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A new device for the care of Congenital Central Hypoventilation Syndrome patients during sleep

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Abstract— **Congenital Central Hypoventilation Syndrome (CCHS) is a genetic disease that causes an autonomous nervous system dysregulation. Patients are unable to have a correct ventilation, especially during sleep, facing risk of death. Therefore, most of them are mechanically ventilated during night and their blood oxygenation is monitored, while a supervisor keeps watch over them. If low oxygen levels are detected by the pulse-oximeter, an alarm fires; the supervisor deals with the situation and, if there is neither a technical problem nor a false alarm, wakes the subject, as CCHS patients usually recover from hypoxia when roused from sleep. During a single night multiple alarms may occur, causing fractioned sleep for the subject and a lasting state of anxiety for supervisors.**

In this work we introduce a novel device that can: acquire real-time data from a pulse-oximeter; provide a multisensory stimulation (e.g. by means of an air fan, a vibrating pillow, and a buzzer), if saturation falls under a threshold; stop the stimulation if oxygenation recovers; wake up the patient or the supervisor if the suffering state lasts beyond a safe interval.

The main aim of this work is to lessen the number of awakenings, improving the quality of sleep and life for patients and their supervisors, and to increase young and adult CCHS patients autonomy.

Initial testing of the device on a CCHS patient and his supervisor has provided encouraging preliminary results.

I. Introduction

Congenital Central Hypoventilation Syndrome (CCHS) is a genetic disease, caused by a mutation in the PHOX2B gene, that leads to an autonomic nervous system (ANS) dysregulation [1][2][3]. The most pertinent problem in CCHS concerns breathing control. Particularly these individuals show an abnormal ventilatory response to hypercapnia and hypoxia that may cause apnea crisis and cerebral injuries with a severe impact on subject health. Deep sleep stages are the most critical, while patients usually demonstrate adequate ventilation during wake [1]. Therefore, mechanical ventilators are connected to patients during sleep [4][5], trying to provide sufficient oxygen exchange in the lungs [1][4]. Contemporarily oxy-hemoglobin blood concentration (SpO_2) is monitored, to serve as an alarm if blood oxygenation falls under a safety threshold. A caregiver or a parent is needed all night long, especially for children and young patients. His role is to serve as a supervisor and to take proper action if the situation worsens. During a single night, ventilator or pulse-oximeter alarms may activate several times, for different causes. For example, patient movements may cause artifacts on SpO_2 measures producing an alarm like an emerging hypoxia. The result is fractioned sleep for supervisors and patients, accompanied by an increasing state of stress and anxiety [5]. Since CCHS is a chronic disease, further problems originate from habituation: patients and supervisors can become less responsive to frequent and repeated stimuli. This can lead to disregarding alarms, underevaluating situations and ultimately failing to react, posing severe risks to patients health and life.

Nowadays the only alarm systems available for CCHS patients are the ones integrated in ventilator and pulse-oximeter, showing the previous discussed limitations. In this work we introduce a novel device that may help face these problems. The objective is to provide a device that can: actuate different multisensory stimulation strategies, depending on patient conditions and SpO2 level; stop the stimulation if SpO2 level recovers; and wake up the patient or the supervisor if the suffering state lasts beyond a safe interval. We will also investigate the possibility that the device be able to induce spontaneous ventilation recovery through multisensory stimulation, as recent studies demonstrated an improvement in breathing of CHHS patients when doing active exercise [6] or passive motion during sleep [7][8].

II. Materials and Methods

A. Device architecture

A scheme of the device main parts and their interconnections is shown in Fig. 1, whereas in Fig. 2 is represented the schematic of the hardware that we had realized. The core of the developed device is an Android tablet, that acquires SpO_2 levels from a commercial pulse-oximeter and dynamically activates different actuators depending on patient current condition. We chose a tablet pc CEM2918S1 with Android 2.3.1 (API Level 9), 1.2 GHz single core processor, 512 MB RAM and a 7 inches capacitive touch screen. This choice is due to the fact that: its operating system comes with a lot of primitives, which make it possible to easily use a number of peripherals and interfaces; it is attractive and easy to use for everybody, thanks to the standard interface composed of a touchscreen

