A Web-Based System for Home Monitoring of Patients with Parkinson's Disease Using Wearable Sensors

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***Abstract*— The paper introduces MercuryLive, a platform to enable home monitoring of patients with Parkinson's disease (PD) using wearable sensors. MercuryLive contains three tiers: a resource-aware data collection engine that relies upon wearable sensors, web services for live streaming and storage of sensor data, and a web-based GUI client with video conferencing capability. Besides, the platform has the capability of analyzing sensor (i.e. accelerometer) data to reliably estimate clinical scores capturing the severity of tremor, bradykinesia, and dyskinesia. Testing results showed an average data latency of less than 400 ms, video latency of about 200 ms and video frame rate of about 13 fps when 800 kbps of bandwidth were available and we used a 40% video compression, and data feature upload requiring 1 min of extra time following a 10 min interactive session. These results indicate that the proposed platform is suitable to monitor patients with PD to facilitate the titration of medications in the late stages of the disease.**

***Index Terms*—Wearable Sensors, Body Sensor Network, Parkinson's disease, Home Monitoring, Telemedicine**

I. Introduction

PARKINSON'S disease (PD) affects more than 500,000 US residents. The main motor features of PD are tremor, bradykinesia, rigidity, and impairment of postural balance [1]. Current therapies are effective in managing Parkinsonian symptoms in the early stages of the disease. However, in late stage PD, patients develop motor complications, namely the abrupt loss of the efficacy of medications at the end of a dosing interval and involuntary hyperkinetic movements referred to as dyskinesia [2]. Monitoring changes in the severity of symptoms and motor complications (referred to as motor fluctuations) could facilitate the titration of medications, an aspect of the clinical management of patients with PD that becomes challenging as the disease progresses.

In clinical practice, information about the severity of motor fluctuations is obtained via self reports and diaries. These methods are subject to perceptual and recall bias. Direct observation by a PD specialist is impractical because motor fluctuations cover the time span of several hours between medication dosages. Wearable systems have the potential to provide a tool to address the shortcomings of existing approaches. Wearable systems have been used to gather data from a variety of different patient populations [3]. Our team and others [4-7] have shown that wearable units equipped with accelerometers can be used to track the severity of symptoms and motor complications in patients with PD.

The translation of these experimental results into clinical practice requires 1) the development of a system with wearable sensors that allow one to carefully manage resources such as battery life and processing power to achieve monitoring over several days and 2) the implementation of a web application to provide remote access to data collected using the wearable units. Recent research has shown that, by carefully managing system resources dynamically, wearable wireless units can collect data for several days without recharging their batteries [8-9]. However, wearable sensors with such capability have never been combined before with software to remotely control the collection of data.

In this manuscript, we present a system called MercuryLive that provides an integrated platform to enable access to data gathered using wearable sensors via a web application. The system provides clinicians with a means to interact remotely with patients in the home setting, to configure the sensor nodes for the application at hand, and to record annotated data. We are currently deploying the system. In the paper, we present preliminary data suggesting that MercuryLive is suitable for use in clinical practice. Collecting data in the home setting using MercuryLive would allow clinicians to improve quality of care and reduce its costs in patients with PD.

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II. System Description

Figure 1 shows the general architecture of MercuryLive. The platform includes software services running at three tiers: central server, patient's hosts, and clinician's hosts. In the following, we describe the services implemented at each tier.

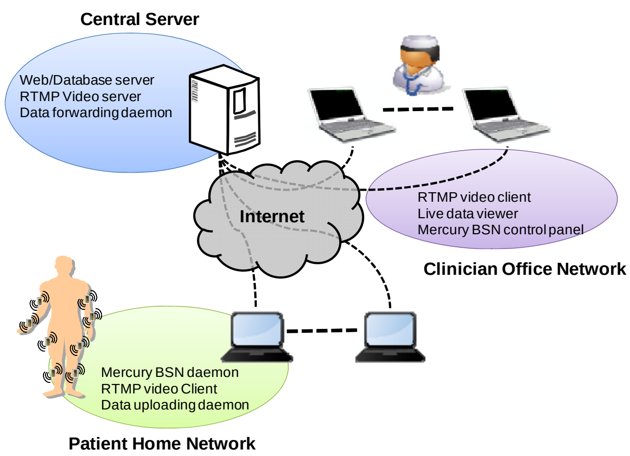

Fig. 1. A schematic representation of the MercuryLive system architecture.

