Towards A Wearable for Deep Water Blackout Prevention

Frederik Wiehr
German Research Center for Artificial Intelligence (DFKI)
Saarland Informatics Campus
frederik.wiehr@dfki.de

Andreas Höh
Saarland University
Saarland Informatics Campus
s9anhoeh@stud.uni-saarland.de

Antonio Krüger
German Research Center for Artificial Intelligence (DFKI)
Saarland Informatics Campus
krueger@dfki.de

ABSTRACT

Freediving relies on a diver's ability to hold his breath until resurfacing. Many fatal accidents in freediving are caused by a sudden blackout of the diver right before resurfacing. In this work, we propose a wearable prototype for monitoring oxygen saturation underwater and conceptualize an early warning system with regard to the diving depth. Our predictive algorithm estimates the latest point of return in order to emerge with a sufficient oxygen level to prevent a blackout and notifies the diver via an acoustic signal.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

wearable, sports, freediving, blackout, oxygen saturation

ACM Reference Format:

Frederik Wiehr, Andreas Höh, and Antonio Krüger. 2020. Towards A Wearable for Deep Water Blackout Prevention. In *AHs '20: Augmented Humans International Conference (AHs '20), March 16–17, 2020, Kaiserslautern, Germany*. ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/3384657.3385329

1 INTRODUCTION

It is assumed that early efforts in breath-hold diving, today known as freediving, were centered on exploration, hunting and gathering [9]. Freediving is a natural method of submersion performed during various activities in the water, relying on the ability of the diver to hold his breath. The Divers Alert Network (DAN), reported a total of 855 breath-hold incidents between 2004 and 2016, of which 78% were fatal, from freedivers who may push past the urge to breathe and experience a blackout underwater [3]. Generally, breath-hold diving includes anything from child's play at a swimming pool, to snorkeling, underwater photography, spearfishing and competitive freediving.

Untrained snorkelers who intend to submerge often mistakenly assume that hyperventilation will increase their underwater time. In fact, it will barely increase their blood oxygen saturation, but further reduce the amount of carbon dioxide (PCO_2) in the blood. The problem is that the urge to breathe is physiologically triggered by an increase in PCO_2, while a blackout is caused by hypoxia (low oxygen) in the brain. Thus, when hyperventilating before submerging, a diver can black out before he feels the urge to breathe. This kind of blackout is also called "shallow water blackout" [5], since it often occurs with inexperienced divers practicing in swimming pools. This apnoeic hypoxia constitutes one of the main risks in freediving. Hyperventilation may cause the loss of consciousness near or at the maximum depth of a dive, described as a static blackout. Such a situation rarely occurs during horizontal dives since the compression effect when descending increases both PCO_2 and PO_2, effectively providing a safety net for the diver in deepness.

The more significant threat develops just before the diver is resurfacing, since the reduction in ambient pressure decreases both PCO_2 and PO_2, but the PCO_2 moves more slowly towards the breakpoint while the PO_2 declines faster by metabolic consumption alone [9]. This kind of blackout, called "deep water blackout" [6], is highly dangerous, since an oxygen level that might keep the diver conscious in greater depths will lead to a direct blackout when ascending. There are no external indications of the diver's imminent blackout, and therefore no possibility for another diver to help and react beforehand. Hence, a combination of reliable blood oxygen monitoring and a real time dive analysis integrated into a wearable could be helpful to ensure the diver's safety. A personal safety wearable has the potential to analyze the dive and notify the diver before the latest point of return is reached.

In this work, we propose an early prototype of a personal freediving safety wearable that detects a high risk of a blackout before resurfacing. Our main contribution consists of the prototype concept and the related algorithm that interprets the data from the medical oxygen saturation sensor in relation to the current diving depth.

2 RELATED WORK

Sieber et al. proposed a new automatic digital blood pressure measurement device [11]. The prototype was explicitly designed to operate up to a depth of 200 meters below the surface, consisting of both analogue and digital electronics inside a Lexan housing, a cuff and a solenoid to inflate the cuff with air from a scuba tank [11]. They confirmed the correct functioning of the system with a test in a swimming pool. Further studies by Sieber et al. showed a method to monitor the blood oxygenation of apnea divers reliably [8].

