Remote, Real-Time Monitoring and Analysis of Vital Signs of Neonatal Graduate Infants

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Abstract— **This paper presents a system for the remote monitoring of a newborn infant's physiological data outside the Neonatal Intensive Care Unit. By providing a simple means for parents to enable monitoring, and physicians a simple mobile application to monitor live and historical physiological information, this system provides the insight once only possible in an Intensive Care Unit. The system utilizes a variety of connectivity means such as Wi-Fi and 3G to facilitate the communication between a multitude of industry standard vital sign monitor and a remote server. A system trial monitoring an infant to simulate neonatal graduate monitoring has determined the system was able to successfully transmit 99.99% of data generated from the vital sign monitor.**

Keywords— **Remote Patient Monitoring, Telemedicine, Neonatal Intensive Care, NICU, Pediatric Intensive Care, PICU, Artemis, Physiological Monitoring, Vital Signs**

I. INTRODUCTION

Within the hospitalized population of newborn infants, there is a number that could be discharged earlier if there was a system in place that would allow for continuous monitoring of their vital signs by hospital staff from home. At present the only places where this level of continuous monitoring can occur is within pediatric step down units, Pediatric Intensive Care Unit (PICU) and the Neonatal Intensive Care Unit (NICU). This limited area where monitoring can occur leads to the utilization of beds for monitoring purposes and not exclusively for active treatment.

In recent years, there has been substantial research completed in the area of telemedicine or remote monitoring. However, these systems are primarily designed for those with chronic illness or the elderly and not the newborn or neonatal population[1]. With such specific systems, it is also commonplace for them to be designed specifically for monitoring particular vitals signs, and providing limited to no functionality beyond that. There are a few examples [2], [3] where some level of automated condition detection is implemented, but it is limited to target value or high-low tracking.

A common point of failure for many remote monitoring systems is connectivity. In many systems, this is the leading cause of system failure or instability [4], [5]. It is also found that with many of these systems, solutions to these connectivity problems are not proposed and generally involve assigning blame to the carriers [4].

With the advent of systems such as Artemis, a platform for real-time temporal analysis of vital signs[6], [7], it has become increasing apparent that the wealth of data generated by various physiological monitors can provide more than just visualization of univariant displays of physiological data such as heart rate and respiration rate to support immediate vital organ management. However the focus of Artemis to date has been the provision of a solution within the hospital setting. In this work we have leveraged this technology to create a system, known as Apollo, that allows for real-time, continuous remote monitoring of newborn babies outside the hospital and NICU/PICU setting. By utilizing the Artemis technology, the system provides the ability to mine the collected data to provide automated condition detection. With this capability, the Apollo system could allow for remote patient consultation. With conditions such as Supraventricular Tachycardia (SVT), physical symptoms are often unclear. Having access to an ECG waveform provides a clear indication of this condition and could provide a cardiologist with the information required to make a diagnosis. Beyond exclusively collecting data from a remote patient, the system also provides a mobile-device application for a physician or healthcare professional to monitor the current and historical data collected from the patient.

The overarching goal of this research is provide a system for real-time physiological monitoring for newborn babies outside the NICU/PICU setting that provides real clinical benefit. The two key benefits of this work are its ability to account for periodic failures in connectivity, and provide output to an analytics platform for future clinical insight. The resulting architecture presented will form the basis for future research in this domain.

II. FUNCTIONAL REQUIREMENTS

Based on consultations with Neonatologists and other stakeholders, requirements were synthesized as follows:

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1. A standard, commercially available vital sign monitor must be utilized.
2. Single value, and waveform physiological data must be collected.
3. Data must be collected and stored remotely at a reliability rate of 95%
4. Remote system must have a battery backup that should last more than 2 hours.
5. The Mobile Application and Remote system must communicate with Artemis in a secure manner.
6. A patient monitoring application must be build and be implemented on a variety of mobile-device platforms.
7. The patient monitoring application must display current vital sign information as well as historical values and trends.
8. The system must provide data to Artemis for real-time analysis, data mining, and data storage.

III. DESIGN OVERVIEW

In Figure 1, the overall structure of the system is illustrated as well as the basic component interactions. The architectural components illustrated are: Remote Client, Remote Client Server, Mobile Application, and Mobile Application Server. The Remote Client application provides the communication layer between the remote vital sign monitor, and the Artemis system. The Remote Client Server handles the Remote Client connections and passes that through to the Artemis sub-system. The Mobile Application server handles requests from the Mobile Application and obtains and transmits the requested data. The Mobile Application receives this data and provides a visualized output.

