

A Portable Platform to Collect and Review Behavioral Data Simultaneously with Neurophysiological Signals

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Abstract—This paper presents a portable platform to collect and review behavioral data simultaneously with neurophysiological signals. The whole system is comprised of four parts: a sensor data acquisition interface, a socket server for real-time data streaming, a Simulink system for real-time processing and an offline data review and analysis toolbox. A low-cost microcontroller is used to acquire data from external sensors such as accelerometer and hand dynamometer. The microcontroller transfers the data either directly through USB or wirelessly through a bluetooth module to a data server written in C++ for MS Windows OS. The data server also interfaces with the digital glove and captures HD video from webcam. The acquired sensor data are streamed under User Datagram Protocol (UDP) to other applications such as Simulink/Matlab for real-time analysis and recording. Neurophysiological signals such as electroencephalography (EEG), electrocorticography (ECoG) and local field potential (LFP) recordings can be collected simultaneously in Simulink and fused with behavioral data. In addition, we developed a customized Matlab Graphical User Interface (GUI) software to review, annotate and analyze the data offline. The software provides a fast, user-friendly data visualization environment with synchronized video playback feature. The software is also capable of reviewing long-term neural recordings. Other featured functions such as fast preprocessing with multithreaded filters, annotation, montage selection, power-spectral density (PSD) estimate, time-frequency map and spatial spectral map are also implemented.

I. INTRODUCTION

Analyzing neurophysiological data simultaneously with behavioral data has its unique advantage in the field of clinical neural engineering studies. Especially in brain computer interface (BCI) studies such as EEG or ECoG, subject's behavioral data such as limb movements need to be synchronously recorded with neural data. In recent years, functional mapping studies based on ECoG combining with behavioral data are also gaining in popularity [1]. However, human studies in clinical environments such as the operating room (OR) and epilepsy monitoring unit (EMU), posed additional challenges to the data acquisition system such as its portability and adaptability due to limited time and space. In addition, offline data review and analysis on large datasets with synchronized video playback is a useful feature that is currently not available in existing open source toolboxes.

This paper presents an integrated system targeting these challenges and describes a complete solution for data collecting, online processing and offline data visualization and

analysis of neurobehavioral data. For offline data analysis, a standalone Matlab GUI software named as CNELab (clinical neuroengineering lab) is developed. Existing Matlab toolboxes such as EEGLab [2] and BioSigPlot [3] are more modularized and implemented broader set of analysis functions compared to CNELab. However, in a typical epilepsy study, recordings in Epilepsy Monitoring Units (EMU) can extend over days with recorded file sizes exceeding hundreds of gigabytes. To the best of our knowledge, freely available toolboxes such as EEGLab [2] and BioSigPlot [3] are not capable of continuously reviewing such large datasets with synchronous video play back.

This system has been used in various clinical studies such as ECoG BCI studies [4], [5], ECoG brain functional mapping [6], [7], intra-operative LFP recording during deep brain stimulation (DBS) surgery [8] and high frequency oscillation (HFO) on epilepsy studies [9]. Considering its completeness, portability and adaptability, this system might be useful to other research groups of clinical neuroscience community.

II. MATERIAL AND METHODS

The whole system can be partitioned into four modules: the hardware interface module, the behavioral data collecting module (CNELBehv), the Simulink online processing module and the offline data analysis module (CNELab). Fig. 1 demonstrates the submodules and data flow diagram of our system. It is worthwhile to mention that neural data collected by bioamplifiers are directly streamed into Simulink real-time system. Each module will be explained in detail in the following paragraphs.

A. Hardware Interfaces

The hardware interfaces can be divided into behavioral system (left, Fig. 2), neural system (right, Fig. 2) and data collecting laptop (middle, Fig. 2). In order to interface external sensors with analog output such as 3-axis

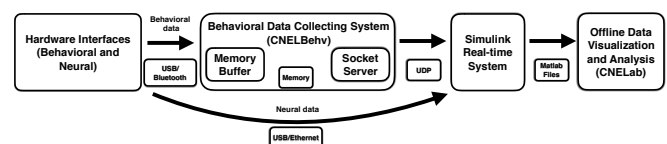


Fig. 1: Modularized diagram of the system. The arrows indicate the direction of data flow. Data communication protocols are shown below the arrows.

