Proc. of the 7thWorkshop on Intelligent Solutions in Embedded Systems (WISES 09) Ancona, Italy, June 25-26, 2009 (Best Paper).

Embedded data logging platform for research in diving physiology

B. Kuch[1], R. Bedini[2/3], A. L'Abbate[3], M. Wagner[4], G. Buttazzo[1], A. Sieber[2]

[1] Scuola Superiore Sant'Anna - RETIS Lab, Italy
[2] CNR - Institute of Clinical Physiology, Italy
[3] Scuola Superiore Sant'Anna - Extreme Center, Italy
[4] University of Applied Science Frankfurt, Germany

***Abstract*—The present paper describes the development of an embedded data logging platform for research in diving physiology. It records oxygen saturation and other physiological parameters like heart rate and electrocardiography, plus physical parameters like water temperature and water pressure in real-time. All measured data is stored on SD-Card in textfiles. Thus easy processing with standard programs like MatLab or LabVIEW is assured. The housing is waterproof and pressure resistant to more than 20bar (breath-hold divers have already passed the 200m mark). It is small, lightweight, power aware and easy to use. Moreover with a standard 1 GB SD-Card the minimum recording capacity is more than 72 hours.**

I. Introduction

Medical concerns about professional (commercial, scientific, rescue, etc.) as well as recreational diving safety derives from two major shortcomings: scanty knowledge of diving physiology and lack of monitoring of vital parameters during diving. Both deficiencies are virtually related to the total absence of instrumentation suitable for underwater measurements of simple but crucial physiological parameters such as heart rate, blood pressure, cardiac function, blood oxygen saturation etc. Actually, none of the available clinical devices used in everyday clinical practice for assessing health status can be used underwater because of a variety of problems related to the liquid environment, its salinity and the high hydrostatic pressure. Thus, with regard to performance of physiological measurements, underwater medicine is back to centuries ago.

In the lack of direct measurements, the results of series of 'models' of underwater diving are considered as valid surrogate and inferences from the clinical world are commonly adopted. Unfortunately, both processes are intrinsically uncertain and scientifically incorrect. Thus, the transfer to the underwater environment of routine clinical instruments would represent a great advancement, both in terms of knowledge and safety, just as it already occurred in space medicine. This task requires designing novel underwater diagnostic and monitoring instrumentation and developing ad hoc support infrastructure. Beyond the design of waterproof instruments, special attention must be paid to selecting, placing and protecting the sensors and transducers especially for long term monitoring.

Measurement of underwater blood pressure was detailed somewhere else [1]. The idea of the present work was to develop a platform that is able to record physiological parameters, but also physical parameters like water temperature and water pressure and store them on a suitable memory. Minimum requested recording time is 8 hours.

For what concerns diving, O2 is in special interest. In normal conditions more than 98% of the O2 in the blood normally binds to Hemoglobin (Hb) in the red blood cells. The rest is dissolved in plasma. In arterial blood, at a normal pO2 of 13 kPa, the arterial O2 saturation of Hemoglobin (SaO2) is about 97.5%. In the venous blood the pO2 drops to 5 kPa which corresponds to a venous O2 saturation of Hemoglobin (SvO2) of approximately 75%. Thus SaO2 reflects the amount of O2 that blood can deliver to the tissues. The maximum possible arterial oxygen saturation depends on the partial pressure of O2 in the gas inside the lungs. The critical value of pO2 inside the lungs should not be fallen below. Otherwise the SO2 will rapidly decrease and may lead to vasoconstriction [2].

During breathhold dives in shallow waters after excessive hyperventilation, the breathing reflex occurs with a time delay. This may help to increase the overall possible diving time, but at the end of the dive the pO2 inside the lungs can reach dangerous low levels that may result in a blackout. In deep breathhold dives the pO2 inside the lungs drops rapidly during ascend. Many accidents occurred during the last meters before surfacing, because of the quick drop of the relative pressure [3].

