Nerites
Underwater Monitoring System of Diver's Respiration and Regulator Performance using Intermediate Pressure Signal

Corentin Altepe[1], S. Murat Egi[2,3], Tamer Ozyigit[2] and Paola Pierleoni[4]
[1]*Bogazici Underwater Research Center, Yavuzturk Sk. 32/1 Altiyol 34716, Istanbul, Turkey*
[2]*Galatasaray University, Comp. Engineering Dpt., Ciragan Cad. 36 Ortakoy 34349, Istanbul, Turkey*
[3]*DAN Europe Research Division, 12 Via Basilicata, Roseto degli Abruzzi TE, Italy*
[4]*Marche Polytechnic University, Information Engineering Dpt., Via Brecce Bianche 12, 60131 Ancona, Italy*

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Abstract: This study is about a system for monitoring the breathing cycles of divers and the functioning of regulators underwater. It warns the diver and other surrounding divers in case of long time cessation of respiration or if the regulator's intermediate pressure is out of predefined limits, enabling immediate intervention to regulator and breathing problems.
The system is equipped with two pressure sensors and a microprocessor. It can be quickly mounted on the scuba diver's equipment to sense distortions in the intermediate pressure and to sense the depth while underwater.
Generally all data, including dive profile, are logged and transferable to PC for post-dive analysis. The low and high level alarms enable immediate intervention in case of breathing or regulator problems.
Major benefits of the system are rapid detection of respiration and regulator problems and ease of locating an unconscious or deceased diver. Additionally, this system aims at contributing to decompression illness research and at helping regulator manufacturers with the data it will collect while underwater.
While this study focuses on the hardware development of the system, breathing detection algorithms are currently being studied and optimized off-line using data collected by the system.

1 INTRODUCTION

1.1 Nerites

The system developed in this study is called Nerites, named after a sea deity from the Greek mythology, son of Nereus and Doris.

1.2 Scuba Diving Accidents History

In 2010, Divers Alert Network (DAN) Europe and DAN America reported 70 percent of the scuba fatalities of their members were caused by drowning, for a total of 112 fatalities of DAN Europe members and 814 fatalities of DAN America members. 14 percent of the DAN America fatalities and 13 percent of DAN Europe fatalities were reported to be caused by cardiac events (P. J. Denoble and Vann, 2010). The Nerites system addresses these causes for the majority of scuba diving fatalities as a method of prevention from drowning and an early alert in case of drowning or cardiac event.

1.3 Two-Stage Regulator

The regulator type used in open-circuit scuba diving is called two-stage regulator. The breathing gas is stored in a tank under a pressure of 5 to 300 bar. The first stage of the regulator drops the gas from the tank's pressure (High Pressure, or HP) to an Intermediate Pressure (IP) of typically 9 to 11 bar above the Low Pressure (LP). The second stage of regulator is then used to drop the gas pressure from IP to LP, which corresponds to the ambient pressure. Nerites system addresses only two-stage regulators for application in open-circuit scuba diving.

Figure 1 displays a simplified mechanism of a reg-

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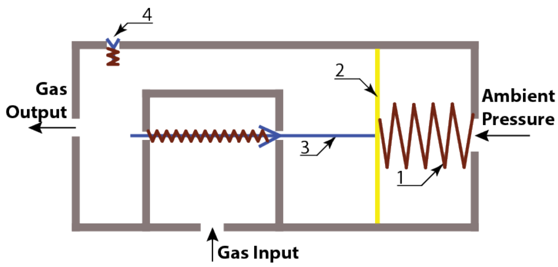

Figure 1: Simple representation of gas pressure regulator mechanism.

ulator, which can be used to understand the mechanisms of both the first and the second stages of a scuba diving regulator. The fluid at ambient pressure enters the right chamber and applies pressure on the diaphragm (2). The ambient pressure and the spring (1) move the diaphragm which in turns moves the valve (3). Once opened, the valve (3) lets the input gas (at higher pressure) enter the main chamber of the regulator. This higher pressure pushes the diaphragm back to its initial position and closes the valve (3). It is then output from the left part of the regulator, at a lower pressure than the input. The mechanical design of the diaphragm (2) and the spring (1) define the pressure of the output gas.

The second stage of the regulator is equipped with the valve (4), which allows the diver to exhale through the regulator. The excess of pressure opens the valve (4) which is lets the gas exit to the ambient air or water. This valve is absent in the first stage regulator.

1.4 Breathing Mechanics

While O_2 consumption of the body is directly linked to the workload, it remains similar for an equivalent activity underwater for scuba divers. Gas pressure in the lungs is normally equal to ambient pressure. At higher depth, gas pressure in the lungs is higher. However, the body needs in O_2 and its CO_2 production remaining the same as dry land, surface equivalent activity, the *respiratory gas exchange rate* designated with the symbol R, remains the same as surface, dry land conditions:

$$R = V_{CO_2}/V_{O_2} \tag{1}$$

Where V_{CO_2} is the quantity of CO_2 produced by the body and exhaled through the lungs, and V_{O_2} is the quantity of O_2 acquired by the body and inhaled through the lungs.