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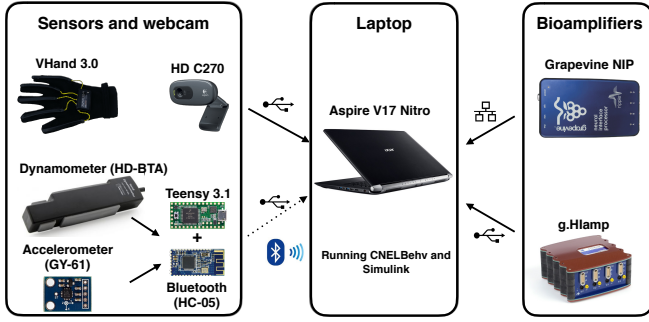


Fig. 2: An overview of behavioral system (left), data collecting laptop (middle) and neural system (right) with implemented modalities.

accelerometers and hand dynamometer, Teensy 3.1, a low cost microcontroller is used to digitize and transmit the data (<https://www.pjrc.com/teensy/teensy31.html>). In a very small footprint, Teensy is a 32 bit, USB-based microcontroller development system running at 72 MHz CPU clock rate. It has 21 analog input channels with 13 bits usable ADC resolution. As the bandwidth of the behavioral data such as tremor, hand/finger movements is within 20 Hz, Teensy is configured to sample its analog inputs at 100 Hz. The analog sensor output digitized by Teensy is transferred immediately to the laptop via USB with less than 20 ms latency. We also integrated Teensy with a bluetooth module (HC-05) to transfer data wirelessly. The wireless data transmission has in average 100 ms latency. Currently, hand dynamometer (HD-BTA) and two 3-axis accelerometers (GY-61) are configured with Teensy to quantify grip force and tremor respectively [10]. One of the biggest advantages of Teensy based data acquisition (DAQ) module is its low-cost and adaptability for additional sensors. In addition to Teensy based system, digital gloves (DG5 VHand 2.0/3.0) with built-in ADC converters and webcam (Logitech, HD270) are also integrated and directly connected to the data collecting laptop through USB. The bending sensors of the digital glove are used to quantify finger flexion/extension while the embedded gyroscopes captured the 3D rotation. The sampling rate of the digital glove is 100 Hz. Two different multichannel bioamplifiers with Matlab Simulink support are used to collect neural data (right, Fig. 2). Both amplifiers have drivers to stream data directly into Matlab Simulink environment for real-time processing and visualization. Specifically, a 256 channel bioamplifier gHIamp (g.tec medical engineering GmbH, Graz Austria) is able to record neural signal at 24 bit A/D resolution with a USB connection to the laptop.

TABLE I: Specifications of integrated hardware

Hardware	Model	Fs	Res	Connection
Webcam	HD C270	15-30 fps	320x240	USB
Digital glove	VHand 2.0/3.0	100 Hz	12 bits	USB
Accelerometer	GY-61	100 Hz	12 bits	USB/BT
Dynamometer	HD-BTA	100 Hz	12 bits	USB
Bioamplifier	Grapevine NIP	$\leq 30K$	16 bits	Ethernet
Bioamplifier	g.HIamp	$\leq 38.4K$	24 bits	USB

Alternatively, a grapevine neural interface processor (Ripple, Inc. USA) can record data at 16 bits resolution with 100Base-T Ethernet connection. A brief summary of hardware specifications is shown in Table I.

B. Behavioral Data Collecting System

The behavioral data collecting system, named as CNELBehv, is responsible for sensor data collection and relay. Written in C++ WinAPI and running in MS Windows OS, the main component of CNELBehv is its UDP server socket written from Windows Socket API. The data server is clocked by a Windows Multimedia Timer which has a minimum resolution of 1 ms. In default, CNELBehv runs at 10 ms resolution (100 Hz) to merge the incoming data from digital glove, webcam (frame number) and Teensy into its internal memory buffer and immediately redirects the data from the memory buffer to the loopback IP address (127.0.0.1) for other client applications to retrieve. In case that the client application was running in a separate computer, it is also possible to transfer data between devices by setting up an external public IP address.

Both USB and bluetooth connection from Teensy to the laptop are recognized as COM ports by CNELBehv. Data are retrieved using Windows serial communication API. Interfacing with the digital glove is separately achieved using the API provided by the manufacturer. For webcam, video capture and record are performed in separate threads of CNELBehv and only the frame number is kept in the memory buffer. To further reduce the jitter of the system timer, the process priority of the running instance of CNELBehv can be set to high from Windows Task Manager.

C. Simulink Real-time System

We used Simulink/Matlab (MathWorks, Inc. USA) to visualize and process the data stream in real time. Simulink is a graphical programming environment for modeling, simulating and analyzing dynamic systems. It provides a rich set of signal processing and visualization libraries that can be

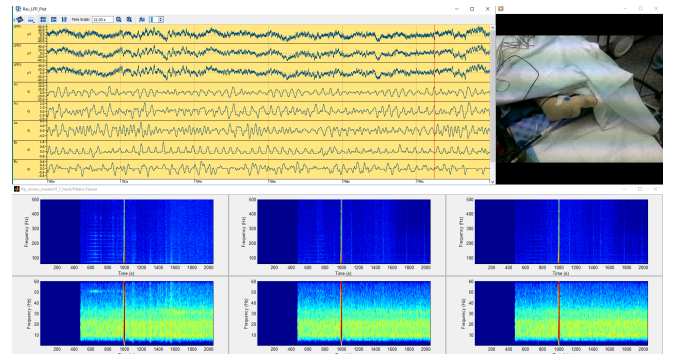


Fig. 3: A screenshot of the running instance of Simulink real-time system that collect LFP and accelerometer data simultaneously. Synchronous video showed the accelerometer attached to the patient's foot for tremor quantification. The bottom part are the real-time time-frequency analysis plots of the data.

