Internet of Connected Devices

Experimental Verification

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1. Items Requiring Verification

1.1. BLE Data Acquisition Android App

The primary function of the C40 project is the creation of an internet of things (IoT) network of home health devices through a central, embedded smart hub. To meet this requirement, the team must produce software to connect the test device (pulse oximeter) to the Raspberry Pi (RPi) embedded system. After many protocol challenges, the team has moved forward with deploying a tablet version of the Android operating system on the RPi and developing an app that links the devices as the Android BLE stack is tailor made for these sorts of solutions and interfacing with Android is a basic use case for many home health medical devices including our pulse oximeter.

Testing for the IoT software developed as part of the project can be organized into the following two categories: connection and data transfer protocol and the procedure for displaying the information within our app. Unit testing will be used where applicable within the software as well as field tests to verify that the connection we create between the devices is robust and the transfer of information is accurate. The storage and data display will be verified in separate testing with trial data. Experiments for proving out the software functionality can be found in section three of this document.

In addition to validating our process for transfer and display, we will also need to check our software against our requirements gathered from customer needs. The usability of the final system will be verified by trial on delivery of the prototype to our sponsor Kent Newberry at Direct Supply. Throughout the development process, we have verified that user interface needs have been met as specified in section 2. This in conjunction with getting the protype in the stakeholders hands will verify customer needs.

1.2. Embedded Hardware Components

The embedded system we have chosen for our project is the Raspberry Pi including accessories such as the power supply and touchscreen display. Health peripherals including the pulse oximeter have been supplied by Direct Supply. As such, all validation of requirements relating to hardware including our customer needs metrics in section 2 will be done based on specifications from the manufacturer as documented alongside the product. Testing of these components relating to our specific uses will be done alongside our software as mentioned above.

Supplied Hardware/Component List
Raspberry Pi
Raspberry Pi Touchscreen Interface
Raspberry Pi Power Supply
DS Pulse Ox

Table 1.2.1 - Hardware component list requiring testing

The hardware we have identified that will need to be verified is included in table 1.2.1. In accordance with our documented customer needs, each component will be verified when it is purchased to ensure it meets all previously listed requirements and that it is capable of operating within the software environment we have created.

1.3. Machine Learning Prediction

Testing the machine learning components of our project falls into several categories. Validation for machine learning can be difficult as the outcome of certain processes does not resolve to a single objective solution. The primary form of evaluation for this section of the project is demonstrating the correct application of machine learning techniques to the analysis and prediction problem our team is solving. Our goal in adding machine learning to the Internet of things portion of the project is to use data from common home care medical devices centralized in one location by our embedded collection system to make predictions about the overall health and daily changes in condition for an individual. The data we have acquired to verify our process comes from the Physionet [14] waveform database and is from a 2017 study on patterns in variability of blood oxygen saturation (SpO2) in aging populations [13]. The methods we have chosen to apply to the data include testing various decision trees and linear regression models based around the nominal and statistically generated variables from the study. We chose to use the Weka collection of tools from the University of Waikato to evaluate the data [15]. To validate our methodology and application of machine learning techniques, we have thoroughly researched various options arriving at our conclusion through input from our advisor Dr. Povinelli. With his help, we have practiced using the tools to accurately generate our machine learning models ensuring proven methodology from the start.

The secondary form of evaluation we will focus on is verifying the accuracy of the analysis performed in Weka. This will be achieved by comparing the outputs of our various decision trees and regressions with expectations created by simplified forms of statistical analysis. The predictions made by the trained software need to be accurate as people will rely on this software for detection of health complications. Once trained, the accuracy of the predictions must be matched with the specific health outcomes as they play out over time. Experimental validation will come in the form of test sets of data producing the correct predictions to a specified degree of accuracy.

Lastly, through experimentation we will evaluate our hypotheses concerning the effect of various external influences on blood oxygen variability in our data set and offer suggestions to Direct Supply regarding the inclusion and usefulness of this sort of analysis in future products. Direct Supply is particularly interested in the application of similar data gathered within the home to track wellbeing and predict factors related to health. Analysis from our study could be useful in implementing other automatic commuter learning environments in this space.

2. Quantitative Customer Needs Validation

2.1. Customer Needs Metrics

Previous C40 design teams surveyed seniors and medical professionals to specify customer needs. The results are shown in table 2.1.1. Section 2.2 explains the verification for the customer needs metrics including standards and experimentation needed as well as evaluation of hardware specific requirements.

