A Miniaturized 4-Channel, 2KSa/sec Biosignal Data Recorder With 3-Axis Accelerometer and Infra-red Timestamp Function

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***Abstract*—In this paper, we describe a miniature biosignal data sensor and recorder device, (NAT-1) with 3-axis accelerometer, and a 2KSa/sec all-channel recording capacity of 24 hours or more with a single zinc-air battery cell. The device measures less than 18x22mm and weighs less than 2.3 grams, including the battery. The device is evaluated in several contexts, including electroencephalography data collection, forearm electromyography capture, and in use as an accelerometer for movement capture in sport. We describe the device, its use, and show examples of some monitoring applications; in all cases, data is collected in an untethered stand-alone mode. The NAT-1 has already achieved translation to commercialization and is the first of a new family of sensors.**

Keywords-Neurophysiology; EEG Recorder; Bio-signal sensors; Medical sensors.

I. INTRODUCTION

The use of biosignal data acquisition is increasingly important in many applications spaces, not least of which is biomedical applications. The use of devices to record EEG (Electroencephalography), EMG (Electromyography), ECG (Electrocardiography) and movement is of particular interest. Often, these measurements are taken in wired or wireless umbilical modes, in other words, within a clinical evaluation setting, with data captured and analyzed over relatively short time windows, and in unnatural settings.

The ability to perform ambulatory monitoring of patients, on the other hand, provides the possibility of long-duration data capture of bio-parameters in a normal living-condition or work-place. This has been an aim for many decades, and it is interesting to contrast how this has been achieved in past and present technologies; ranging from early magnetic tape based data capture [1], digital systems [2], Custom Integrated Circuits [3,4] and medical data recorders [5,6]. Such capabilities are identified by many clinical researchers as being desirable, and the opportunity to learn more about medical conditions, as well as the condition of individual patients themselves is seen as a major motivator for developing suitable devices.

The motivation of our project "NAT" (Neural Activity Tracker) is to produce a multi-purpose data sensing and recording solution that is extremely small, lightweight and having a recording capacity of days to weeks, dependent upon the selection of parameters such as sample frequency. The NAT is such a device, and it is this which we describe in the remainder of this paper. We believe that the device, even in its current implementation, is capable of being used in many applications, including non-obtrusive use in wearable patient monitoring.

This paper presents the NAT in detail in Sections 2, 3 and 4, whilst Section 5 documents some initial experimental applications of the device. Section 6 highlights the additional resources developed alongside NAT, including docking station, control software and data analysis tools, and the infra-red data signature time-stamp daughterboard. A brief state-of-the-art context is given in Section 7, and conclusions in Section 8.

II. A SMALL FORM-FACTOR DATA-RECORDER

The Neural Activity Tracker (NAT) is a device only 18x22mm in size, less than 10mm in height (primarily due to the battery module), and weighs less than 2.3 grams, which means it is attractive in applications where regulatory constraints apply (e.g., use with small animals). It is so light in weight that it is almost unnoticeable in normal use as a human-subject wearable body-sensor. This low-weight attribute also means that multiple devices can be worn individually or in small groups where appropriate, without causing encumbrance of the subject's normal movements and behavior. The NAT is shown in the image of Fig. 1, with a ball-point pen of normal size for scale. In the photograph provided in Fig. 1, one can see some interesting features. First of all, the major part of the device has a profile of less than 4 mm. Also visible in Fig. 1 is a specially designed battery clip for housing a zinc-air cell (as used in hearing aids). This is the gold-plated metal structure. The use of flatter button cells can be envisaged to make a smaller profile possible, though this has weight implications.

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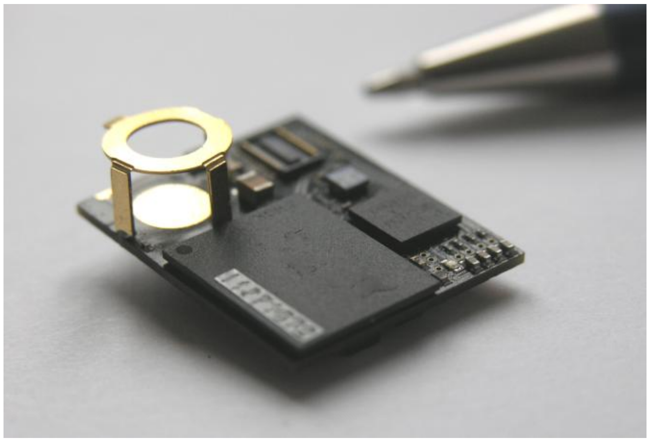