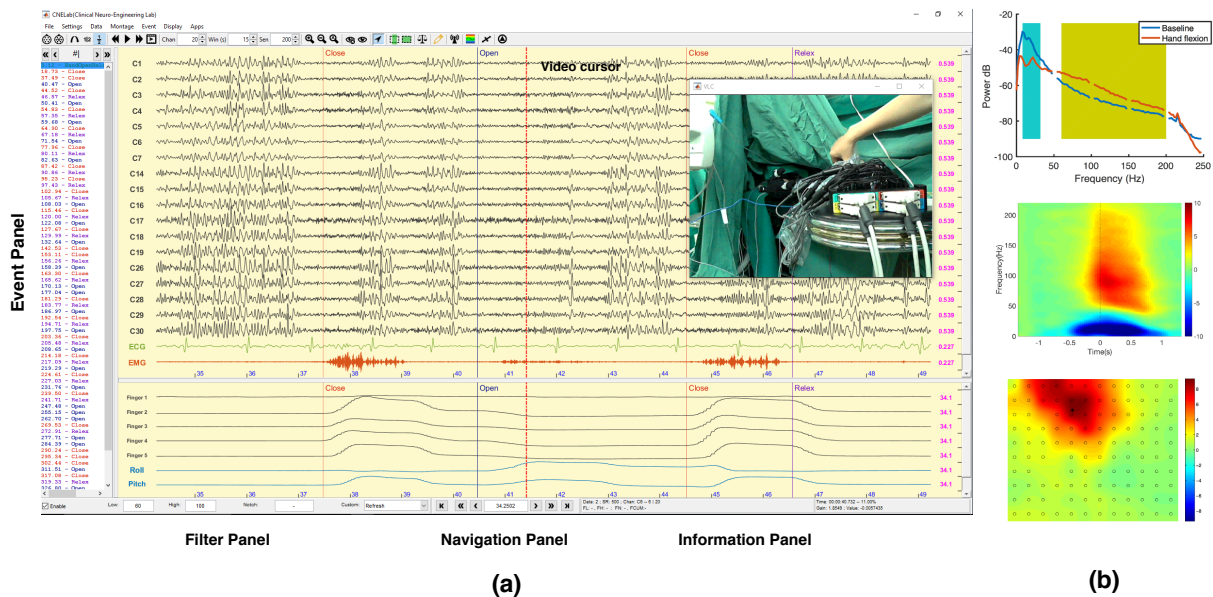


Fig. 4: (a) CNELab’s main interface. ECoG, electrocardiogram (ECG), electromyogram (EMG) (top) and digital glove data (bottom) are synchronized and visualized simultaneously for BCI or functional mapping applications. Signals from different modalities are filtered in different bands and displayed in separate scales. Event panel on the left side lists all annotations with related timestamps (s). (b) Power spectral density estimation (top), time-frequency analysis (middle) and Spatial spectral map analysis (bottom) of CNELab.

easily plugged in. We developed a real-time pacer based on Windows API (QueryPerformanceCounter) with submillisecond resolution to clock the system by enforcing a dynamic sleep period between execution cycles to achieve real-time data acquisition and processing. A UDP client block written in Level-II Matlab S-Function based on Matlab Instrument Control Toolbox is used to retrieve sensor data from the loopback IP address set by CNELBehv (e.g. 127.0.0.1). The customized UDP block flushes the buffer at a given threshold to minimize the latency of UDP transmission. Time-frequency analysis is also implemented to provide real-time feedback on time-varying spectral dynamics of the selected data streams (Fig. 3). The g.HIamp high-speed simulink online library is used to visualize the raw data waveforms. In addition, for a uniform interface control during data recording, Matlab system is able to send commands to CNELBehv via UDP to control the sensory data collecting procedure. A screenshot of the running instance of Simulink real-time system recording LFP, accelerometer and video is shown in Fig. 3.