Metrics	Units	Marginal Value	Ideal Value
Persons needed to operate	# of People	4	2
Lifespan for majority of systems	Years	1-2	4-5
Power Source	Type	Connected to outlet power source at all times	Rechargeable Batteries & Power Source
Time to setup system	Minutes	<10	<3-5

Battery life per charge	Hours	5	10
Market Cost	US Dollars	$300-$400	$150-$300
Data Storage Length	Months	1	12
Feedback Response	Type of Response	Audio/Visual	Tactile + Audio/Visual
Total device volume	Inches (HxWxD)	10x7x0.2	8x5x0.3
Component mass	Pounds	2	1

Table 2.1.1 - Customer Needs Metrics Identified

2.2. Experiments

For 1st metric, “Persons needed to operate”, the ideal situation is that one person sets up equipments, another person analysis data; for marginal solution, in details, in setting up equipments part, one person is in charge of putting Pulse Ox on for patient and explaining process, second person help sets up Raspberry Pi and the connection between devices; for analysing data, third person makes graphs based on data and presents all results to last person, forth person makes conclusion from results and explains what is going on to patient. The RPi is operable by a single user and our testing has confirmed that we meet our goal for number of system users

For 2nd metric, “Lifespan for majority of systems”, the team looked up the instruction manual for Raspberry Pi and Pulse Ox because they are the majority parts in our project. If we used them well in good condition, they can be used for around 4-5 years; otherwise, if the environment for using is bad or if there is any human factor like dropping them down on the ground, it will shorten the lifespan. Ideal situation is that used them in the room, temperature and humidity are good for system; marginal situation is that used them outside, environmental elements influence the whole systems; factitious elements also influence like dropping down the pulse Ox or punch the touch screen of Raspberry Pi by accident.

For 3rd metric, “Power Source”, the team tried to buy an extra battery to support outdoor activities; however, it is not the main issue for the project and there is no proper extra battery to support the Raspberry Pi, the team determined to continue to use the charger. Ideal situation is that set up an extra battery behind the device then we can use the Raspberry Pi without charger; marginal here is that there is no proper extra battery can supply stable and powerful electricity that is why we chose to use charger only.

For 4th metric, “Time to setup system”, the team first calculated the time to setup the RPi system running our bluetooth app. Before the experiment, the team separated the Raspberry Pi and pulse Ox into different boxes. Then the team started a timer while assembling the system. After the system is ready to use, the team begin to open the application and set up the connection. Total time for this condition will be around 10 minutes. The team calculated the time for ideal condition secondly. Here, Raspberry Pi and pulse Ox are placed together and we only need to wake up the system and the application. It is much quicker and only takes around 5 minutes. Ideal situation keeps the device in sleep mode after use every time then we can wake up quickly and there is no need to shut off the bluetooth function in Raspberry Pi also place pulse Ox and Raspberry Pi together. The marginal situation is that need to wait for system start every time after we shut down whole system (main reason for waiting) and need to open the bluetooth function; need to cost more time to find pulse Ox and Raspberry Pi if we place them separately.

For 5th metric, “Battery life per charge”, the team changed Raspberry Pi into two different battery modes and run them until the battery dies. In “battery save” mode, it lasts much longer time than “best performance” mode. The elements different in two modes are like brightness of the screen, volume. Ideal situation is that we use the Raspberry Pi in battery save mode. Marginal situation is that we use the Raspberry Pi in best performance mode.

For 6th metric, “Market Cost”, the team searched the price for Raspberry Pi and pulse Ox. We have selected componentry within the specified range of $150-$300 only to meet this requirement.

For 7th metric, “Data Storage Length”, the team chose the size of the SD card based on the OS images and data. Ideal situation here is that we will delete part of previous data (like 1 month before) and only keep critical data in period; marginal situation is that we save all of the data including graphs. The system is capable of holding all relevant information from the critical period using the 16GB SD card we purchased.

For 8th metric, “Feedback Response”, the team used the tactile to simulate the pulse. It is much clearer to feel with tactile than only with visual data. Ideal situation here is sending feedback through tactile then we can know the results more clearly like how pulse feels like; marginal situation is that audio and visual are limited in some way.

For 9th metric, “Total device volume”, the team measured the size of raspberry Pi and pulse Ox themselves. The size of each is convenient to carry with. However, with the cases for Raspberry Pi and pulse Ox, keyboard and wireless mouse, it gains more volume. Ideal situation is smaller volume making whole system easy to carry out and only Raspberry Pi and Pulse Ox are enough to use. Marginal situation is for Larger volume because of case, keyboard or wireless mouse for raspberry Pi which leads they are not convenient for outside use.

For 10th metric, “Component mass”, the team measured the weight of raspberry Pi and pulse Ox themselves. The weight of each is convenient to carry with. However, with the cases for Raspberry Pi and pulse Ox, keyboard and wireless mouse, it gains more weights. Ideal situation is that lighter mass makes whole system easy to carry out and only Raspberry Pi and Pulse Ox are enough. Marginal situation is for heavier mass because of case, keyboard or wireless mouse for raspberry Pi which causes they are not convenient for outside use.