A. Central Server

A central portal server provides a secure central location for coordinating data collection and video conferencing services. The portal server resides in a secure healthcare provider data center and allows access only over securely encrypted services, including SSL, SSH, and VPN. Using secure channels, both patients' and clinicians' software clients cab access the database, web server, video conferencing service and a live data forwarding service to perform background data logging and live interactive sessions.

Three network services run on the central server. The web/database server provides data storage and access control to the patient data. A live video streaming service, provided by open source Red5 server, runs on the central server. A third daemon that runs on the central server is a live data forwarding daemon. This daemon forwards a decimated version of a patient's live data stream to the clinician's web GUI.

B. Patient's Host

The patient's host runs Mercury, a body sensor network (BSN) platform developed by our team [8] that is based on the SHIMMER sensor [10]. Mercury provides clinicians with the ability to adjust remotely different parameters of the sensor nodes (e.g. number of recorded sensor channels, sampling rate, and data features estimated on the node). Clinicians can set a desired battery life and Mercury adjusts how system resources are used to achieve the target battery life. This requires tuning sensor operations based on power consumption. As sensor data is being collected, a data uploading daemon runs in the background to connect to the central server and upload sensor data opportunistically. A web-based Flash video conferencing client running on the patient's host provides live video interaction features. During an active video session, the Mercury sensor network streams decimated raw signals through the live data forwarding services at the central server.

We implemented several techniques to improve the robustness of Mercury and prevent data loss. First, the firmware running on the SHIMMER sensors periodically stores checkpoint states to a specific sector of the Flash storage. When the sensors encounter software errors that crash the firmware, a watchdog timer will reboot the node. Once the node boots up, the firmware loads the previously stored checkpoint information from the Flash and resumes data collection. Data during the rebooting process is lost. When such failure happens, a SHIMMER sensor can recover within 10 s. The data uploading daemon may encounter loss of Internet connection to the central server. When that happens, the data uploading daemon will attempt to reconnect to the server periodically. Such a connection problem will delay the data uploading to the database but will not cause data loss.

C. Clinician's Host

Besides collecting, storing and securely providing patient data, our system also supports live video communication capability between clinicians and patients. Using the video interaction feature, clinicians can remotely conduct supervised data collection sessions. Clinicians can access the patient data and choose to speak to patients using the video conferencing service if needed. Figure 2 shows the web-based GUI for clinicians to conduct supervised data collection sessions and view data in real-time. To provide a user-friendly interface, we implemented a cross platform web-application which runs as a Flash plug-in. This application contains a GUI to display live decimated accelerometer data alongside the video session to allow clinicians to perform spot checks. Clinicians can also annotate events using integrated annotation tools. Finally, using MercuryLive, clinicians can access and download data.

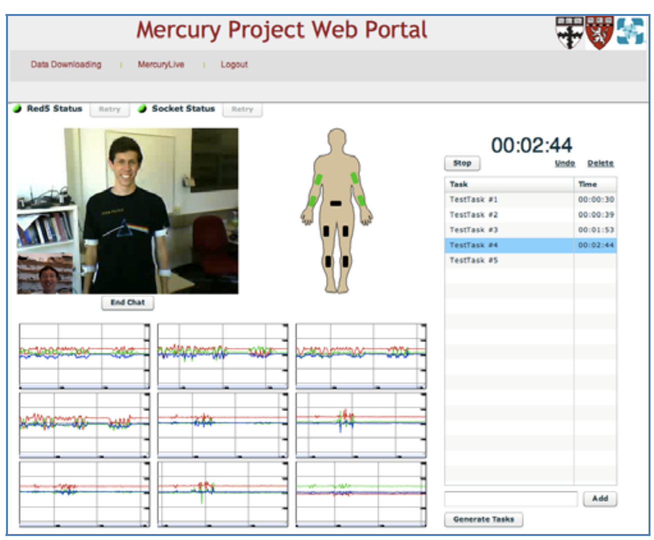

Fig. 2. A screenshot of the MercuryLive GUI as seen by the clinician.

