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A novel wearable biometric capture system

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Abstract— **In the present paper we introduce a novel wireless system capable of simultaneously track and monitor the motion of the body and the associated muscular stress. The device provides with an array of four inertial and magnetic measurement units combined with up to 32 independent high sensitivity ADC channels. An embedded computing system does allow the high speed (4 KHz) EMG acquisition and filtering, combined with (100Hz) motion reconstruction and relevant features (20Hz) detection. The device connects to any receiving host using a portable server architecture and an extensible computing system which uses a web interface and a plugin architecture based on shared library.**

The device has been conceived to monitor body activities in application on-the-go, where the use of wired devices is not suitable and the need for a strict synchronizations among the motion reconstruction and the myo-electric signals is fundamental. In what follows we will describe the general architecture of the system, the embedded algorithms for motion and EMG reconstruction and the software architecture of the host system.

I. INTRODUCTION

To date biometric devices can be grouped into of three classes: High performance/quality EEG/EMG/ECG devices which are instrumented as laboratory tools [1], [2] or as small distance portable systems [3], [4], [5]; Wearable motion capture systems [6] provided with different flavours of sensing and wireless options [7], [8]; and low cost combined motion and EMG sensors which recently appeared on the market (Liveathos™, and Myo™). Laboratory tools are very accurate and can be scaled to complex situations, but their settling prevent the portability of the system. A wide set of wearable motion or EMG systems [9], [10], [11], [12] was already provided in the recent past for different tracking or medical support. Their design is however specific to one of the two applications and these systems do not exploit the capabilities offered by a combined tracking. The few combined sensors which recently appeared on the market only offer reduced motion tracking capabilities (mostly gyroscope only) combined with a single EMG track recording.

One of the most promising application of these systems is in the assessment of the human activities for sport, work analysis and disease prevention[13]. For this purpose a the use of myo-electric signals [14] and motion data [15] have demonstrated a valid support to generate clinical data for disease prevention and rehabilitation [16].

In this paper we will review a novel biometric capture system (BCS) that allows capturing and analysis of distributed motion and EMG signals. Such architecture is composed of an embedded wearable device and a modular server.

The device is provided with on-board computing capabilities to filter and remove electrical artifacts on the EMG data and to stream data collected at constant rate using wireless connection.

The server is written in portable code and can be run in a different set of operating systems from desktop to portable like Android. The server provides efficient management of the following features: it handles, parses and organizes all kind of data received wireless; it exposes a web-server architecture to access, control and visualize data using http requests and web sockets[17]; it loads external plugins in the form of shared objects, interconnects them accordingly to scripting schemes and synchronizes the computation with the captured data.

The rest of the paper is organized as follows: first we provide a general overview of the underlying hardware/firmware; second we introduce to the software architecture to manage the biometric information; third we provide an highlight of the data visualization facilities.

II. THE CAPTURING SUBSYSTEM

The capturing subsystem is composed of one main board and three slaves sensors interconnected together. The slave sensors attach to different part of the body and their role is to collect distributed motion-stimuli. The interconnection among the master board and the slave sensors is achieved through I2C bus.

The size of the main board is the same of a 5 inches mobile phone (136mm x 70 mm x 9mm) and can be hosted in an armband strip for being used during working operation. The overall weight of the system including the three motion boards is less than 80 grams.

The main board is powered by a STM32F407 processor which runs at 168MHz and provides the necessary floating point capabilities to process and filter all the incoming data in real-time.

Figure 1 highlights the main services running on the computing board. Each EMG interface connects to a TI ADS1298 and serves 8 channels, 24 bit, ADC converter, using the SPI interface. Given the bus organization of the CortexM architecture (which is organized into a matrix). Data transfer have been delegated (wherever it was possible) to DMA transfers that operate in parallel to computation without memory access conflicts.