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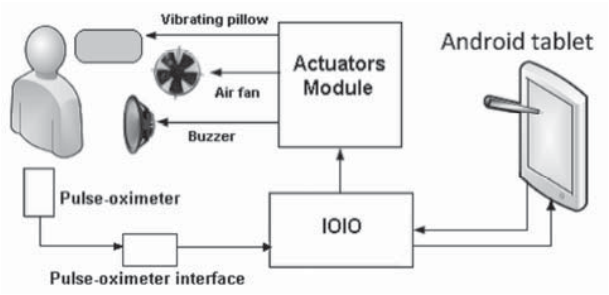

Figure 1: Scheme of the main parts of the device and their interconnections

and an LCD display; and finally it has a reasonable price (about 150$). A specific application running on the Android tablet was designed to supply intelligence to the system. It decodes the $Sp0_2$ data when needed, implements the stimulation strategies and consequently manages the actuators, provides the user interface through its touchscreen, allowing the setting of monitoring and stimulation parameters and showing on a graph the saturation data. The software logs every activity, storing any useful information to evaluate the most effective stimulation strategies.

The IOIO module is an electronic board (hardware version SPRK0016) with a microcontroller that runs firmware (version IOIO0310) designed to communicate with an Android device through a standard USB port. This board gives any Android device the capability of acquiring analog and digital signals and communicating with other devices through standard peripheral ports (USART, SPI, etc.). Moreover, easy-to-use ad hoc libraries for IOIO management are available, such as the IOIO v1.4 and the IOIOBT v1.5 for the Anywhere Software Basic4Android IDE. The IOIO represents the interface between the Android tablet and the external modules. It uses a digital input to receive a TTL signal coding SpO_2 levels from the pulse-oximeter interface module. Alternatively it can receive an analog signal directly from the pulse-oximeter device when a digital signal is not available. A number of IOIO digital outputs are used to control the actuators module. They carry simple high or low levels or PWM signals, depending on the type of actuator to be driven.

The pulse-oximeter interface (Fig. 2) connects the pulse-oximeter device to the IOIO board. More recent pulse-oximeters show a digital output carrying SpO_2 levels in a codified way, where data coding is different from manufacturer to manufacturer and even from device to device. A larger number of pulse-oximeters from different brands have an analog output which codifies SpO_2 levels with a voltage in the range from 0 to 1 V. This analog output is affected by reduced accuracy and greater sensitivity to ambient noise with respect to the digital one. On the other hand the use of digital outputs require the development of customized decoding algorithms for each oximeter. Our device is able to manage both kinds of signal either directly with the IOIO board (analog signals) or through the pulse-oximeter interface module (digital signals). The pulse-oximeter interface module (Maxim MAX3232CUE) transforms the RS232 signal from the pulse-oximeter to a TTL signal compatible with the IOIO board. Till now we have developed protocols for the acquisition of digital data from two common commercial pulse-oximeters: Nonin Avant 4000 and Nonin Avant 9600.

The actuators module (Fig. 2) provides the electric power circuits to drive the actuators. IOIO digital outputs are

