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Integration of electrocardiogram and skin conductivity sensors in virtual reality controllers: an open-source prototype and signal quality analysis

Matthieu Mesnage¹, Bertrand Massot¹, Matthieu Blanchard², Pierre Raimbaud², Guillaume Lavoué²

Abstract—This paper presents the Nervous toolkit, an open-source hardware and software initiative to integrate physiological sensors into Virtual Reality (VR) controllers. The toolkit includes electrocardiogram (ECG) and skin conductivity (EDA) sensors designed to assess cardiac and electrodermal activity. Both sensors use a wireless communication and are intended for an easy use in VR experimentations involving physiological data acquisition. An integration into Valve Index controllers is proposed by designing a clip-on accessory, with electrodes placed on the palm and forearm, and a Python package developed to facilitate data collection and streaming. The signal quality was assessed during VR activities, thus revealing an accurate detection of R-peaks on the ECG. However, the EDA integration presented movement-related noise. This variability is dependent on the type of movement, thus providing valuable insights into how different movements affect the signal for further experiments. The study highlights a promising system for non-intrusive, transparent physiological monitoring during VR experiences.

Clinical relevance— This work is intended to provide tools for physiological monitoring in virtual reality, which can be useful for applications such as stress and mental workload assessment in training, rehabilitation contexts, or during psychophysiological studies conducted in virtual environments.

I. INTRODUCTION

A significant number of Virtual Reality (VR) experiments now incorporate physiological feedback through sensors such as electrocardiogram (ECG) or electrodermal activity (EDA), providing valuable insights into users' emotional and physical states [1]–[3]. Complementary to evaluation questionnaires assessing the quality of the virtual reality experience, biofeedback enables the quantification of stress levels, a valuable tool in immersive learning environments [4]. This method is also particularly suited to fields such as exposure therapy and rehabilitation, where stress management is crucial to the therapeutic process [5], [6].

However, integrating sensors presents a considerable challenge, especially in six degrees of freedom (6DOF) VR experiences, i.e., where the user can move and interact in the virtual environment. Optimizing electrode placement is essential to ensure accurate measurements while

preserving the immersive nature of the VR experience and minimizing discomfort associated with electrode placement. At present, some sensor integration methods can be viewed as costly and intrusive, particularly for heart rate and heart rate variability (HR-HRV) measurements, as they often require participants to modify their clothing or wear additional equipment. Whether using wearable devices such as abdominal belts [1] or placing electrodes near the chest [3], integrating sensors into the controllers offers a potentially less intrusive alternative. Moreover, for EDA sensors integration, ergonomics issues arise when electrodes are placed on the fingers, as this interferes with the player's ability to properly hold the controller [3]. Recent innovations have introduced solutions such as palm-hand dry electrodes placed directly on the controllers [2], which hold promise by eliminating the need for players to wear electrodes on the fingers. However, in applications involving user movement, intermittent contact between the hand and the electrode may introduce noise, affecting data quality.

This paper presents the Nervous toolkit¹, an open-hardware, open-source initiative that includes low-cost, low-energy, wireless ECG and EDA sensors, miniaturized for integration into VR controllers, with potential applications beyond VR. As part of this effort, the sensors were integrated into the Valve Index Controllers and tested in a virtual environment with a custom-designed accessory. A user study assessing the quality of signals collected during various activities is also presented, aimed at evaluating the system's ability to accurately measure the user's mental state without disrupting the VR experience.

II. MATERIALS AND METHODS

A. Electronic architecture and software of the sensors

The EDA and ECG sensors were designed to operate on separate electronic circuits to avoid limiting their use to a specific application. Nevertheless, they share a very similar electronic architecture. Furthermore, the size of the Printed Circuit Boards (PCB) as well as the positioning of the connectors, buttons, and LEDs are identical. This allows them to be swapped in a common casing, whether directly in VR controllers or in enclosures to wear the sensor on the wrist. Both sensors make use of the nRF52840 microcontroller from Nordic Semiconductor. This one integrates a Bluetooth Low Energy (BLE) interface, which is used to control the sensor and to transmit the measured signals to a remote device. They share common

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¹<https://github.com/sensors-inl/Nervous-Toolkit>

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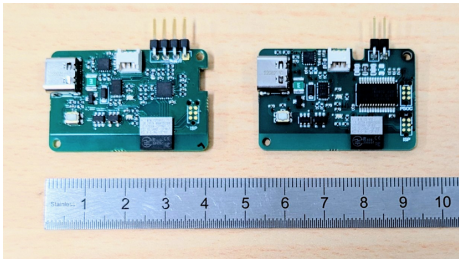


Fig. 1. Pictures of the PCBs for the ECG (left) and EDA sensors (right) with dimensions of 26 mm × 40 mm.