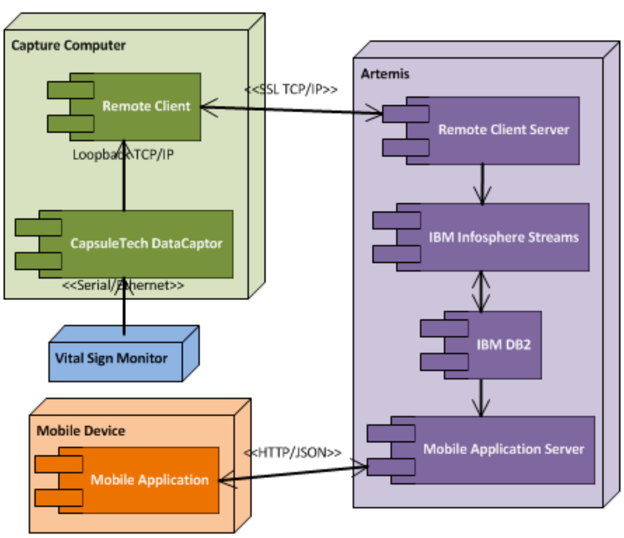

Figure 1. *System Structure*

IV. PROTOTYPE IMPLEMENTATION

Based upon the design presented, a prototype has been implemented. The goal of this prototype is to provide a proof-of-concept system to be evaluated for both system performance and clinical relevance. In the following sections, the prototype design is presented based on the four major design components: Remote Client, Remote Client Server, Mobile Application, and Mobile Application Server.

A. Remote Client

Hosted on a capture computer (Atom PC), this application utilizes CapsuleTech DataCaptor as a middleware to read monitor data, translates it into an Artemis-compatible protocol, and transmits it. All transmission of data is done via an SSL-encrypted TCP connection between the Client and Server. This connection is established via Ethernet, Wi-Fi, or 3G. The system utilizes network latency calculations to determine the fastest Internet connection at a given time and connects to the server based on the lowest value. If at any point latency surpasses 2 seconds, the connection is considered down and any connections are re-established on another.

Connections to various different monitors can be made over Serial (RS-232 / RS 422), or Ethernet. The capture computer handles these connections and provides a platform for the DataCaptor data collection software as well as our Remote Client software. The DataCaptor software provides an XML output. In the Remote Client software, this XML is transformed into a more streamlined format for better data transmission.

To meet our requirement of having a battery backup, the system was able to run on a Tekkeon MP3450 R3 Lithium-ion battery pack in a 116 Watt/hour configuration. The capture computer, a small Intel Atom-based was selected for its 8-Watt peak power consumption. By combining the two systems, a theoretical runtime of 14.5 hours could be achieved.

Figure 2 provides an overview of the system form factor.

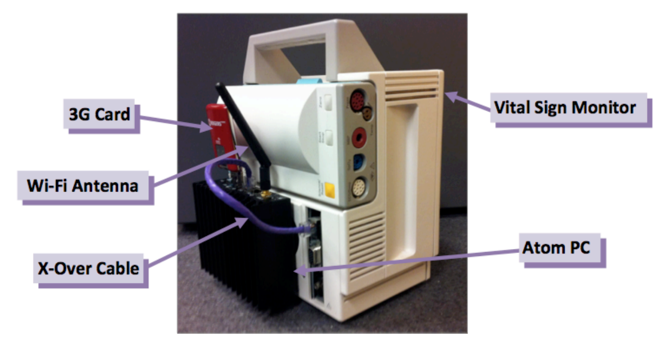

Figure 2. *Remote Client System Form Factor*

B. Remote Client Server

Managing the connections from various clients, the remote client server feeds data into Artemis. This component handles the failing over between multiple Internet connections and ensures seamless data transmission and recording. The software provided data feeds to a variety of different sources to support future expansion to various real-time analytics, monitoring, and visualization software.

Both the Remote Client Server and Remote Client and been implemented in Java to ensure interoperability with the other components and different platforms within Artemis.

C. Mobile Application

The mobile application component provides mobile access to raw physiological data together with derived temporal abstractions as they relate to certain condition onset behaviors. This system presently provides historical averaging aggregations, but could be tailored for use by parents/caregivers as well as supporting specialists.

Data for the application is retrieved in the JSON (JavaScript Object Notation) format from the mobile application server over a SSL HTTP connection.

Figure 3. *Real-Time View of Current Vital Signs*

In Figure 3, vital sign information is retrieved every second from the application server. It is then rendered and displayed. Each vital sign can be clicked and historical trends displayed.

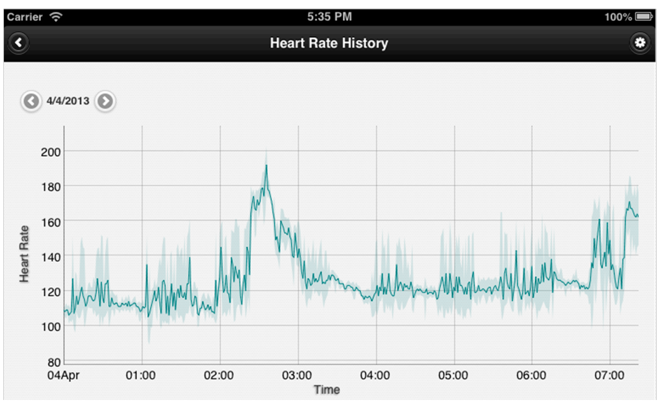

Figure 4. *Historical Trend View of Heart Rate*

Figure 4 illustrates the historical trends for a patient's heart rate. The bold line represents the one-minute average that is aggregated from one-second values recorded. The shaded line surround the line shows the variance (Max / Min of each minute aggregation) within each aggregation, demonstrating a form of abstraction that can be performed on the data and displayed. Other example analytics for detection of late onset neonatal sepsis and spells are in [8], [9], [10], [11].