Most medical studies have researched impacts on humans under submerged conditions like increased pressure. There are also systems available to measure dive information, as well as systems to improve safety when freediving. To the best of our knowledge, there currently exists no prior work that tracks dive information, continuously monitors oxygen saturation, and in real time generates a predictive warning for the diver to prevent a blackout.

AHs '20, March 16–17, 2020, Kaiserslautern, Germany

ACM ISBN 978-1-4503-7603-7/20/03.
https://doi.org/10.1145/3384657.3385329

3 PROTOTYPE

To describe our wearable prototype, we first give an overview of the hardware setup, which consists mainly of a waterproof backpack case that still gives the oximeter and pressure sensor access to the environment. Secondly, we realize a continuous underwater oxygen saturation measurement system that works in combination with depth and automatic dive duration tracking. Lastly, we propose our preventive warning algorithm which generates a notification for the freediver when he should ascend.

Hardware. All computations are executed on a microcontroller (ESP8266EX) that receives and stores the sensor data. For this, we used an external SD card module (FAT32 formatted, 16GB). To design the waterproof case, we laser-cut several wood prototypes to fit the electronics and optimize the overall volume. The final version was cut out of acrylic. The lid consists of two layers of acrylic that overlap each other to form a double seal, which was then fastened with wing screws in the exterior of the seal area. As seal material we used sticky nitrile rubber (NBR) tape. The case's edges are further waterproofed and reinforced with an additional layer of polyurethane (Soudal Soudaflex 40FC). For the integration of the sensors, we created 3D models and printed them as brackets for the RS232 plug (oximeter) and the pressure sensor. The brackets were filled with epoxy and glued into the apertures.

Measurement of oxygen saturation The approach by Sieber et al. [8] showed a reliable way to measure a diver's oxygen saturation continuously. As a probe, we use an 8000R reusable reflectance pulse oximetry sensor by Nonin [1] that can be placed on the forehead of the diver. In contrast to a transmissive probe, we can avoid the effect of vasoconstriction. The sensor is glued to the forehead with medical tape, and the cable is guided along the diving goggles so as not to interfere with the diver's view or his freedom of movement. The probe is connected to the OEM III pulse oximeter module by Nonin. The module itself is connected to the microcontroller via UART [1, 2]. If the sensor is not able to compute oxygen saturation and heart rate, the system will send a missing data indicator, resulting in a heart rate value of 511 and oxygen saturation value of 127, respectively.

Automatic tracking of depth and dive time To track the essential dive information, we use the MS5803-05BA barometer sensor from TE Connectivity [4] because of its high resolution (30 cm) for up to 40 meters of total depth, well suited for freediving. The sensor features a high linearity pressure sensor and a 24-bit analog-to-digital converter with internal factory-calibrated coefficients that are used for the computation of temperature and pressure. They can also be used for a cyclic redundancy check to verify the integrity of the module. Since it is heat sensitive, it was soldered on a breakout board with a low-temperature solder paste at 200℃ in our reflow oven.

Blackout prevention warning algorithm Taking into account the medical background, the algorithm needs to compute a reliable assertion on the diver's condition. As input it takes the current oxygen saturation, depth, dive duration and pressure to predict a possible threat when ascending. An oxygen saturation of 80% at emersion is chosen as a reference value to avoid life-threatening consequences such as loss of consciousness or heavily impaired mental function. Nevertheless, this value is adjustable for trained freedivers who know their limits. Still, we would like to be conservative and cover individual differences for less experienced divers.

As an ascent velocity, the system assumes nine meters per minute, since it is recommended by several organizations as a maximum ascent rate and most divers have the tendency to ascend faster [12]. The current depth and pressure are correlated as one bar corresponds to ten meters of water depth (with slight differences in salt and fresh water), lowering the partial pressure of oxygen in ascent. Compressed oxygen volume directly influences the oxygen saturation according to the haemoglobin-oxygen dissociation relation as described before. The influence of water pressure (IWP) will be computed with the formula

$$\mathrm{IWP} = \frac{\text{pressure}}{1000\ \text{mbar}}.$$

The formula describes the decreased lung volume capacity, e.g. at 10 meters' depth, IWP = 2, equivalent to the gas compression according to Boyle's Law [14]. The metabolic oxygen consumption (MOC) during ascent will be computed with

$$\mathrm{MOC} = \frac{9\frac{\text{m}}{\text{min}}}{\text{depth}} * \text{x},$$

where x describes the average metabolic oxygen consumption that will be computed by subtracting the current oxygen saturation from the value at the beginning of the dive and dividing the interim result by the dive duration:

$$\text{x} = \frac{\mathrm{SpO}_{2,\ \text{beginning}} - \mathrm{SpO}_{2,\ \text{current}}}{\text{dive duration}}.$$