Figure 1. Top-view of NAT-1 device

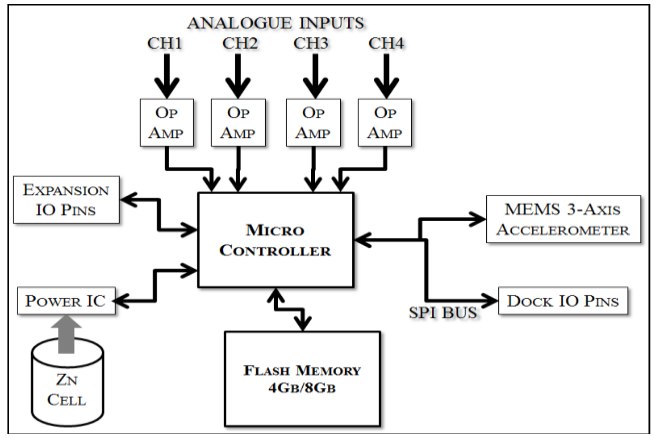

Figure 2. NAT Device – Sub-component Block Diagram.

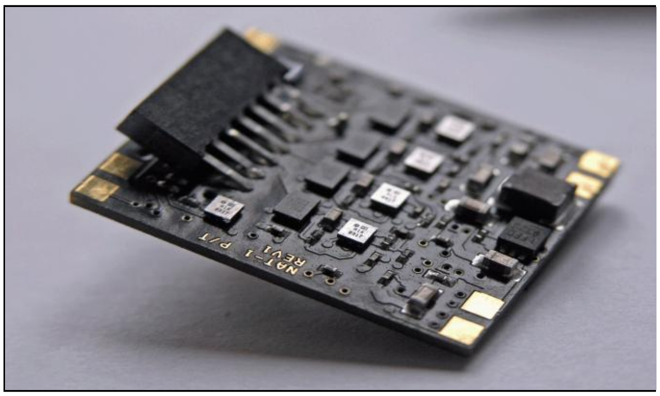

Figure 3a. Analogue Connector Port on NAT-1 Underside.

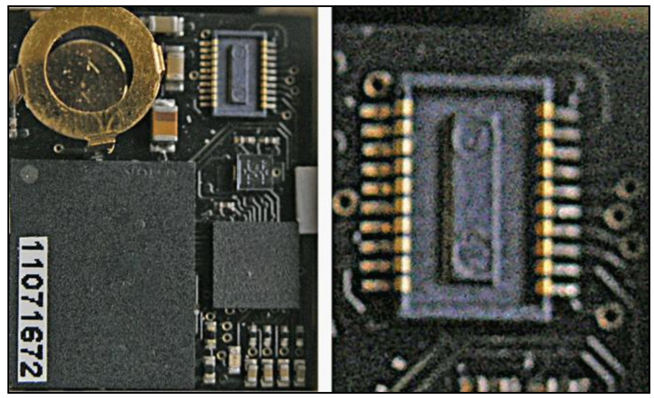

Figure 3b. Overhead view of NAT-1 and close-up of Daughterboard

Near the tip of the ball-point pen, one can see a small low-profile connector socket, which is actually a mezzanine daughterboard connector port. This permits a range of possible extension modules. Fig. 2 shows the system level block diagram.

The NAT device comprises of three key components – a flash memory chip (largest chip in Fig. 1), a proprietary CPU (mid-sized chip of Fig. 1), and a proprietary MEMS (MicroElectroMechanical System) device for accelerometer (smallest chip of Fig. 1). Additional analogue front-end components provide appropriate signal conditioning for the signal ranges typically encountered in a range of biosensor and biomedical applications.

III. Zinc-Air Power Cell Design Considerations

A particular feature of NAT-1 is the use of a single zinc-air power cell. Such cells are widely used in hearing aids, and have an active power-delivery life-span of around two weeks, after which the cell begins to lose its effectiveness. This degradation begins as soon as the air-seal is removed from the cell, but allows for long-duration continuous power delivery from a very small and light power cell.