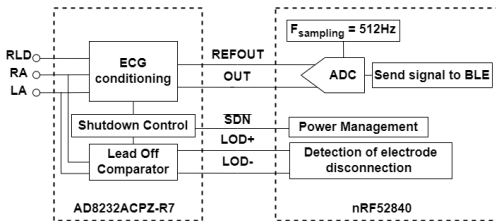


Fig. 2. Flowchart of signal acquisition and processing of the ECG.

hardware functions such as an embedded battery charger, a USB Type-C connector, a fuel gauge for monitoring the battery charge status, a power on/off button, and an RGB LED to indicate the system status. Both PCBs have a size of 26 mm × 40 mm (Fig. 1) and are powered by a 3.7 V LiPo battery with a capacity of 155 mAh. The battery, measuring 4 mm × 20 mm × 25 mm is sized to fit the system form factor.

For the ECG sensor, the signal is conditioned using the AD8232 integrated circuit, which was chosen for its low power consumption and the ability to adjust the topology of the conditioning circuit. In our case, the selection of passive components was made in accordance with the application note provided by the manufacturer, Analog Devices, to prioritise the detection of R-peaks when the measurement is taken from the hands [7]. Thus, the transfer function of the interface circuit includes a 4th-order bandpass filter in the range 7 Hz to 24 Hz, with a maximum gain of 56 dB at 13 Hz. The signal is sampled at a rate of 512 samples per second and transmitted via the Bluetooth Low Energy connection by the nRF52840 (see Fig. 2). The sensor connects to three external electrodes: RA and LA are the measurement electrodes placed on right and left hand, and the RLD one is used as the active reference electrode [8].

For the EDA sensor, the measurement of skin conductivity is based on continuous impedance spectroscopy, a method recently proposed [9]. The programmable component PSoC CY8C4A45PVI-481 from Infineon (formerly Cypress Semiconductors) is used for generating a multi-sinusoidal signal injected through two electrodes via a programmable current source. The current and voltage signals are then conditioned by a transimpedance amplifier and a voltage follower, respectively, before being sampled by the nRF52840 (see Fig. 3). The latter is responsible for calculating the resulting impedance at each of the 16 frequencies that make up the originally generated multi-sinusoidal signal, and for transmitting the values via

the Bluetooth Low Energy connection.

Regarding their respective power consumption, the ECG sensor only draws 0.93 mA when measuring and transmitting a signal, leading to a 7-day battery life. However, the EDA sensor draws 6.12 mA, due to more complex electronics and higher processing power requirements, still providing more than a full day of autonomy. Both consumptions include 0.2 mA for a steady green LED that indicates data transmission over BLE.

To collect signals from sensors via BLE communication on a remote computer, we developed a dedicated Python package named nervous-sensor. This package uses the Bleak Python API for managing BLE connections and communication. Data can be plotted in real-time and stored in a .csv file. A key feature of the package is the ability to broadcast collected signals through a Lab Streaming Layer (LSL) interface, thus facilitating the synchronization with other data sources, such as those from the virtual environment [10]. One major benefit of this feature is that it facilitates the concurrent analysis of behaviour, cognitive state, and the user's environment in VR.

B. Integration on VR controllers

Our research on integrating the measurement system focused on the Valve Index VR controllers. This model features a strap that keeps the controller in contact with the palm, even when the user extends their fingers, creating a constant contact area ideal for electrode placement. Valve provides an additional 3D model² designed to be clipped onto the controllers, originally developed to accommodate larger hands and improve comfort and usability. For our study, we further modified this model to integrate our sensor into the design. Specifically, we incorporated an extension for encapsulating the electronics, added grooves for wire routing, and created openings in the palm area for electrode placement (see Fig. 4). Snap buttons are mounted into the electrode openings to accommodate a wide range of commercially available electrodes.

Early testing with disposable ECG electrodes on the accessory showed that the extremely small signal amplitude on the palms becomes unrecoverable due to additional noise that occurs when the user moves their hands in the Virtual Environment (VE). As a result, some electrodes were moved

²<https://github.com/ValveSoftware/IndexHardware>

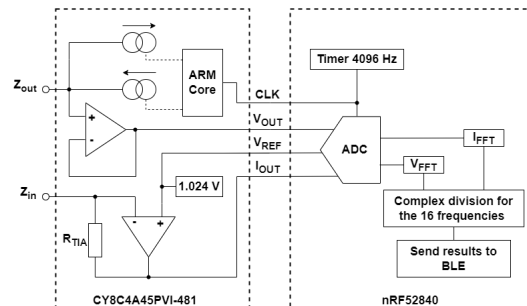


Fig. 3. Flowchart of signal acquisition and processing of skin conductivity.