D. Offline Data Visualization and Analysis

CNELab is initially developed as a self-contained data visualization toolbox to read Matlab files (*.mat) and several popular data formats (edf, fif, etc.). A screenshot of the GUI of CNELab is shown in Fig. 4. The recommended data structure to use with CNELab is mat file with predefined fields listed in *CommonDataStructure* class (*CDS*). Instead of loading the entire dataset into the computer memory, multiple files from long-term recordings organized in *CDS* formats can be uploaded by CNELab for continuous review. In this

case, CNELab dynamically load files into memory while navigating through the dataset. The key features of CNELab are listed as follows:

- Synchronous video playback.
- Buffered data preprocessing, multithreaded filtering and subsampling for visualization.
- Montage and annotation.
- Power spectral density (PSD) estimation, time-frequency analysis and spatial spectral map.

Synchronous video playback with dataset (Fig. 4 (a)) is a convenient feature which is usually only available in commercial software such as NeuroWorks (Natus Medical Incorporated). In CNELab, it is implemented based on activeX controls: Windows Media Player (WMP)/VLC. Navigation through the video automatically triggers data reposition and vice versa. In addition, a video cursor is provided in the data plot which can be easily manipulated (Fig. 4 (a)). The time offset between video and dataset can be adjusted for better synchronization.

Data preprocessing in CNELab is incrementally performed while navigating through the dataset. Customized C++ mex files are written to accelerate filtering in Matlab via multithreaded programming with cross-platform compatibility. In detail, second-order Butterworth IIR filters are implemented with forward and backward filterings to achieve zero phase shift. One convenient feature of CNELab’s multithreaded filtering is to apply different filters on different channels which are also not available in other toolboxes such as EEGLab and BioSigPlot [2], [3]. It is especially useful when the dataset comprised multi-modality dataset such as EEG, EMG and ECG which need to be explored in differ-

ent subbands. In terms of power line frequency denoising, CNELab provided a series of notch filters at customizable stop band with 2 Hz bandwidth to remove the harmonics. Based on the fact that the computer screen resolution is usually inadequate to visualize every sample of the recording, CNELab automatically performs downsampling to accelerate data visualization.

Montage can be used to rename and rearrange channel orders in CNELab (Fig. 4). It can be read or saved in external files in comma-separated format (CSV). Montage file columns include channel name, montage transformation and optionally channel group name from left to right. Montage transformation is a way of specifying channel combinations. For example, assuming the original channels are named as C1, C2, . . . Cn, ECG_L and ECG_R, the montage file might be written in a similar way as Table-II.

TABLE II: An example of montage CSV file

%Channel name,	Montage transformation,	Group ¹
Bipolar ECG,	ECG_L-ECG_R,	ECG
Mean Ref,	0.75×C1-0.25×C2-0.25×C3-0.25×C4,	EEG

Annotation is another frequently used feature in neural signal analysis (Fig. 4). In CNELab, they can be either imported from external files or manually created while navigating the dataset. Navigating on the annotations of the dataset also triggers the data navigation. An example of annotation file is provided in Table-III which includes timestamp, text, RGB color (optional) and code (optional) columns.

TABLE III: An example of event CSV file

%Time (s),	Text,	RGB color ¹ ,	Code ¹
0,	Task start,	0 1 0,	0
200,	Task end,	0 1 0,	0

CNELab implements Welch’s methods to estimate the power spectral density (PSD) of selected channels as a routine practice. Time-frequency analysis in CNELab is based on Short-Time Fourier Transform (STFT). Both PSD and time-frequency analysis in CNELab can be constrained to a selected range. To avoid biased PSD estimation from multiple segments, a weighted summation of the individual segment’s PSD based on its length is adopted. Averaged PSD and time-frequency analysis from single trial experiments are also provided. Additionally, CNELab provided a spatial spectral analysis which is frequently used in our previous research [4], [6], [7]. Examples of the PSD estimation, time-frequency analysis and spatial spectral analysis are shown in Fig. 4 (b).

III. CONCLUSION

Based on the unique demand in clinical neuroscience research, we developed a complete and modularized system for neural data and behavioral data collecting, online processing

¹Optional column, default values will be provided if not specified explicitly.

and offline analysis. The modularized subsystem can be easily adapted for customized usage. A rich set of sensors have been integrated and customized sensor support can be easily achieved in Teensy based sensor data collecting module. The offline data analysis software (CNELab) is developed as a standalone software package. It is capable of reviewing continuous long-term recordings with synchronized video. Frequently used data review features such and montage and annotation were implemented in a user-friendly way.

All system packages are freely available under the GNU General Public License V3.0 (GPLv3) (<http://incelab.bme.uh.edu/tools/>). As the system is still under development, continuous updates and bug fixes are to be expected. In the near future, we plan to organize the source code of our system to make it easier for third party development. A fully documented guideline of the system with prerequisites and installation details are going to be provided along with the system software on our website (<http://incelab.bme.uh.edu/tools/>).

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