Because of the zinc-air reaction mode of power generation in the specific cell mentioned, it is not possible to draw power above a certain ceiling, which is limited by the capacity for air circulation into and out of the cell rather than its lifetime power delivery capacity. Consequently, it is necessary to spread power utilization to avoid frequent peak-power drainage. Failure to do so results in cell depletion and CPU brown-out. This is unlike a standard power-cell such as a button-cell, where current is limited by the device's ability to operate within a safe discharge rate rather than by a continuous power availability driven by an external reaction factor. Nonetheless, we have developed the NAT-1 with a continuous recording capacity in excess of 24 hours at full design-spec sample rates (see later power data for details).

IV. Device Specifications

The NAT-1 has the specifications as outlined in Table 1. The device has a wide range of possible sample rates, ranging from 100Sa/sec to 2KSa/sec via the user interface software application. At 2KSa/sec, the device consumes 4.8mA of current from a single 1.4-volt cell, and can record for up to 12 hours. An 8-GBit flash option is possible and would have up to 24 Hours of recording capacity at maximum rates. At lower sample rates, the capacity of the

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flash is extended to many days, and power consumption reduces to allow for longer recording times. This compares well with reported state of the art [3,4], given that the system is comprised of readily available commodity integrated circuits. The device has three important connection mechanisms, these being the analog input connector (angled connector block to left of device in Fig. 3a), the daughterboard extension socket (Fig.3b) and the docking-shoe connectors (seen in Fig. 3a as small gold contacts at the board corners).

V. DEVICE USEAGE EVALUATIONS

To date, most of the testing of the device has been limited to engineering development contexts, but using live EEG and EMG data collection with additional test scenarios. This does not include validation in a clinical certification context.

Three test scenarios are reported. EEG and Accelerometer data collection from mice in live test scenarios has been undertaken by researchers at the University of Aberdeen. This work continues and will build a validation case for clinical use. We have undertaken preliminary EMG testing scenarios at the University of York, mainly to evaluate the signal range suitability for gel-electrode signal capture.

TABLE I. NAT-1 SPECIFICATIONS

Parameter	Limits	Units
Analogue inputs	4	channels
Bits per channel recorded	11	bits
Accelerometer	3	Axis
Bits per Accel. Axis	8	bits
Sample rate (max)	2000	Sa/Sec x 4 ch
Max Current 2KSa/s 500Sa/s	4.8 2.4	mA mA
Data Capacity	4 or 8	Gbits
Recording Time at 2KSa/Sec	12 or 24	Hours
Analogue Range	± 1000 ± 4000	uV (NAT-1) uV (NAT-2)
Accelerometer range	Selectable 2 or 8	G (G-force)
Accelerometer sensitivity	18 72	mG at 2G range mG at 8G range

To test the accelerometer capabilities, the device has been used as a golf-club attachment to capture golf swing behaviors in terms of club rotation, side-movement and swing-path motion. In all cases, the device was used untethered and powered exclusively with a single zinc-air cell. These cases are shown in our test data of Figs. 4a, 4b, 4c and 4d, and are described in the following sub-sections.

A. EEG Measurements

Data has been captured with a wide range of sample rates, ranging from below 200Sa/sec to 2000Sa/sec. Whilst it is generally accepted that useful frequency ranges for EEG are in the region below a few hundred Hertz, the advantage of a higher frequency sampling regime comes from the ability to determine precise timing and time-separation of events, either within the EEG and Accelerometer data streams, or from an external trigger action. The NAT-1 has an extension board that can record Infra-Red-Timecodes within the data stream and this can be used to record trigger events and subsequent EEG responses with high accuracy in the time domain. Higher frequency sampling also allows for improved noise performance, since downsampling and digital filtering can be applied to the data stream after capture.

Experimentally, it has been found that the device performs well with mice as subjects, as expected. Rats however have a larger EEG signal range, and the NAT-1 device was originally not designed for this purpose. However, the NAT team is currently implementing a new programmable gain function to permit a wider range of signal input ranges to be captured without saturation or clipping artifacts. This NAT-2 device is undergoing testing at the time of writing and is not reported here. Examples of mouse EEG data captured with NAT-1 are given in Fig. 4a, which also shows accelerometer and IR-event code side channel. It can be seen that the IR event code correlates to regions of increased EEG activity. This NAT-evaluation data was provided by a well-established team with a long experience of using rodent EEG data recorders [7,8,9].