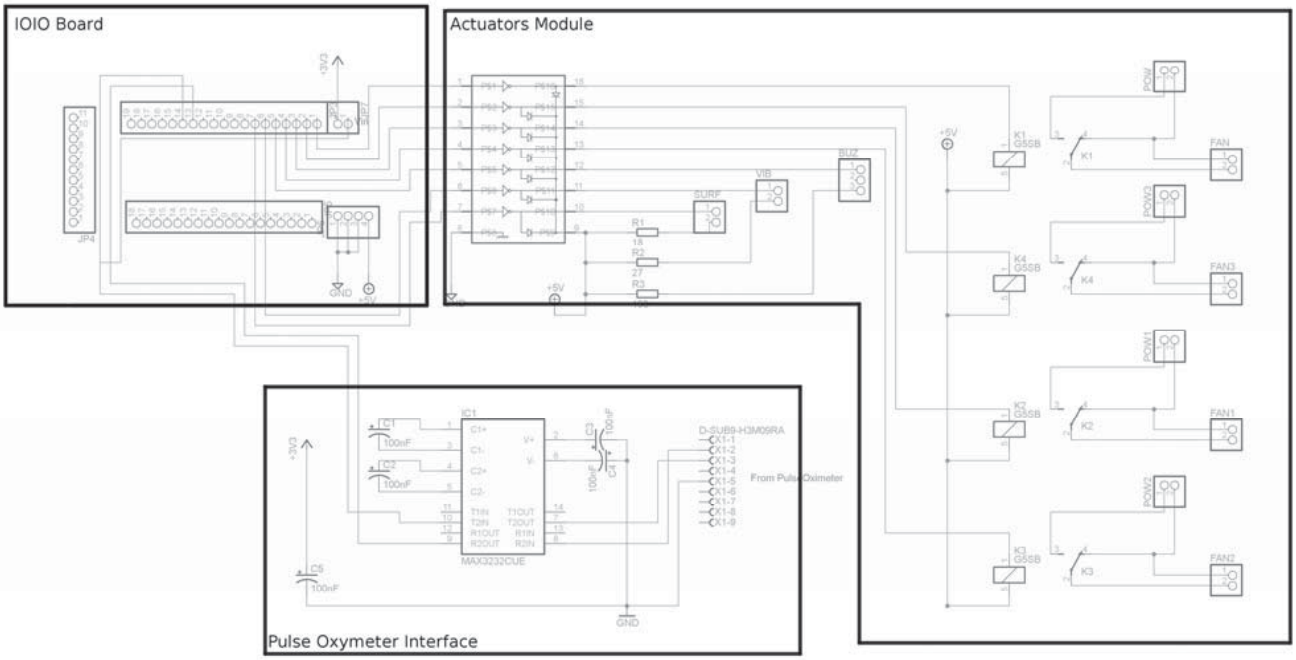

Figure 2: Hardware schematic and description blocks

directly connected to the base of darlington transistors that switch the actuators on and off, or in some cases the relays that command them. When an IOIO output is high, the actuator is activated, when it is low, the actuator is deactivated. The developed system is able to host and control any kind of electrical appliance, thanks to the use of relays on the actuators board, which allows to activate independent channels, each with its own power supply voltage level. If the appliance requires a high frequency square wave as input, a relay is not suitable because its switching time is too long compared to the frequency needed by the device to properly work. For example, a buzzer resonant at 2 kHz, which is in the range of the best human audible sound frequencies, needs a switching time shorter than 250 μs, well beyond the capability of any relay. In this case the appliance is connected directly to the darlington transistor, eventually with a small resistor to limit the current and prevent overheating.

We chose a number of different actuators, according to the requirements to be able to stimulate many sensory channels (acoustic, tactile, etc.) in a varied mode. Particularly, three different actuators are currently used: a piezoelectric buzzer (CET12A3.5), with a resonance frequency of 2048 Hz, driven by a square wave between 0 and 5 V, directly connected to the darlington transistor and activated by a PWM output from the IOIO, that provides acoustic stimuli; a small air fan (Blower – Squirrel Cage, Sparkfun Electronics), outlier diameter 33 mm, rated airflow 16 CFM, fan speed 3000-3500 rpm, operated at 12 V in continuous current and connected to a relay on the actuators board, that sends an air flow to the subject's face, providing tactile stimulation; a commercial vibrating massage pillow (Pillow-massager E.R. Rovera), dimensions 30x16.5x13 cm, driven by a square wave between 0 and 5 V, directly connected to the darlington transistor and activated by a PWM output from the IOIO.

B. *Stimulation strategy*

The stimulation strategy was designed to give importance to both the total time when SpO_2 is below the normal threshold and the SpO_2 value itself, since even a mild hypoxia represents a severe condition for the patient if it goes on for a long time [9,10]. For this reason four different severity levels (SL), that can be set by the user, were defined in order to describe the conditions that may occur. Each state is characterized by two parameters: the minimum SpO_2 value and the maximum time allowed for SpO_2 to remain between the minimum value and a normal value. The state SL0, normal state, is defined by one parameter only: SpO_2 normal value (usually 95%). The other SL states are: SL1, mild hypoxia (possible settings: $95\% > SpO_2 \geq 90\%$, maximum allowed time: 1.5 minutes); SL2, moderate hypoxia (possible settings: $90\% > SpO_2 \geq 85\%$, maximum allowed time: 1 minute); SL3, severe hypoxia (possible settings: $85\% > SpO_2$, maximum allowed time: 0).

The device goes from one SL to another, according to the patient's conditions. When the condition worsens beyond the SL thresholds, the SL state immediately increases. On the contrary, when SpO_2 level rises, the SL state does not decrease until SL0 condition is reached; at that point the device suddenly returns to SL0 state. An example of this strategy is shown in Fig. 3. In addition, a set of stimulation parameters is associated to each SL state, including which actuators to use and stimuli intensity and frequency, thus allowing stimuli customization for each subject. For example, in SL1 state you can choose to use just the vibrating pillow, with low massage intensity, in SL2 you can increase the pillow stimulation intensity and add another actuator, such as the air fan, and so on.