The main board provides to record 32 EMG channel at a constant frequency of 4 KHz, and the data from the four motion sensors (9 axes: acceleration, gyro and magnetic

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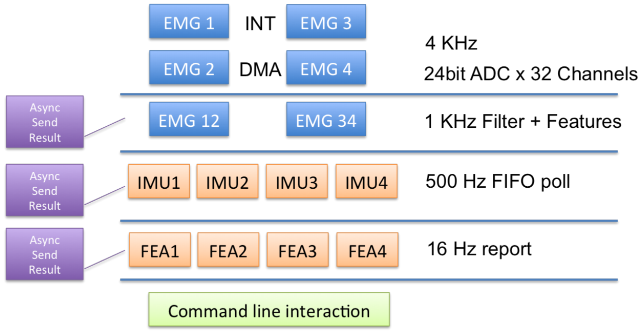

Fig. 1. The firmware architecture. The board hosts no operating system and all scheduling is performed through interrupt services whose priorities have been arranged into different priorities. The higher is the service rate the higher is the priority. Communication through Bluetooth is served by low priority asynchronous interrupt.

information) at a constant rate of 100 Hz. Both the external electronics, the data conversion devices and the master computing system implements a chain of electrical/software filters to reduce disturbances and prevent aliasing during AD conversion. In addition an internal software filter allow to manage the EMG information accordingly to the common practice in bio-medical application.

A. The Filtering Subsystem

In most EMG systems processing of acquired signals is performed out of the data measurement unit. This choice requires the presence of a a high performance host computing system and the existence of a high bandwidth connection link. The combination of the above prevents any use in a portable environment where the host client (such as a tablet) can have reduced computing/communication capabilities. In our approach we delegated the biometric capturing system to perform the relevant early stages of data analysis: linear filtering, features identification and signal decimation.

EMG data are collected at high frequency in order to reduce the aliasing frequency and to achieve a more accurate filtering procedure.

Before data sampling a first order RC electrical network ($\tau_m = 10.34 \cdot 10^-6s$) provides to reduce the aliasing effects during sampling. Data are then sampled within the ADS1298 at a base rate of 512 KSPS and filtered through a cubic, anti-aliasing, LP digital-filter which transfer function is the following:

$$TF_{ADS}(f) = \left| \frac{sin(\frac{N\pi f}{F_D})}{Nsin(\frac{\pi f}{F_D})} \right|^3 \qquad (1)$$

where $F_D = 512KSPS$, and N is the decimation factor computed as $N = F_{in}/F_{out} = 512/4$.

The output of the anti-aliasing filter is then send at 4KHz through SPI interface.

Each EMG channel is filtered through a sixth order band-pass filter (1-5) with one pole at low frequency (3Hz) to remove the motion artifacts and five poles to achieve a Butterworth filter at 500Hz.

The resulting filter has been decomposed as a cascade of three second order digital filters that run at the base rate of 1mS.

$$TF(z) = \prod_{i=1}^{3} \frac{N_{0,i} + N_{1,i}z^{-1} + N_{2,i}z^{-2}}{1 + D_{1,i}z^{-1} + D_{2,i}z^{-2}} \qquad (2)$$

The choice is inline with common signal management provided in literature where the typical bandpass frequencies range from 10-20Hz (high pass filtering HPF) to 500-1000Hz (low-pass filter LPF). HPF is required to remove movement artifacts which are comprised of low frequency components (typically $\leq$10Hz). LPF is desirable to remove high-frequency components to avoid signal aliasing[18].

It is also common to remove power-line (A/C) noise components (i.e. either 50 or 60Hz) by using a sharp notch filter. However notch filter causes several motion distortion since EMG has relevant contributions at these and neighboring frequencies.

In our BCS notch filter is not necessary given that the system is powered through batteries and that the ADC converters have a very high CMRR (115dB).

Poles and zeros of each SOS have been re-organized in order to match their respective frequencies as closer as possible. This choice improves the numerical stability of the overall filter.

The implementation of the SOS has been optimized to be used on the ARM vFPU4 available on the Cortex-m4 processor. To compensate for the difference of sampling time among the acquisition rate and the filtering rate, at each step, the filter is recursively called four times with the last four acquire inputs. The filter however only provides one output each 4-by-N cycles thus simultaneously providing a decimation in the loop.

B. The Featuring subsystem

The device provides on-board the parallel computation of a wide set of features that can be broadcasted at lower frequencies for better computation and analysis even on low performances devices.