ECG recording underwater requires special attention to both, the recorder and the electrodes. For electrical biopotential processing, an amplifier with a high-input impedance is necessary. Water (especially sea (salt) water) represents a good electrical (ionic) conductor means with respect to the typical ECG electrode-skin impedance. For example the impedance between two metal electrodes (with each a surface of about 1 cm^2) may drop to some hundred Ω in fresh water and to values below 10 Ω in salt water. From the electrical point of view, the low resistance of water is in parallel with the amplifiers input impedance i.e. it acts like a shortcut for poorly insulated electrodes as a consequence the recording of significant biopotentials becomes impossible. Thus, without a suitable electrical insulation, ECG signal recording on a water immersed body is difficult (fresh water) to impossible (sea water), even if the diver uses a typical humid neoprene suit. Moreover, putative field tests on large diver cohorts require cheap electrodes and effective insulation.

Authors first attempts were based on the use of adhesive electrodes, clinically used for electro-stimulation, which were well insulated with silicon grease. Signal quality was adequate, however several limitations manifested: the electrodes high cost, the low acceptance by the divers, the difficulty of removing silicon grease from diving suits. Thus, we used standard ECG (self-) adhesive electrodes together with a suitable insulation technique. The two component impression material [Elite H-D+, Zhermack Hydrphilic Vinyl Polysiloxane] was chosen for its suitable characteristics like fast curing, biocompatibility, and waterproof [4].

II. METHODS

A. Hardware

The main idea for the novel physiological data recorder was to combine a two channel ECG with a pulseoximeter and a pressure sensor (see figure 1). A suitable basis for in field physiological recordings are PDAs together with exiting interfaces. Unfortunately PDAs are neither water nor pressure resistent and underwater housings are not available. Additionally PDAs are bulky and have only a short operation time. An alternative is the development of an dedicated embedded system, which is as small as possible, so that a diver can carry it easily, without getting disturbed during a dive. Since some field tests require long term recording, overall power consumption is an issue. Thus a low power 8-bit microcontroller was chosen as core element.

1) Data logging module: The core component is a hardware module with an Atmel ATmega644p 8-bit RISC microcontroller [Atmel] with the following specifications:

- 4 Kbytes SRAM
- 2 Kbyte EEPROM
- Up to 20 MIPS Throughput at 20 MHz
- Power consumption at 1 Mhz $\approx$ 0.4 mA in Active Mode

A secure digital memory card (SD-Card) connector is connected to the serial peripheral interface (SPI) of the microprocessor. Low-drop, linear regualtors are used to provide 3.3 V. For visualization of active data a 16x3 alphanumerical display is integrated on the board and interfaced via software SPI to dedicate the microprocessor's inbuilt SPI solely to the SD-Card. For depth and temperature measurement a digital sensor was integrated [Intersema MS5541B, Switzerland]. It is specified for a depth of 150 m, but unofficially depth measurements down to 330m are possible. The overall low power consumption allows powering the whole circuit via a single LiIon battery. The hole device is housed in a lexan tube.

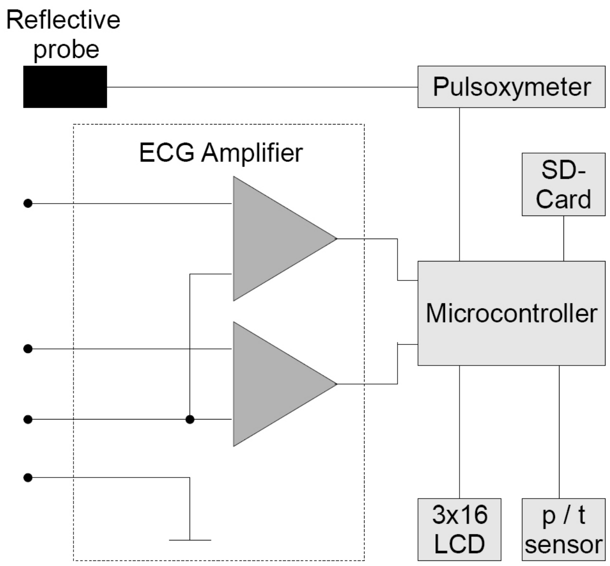

Fig. 1. Principle design of the module

2) SO2 measurement: Clinical SO2 meters (pulseoximeters) are normally based on transmissive light absorbance measurements with red and near infra-red light. Probes are usually attached on the ear lobe or on a finger [5][6]. O2 saturation while breath holding was already investigated in [7]. There a standard transmissive pulsoxymeter was used.