In consequence, the respiratory rate or breathing frequency of the diver remains the same at depth (Bennet, 2003). A normal respiratory rate for an adult is known to be 12 to 20 cycles per minute (M. A. Cretikos and Flabouris, 2008).

2 DETECTION OF BREATHING

2.1 First Observations

An analog gauge was placed on the IP and it was observed visually that the IP would slightly oscillate while the diver inhales gas from the second stage of the regulator. The amplitude of the oscillation would not go over 0.5 bar. There was no such phenomenon observed at the diver's exhalation due to the one-way valve of the second stage of regulator -item 4 displayed in Figure 1- letting the diver exhale through the second stage regulator directly to the water. This effect can be explained by the mechanism of the regulator, triggering gas input to the IP only when the IP drops.

2.2 Digitization of IP

A digital sensor MS5541C was connected to the IP and plugged to a development board. The pressure sensor used has a resolution of 1.2 mbar and a maximum pressure of 14 bar. The maximum sampling frequency obtained with this sensor was 2 to 4 Hz.

Although the sampling frequency enabled by the pressure sensor was low -a normal breathing frequency for an adult is between 12 and 20 breaths per minute, so a breathing cycle every 3 seconds- it was expected to be sufficient to observe the phenomenon on the IP signal.

The microcontroller MSP430F5529 was programmed to acquire the IP sensor measures as fast the sensor allowed, to acquire the ambient pressure measures at a rate of 1 Hz, and to transmit the live measures to the USB interface.

A User Interface (UI) was developed on PC, using the .NET Framework 4 and Visual Studio as development environment. The PC was connected to the development board by USB and the user interface displayed the live measures received from the microcontroller.

Figure 2 shows the UI during the acquisition of the live measures from the development board, for a total recording time of 107 seconds and 272 IP samples. The normal IP, when the diver is not inhaling, is about 148 psi (10.2 bar). The ambient pressure at time 107 second is 14.6 psi (1.007 bar).

Each drop in the IP corresponds to an inhalation through the second stage of the regulator. In Figure 2, a total 10 inhalations are observed, with different duration and intensities. At time 85 sec, a very shallow IP drop is observed, corresponding to a very short, low volume of inhalation by the diver.

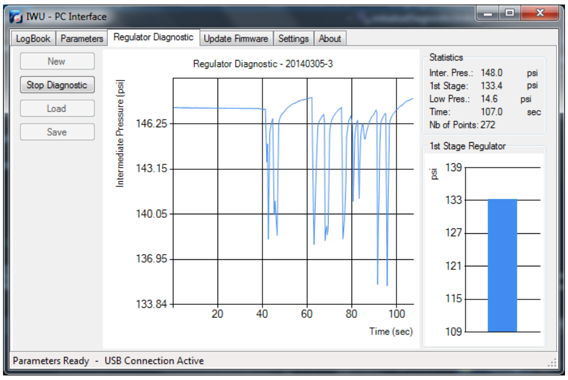

Figure 2: First UI and digitization of IP at an average sampling rate of 2.54 Hz.

At each inhalation, the IP starts dropping until a certain trigger level where the first stage of the regulator rapidly balances the IP by injecting higher pressure gas from the tank.

In the observation of Figure 2, excluding the drop at 85 sec, each inhalation results in a drop in IP of 6 to 13 psi (400 to 900 mbar). The slopes could not be measured accurately due to the low sampling frequency.

2.3 Automatic Breathing Detection

In order to detect the breathing events automatically, algorithms are being studied and developed off-line, using data collected from tests carried out with Nerites. Eventually, Nerites system will implement an algorithm for real-time detection of breathing events, enabling automatic breathing monitoring for the diver's safety.

3 REGULATOR PERFORMANCE MONITORING

As recalled in Section 1.3, a first stage regulator is designed to drop the gas pressure from the tank to an Intermediate Pressure of 9 to 11 bar above the ambient pressure. The exact value of the IP differs from manufacturer. However an accurate IP is important for the effective operation of the second stage of the regulator, the mouthpiece used by the diver.

If the IP is not properly regulated by the first stage regulator and is higher than its design range, there is a risk for the second stage regulator to let the gas free flow, uncontrollably letting the gas from the tank escape to the water during a dive. The diver may end up without sufficient breathing gas to surface and drown.

In a similar manner, if the IP is lower than its defined range, the diver may experience difficulty in breathing due to excessive Work of Breathing (WoB). Whereas a mild WoB may only cause discomfort, an excessive WoB will cause the diver to physical exhaust, hypoxia, or drowning.