III. System Characterization

A. Command Latency

Command latency is the time between when a command is issued on the clinician's host and when it is received and acknowledged at the patient's host. Commands are issued by the clinician's host to reconfigure the BSN (e.g. change in data sampling rate). Three services contribute to the total command latency value: the clinician's GUI, the data forwarding daemon, and the Mercury BSN daemon. Simulations were performed to quantify the command latencies introduced by each service. A latency of approximately 620 ± 240 ms was introduced by the Mercury BSN daemon, whereas latencies lower than 10 ± 5 ms were introduced by the clinician's GUI and the data forwarding daemon. It is worth emphasizing that the Mercury BSN daemon needs to communicate with each sensor node, execute the command, and send back an acknowledgment. The Mercury BSN daemon latency was derived for a system with 9 sensor nodes. In a clinical scenario, we anticipate that fewer sensor nodes would be needed and thus the latency would be lower.

TABLE I
MercuryLive Video Latency

Latency (ms) Frame Rate (fps)		**Video Compression**		
		80%	**40%**	**none**
Available Bandwidth (kbps)	**80**	2098 ± 788 4.7 ± 2.1	2930 ± 795 3.3 ± 1.6	4709 ± 3494 1.1 ± 0.4
	800	235 ± 30 13.2 ± 1.0	209 ± 22 13.5 ± 1.1	556 ± 211 3.2 ± 0.9
	Unlimited	229 ± 27 13.1 ± 0.9	225 ± 33 13.3 ± 1.1	511 ± 68 3.0 ± 0.6

B. Data and Video Latency

Data latency is the delay in the live streaming of the decimated version (from 100 Hz to 10 Hz) of the sensor data. Estimates derived over a 10 min period (with 9 sensor nodes) showed a data latency of 373 ± 182 ms/packet (30 samples/packet). The latency time was estimated as the time between when a sensor sends a packet to the time when the packet is received by the clinician's host for display. Fewer sensors would lead to a reduction in back-off times, which would result in a lower latency value. Back-off time is the time a sensor waits before sending a packet if a collision occurs.

Video latency is the time between when a frame is generated at the patient's end and when it appears at the clinician's end. We measured the video latency of our system using vDelay [11]. vDelay is based on transmitting EAN-8 barcodes with an embedded timestamp. At the receiving end, the timestamp is decoded and compared with the local clock. To test the effect of different bandwidth conditions, we used Traffic Shaper XP [12]. The software was used to determine how video latency and frame rate are affected by bandwidth conditions. We simulated different video compression values.

Table 1 summarizes the results of our simulations. As the video compression increased, the video latency time decreased and the frame rate increased. A simulated available bandwidth of 800 kbps with a 40% video compression level provided acceptable latency values and frame rates. This result indicates that any home broadband Internet service with 1 Mbps two-way bandwidth can easily support MercuryLive. It is worth emphasizing that bandwidth requirements for transmitting the decimated version of the sensor data (4 kbps), raw data sampled at 100 Hz (43 kbps), and data features derived from 5 s segments of accelerometer data [7] (1 kbps) are all negligible compared to the bandwidth requirement associated with video conferencing.

C. System Recovery Latency

System recovery latency is the time required by the system to start functioning again after a system failure. With our current implementation, if a failure causes a sensor to reboot, the recovery time for its live data stream is about 13 s and the maximum full resolution data loss is about 63 s. Live data stream recovery is required when there is a network connection problem from the data uploading daemon to the data forwarding daemon on the central server. Factors that influence live stream recovery time are: real-time sample refresh period (10 s), watchdog timer (which checks for system failures every 1 s) and firmware boot delay (2 s). Maximum data loss (63 s) is determined by watchdog timer (1 s), firmware reboot (2 s), and a checkpoint mechanism that stores information such as amount of samples on flash and the battery charge. This mechanism is set to run every 60 s. After an Internet connection failure on the patient's host, the live stream will resume in about 1 s (after Internet connection is re-established) as the auto-reconnect timer is set to 1 s.

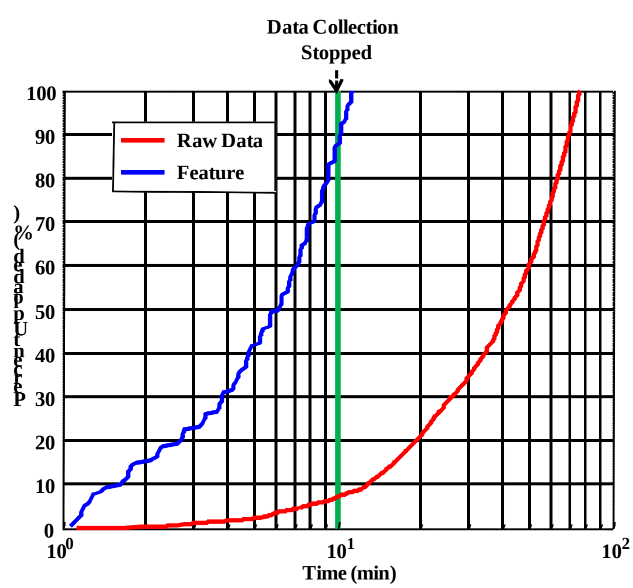

Fig. 3. A plot of the time required to upload 10 min worth of full resolution data (red) at 100 Hz and related features (blue) for 9 sensor nodes each sampling 3 axes of accelerometer data.