Underwater tests were carried out using standard transmissive pulseoximeter probes attached to the finger but did not produce significant data. Physiological adoptions to immersion in cold water are understood under the term ”diving response”. The vasoconstriction phenomenon, where peripheral parts are most affected, reduces the peripheral blood flow thus inhibits SO2 measurements on a finger. Immersions in cold water may further intensify vasoconstriction.

An alternative to transmissive pulseoxymetry is reflective pulseoxymetry. Reflectance pulsoxymetry is not based on transmissive absorbance anymore. Light transmitter and receiver are situated in a probe in a short distance like 8 mm next to each other. Light is transmitted into the underlying tissue and the reflected light is received and measured. The intensity depends then on the O2 saturation of the blood in the underlying tissues. For placing the reflective probe it is possible to select particular parts of the head that are certainly less affected by vasoconstriction and can be easily protected from cold water temperature (i.e. the glabellar or temple artery zones).

For the prototype a commercial pulseoximeter module [OEM III, Nonin] is chosen. It is interfaced to the microcontroller via USART at 9600 Bit/s. To avoid the measurement problem caused by the ”diving response” a reflectance probe [8000R, Nonin] was chosen, which can be placed on the forehead or the temple. Due to its small size integration in a commercial diving mask is possible. Alternatively it may also be glued directly to the skin with adhesive tape.

3) ECG measurement: The data logging module has to record 2 different ECG channels. The analogue part of one ECG channel consists of one instrumentation amplifier [AD623, Analog Devices], a bandpass filter (2Hz ... 100Hz) and an operation amplifier to level the ECG signal to the 0-3.3V input range of the microcontrollers 10 Bit AD converter. The ADC is read in with 2 single ended AD channels.

B. Software

1) Firmware: The main functionally of the data logging module is to

- to start and read out a raw temperature measurement in 1sec intervals
- to start and read out a raw pressure measurement in 1sec intervals
- to convert the raw temperature values into grad Celsius
- to convert the raw pressure values into mbar
- to read out ECG channel 1 at up to 500Hz
- to read out ECG channel 2 at up to 500Hz
- to store all measurements in a FAT16 Text file on SD-Card

The firmware of the module is developed in C with the GNU C compiler under AVR Studio 4.13 [Atmel]. ECG channels are sampled with 500Hz each. Parallel read out of several channels of the microcontroller is not possible, thus the channels are read out one after the other in 1ms intervals. The pressure/temperature sensor has to be read out in 1 second intervals. Additionally every second the pulsoximeter sends the measured heart rate and oxygen saturation via USART to the microcontroller. Quasi in parallel to that, the data has to be visualized on the display and stored on SD card.

Storing data on SD-Card can be done in 3 different ways. One way is to simply write the data into the memory blocks. This method is fast, but since this method does not use a FAT file system, data processing afterwards is complicated. Using a FAT filesystem to store measurements is more efficient, because the data is stored in a file and the data access via PC-applications is uncomplicated. Data storage in a FAT filesystem is possible in 2 ways - storing the data in binary or in ASCII form in a file. For the prototype the last opportunity was chosen as it allows easy processing. Data is stored in a FAT16 filesystem in ASCII format in hexadecimal values and the data is written in 512 Bytes blocks. Measurements are stored in a buffer. As soon as the buffer size is 512 Bytes, the block is written to the SD-Card. Storage of 1 block takes up to 18 ms.

Advanced scheduling is necessary, to be able to handle all these tasks within an 8 Bit RISC microcontroller operating at 8 MHz. To achieve a precise timing of analogue sampling of the ECG, the AD conversions are interrupt controlled. The internal Timer2 of the ATmega644p is triggered every 1ms and creates an interrupt. The last converted ADC value of one channel is then read out and stored in a FIFO buffer and the conversion of the other channel is initiated. As soon as there are 2x10 entries in the FIFO buffer, the data is stored on SD-Card.

Considering a sampling frequency of 500 Hz, data storage occurs in intervals of 20 ms. Writing a data string on SD-Card takes up to 18 ms, thus there is not much time left. To avoid resource conflicts between the complex data management and storage, it is important to schedule all other procedures carefully. For each task only a small time window can be dedicated, as in the worst case only 2 ms (20 ms intervals 18 ms for data storage) are left. Fortunately the other procedures do not need such a high sampling frequency like the ECG processing. The pulseoximeter sends heart rate and oxygen saturation every second via USART. That is the reason why all other procedures are triggered in 1 second intervals, too. Since the time window is 2 ms and the interval time for everything, which does not correspond to ECG recording is 1 second, all other processes are distributed into <2 ms long tasks and triggered by a scheduler within the 1 second interval (see figure 2).

