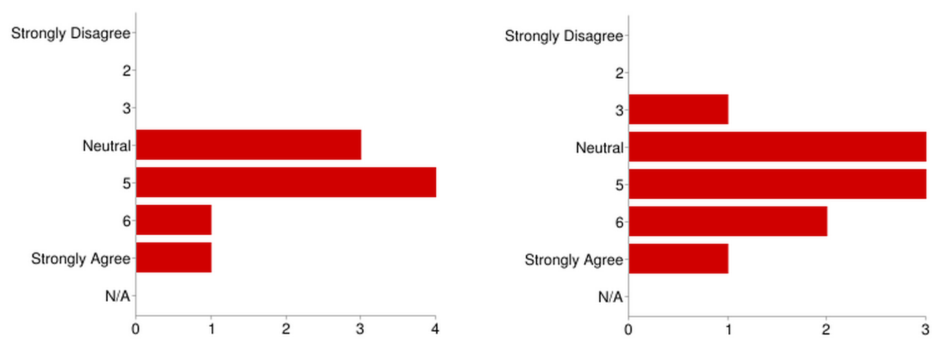

Figure 23 Question: I am comfortable using my face video to measure heart rate.

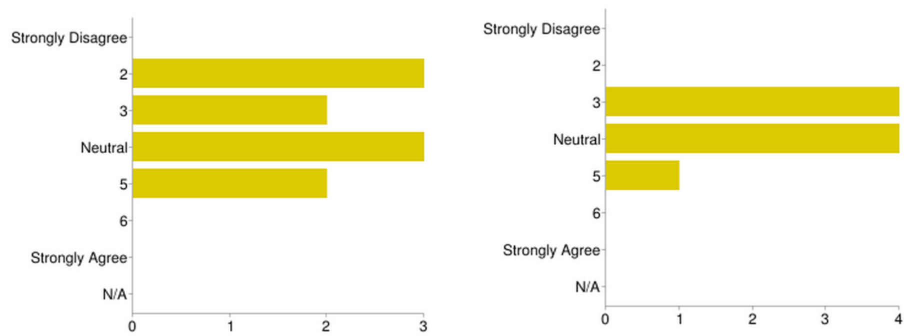

Figure 24 Question: I think measuring my heart rate through a video of my face will produce accurate results.

From figure 22, we can see that people's responses don't change much after they used the application. It indicates that their actual experiences with the face-based heartrate estimation match with their expectation. In post-study survey, we received a comment saying that the face-based heartrate estimation sometimes crashes which makes it difficult to use. Therefore, in the future, we can improve the stability of the application to increase usability. Figure 23 shows users' responses about accuracy of face-based heartrate estimation change in a positive manner, which indicates that they are more convinced that they can get accurate heartrate estimation via face-based algorithm after playing with the application.

5. Reflection

Originally, I planned to build offline pipeline in Android which takes video as input and then estimate the signal based on analysis of the video. However, things don't always go as what I planned. After I built the offline heartrate calculation pipeline in Android, I found that it took more than 30 minutes to analyze 30-second video on an Android phone. After close examination, I found face-detection for each frame of the video slows down the whole process. Then I made tradeoff between overall face-detection accuracy and processing speed. Based on the assumption that users would not change their face position a lot during video recording, I changed the pipeline to perform face-detection to update face position every other second, which greatly speed up the pipeline. After the offline pipeline implementation, advisor Daniel Aranki popped up an idea to develop an online heartrate calculation pipeline in Android, which processes the video preview frames and gives users heartrate estimation in real time. I agreed with his idea and implemented online heartrate calculation pipeline in Android with him, because I think that would not only improve the usability of the application but also further improve the performance of pipeline because the online pipeline doesn't have to write each video frame into storage which is expensive in terms of both speed and space.

With respect to insights about project management, I think communication plays a crucial role in project management. It is important to keep everyone updated with your individual progress and setbacks. In our project, every team member works on a part of the Android tele-monitoring application. In the end, we have to integrate all parts together. If others understand your individual progress, the integration process would be much easy and efficient. In addition, team members in our team have different technical backgrounds. Therefore, when you meet setbacks, your teammates may help you to resolve setbacks quickly. So I suggest each individual to have a small presentation (with slides) to report their goal of last week, what they have done, what setbacks they met, and what questions they have during weekly meeting.

For future research, I suggest to explore the possibility to speedup face detection. Currently, our pipeline performs face-detection once every other second due to the high cost of face-detection in terms of time. It would certainly improve the accuracy of heartrate estimation if the pipeline could perform face-detection for every frame in real time, because heartrate signal is so weak in the face video that any inaccurate face position might adversely affect the estimation accuracy. In addition, I suggest to explore the influence of light condition and users' skin color to the performance of the pipeline.

If someone wants to continue with my work, I suggest them to read the report first to have a general idea about two heartrate calculation pipelines. Then they should make themselves familiar with Android and MATLAB programming. After that, they could consult our advisor Daniel Aranki about the structure of our tele-monitoring application.

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