By monitoring the ambient pressure with a digital pressure sensor, it is possible to compare the IP and the ambient pressure (also called Low Pressure or LP). Monitoring the $IP - LP$ value enables monitoring the proper functioning of the first stage regulator.

As a regulator will generally not start delivering an IP out of its design range suddenly, but rather slowly on the course of several weeks or several consecutive dives, often due to a lack of maintenance, monitoring the value $IP - LP$ continuously allows detecting the improper functioning of the regulator before it generates serious consequences for the diver's safety.

While detecting the breathing requires a sampling rate of 20 Hz from the IP sensor, the ambient pressure cannot change quickly due to restrictions on diving practise. Recreational diving limits ascending and descending speeds to 10 $m.min^{-1}$. Technical diving generally limits descending speed to 30 $m.min^{-1}$ and ascending speed to 15 $m.min^{-1}$. Therefore, the maximum absolute value of ambient pressure derivative in open-circuit scuba diving equals:

$$\begin{aligned} &\frac{30}{60}.(100.518)[m][s^{-1}][mbar.m^{-1}] \\ &\qquad = 50.259[mbar][s^{-1}] \end{aligned} \tag{2}$$

where 100.518 $mbar.m^{-1}$ represents the standard pressure variation with depth variation in salty water, often rounded to 100 $mbar.m^{-1}$.

The typical acceptable range for a first stage regulator being 2 bar (from 9 to 11 bar, typically), a sampling rate of 1 IP measure per second is far sufficient. For comparison, dive computers generally record depth measures once every 2 to 10 seconds, depending on the model.

A resolution of 1 *cm* of salty water, equivalent to 10 *mbar*, is required in order to monitor the proper functioning of the regulator and to record the depth of the diver in a dive log.

4 SYSTEM COMPOSITION

Following the initial test on automatic breathing detection, a system was designed for underwater application.

The main difference in its composition is that the sensor used for the IP was of better performance. It was selected to reach a sampling frequency of 20 Hz, with a 24-bit resolution and withholding a pressure up to 30 bar, corresponding to the IP at a depth of approximately 100 meters in salty water.

4.1 Brief Specifications

The system has the following characteristics:

- Single piezo-switch button and four LEDs for minimal user interface
- USB connector for connection to PC and advanced UI
- Two buzzers to be heard easily underwater
- One bicolor LED: green to indicate the charge of the battery, red to indicate the low level of the battery
- One yellow LED: blinking when a the diver's breathing is detected to indicate its proper functioning
- One red LED: blinking when an alarm is triggered (non breathing or regulator performance alarm)
- Pressure sensor 89BSD: 0 to 30 bar, 24-bit resolution and sampling frequency used at 20 Hz
- Depth detection using a second 89BSD pressure sensor, with a sampling rate of 1 Hz
- Operation depth: 0 to 100 meters (0 to 11 bar ambient pressure, 12 to 29 bar IP)

A microcontroller Texas Instruments MSP430F5529, selected for its ultra-low power characteristics and its USB implementation, acquires the signal from the IP sensor, stores the data in an internal flash memory and controls the buzzers and LEDs.

4.2 PCB Design

The system was designed for an easy integration into a waterproof casing. It aimed at being easy to use for the diver, therefore staying as small as possible.

The components used for the electronics were selected for their small footprint, their availability and their price. The PCB was designed to remain as small as possible while allowing soldering its components with limited equipment for a limited series. As a result, all of the selected electronics components are Surface-Mount Devices (SMD), with a small footprint but large enough to solder using a hand iron. None of the parts is of Ball Grid Array (BGA) footprint, which can only be soldered using a oven (not available).

Figure 3: Nerites 3D-printed prototype.

Figure 4: Nerites final design.

4.3 Casing

The casing was redesigned several times to fit best the diver's equipment and minimize its size.

It was designed to be plugged to the diver's equipment, between the buoyancy compensator (BC) and the IP hose. Its single button allows the diver to start the device, turn it off, trigger manually an alarm while underwater and turn off any alarm. The case was designed to minimize the interaction with the diver. It should be used only in case of emergency, and in such case, be used very quickly and easily.

Figure 3 shows the 3D-printed prototype of Nerites, with it PCB mounted. Figure 4 shows Nerites system mounted on a BC. Figure 5 shows Nerites mounted on a diver's equipment for a first test.

4.4 Product Use Cases

As described in Figure 6, Nerites can run in three different modes-

- Sleep mode: the user doesn't use Nerites. The battery can be charged while in sleep mode.
- In Use: either on the surface or while diving

Figure 5: Nerites equipping diver for a first test.