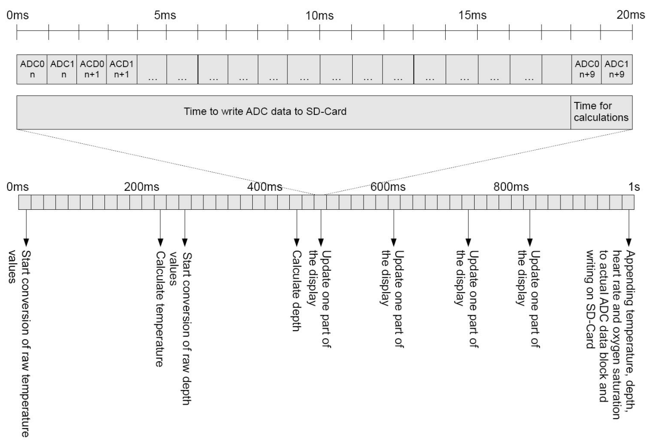

Fig. 2. Software scheduler to trigger time critical tasks

At first the temperature and pressure is measured. The MS5541B needs up to 40 μs to measure the raw temperature/pressure. Since this is too long, the measurement procedure is split into starting, reading and converting the measured value into a usable value. Afterwards the display is updated in 4 tasks. And last but no least the received heart rate and oxygen saturation is appended together with temperature and pressure to the actual ADC data block and written on SD-Card.

The systems runs as long as it is switched into standby mode. This is done by an external interrupt on INT0. A reed contact together with a magnet is used to initiate standby mode. In underwater applications magnetic switches are preferred as they require no mechanical connection to a switch thus avoiding o-rings. To wake up the system, only an additional external interrupt via INT0 is required. The hole program flow is shown at Figure 3.

and converted from hexadecimal to decimal values. Later on these values are shown in six graphs.