The table calculated by Severinghaus (S) [10] is used for a fast computation of the predicted oxygen saturation (POS) from the current oxygen saturation (COS):

$$\mathrm{S(POS)} = \frac{\mathrm{S(COS - MOC)}}{\mathrm{IWP}}.$$

Initially, the first SpO_2 and pressure values are stored internally as the starting references. For immersion detection, we compare the pressure values every five seconds. As soon as the pre-calibrated depth is reached for the set time, the dive begins. After initializing the module with an oversampling resolution of 4096 to increase accuracy, we can periodically read the pressure value via the I^2C bus. As soon as a predicted oxygen saturation below the threshold of 80% is reached, a connected piezo speaker starts buzzing to alert the diver. This recommends the diver to ascend immediately.

4 OUTLOOK

We have plans to verify the predictive algorithm with real recorded oxygen saturation values after resurfacing under supervision of freediving specialists and dive instructors in the apnea training group of our university. Also, participants will be asked for qualitative feedback, on appropriateness and modality of notification.

We are optimistic that we will be able to minimize the volume of the wearable, thus reducing the buoyancy. The system could also be integrated with an inflatable jacket, e.g. the Freediver Recovery Vest (FRV) [13], as last resort if the wearable detects a critical state of the diver. Kiss et al. proposed a system to improve directional perception for swimmers through lights mounted on swimming goggles [7], which inspires an alternative modality for feedback.

REFERENCES

[1] 2019. OEM III Module - Internal OEM Pulse Oximeter. https://www.nonin.com/products/oem3. [Online; accessed October 30, 2018].

[2] 2019. Reusable Reflectance Pulse Oximetry Sensor. https://www.nonin.com/products/8000r. [Online; accessed October 30, 2018].

[3] P. Buzzacott and P. J. Denoble. 2018. *DAN Annual Diving Report 2018 Edition - A Report on 2016 Diving Fatalities, Injuries, and Incidents*. 1–112 pages.

[4] TE Connectivity. 2019. MS5803-05BA Miniature Altimeter and Diving Module. https://www.te.com/usa-en/product-CAT-BLPS0011.html. [Online; accessed June 3, 2019].

[5] P. Dickinson. 2014. Shallow Water Blackout. In *Bierens J. (eds) Drowning*. Springer.

[6] Lars Eichhorn and Dieter Leyk. 2015. Diving Medicine in Clinical Practice. Deutsches Ärzteblatt International 112.9, 147–158.

[7] Francisco Kiss, Paweł W. Woundefinedniak, Felix Scheerer, Julia Dominiak, Andrzej Romanowski, and Albrecht Schmidt. 2019. Clairbuoyance: Improving Directional Perception for Swimmers. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA.

[8] Benjamin Kuch, Remo Bedini, Antonio L'Abbate, Matthias Wagner, Giorgio Buttazzo, and Arne Sieber. 2011. Embedded data logging platform for research in diving physiology. In *Solutions on Embedded Systems*. Springer, 45–57.

[9] NW. Pollock. 2008. Breath-hold diving: performance and safety. Diving Hyperb Med. Vol. 38(2), 79–86.

[10] John W Severinghaus. 1979. Simple, accurate equations for human blood O2 dissociation computations. *Journal of Applied Physiology* 46, 3 (1979), 599–602.

[11] Arne Sieber, Benjamin Kuch, Antonio L'Abbate, Matthias Wagner, Paolo Dario, and Remo Bedini. 2008. An underwater blood pressure measuring device. *Diving and hyperbaric medicine* 38 3 (2008), 128–134.

[12] Scott Smith. 2012. Ascent Rates. http://www.alertdiver.com/Ascent. [Online; accessed November 2, 2018].

[13] Oceanic Safety Systems. [n. d.]. Freedive Recovery Vest. http://oceanicss.com/. [Online; accessed April 4, 2019].

[14] Peter Wilmshurst. 1998. ABC of oxygen: Diving and oxygen. *BMJ: British Medical Journal* 317, 7164 (1998), 996.