B. EMG Measurements

Initial experimentations with EMG measurement are promising. The device was attached to a subject's forearm and used to measure repeated muscle contraction-relaxation cycles and simultaneously record 3-axis accelerometer readings. The device was connected directly to standard clinical Ag/AgCl disposable adhesive surface electrodes. Again, the NAT-1 was not originally intended for this application, but we wished to evaluate its potential and identify improvements required. For this experiment, no pre-amplification or attenuation was applied to the electrode feeds, and as would be expected this means that the signal range captured does not perfectly match the analogue input range of the NAT-1 device in this initial setup. Nonetheless, it can be seen in Fig. 4a, that the muscle contraction results in repeatable EMG signals. It is also seen in Fig. 4a that clipping occurs frequently.

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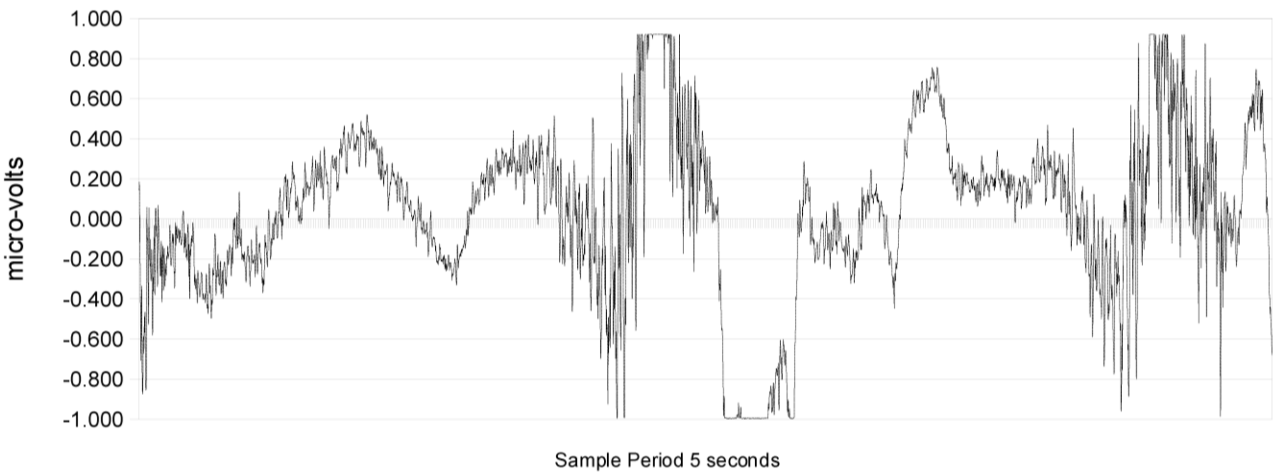

Figure-4a. Electromyography test case, repeated bicep contraction regime, with gel-electrode contact.