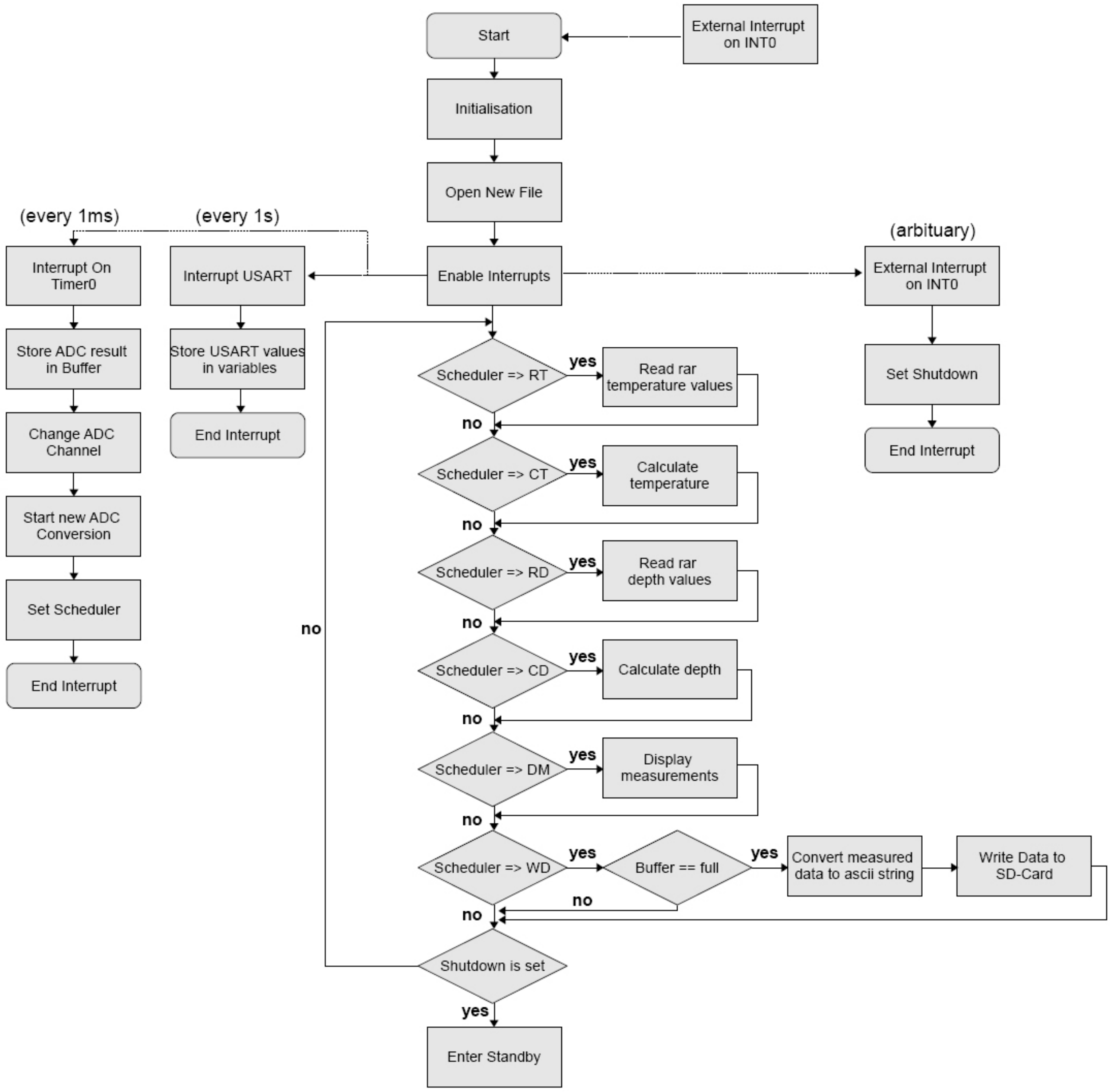

Fig. 3. Program flow of the prototype

C. Data Processing

For post dive data visualization and processing a graphical user interface was developed under National Instruments LabVIEW 8.5. In six graphs depth, temperature, SO2, heart rate prole and the two ECG channels are detailed.

The software reads the data, line by line, which is originally stored on SD-Card. This data is loaded into system memory

Figure 4 shows a screen shot of the graphical user interface. The six graphs visualize the measured values, which were stored on SD-Card. The first and second graph show both ECG channels. The third graph shows the heart rate. The fourth and fifth graph visualize oxygen saturation and depth. The last graph visualizes the environmental temperature. The graphs are connected to each other. By scrolling through one graph all other graphs are scrolled, too. Thus, on an arbitrary point during a recorded dive, all measured values are visible.

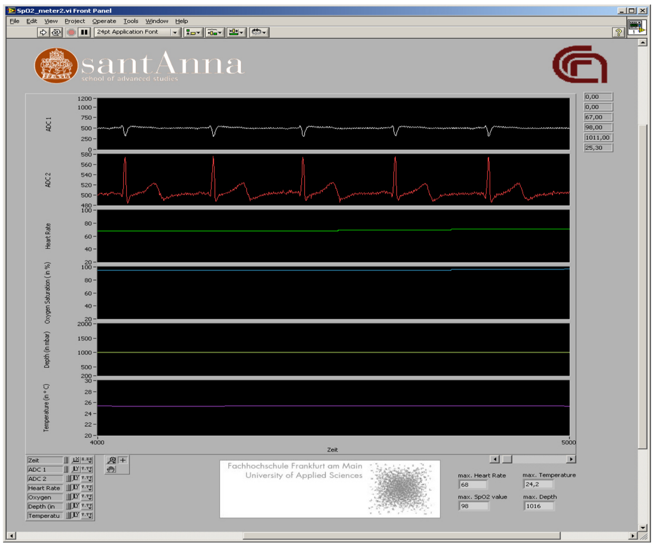

Fig. 4. LabView software for data processing

D. Validation

Figure 5 shows the validation of the device in the public swimming pool of Pisa, Italy. Volunteer apnoe divers of the Italia Apnoe Diving Academy were chosen as subjects. Measurement results were compared to processed results of a commercial available pulseoximeter [ChipOx, Weinmann Medical Technology]. Since a ChipOx pulseoximeter measures pO2 via a transmissive sensor at the fingertip, which is affected by vasoconstriction, comparative measurements could only be performed in warm water. Moreover the reference pulseoximeter was connected via cable on a laptop and the fingertip sensor was pressure / water resistent only up to 1 m. Thus test were only performed in static apnoe.