Among these features we implemented:

1) Mean Square: an averaged measure of the signal power which is computed on 64 filtered samples (each 64 ms) using the data coming out of the decimation filter. We avoided the common practice of using the root signal (RMS) to simplify the operation on the embed FPU.

$$F_{RMS}(K) = \sum_{i=1}^{64} \frac{EMG_{chan}(K*64+i)^2}{64} \qquad (3)$$

2) Average Rectified Value, this method provides to extract an approximation of the enveloping function:

$$F_{ARV}(K) = \frac{1}{64} \sum_{i=1}^{64} |EMG_{chan}(K*64+i)| \qquad (4)$$

3) number of Zero Crossing (ZC): this method is a simplified version for measuring the spectral properties

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of the signal and turn to be useful in the assessment of muscle fatigue and in the maximum contraction of the muscle. The implementation of the method has been provided with a state machine that observes the number of crossing. To avoid false measurements deriving from noise a minimum crossing threshold has been implemented.

4) number of peaks (DZC): this feature has been implemented as a zero crossing analysis on the derivative signal. The peak is counted only is the rectified value of the signal is above a given threshold.

III. THE SOFTWARE ARCHITECTURE

The remote server application is based on a modified mongoose server [19] a single source code embedded portable web-server among different architectures including the ones addressed by our BCS.

In our case the web server has been extended in order to serve the incoming Bluetooth connection, decode the data into several streams and make them available as web-socket services. At each web-socket request the server will reply with the most recent bio-metric data decoded from the stream.

The web socket fruition is best-effort and in the case of slower or remote client, it only provides a sub-sampling of the effective data read by the capturing subsystem. In order not to loose data for accurate analysis the server also supports real-time file recording which has been synchronized with data coming from the wireless connection.

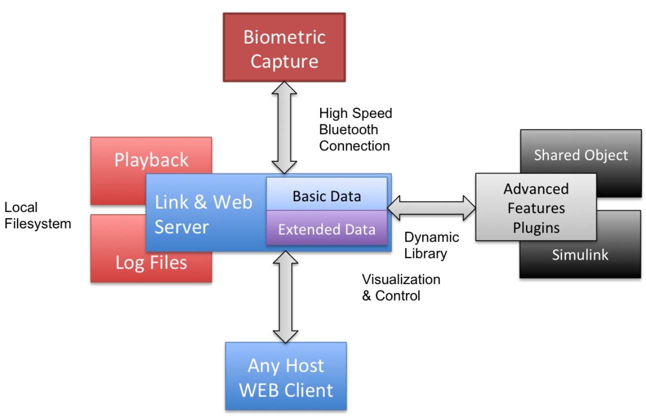

Fig. 2. The software architecture.

A. Webserver Interface

B. The Plugin Architecture

The host server support loading at startup for external plugins. Each plugin is an object which export the function `PlugService` *plugDiscover(), where the returned variable include the following fields:

- **name** a NULL terminating string describing the exported functionality;
- **plugInfo** a const char returning function that describes how the plugin works;

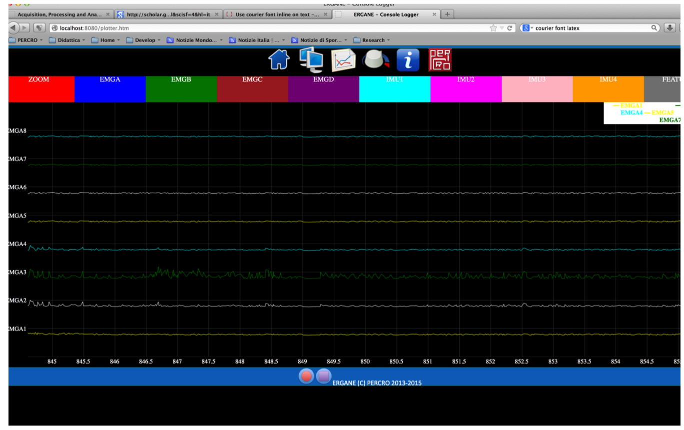

Fig. 3. The web client interface. The picture shows a snapshot of the web client interface when the device is configured to report the EMG raw data reading. The real-time plot has been designed with a combination of web-socket queries and the dygraphs real-time plotting tool.