The Mobile Application is written in HTML5 and JavaScript and utilizes AJAX requests for retrieving data from the Mobile Application Server. The system was developed using JQuery and JQuery Mobile. The application was built using PhoneGap to provide native application wrappers for both iOS and Blackberry OS.

D. Mobile Application Server

The mobile application server is responsible for the secure delivery of physiological information from Artemis to the mobile application. Data residing in an IBM DB2 database is retrieved based on the requests from the mobile application and served in JSON format from each AJAX request.

The application utilizes an Apache-based web server as a host and has been implemented using PHP5. To improve the application performance, and decrease database load for commonly requested data, a Memcached server was implemented to provide an in-memory cache. This increased performance and provided a high level of scalability.

V. Results and Discussion

Initial testing was performed utilizing patient emulator data within a controlled setting to focus on network traffic and potential failure and bottleneck points. It was found however that the extreme verbosity of the XML data exchange format resulted in a large data bottleneck in data transmission between the remote client and server. This resulted in the inability to transmit all waveforms (Respiratory Impedance at 65.8Hz, and ECG at 1024Hz) simultaneously from our Philips Intelivue MP50 test monitor. During this testing process a total of 168 hours of data were recorded and a very high level of data transmission reliability was experienced.

Further testing of connectivity fail-over was carried out as part of system verification testing. The system was given 10 seconds to determine the failure, and reconnect via the next available link. If multiple were found, the next connection with lowest latency was used. A total of 9 connectivity failure conditions including:

1. All three connectivity means connected, disconnect active and monitor failover to the least latent backup connection (6 Conditions).
2. Two connectivity means connected, disconnect active and monitor failover to the standby (6 Conditions).
3. Single connectivity means connected, disconnect and reconnect 2 minutes later. Monitor for transmission of missed data, and present data (3 Conditions).

These tests demonstrated Apollo operated as designed. Fail-overs occurred at all instances in less than 10 seconds.

Hardware system verification was carried out to test the battery life requirement of a minimum of two hours, a two-trial test was conducted. For this test, data was captured from a Philips M4 monitor while the system was not connected to an outlet. Over the two trials, the battery life averaged 14.1 hours. This surpassed our requirement, but fell short of our theoretical run time of 14.5 hours.

In this paper we report results from an initial real-world case study that was completed over the course of a 3-night field study with a newborn infant. During this study, numeric vital sign information was transmitted. Parents were responsible for hooking their child up to the monitor each night and enabling the data capture. This was part of a research study approved by the University of Ontario Institute of Technology Research Ethics Board. Table I presents the test results from this study. Overall results from this study yielded a successful transmission and recording rate of 99.99%. Though the system displays a very good result from a technical aspect, the system was found to be slightly cumbersome in the method connecting to the capture computer to enable data capture. Initial connection to the capture computer was completed through Remote Desktop software on the parent's computer. This process often took upwards of 5 minutes complete, and represents an area for future optimization.

TABLE I. ACCEPTANCE TEST RESULTS

Test	System Testing	Field Study	Field Study
Connection Type	Wi-Fi	Wi Fi	3G
Hours of Data	168	16 (2 Nights)	9 (1 Night)
Data Loss	**0.01%**	**0.0%**	**0.0%**

VI. FUTURE WORK

Though the system presented has demonstrated a high level of success, there remains much work to improve the system and further its development.

A primary stumbling block during development was the extreme verbosity of the XML format utilized. To mitigate this problem, a compression system such as EXI [12], could be implemented. There are many such examples which have demonstrated good compression ratios and could provide a viable solution [13]. Alternately, an alternative protocol could be developed that is more lightweight.

One of the key focuses of this system was its integration with Artemis. Future work to enable the visualization of Artemis temporal abstractions on the mobile device as performed in real-time by the Artemis framework will allow for real-time monitoring of patients and provide more analytics. This output can be rendered in a thoughtful way, and provide the unique ability for the system to provide more insightful alerts to both clinician's and patients.

VII. CONCLUSION

In this paper, a system for remote monitoring physiological data from newborn babies has been presented. The system consists of a capture device, which streams data remotely to be recorded, and a mobile application to view current and historical physiological data. By leveraging multiple connectivity means, the system demonstrated a high level of quality and reliability throughout the various stages of testing. The system utilizes Artemis for data recording and interpretation. Future implementation of specific algorithms and visualizations will provide a degree and variety of clinical insight not previously available. This study demonstrates a viable alternative to enable remote patient care for the newborn, neonatal graduate population.

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