III. Results

Initial testing of the device was performed developing a specific software able to simulate the data generated by a

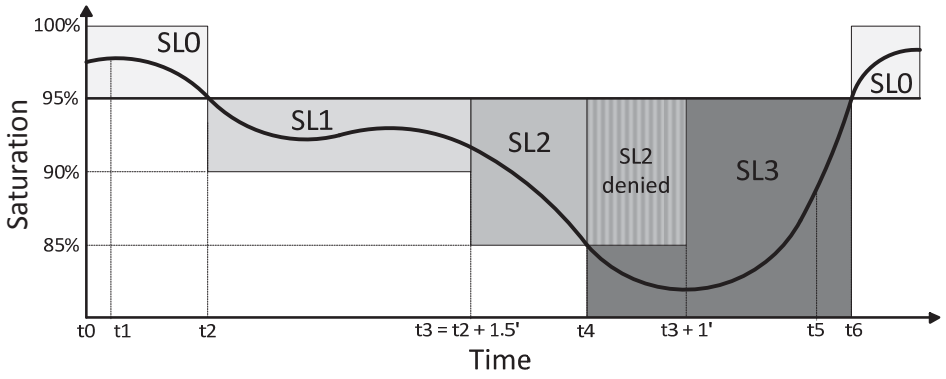

Figure 3: Example of stimulation strategy with four SL states. SpO_2 values are represented by the thick line.
Starting from time t0, device in SL0 state, we observe:
- t1: device in SL0, normal condition (SpO2(t1) > 95%);
- t2: device enters SL1 state, mild hypoxia ($90\% < SpO_2(t2) < 95\%$);
- t3 :device enters SL2 state, moderate hypoxia (t3 = t2 + 1.5');
- t4 :device enters SL3 state, severe hypoxia ($SpO_2(t4) < 85\%$);
- t5: device in SL3 state (even if $SpO_2(t5) > 85\%$, the device cannot return to a minor SL state until SpO_2 completely recovers. For the same reason, the dashed area of SL2 becomes "denied" after SpO_2 entering SL3 state).
- t6: device enters SL0 state, normal condition ($SpO_2(t6) > 95\%$)

pulse-oximeter. Elaboration and management of the saturation data by the Android application were verified, checking proper activation of the actuators. Different situations (e.g. mild and high SpO_2 level variations, pulse-oximeter disconnection, etc.) were simulated till the device behavior matched the expected one. A second test consisted in experiencing effects of different actuators stimulations by a young healthy volunteer subject during several nights, in order to prove their tolerability and efficacy. No problems related to the given stimulations were reported and the subject found every kind of stimuli quite comfortable and tolerable, even at the maximum intensity. Moreover actuators demonstrated their efficacy in waking up the subject. The third step, which is still going on, involved a volunteering family of a CCHS patient. The device was interfaced with the patient's pulse-oximeter and the actuators were initially placed near the caregiver. The caregiver has already reported a better quality of sleep and resting sensation in the morning, as a consequence of both reduction of false alarms and gentle and progressive awakening in alarm conditions.

IV. DISCUSSION

A new device was built with the objective to improve quality of life for CCHS patients and their caregivers, by making it easier to manage nighttime hypoventilation events. The key feature is to combine multiple sensory stimulations, trying to be more effective than traditional acoustic alarms. In particular we aim to progressively increase stimulation, waking up the subject or the caregiver only when really needed and as gentle as possible. To achieve these purpose we chose different actuators, whose stimulation parameters are fully configurable by the user through a software interface, in order to suit individual characteristics. Preliminary testing of the device by a healthy subject and by the family of a CCHS patient seems to confirm its efficacy in facilitating a comfortable awakening by means of different types of stimulations. In the case of the CCHS patient, the device also showed its potential in reducing false alarms. Moreover the caregiver, that usually go to sleep with the awareness that someone else's life depends on him, reported a subjective reduction of anxiety and stress. Many improvements suggested by the caregiver have already been adopted, such as sequential activation of every actuator to verify its functioning before night use, or temporary suspension of stimulation to allow handling the patient without any disturbance when a desaturation may occur.

Further planned testing will investigate customizing system configuration for different kinds of patients and for the evolving situations of each patients.

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