- **plugInit** the function that initializes the plugin before it is executed;
- **plugUpdate** the function that provides to manage the plugin input data;
- **plugCommand** a function that may be called to setup plugin parameters;
- **plugTerminate** the function which destroys the plugin structures before the server exits.

Each plugin function is provided with a data descriptor which identifies all input/output/parameters made available to the plugin. For this purpose the server may initialize array of variables which are labeled with an identified and whose pointers are passed to the plugin structure.

Using this structure the server can be initialized through a configuration file with a syntax like the following:

```
LOAD mplug/ArmLeft
DEF Result 12
CONNECT ExtMode([IMU1,IMU3, IMU4, EMGA],[Result],[])
TRIGGER IMU1
```

where the 'LOAD' command instructs the server to load the associated shared library; the 'DEF' command instruct the server to generate a named variable with the given size; the 'CONNECT' command instruct the server to find by the plugDiscover method the give plugin interface and create for this association an '[inputList][outputList][parameterList]' array as described in the parameter list; the 'TRIGGER' command finally inform the server which receive even from the BCS system should trigger the update function in the plugin.

The server adds by default all the standard variables received by the BCS: IMU1-IMU4, EMGA-EMGD. In addition, using this interface, the server generate and manages additional 'named' variables without having to enter in the specific meaning of each variable.

A typical use of the plugin structure is to elaborate raw data incoming from sensors with specific motion and EMG analysis algorithms such as: skeleton reconstruction, mus-

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cular activity and force analysis, complementary or Kalman filters [10].

Data handling in this architecture is based on shared memory whichever operating system is hosting the server. This solution reduce the number of operations to be performed for sharing data among plugins and optimizes the performances of the system. The server allocates the memory for all external plugins and pass the relative pointer to them in the 'data descriptor'.

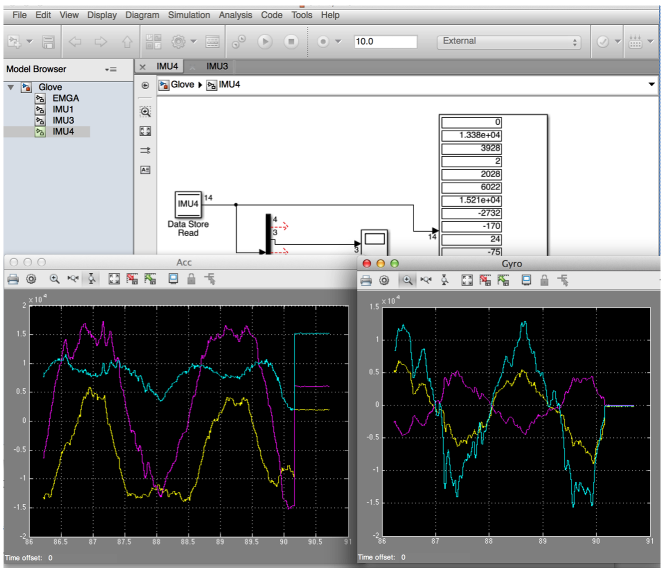

Fig. 4. A Simulink plugin interconnected using the external mode interface. The plugins captures data coming from 3 different accelerometers and one EMG interface (8 channels). The figure shows the real-time plots within the Simulink interface as they can be collected using the standard external mode interface.

In order to optimize the fruition of the plugin in a shared environment, a Matlab-Simulink Real Time Workshop (RTW) target has been created (see Figure 4). The RTW target makes use of inlined (TLC) SFunctions for generating two plugin interfaces for each model: a standalone interface and an external mode interface. According to this approach the user can connect the plugin extension to the server in two different modalities: a performance modality (that uses the standalone method) and a debug modality (which makes use of the External mode interface). When the external mode interface is selected the Matlab Simulink environment can connect directly to the server through the external mode support and debug underlying algorithms in real-time.

The plugin infrastructure recreates in a minimalistic approach, the same publisher-subscriber architecture which is common in most robotic operating systems (such as ROS, YARP and OROCOS). In this case however we sacrificed the online possibility to subscribe and register, with a static configuration that is load from file at process start. In such a way the whole computing system can have a stricter integration and may achieve high performances even on low cost portable systems.