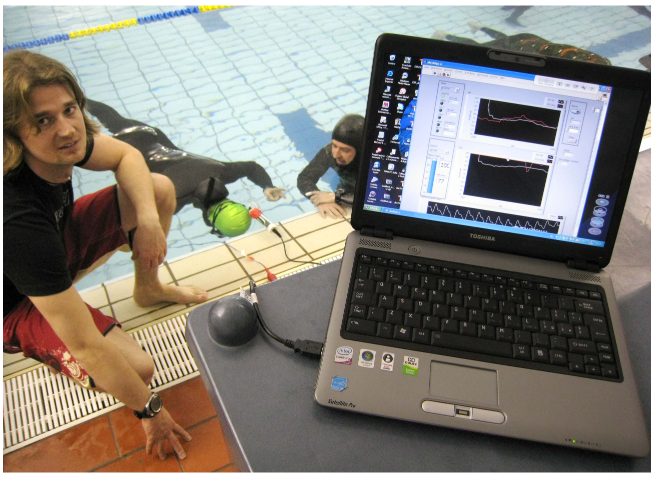

Fig. 5. Validation of the pulsoximeter part of the prototype

III. Results

A prototype (figure 6) was build and housed in a Lexan tube with 42 mm outer diameter and a length of 100 mm. The tube is rated to 200 m. The device is powered by 3x1.5V rechargeable AAA batteries (900 mAh). The overall power consumption is approximately 30 mA which allows 30 h continuous recording. For the ECG two sampling frequencies, either 250 Hz or 500 Hz can be selected. This result in a data storage rate of 2 respectively 4 kByte/s. SO2, heart rate, depth and temperature are recorded with 0.5 Hz.

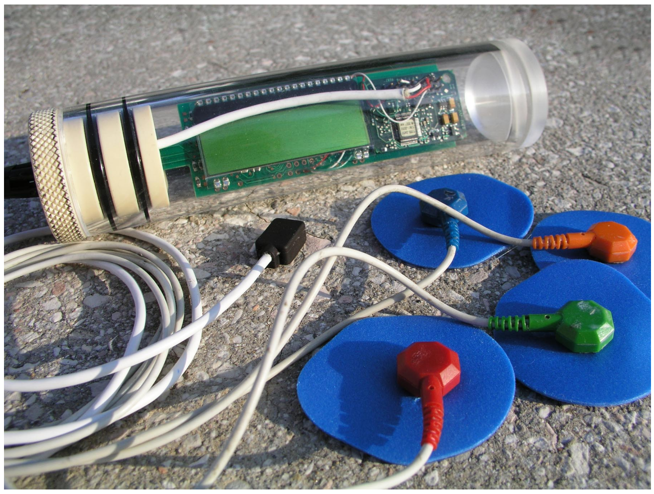

Fig. 6. First prototype in a Lexan housing

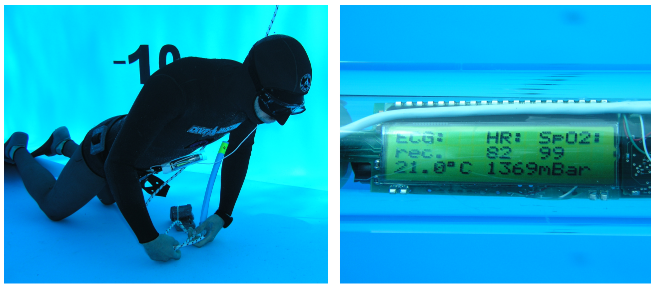

Fig. 7. Field tests in the 10.5 m deep research pool

First field tests were carried out in the 10.5 m deep research pool at Divesystem, Massa Marittima, Italy (figure 7). Four electrodes were placed and carefully sealed. To get a clear signal, the reflectance forehead pulseoximeter sensor is fixed with tape on the temple of the apnoe diver and kept on the right position by the hood of the diving suit. The next generation of prototype will have a special prepared scuba mask to place the reflectance sensor on the right position. A series of breath hold dives were conducted to 10.5 m for a maximum duration of 3.5 min. During all the dives the quality of the recorded data was good, the reflectance probe showed significant values.