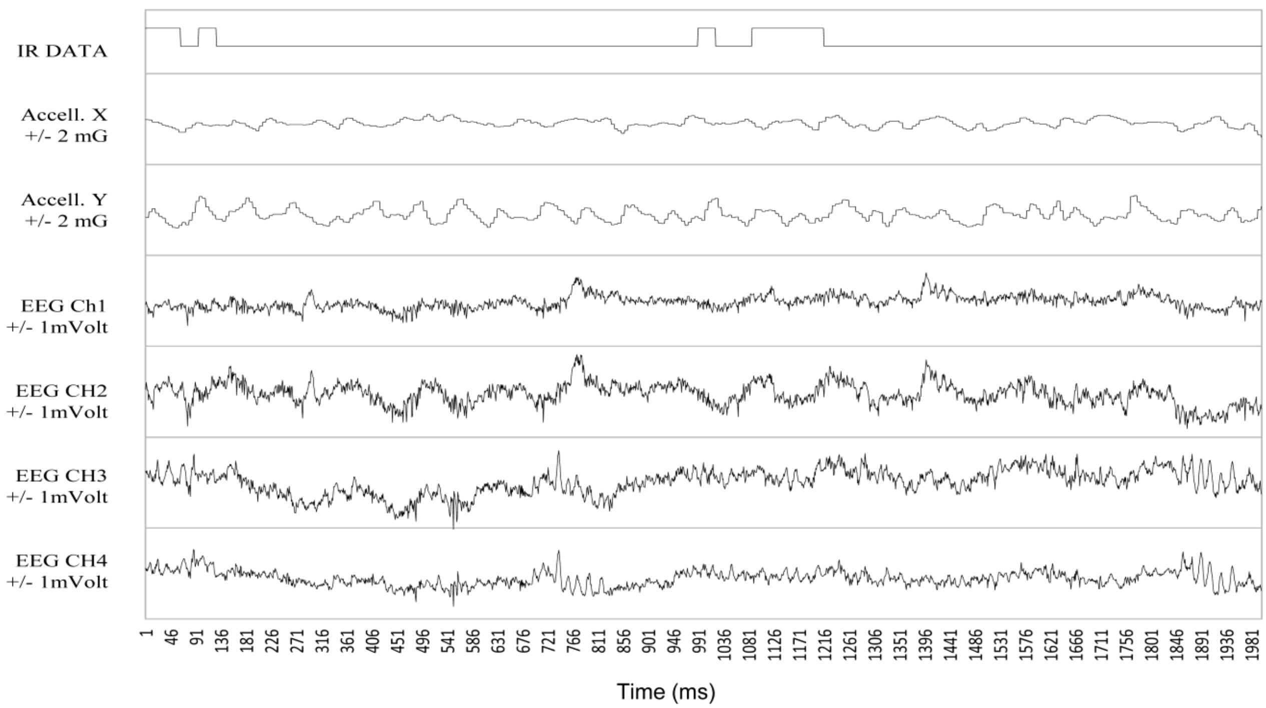

Figure 4b. EEG data collection in tandem with 2-Axis Accelerometer. And Infra-Red Pulse Code Recording.
(top trace – IR channel, mid - 2 axes of accelerometer , and bottom – 4 EEG channels)

In this experimental set-up with no attempt to pre-scale the input signal to the NAT-1 input range, it is not surprising to see this effect. The revised device, which incorporates programmable gain features, will allow for such signal measurements to be properly scaled and ranged to permit full-scale capture without clipping. The combination of accelerometer, and EMG recording in a very small lightweight package make this an attractive device for monitoring of symptoms such as essential tremor, Parkinson's disease, and other symptoms. That application will be a high priority for the York group's future focus.

C. Golf-Swing Accelerometry

This experiment was conducted in order to gather accelerometer data with a full-scale and saturation condition, including under extreme-G conditions. The device survived intact and retained battery supply integrity throughout the testing, due to the specially designed battery retaining clip. It might have been expected that the extreme forces of impact might lead to physical battery disconnects. However, no evidence was observed in the test data, indicating that the clip was highly effective.