IV. THE DATA VISUALIZATION

The included webserver uses modern data sharing standards and visualization such as Websockets [20], WebGL [21], jQuery [22] and dygraphs JS library (dygraphs.com). The above combination preserves the same inter Operating system portability as implemented in the basic system design and allows to run the whole GUI from any client system.

A core component of the BCS is its visualization architecture. The device provides a variety of different information starting from the the networked four IMUs and the on-board 32 EMG channels. IMU data contain 3D information on linear acceleration, angular velocities and magnetic field direction at a constant rate of 100Hz. These information can be visualized as acquired by the server using WebSocket queries and WebGL display.

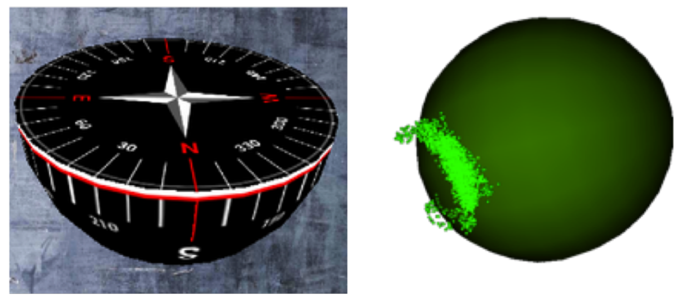

Fig. 5. The standard visualization set for magnetic field direction and the related polarization ellipsoid.

The figure 5 shows the particular case of displaying the IMU's magnetic data related to one of the IMUs on-board. Similar displays can be shown for the acceleration and gyro data, or can be plotted as timeseries using the

V. REVIEW OF PERFORMANCE

The performance of the system are limited by three concurrent factors: the internal capabilities of the embedded acquisition board; the bandwidth limitation of the wireless communication link and the local capabilities of the server-host.

The embedded computing system has been designed in such a way the processor load is close to 85% when all the service are running in parallel: 32 channels acquisition and filtering with 1KHz output; 4 IMUs running with 100 Hz output; full feature analysis; communication link running at 921600 bit/s.

The wireless link is the most critical component component in the system. To date there exist no low-power wireless solution who can transport all the amount of information which can be generated by the board. Common standards are limited in bandwidth (such as the ZigBee^{TM}) or power consuming (such as the Wi-Fi 802.11g).

Our choice was to use a recent Bluetooth module which can support transfers up to 760Kbit/s.

In term of performances the result is much depending on the number and complexity of plugins, the associated number

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	Number of Float To Send (4 bytes each)						
Rate (Hz)	1F	2F	4F	8F	16F	24F	32F
10	400	800	1600	3200	6400	9600	12800
50	2000	4000	8000	16000	32000	48000	***64000***
64	2560	5120	10240	20480	40960	61440	81920
100	4000	8000	16000	32000	64000	96000	128000
128	5120	10240	20480	40960	81920	122880	163840
200	8000	16000	32000	64000	128000	192000	256000
250	10000	20000	40000	80000	160000	**240000**	**320000**
256	10240	20480	40960	81920	163840	245760	327680
500	20000	40000	80000	160000	**320000**	480000	640000
512	20480	40960	81920	163840	327680	491520	655360
1000	40000	80000	160000	**320000**	640000	960000	1280000

Standard 19200

Extended 115200

Reachable 460800

Requires 700Kbit/s

Fig. 6. An analysis of the link transport performances. The table reports the achievable data rate and number of channels versus the wireless bandwidth. The chosen solution allow us to enable almost all transport modalities within the guaranteed bandwidth of the device.

of threads, the use of external interfaces as the Simulink connection and, obviously, the performance of the hosting platform. On the testing platform the system (OSX64, Intel Core i7, 2.6GHz) can manage to read and apply calibration and motion reconstruction filters, and visualize them from Simulink without any sensible loss of data.

VI. Conclusions

This paper discusses the software architecture and the characteristics of a novel biometric system that aims at providing integrated force and motion capabilities. The system is currently being tested in e variety of sectors. A domain of application is the one related to the assessment of work injuries performed in ecological conditions [23]. Another domain of application is the one of sport training, in particular for the purpose of assessing rowers technical capability in indoor and outdoor conditions [24].

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