IV. Discussion

Figure 8 shows a typical dive profile. After approximately 2 min of apnea at 10.5 m the SO2 starts to drop. At the beginning of the ascent the SO2 has reached a value of approximately 90%. On the surface the values dropped to nearly 70%. The reason for the fast decrease is that by returning from 10 m to the surface, the pressure drops from 2 to 1 bar. Thus also the partial pressure of O2 inside the lung decreases rapidly.

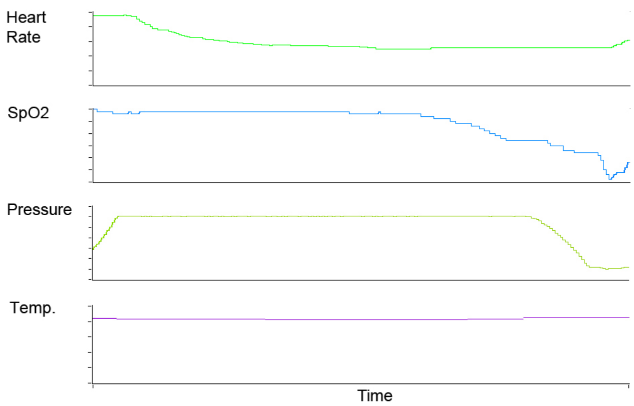

Fig. 8. Analysis of measured data

During deep breath-hold diving the alveolar pO2 increases proportional to the increase of environmental pressure. So even if the fraction of O2 is low, due to the increased ambient pressure at depth the alveolar pO2 might still be high enough. When surfacing it then drops rapidly, particularly in the last meters before surfacing, as the relative pressure drop per meter of depth reaches the highest values. This is one major reason for fatalities in deep breath-hold diving. Thus, it is obvious that the measurement of SO2 can definitely contribute to a better understanding of diving physiology as well as be an important warning factor for safety assurance.

V. Conclusion

The presented prototype allows simultaneous recording of 2 channel ECG, SO2, heart rate, depth and temperature. Additional AD inputs allow easy expendability and extension of the device with additional measurement parameters. The device was successfully validated against a transmissive pulseoximeter. Several long time tests were done in the laboratory and several test dives were successfully conducted in the 10.5 m research pool (Dive System, Massa Maritima, Italy). We envisage that this novel device will lead first of all to a better understanding of the human diving physiology and second will provide a novel tool to add physiological information necessary to safer and more effective training.

VI. Future work

Future work will include the development of a dedicated apnoe diving computer. Next to displaying and recording SO2, heart rate and depth it will also be capable of storing the complete plethysmogram with a sample rate of 75Hz. This then will also allow a RR-analysis and estimation of the heart rate variability even without having ECG derivations, which is of great advantage, especially when performing measurements in salt water.

References

[1] Sieber A., Kuch B., Wagner M., L'Abbate A., Dario P., Bedini R. Underwater Blood Pressure Measurement Device. *Diving and Hyperbaric Medicine*, 38(3):128-134, September 2008

[2] Silbernagl S., Despopoulos A. *Taschenatlas der Physiologie*, Georg Thieme Verlag. ISBN 3-13-567705-2. p. 120-135.

[3] Ehm O. F., Hahn M., Hoffmann U., Wenzel J. *Tauchen noch sicherer - Tauchmedizin fuer Freizeittaucher, Berufstaucher und rzte*, Mller Rschlikon Verlag AG, ISBN 3-275-01484-6

[4] Sieber A., Bedini R., Yong X., Navarri A., Dalle Luche M., L'Abbate A., Dario P. High resolution ECG and depth data logger. *Proceedings of EUBS 2007*, Sharm el Sheikh, Egypt 2007

[5] Zonios G., Shankar U., Iyer V. K. Pulse Oximetry Theory and Calibration for Low Saturations, *IEEE Transactions on Biomedical Engineering*, 51(5), 2004

[6] Dresher R.P., Mendelson Y. A New Reflectance Pulse Oximeter Housing to Reduce Contact Pressure Effects, Department of Biomedical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609 (IEEE), 2006

[7] Schagatay E., Lodin A., Richardson M. Diving response and arterial oxygen saturation during apnea in apneists and untrained subjects of both genders, *Proceedings of EUBS 2007*, Sharm el Sheikh, Egypt, 2007