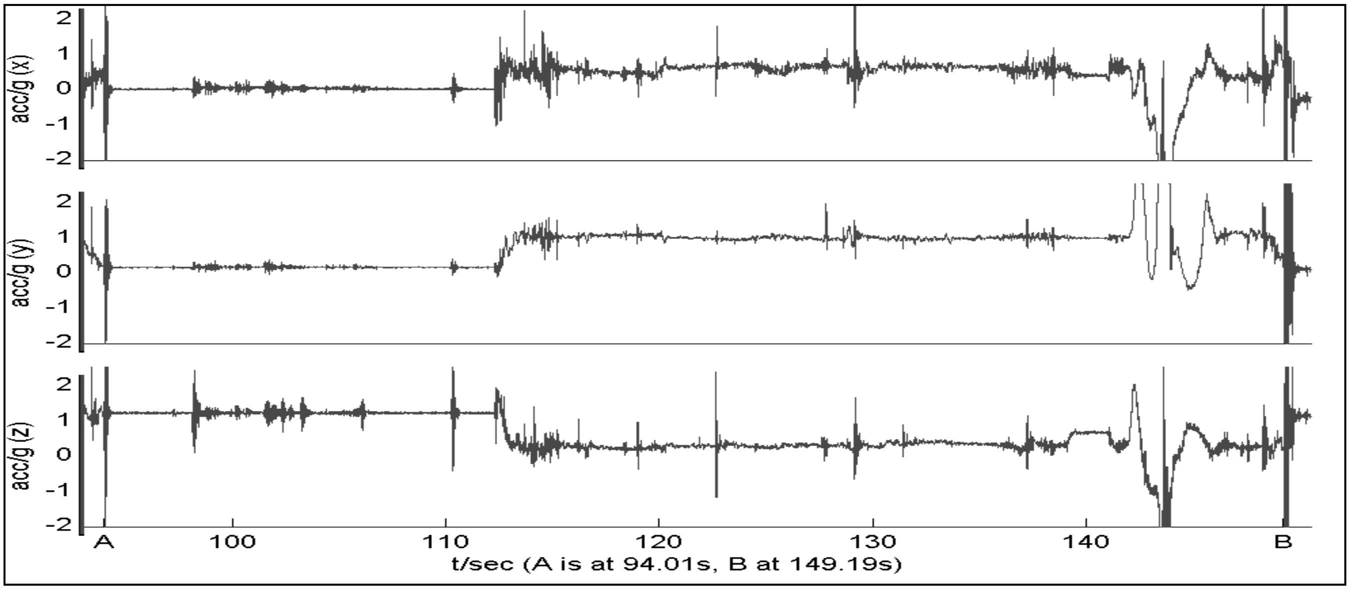

Figure 1. Top-view of NAT-1 device

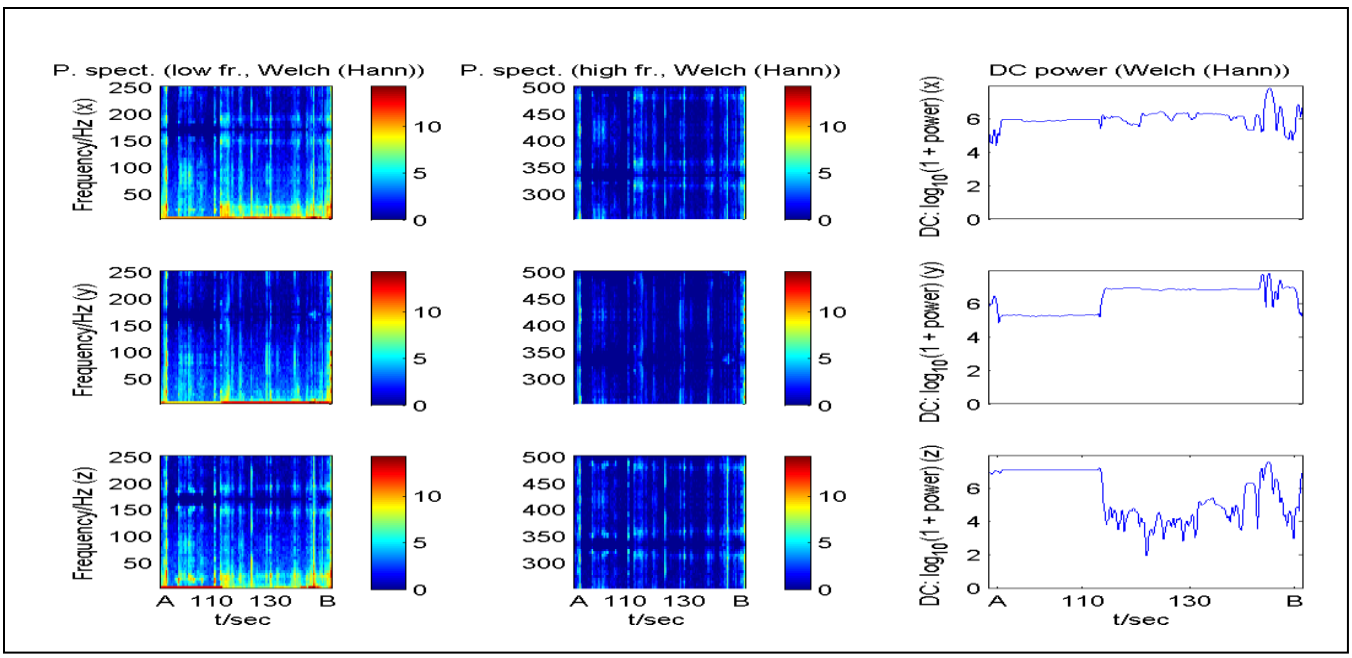

Figure 4c. Accelerometer data collection for Golf Club Swing Test (*Sample rates set to 1500 Hz, with (right) Spectral Plots using Welch function)*