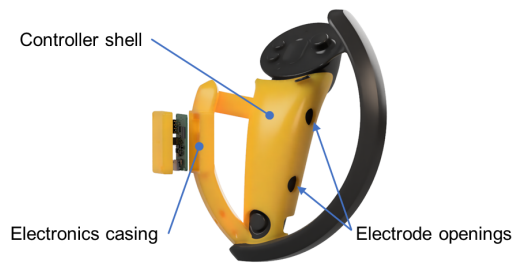


Fig. 4. 3D model of the accessory fitting on the Valve Index controller.

to the forearm instead of all being placed on the controller shell. The overall configuration is as follows: for EDA measurements, the controller houses the EDA board, and the two electrodes for skin conductivity measurement are integrated into the controller shell, as the palm is one of the preferred body sites for electrodermal activity analysis. For ECG measurements, the controller houses the ECG board, but only the RLD electrode is placed in the controller shell, while the RA and LA electrodes are placed directly on the right and left forearms of the user. A cable of 1.8m is used to connect the electrode on the opposite arm from the sensor location (see Fig.5). To minimise noise due to the triboelectric effect of this cable, we used the low-noise Belden 9239 coaxial cable that is shielded to the electrical ground of the sensors. We found that careful choice of the cable, firm attachment of the electrodes on forearm using adhesive tape, and an electrode placement 20 mn prior to the measurement, are deeply required to achieve the performance obtained in the following signal quality tests.

C. Protocol for the evaluation of signal quality

To evaluate the signal quality achieved by these systems in a VR experience, a single protocol was designed for both sensors. The experiment involved 7 healthy volunteers, aged between 22 and 51, including both male and female participants. This protocol was previously approved by the institutional ethics committee of Lyon University (CER UdL) under the number 2024-03-14-003. Each participant was requested to execute it twice: initially with the ECG sensor integration on the left controller, and subsequently with the

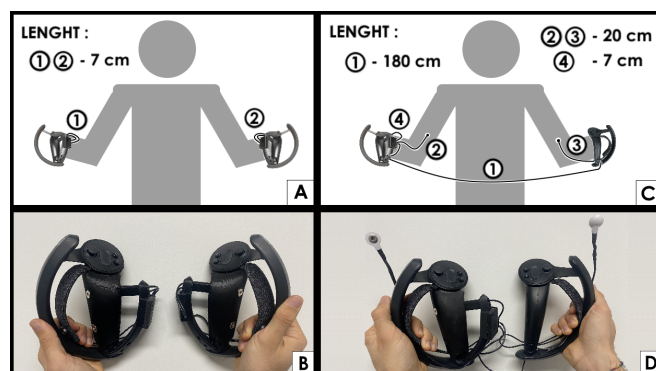


Fig. 5. (A) Schematic of the wiring for EDA electrodes – (B) Picture of the complete mounting of two EDA sensors on the VR controllers – (C) Schematic of the wiring for ECG electrodes – (D) Picture of the complete mounting of ECG sensor on the VR controllers.

EDA integration on both controllers, as shown on Fig. 5. The volunteer stood in the VE and alternated specific hand movements, guided by a virtual character to follow this sequence:

- 1) Standing still (Idle phase) - 1 min;
- 2) Waving a Hello (left arm, then right arm) - 40 s;
- 3) Giving a Thumb up (left thumb, then right thumb) - 50 s;
- 4) Grabbing an Object (left hand, then right hand) - 55 s;
- 5) Walking in the room (left hand immobile first, then right hand immobile) - 55 s;

For both protocols, electrodes were placed 20 minutes before entering the VE for stabilisation of the skin-electrode interface. The electrode model used for ECG was the 3M Red Dot 2560, which provide a firm attachment to the skin, while the electrode selected for EDA were the AMBU White Sensor 40713 which are smaller for placement on the controller shell. For the evaluation of ECG signal quality, we assessed whether the results provide correct hear rate computation results using the Pan and Tompkins algorithm [11]. We specifically computed the percentage of accurate detections made by the algorithm with respect to a manual human R-Peak labeling across the same signal, for each of the five sequences of movements. For the evaluation of skin conductivity quality, both controllers were equipped with two different EDA sensors, allowing skin conductivity to be measured on both hands simultaneously. Although electrodermal activity is known to not be strictly identical on both hands [12], we assumed that the difference in skin conductance responses would not be significant during the Idle phase. Signals were first processed using a 2nd order high-pass filter with a cut-off frequency of 0.08 Hz to remove the baseline which can largely vary between the two signals, due to the difference of site of measurement and electrode-skin interface. The signals were aligned by matching their amplitude in this steady phase. Consequently, any observed differences in movement phases would be primarily attributed to movement artifacts rather than differences in skin conductivity. The similarity of both signals during each movement period was evaluated using a Bland-Altman analysis to extract the median difference and the 95 % limits of agreement (± 1.45 interquartile range) of both signals [13].