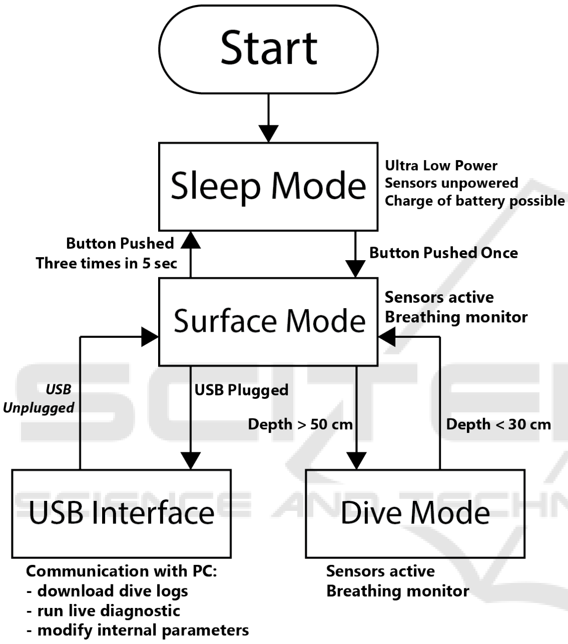

Figure 6: Modes of operation.

- USB Interface: Nerites is connected to a PC to either download dive log, run a regulator diagnostic or configure the internal parameters

While in Use mode, the breathing monitor is active. The breathing monitor is a part of the program which was prepared to implement the breathing detection events (currently in development). At each new IP measure (20 Hz) or LP measure (1 Hz), the breathing monitor verifies the alarms conditions for breathing detection and regulator performance (see section 2.2). It triggers the alarms if their respective conditions are met.

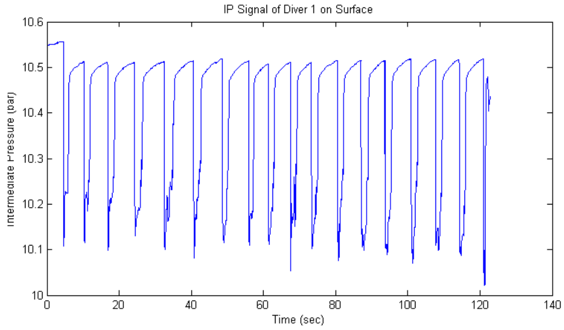

Figure 7: Breathing pattern recorded with the system for two minutes on one diver.

5 CONCLUSIONS

The system has allowed collecting IP signal data while on surface. Breathing signals for a length of one minute were recorded for six divers on the surface using a total of two different regulators. These profiles were later used in the CADDY project, aiming at identifying the diver health status (normal, in panic, or in danger). CADDY is a collaborative project funded by the European Community's Seventh Framework Programme FP7 which aims to establish an innovative set-up between a diver and companion autonomous robots (underwater and surface) that exhibit cognitive behaviour through learning, interpreting, and adapting to the divers behaviour, physical state, and actions(S. M. Egi, 2015). Nerites system is also expected to help regulator manufacturers to measure the performance of their products while underwater.

The developed User Interface allows easy customization of the parameters to fit the equipment specifications and the habits of the diver. The UI also allows running a full, live diagnostic of the regulator while on surface, helping the maintenance of equipment.

5.1 Regulator Mechanism

Figure 7 displays the IP signal of a diver using Nerites for about 2 minutes, with a total of 18 inhalations. With a sampling frequency of 20 Hz, it allows a more detailed observation of the regulator mechanism but only confirms the preliminary observations of Section 2.2.

Each drop of amplitude 350 to 500 mbar in the IP corresponds to an inhalation through the second stage of the regulator. At each inhalation, the IP starts dropping until a certain trigger level where the first stage of the regulator rapidly balances the IP by injecting higher pressure gas from the tank.

6 FUTURE WORK

The algorithm for breathing event detection will be developed in order to implement a real-time, efficient and reliable breathing event detection on Nerites. Although the system Nerites was used to record six divers on surface, with a total of two different regulator models, the system will be used to gather further data.

The factors preliminarily identified which are believed to influence a breathing event IP signal pattern are:

- Model / Brand of the regulator
- Tank pressure
- Depth

Therefore, several additional tests will be carried out in order to collect data at different depths, tank pressures and using different models of regulator. These collected data will later be used off-line to develop and compare on a bench test the reliability and efficiency of each event detection algorithm.

The system Nerites has yet to be used underwater and in pressure chambers, as the manufactured prototype casings have not allowed testing under higher than surface pressure.

As the model and brand of the regulator is believed to greatly influence the IP pattern of breathing event, a calibration will have to be run in order to optimize and adapt the breathing detection algorithm parameters to the diver's equipment. Such a calibration process will be implemented in the User Interface such that it will be guided and automatic. It will guide the diver step by step into the calibration process such as opening the first stage regulator and inhaling from the second stage when required.

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