The sensor was attached to a golf club at the mid-point of the club shaft (not at the head). This provides a good measurement point to permit shaft-rotation to be measured on one axis, the back/forward swing on a second axis, and any side motion to be captured by a third axis. The data was gathered from 100 golf-swings of varied competence. Examples are shown in Fig. 4c.

The golf data can be examined and can be seen to represent a back-swing and drive, followed by impact. This data was further analyzed using a spectral analysis method to yield the spectral time-series graphs shown in Fig. 4d. The data was processed using a Welch algorithm [10] and Hann windowing function [11].

VI. Docking Station, Analysis Tools, and Extension Daughter Boards

The NAT device has the advantage of being provided with a bespoke docking station, for download of data from flash via USB. This is illustrated in Fig. 5. Once downloaded, the data can be processed using Cybula Ltd Signal Data Explorer software suite, which can be trained to perform auto detection and classification of signal behaviors and events (see screenshot in Fig. 6). The device programming tool is shown in Fig. 7, and shows a screenshot of the user interface allowing programmability of a wide range of device features.

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A final aspect of the current NAT-1 system suite is the infra-red time-code recording daughterboard. This extremely small add-on (see Fig. 8 for a picture of devices with coin for scale) allows recording of an infrared pulse code stream along-side the analogue channels and accelerometer.

For NAT-1 devices, one accelerometer axis is sacrificed to permit IR time-stamping data recording. The pulse codes recorded are generated from a custom IR key-coding terminal or from triggered sensors in a maze, for example. These may be decoded later by software data analysis.

Future developments for the daughterboard connector could include RF telemetry functions. It is also possible to use the daughterboard connector to act as a micro-backplane to permit multiple NAT-1 devices to be ganged and synchronized to perform something like 16 or 32 channel acquisition, by linking multiple NATs in a synchronization.

VII. Brief Context And State Of The Art

The use of ambulatory EEG monitoring, be it in animal behavior studies or in human patients, is increasingly valuable. This has importance for the role of extended out-patient monitoring of EEG as a diagnostic aid and guide to treatment [12,13]. Recent work in this field includes many wireless approaches to ambulatory monitoring, but these are effectively 'tethered' via a secondary monitoring or recording station [14,15]. Recent literature reports an 8-channel EEG sensor node which “measures 35mm x 30mm x 5mm excluding Li-ion battery” [14], and power consumption in the range of 27-42mW, implying around 35mW for a four-channel system. The NAT, in contrast, consumes approximately 3.4mW with a 4-channel 500Sa/sec sampling regime. This is in part due to the elimination of wireless connection, though the use context of the two devices do not completely overlap – NAT is primarily designed for offline data analysis. Meanwhile, a full-ASIC dedicated solution can outperform NAT in terms of power consumption [15]; but, again, this generally requires a wirelessly tethered auxiliary system in the locale of the patient at all times to receive data. On-board classification and signal event detection has been used to reduce the RF overhead in some devices and systems, such as on-board seizure detection [4]. However, there is significant benefit in having a continuous recording of live data and especially where the purpose is to gather data to inform the development of such diagnostic/classification approaches.

VIII. Conclusions And Ongoing Work

We believe that the NAT-1 is a versatile and very compact device, with a low weight and long-duration high frequency recording capacity. Its application in areas such as EEG, EMG and in more complex monitoring scenarios, such as tremor-motion and EMG signaling in patients with conditions, such as Parkinson's disease, are the areas of greatest interest for this project.