3. Experiment Manifest and Description

3.1. BLE Connection Verification

The purpose of this experiment is to demonstrate that we can successfully make a connection between the peripheral device and our smart hub on a regular and consistent basis. We conducted the following experiment off the RPi using an Android phone.

Experimental Procedure	1. Start Up C40 Health App on Raspberry Pi 3 Hardware 2. Begin Connection Procedure 3. Observe Connection between Pulse Oximeter and C40 4. Close and reopen app 5. Observe if connection is maintained 6. Repeat steps 1-5 with C40 app running on Android Phone
Equipment	1 - Pulse Oximeter 1 - Android Phone 1 - Raspberry Pi Running Android
Results	We were able to verify that a connection is made and maintained consistently. On occasion the pulse ox is not displayed under the list of available devices. Currently this problem has not been reproducible and we are looking into solving it.

Conclusion	Our team found that the Bluetooth Low Energy connection is created with a level of regularity to make us believe that a non-connection is an anomaly.

Table 3.1.1 - Connection Verification Experiment

3.2. Data Transfer Accuracy Validation

We theorize that by examining the data outputs of two separate pulse oximeters we'll be able to see whether or not our data collection has an acceptable level of precision.

Experimental Procedure	1. Start Up C40 Health App on Raspberry Pi 3 2. Attach Pulse Oximeter to user and start device 3. Pair the device with Health App 4. Observe if values shown on app are consistent with the physical device
Equipment	2 - Pulse Oximeters, 1 - Raspberry Pi Running Android
Results	All data points shown on our app are consistent with what the physical device is reporting. There was not a single faulty data point in our testing.
Conclusion	The C40 health app currently correctly interprets information it receives from the Pulse Oximeter. Both pulse oximeters showed the same values after a small amount of time, showing that they are precise. No change is needed to the app.

Table 3.2.1 - Data Transfer Accuracy Experiment

3.3. Visualization Verification

This experiment will verify that our app creates accurate graphs and visualization, and that these are readable by the user.

Experimental Procedure	1. Start up C40 Health App on Raspberry Pi 3 2. Attach Pulse Oximeter to user and start device 3. Collect data from pulse oximeter 4. Use app to create visualization 5. Determine whether the visualization accurate represents our data points 6. Show visualizations to third party to gauge readability
Equipment	1- Pulse Oximeter 1 - Raspberry Pi Running Android

Results	This test has not yet been performed as we are still currently implementing visualizations to our application.
Conclusion	Depending on the results, this test will determine what changes we make to our data visualization.

Table 3.3.1 - Visualization Verification

4. Experimental Results

4.1. BLE Data Acquisition Android App

Constraints with the distribution of Android we are running on the RPi have limited full system testing. We have however emulated the app on a phone running Android as a proof of concept for the integral parts of the bluetooth functionality. The particular section we have worked hard to verify through experimentation is the cryptographic check portion of the protocol. The code provided by Onkol creates the basis for us moving forward with writing our own implementation of the protocol drawing heavily from libraries they created that automatically poll the pulse oximeter for specific hardware information necessary to the cryptographic check including the serial number. Similarly, we have referenced Onkol's implementation of the BLE stack which uses event handlers to capture and maintain pairing between the devices.The experiments listed in the manifest in section 3 demonstrate our success in connecting the devices and implementing the the communication protocol defined for the pulse oximeter. Using this prototype app, we have met the requirements for establishing and maintaining a connection. Using this connection, we have transferred real time pulse oximetry accurately. This demonstrates a successful proof of concept.

4.2. Weka Analysis

A statistical analysis on the raw pulse oximeter data from the Physionet database showed small correlations between the study attributes and the variance in the blood oxygen data. Table 4.2.1 shows the relevant relationships between variance and study attributes. Prior smoking status had the greatest influence on the overall variance despite discrepancy in smoking history representing a very small portion of the data. We chose to focus on predicting smoking expecting the best possible results.