D. Data Upload Latency

MercuryLive opportunistically uploads data from the sensor nodes to a database hosted at the central server. Due to bandwidth and battery life limitations, MercuryLive does not provide real-time access to the full resolution data. Instead, raw data and/or data features are logged to the onboard flash memory and uploaded to the central server when possible. Figure 3 shows the background uploading service progress over time during and after a 10 min interactive session. In this experiment, the full-resolution data is available on the MercuryLive portal about 80 min after the interactive session ends. Data features are available within 1 min from the end of the data collection. These numbers are for 9 active sensor nodes, with each node sampling 3 accelerometer channels at 100 Hz.

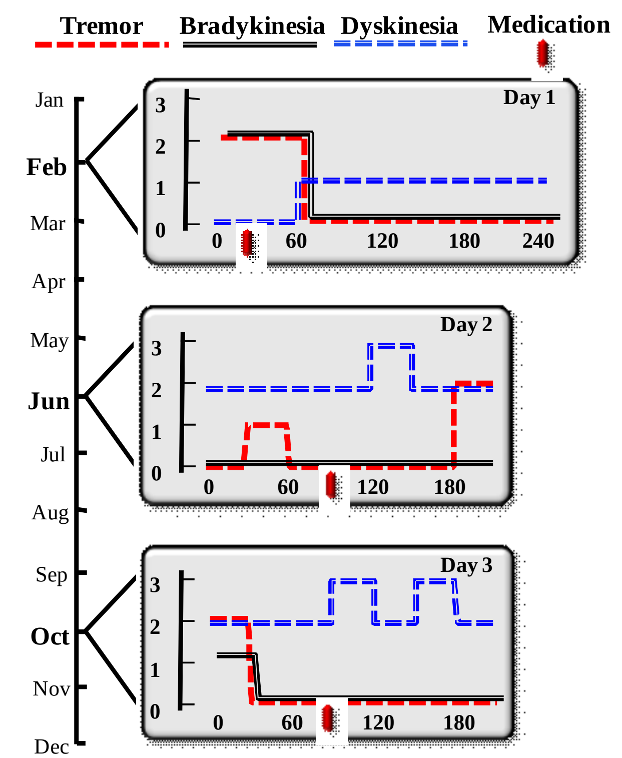

Fig. 4. A representation of clinical scores to be provided to clinicians at the end of the monitoring period.

IV. Preliminary Deployment

MercuryLive is currently undergoing testing in patients with PD in the home setting. During the tests, we are placing sensors on the patient and we are giving them a laptop (patient host) with a webcam to interact with a clinician who monitors the patient from a clinical site. The clinician instructs the patient to perform motor tasks from the Unified Parkinson's Disease Rating Scale (UPDRS) [13]. Testing of the platform includes the use of algorithms [7] that estimate clinical scores capturing the severity of tremor, bradykinesia and dyskinesia based on the analysis of accelerometer data. An initial implementation of a GUI to display such results is shown in Figure 4. These results provide clinicians with information that can be used to adjust patients' medication regimen.

V. Conclusions

To our knowledge, the one herein presented is the first platform to remotely monitor patients with PD in the home setting using wearable sensors. The system is an integrated platform that includes: 1) wearable sensors used to gather accelerometer data; and 2) a web-based application that allows for two-way communication between patient and clinician. Via the proposed platform, clinicians can access sensor data, upload feature datasets, and estimate UPDRS scores. The system is currently undergoing extensive field testing, but preliminary results support its suitability to monitor patients with PD in the home setting and to gather information to facilitate the titration of medication in late stage PD. Future work will be focused on exploring the use of mobile devices as a gateway to collect data. Furthermore, we plan to explore the use personal health records to store and display the results of the analyses of data gathered in the home setting.

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