Figure 5. NAT USB docking station

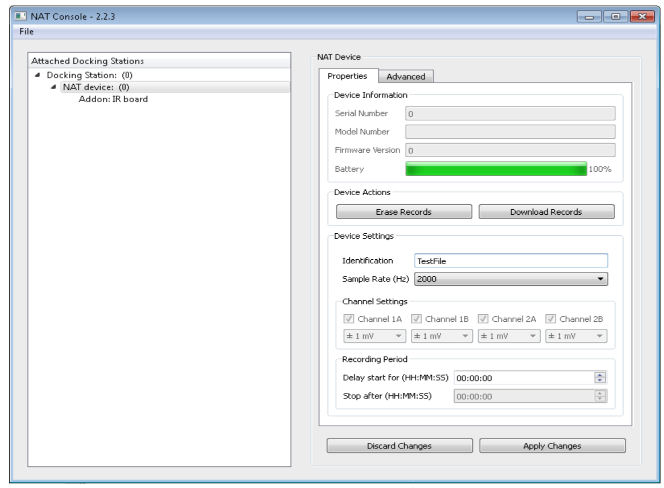

Figure 6. SDE (Signal Data explorer) Software toolset developed by York/Cybula

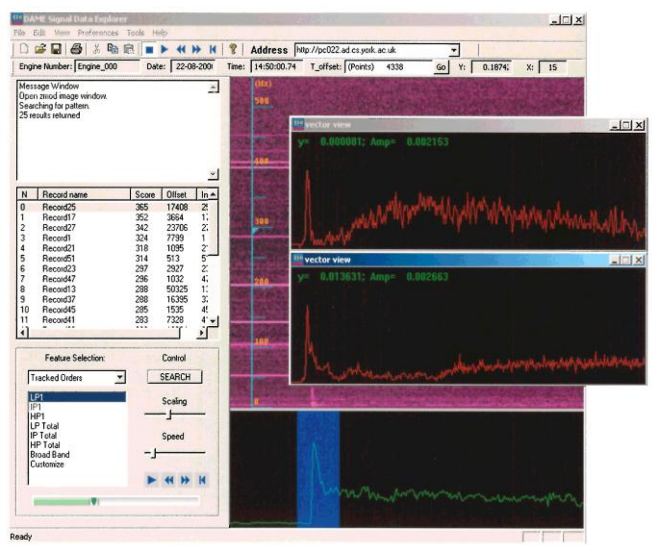

Figure 7. Control Panel Umbilical software showing typical device configuration parameter entry panel.

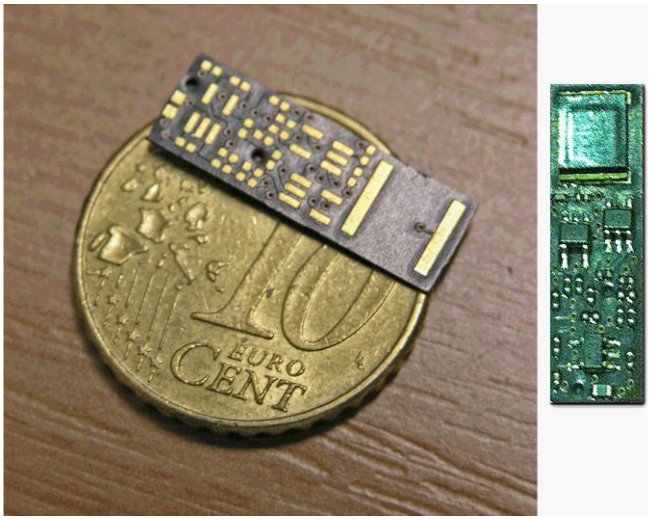

Figure 8. NAT Infra-red Receiver Daughter-Board

The York team [16] and partners CYBULA Ltd. [17] are very interested in developing collaborative partnerships and would welcome enquiries from prospective evaluators and end-users.

Current improvements are focusing upon a revised device design with individually programmable channel gain capabilities. This will allow a wider range of applications and signal ranges to be accepted by the device without the clipping observed in our preliminary EMG tests for example. It also allows for the possibility of multi-sensor recording, with for example scalp electrode EEG on several channels and EMG input with different gain settings on another channel.

The device has also been operated in a live-streaming mode, and to date this has allowed the development of a monitoring station for observing signal behaviors acquired by the device in situ.

Finally, the use of multiple devices is an area we have further interest in expanding. Ganging of multiple devices with synchronization via the expansion connector would allow arbitrary channel combinations, whilst in a live streaming mode, acquiring and logging data from multiple devices simultaneously is possible (though the device is ultimately intended as an untethered ambulatory system unit).

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