Attribute	**Variance Correlation**
Gender	-0.108
Smoking Status	0.314116
BMI	0.185245
Age	0.236607

Table 4.2.1 - Statistical analysis of Oxygen Variability Physionet Study [13]

From this information several analysis were performed using Weka. The two most relevant machine learning tests conducted include a J48 decision tree will all study attributes being used to predict smoking history and a simple linear regression predicting BMI based on variance. The results are shown below.

```
=== Stratified cross-validation ===
=== Summary ===

Correctly Classified Instances          26               72.2222 %
Incorrectly Classified Instances        10               27.7778 %
Kappa statistic                          0.0649
Mean absolute error                      0.1864
Root mean squared error                  0.3519
Relative absolute error                 88.6063 %
Root relative squared error            112.7578 %
Total Number of Instances               36
```

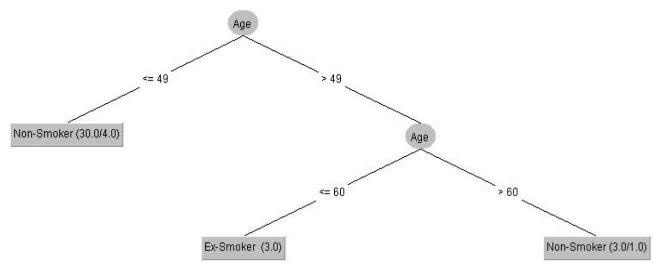

Figure 4.2.1 - J48 Decision tree predicting smoking using all attributes (tree created with age)

Figure 4.2.1 shows the major problem with the Physionet data set. When asked to create a decision tree for the smoking characteristic based on the other attributes including the desired variance attribute, the tree that provided the most accuracy was created using age and still featured 27% error. This is level of prediction is not accurate enough to meet the prediction requirements and while the correlation between age and previous smoking status is interesting, it does not provide any useful aid in predicting current patient conditions as part of our project. For this reason, this tree will be removed from further analysis.

=== Cross-validation ===
=== Summary ===

Correlation coefficient	-0.0363
Mean absolute error	2.3478
Root mean squared error	2.8105
Relative absolute error	101.722 %
Root relative squared error	100.2935 %
Total Number of Instances	36

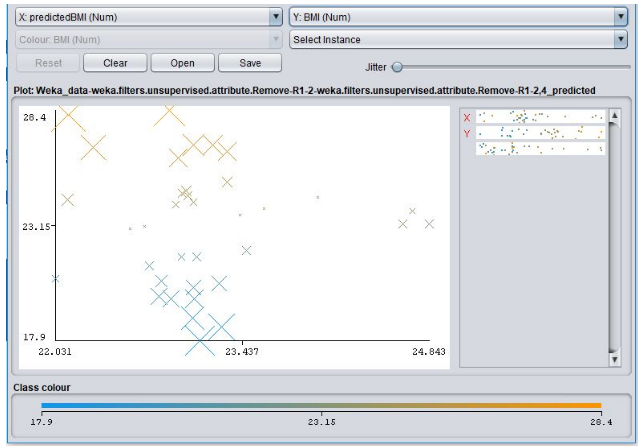

Figure 4.2.2 - Analysis results for simple linear regression predicting BMI with variance

Similarly, we had challenges when predicting other attributes of the data such as BMI. Figure 4.2.2 shows the results from a linear regression analysis predicting BMI using only the variance of SpO2 readings. Outliers within the data set resulted in a few wildly inaccurate predictions with most falling relatively close to their expected range, though nowhere close to the accuracy necessary to make determinations on personal health. A conclusion of the study cited was that resting SpO2 varies across other more immediate factors. Again, using only data from healthy participants held us back from seeing abnormal readings that would make prediction easier.

5. Experimental Conclusion

5.1. Performance Claims

Our hub device will be able to make a consistent and stable connection to the pulse oximeter peripheral over the BLE protocol. The pulse oximeter makes stable connections over BLE with our Android software in independent tests on a seperate phone. The next step in prototyping our smart hub is to load the app onto the RPi and complete testing on this system. Through our tests we’ve been able to find that our pulse oximeters measure pulse and blood oxygen with consistent results. The device will create visualizations of pulse and blood oxygen data over time, and this feature will be implemented soon. The visualizations will need to be effective in portraying the data that the device has collected.

5.2. BLE Android App Project Recommendations

Our tests demonstrated that the basic functionality of the app is working as intended. Improvements are going to be made to streamline the experience for consumers. We need to have the connection work as close to 100% of the time as possible, and ideally automatically connect the device after it is paired. This is essential for our older consumers to use our device effectively. Having the required features implemented flawlessly will allow us to add extra components to further improve the app in the future.

5.3. Machine Learning Project Recommendations

Based on our work with the pulse oximeter data, we have concluded that blood oxygen is incredibly static across healthy adult individuals staying between 96-99%. Going forward with the project, we will need to expand the data set we are working with as 36 individuals is to small a study to draw effective conclusions. In many cases the data is to individualized to give the level of accuracy in predictions we need to move forward in predicting symptoms. The attributes in the study are not strongly correlated to SpO2 readings to categorize cases with which to train the learning algorithm. To improve the study we will need to increase the scope of our data to include other useful tags particularly sickness where the variation in SpO2 should be higher than in healthy people.Moving forward with the machine learning portion, we are looking to expand our research to include another study relevant to the home health space.

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