III. RESULTS

Regarding the quality of the ECG obtained from the 7 participants across the five movement phases, the Pan and Tompkins algorithm achieved 100 % agreement in R-peak detection with manual detection, except for one subject during the 'Waving a Hello' phase (95 %), and for two subjects during the 'Grabbing an Object' phase (90 % and 95 %, respectively). For the subject for whom detection was most difficult for the algorithm, the signal showed a significantly lower signal-to-noise ratio compared to the other subjects, due to a naturally lower amplitude of the ECG signal. For the EDA evaluation, the Bland-Altman analysis performed on each sequence of the protocol, including the

idle phase, showed an absolute median difference below $0.02\ \mu\text{S}$. This was expected, as the high-pass filter removed the tonic component of the electrodermal activity before analysis. To analyse the similarity of signals obtained from the right and left hands, boxplots of the distribution of the limits of agreement (± 1.45 IQR for non-parametric distribution) are shown in Fig. 6.

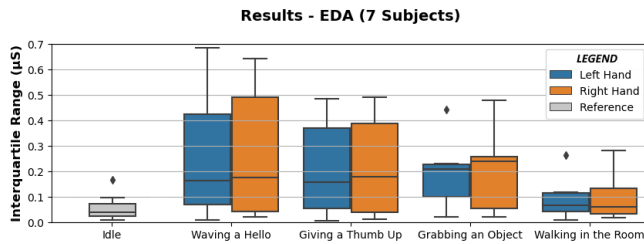


Fig. 6. Results from EDA evaluation protocol

It can be observed that hand movement during the VR experiment has a non-negligible impact on skin conductivity measurements. Indeed, the results for the Idle phase serve as a reference for the similarity that can be obtained between the two hands. However, moving either hand clearly increases the limits of agreement, as shown by the boxplot. The 'Waving Hello' phase exhibited the highest limits of agreement (median $0.17\ \mu\text{S}$, max. $0.7\ \mu\text{S}$), while the 'Walking in the Room' phase showed the lowest (median $0.08\ \mu\text{S}$, max. $0.3\ \mu\text{S}$). These results should also be compared to the amplitude of electrodermal responses, which are the events to be detected in the signal. These responses typically fall within the range of $1\ \mu\text{S}$ to $3\ \mu\text{S}$, although minimal thresholds are commonly set as low as $0.05\ \mu\text{S}$, and even lower amplitudes can be detected using precise, low-noise measurement systems.

IV. DISCUSSION

Regarding the ECG signal, the sensor system, combined with the protocol, led to very good results in terms of quality of detection in our user study. However, it is important to note that the user movements still generate noise and the quality of heart cycle detection is thus highly dependent on the natural amplitude of the signal. To obtain good results we recommend securely attaching the electrodes, using low-noise shielded cables, and placing the electrodes several minutes before conducting the measurements. For the EDA signal, the results showed that placing the electrodes directly on the shell still generates noise during movement, compared to an immobile hand. The primary hypothesis of this study was that the area of the palm where the hand is in constant contact with the shell would be an optimal location for integrating electrodes. However, it was observed that the mechanical constraints induced by the opening and closing of the hand, such as the stretching of the electrode, resulted in higher noise levels than anticipated. Nevertheless, our solution still produces exploitable results with levels of noise below the amplitude of standard electrodermal responses ($1\ \mu\text{S}$ to $3\ \mu\text{S}$). Integrating electrodes with greater robustness

and reduced deformability should allow our system to equal the robustness of conventional electrode placement on the distal phalanx of the fingers.

V. CONCLUSION

We presented here a lightweight, all-in-one, easily implementable, and reproducible design and integration of two physiological sensors attached to Valve Index controllers, measuring electrodermal and cardiac activity in a VE, to collect physiological data for the evaluation of emotional and physical states. The design of an additional support, which clips onto controllers and features slots for the electrodes, helped reduce the number of wires from the sensors, thereby improving signal routing from measurement points to the sensors. From evaluation, our test results are promising and would benefit from electrode improvements. Conducting experiment with a larger sample of participants would also allow for a better characterisation of this promising design and integration solution.

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