NOVEL CONTROLLER FOR REBREATHER DIVING SYSTEMS
True Sensor Signal Validation and Safe Oxygen Injection

A. Sieber[1,2], B. Koss[2], R. Bedini[3], K. Houston[2], A. L'Abbate[2] and P. Dario[2]
[1]*Profactor Research and Solutions GmbH, Seibersdorf, Austria*

[2]*Scuola Superiore Sant'Anna, Pisa, Italy*
[3]*CNR, Istituto di Fisiologia Clinica, Pisa, Italy*

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Abstract: In electronically controlled closed rebreather diving systems the partial pressure of oxygen ($p\ O_2$) inside the loop is controlled with 3 pO_2 sensors, a microcontroller and a solenoid valve, critical components that are prone to fail. State of the art failure detection integrated in rebreather diving systems for recreational purposes does not offer the necessary reliability required for life sustaining systems. The present paper describes a novel controller that combines true sensor signal validation with safe oxygen injection.

1 INTRODUCTION

In the past 30 years, underwater activities have registered a steep increase across Europe, going from few thousands of people in the 1980s, when diving was prevalently an elite activity, to 1.000.000 in 1990s, with scuba and apnoea EU divers engaged in diving activities worldwide (Divers Alert Network, 1992). Today about five million EU people are practicing diving activities. With an increasing number of divers also the diving industry is growing, presenting a continuous need for research and development in the field of recreational diving.

1.1 Open Circuit Diving

The breathing gas providing part of typical open circuit diving equipment for recreational purposes consists of a gas storage tank (typically 10 – 18l, 200 bar) and a two stage pressure regulator (SCUBA) (U.S. Navy Diving Manual, 2005), (NOAA Diving Manual). The first stage reduces the tank's pressure to a intermediate pressure around 8-10 bar higher than ambient pressure. The second stage, also known as the regulator, reduces the intermediate pressure to ambient pressure thus allowing the diver to breath underwater. Exhaled air is then vented through an exhaust valve into the water.

The maximum time a diver can stay under water is mainly determined by the amount of gas he is carrying with him, the depth, and the breathing volume per minute. So what is the gas efficiency of open circuit diving?

A normal relaxed diver metabolizes approximately 0,8 to 1 bar l /min O_2 (Noaa, Navy). This O_2 consumption may increase up to 2,5 to 3,5 bar l / min in the case of hard physical activities. As an example: A diver has a typical surface breathing minute volume of 25 bar l / min. This volume contains approximately 5,25 bar l O_2. But only 0,8 bar l are metabolized – means only 0,8 l of the 25 l are really needed. This results in a gas efficiency of approximately 3%. As the pressure increases with depth, this ratio decreases. At 40 m our example diver breathes now at 40 m again 25 l /min, but due to the increased ambient pressure (5 bar now instead of 1 bar at the surface), the consumed gas is 125 bar/l min. The O_2 metabolism is still the same 0,8 l/min, so the gas efficiency at 40 m drops to approximately 0,6 %. A tank with 10l volume, 200 bar pressure contains in this case enough gas for a period of 16 minutes. Besides the low efficiency, open circuit diving has additional drawbacks like very cold (due to expansion the gas is cooled) and dry (compressed air contains only a negligible amount of humidity) breathing gas and relatively high weight (~20kg for a 10l tank including the regulator and the buoyancy compensating jacket).

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1.2 Rebreathers

A solution to increase the gas efficiency is using a rebreather, where the diver breathes in a loop instead of venting the exhaled gas into ambient. In a rebreather (figure 1 shows the schematics of an oxygen rebreather) (U.S. Navy Diving Manual, 2005) the diver exhales in a bag – the so called counter lung. A scrubber removed carbon dioxide and fresh gas is added to substitute metabolized O_2. This recycled gas is then inhaled by the diver again. In the case of a pure O_2 rebreather, the loop contains mainly O_2. The partial pressure of O_2 (pO_2) inside the loop is dependent on the depth, for example 1 bar at the surface and 2 bar in 10 m depth (each 10 m of depth the ambient pressure is increased by 1 bar). Such a rebreather has the advantages of maximized gas efficiency, bubble free and silent diving and warm and humid breathing gas.

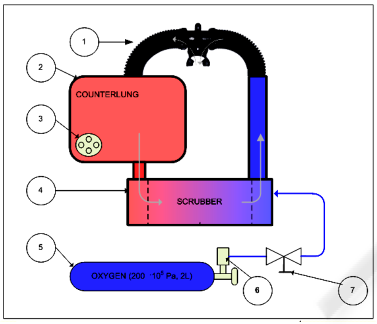

Figure 1: Schematics O_2 rebreather (1: mouthpiece, 2: counterlung, 3: overpressure valve, 4: scrubber, 5:oxygen tank, 7: manual valve).

The absolute pO_2 limits for a live sustaining breathing gas is 0,1 bar as the lower limit and 1,6 bar as maximum. A pO2 above this limit may lead to a oxygen intoxication, which can result in an epileptic fit like convulsion. In such a case the diver will loose his mouthpiece, drown and die. A pO_2 lower than 0,1 bar will lead to unconsciousness (Mount, T., Gilliam, B., Bohrer R., Taylor, L., Sommers, L.H., Crea, J., Nordsteam, R., 1992), (Ehm, O.F., Hahn, M., Hoffmann, U., Wenzel, J., 1996).

The maximum pO_2 limit of 1,6 bar sets the depth limit for pure O_2 rebreathers to 1,6 m and are normally used for military applications. Rebreathers used for recreational purposes are mostly either semi closed rebreathers (SCR) or manually or electronically controlled completely closed rebreathers (mCCR or eCCR).

In an SCR O_2 enriched air is being brought in the loop via a constant flow injector (commonly a orifice, typically 6 – 12 bar l / min) from tank to substitute the metabolized O_2. Every 4th or 5th gasp excessive gas is then vented through an overpressure valve. The maximum depth for SCR's is mainly limited by the percentage of O_2 in the supply gas.

In a mCCR or an eCCR the pO_2 is usually kept at constant level (Dederichs, H., Floren, G., Waldbrenner, M., Wilhelm, R., 2004), only the metabolized O_2 is substituted. To avoid the depth limit of 1,6 m of pure O_2 rebreathers, the breathing gas in a closed rebreather contains also N2 or He (He or He N_2 mixtures for deeper dives, normally known as technical dives).

To be able to keep the pO_2 at a constant level, a kind of regulation loop is needed (Straw, P.E., 2005). Therefore electrochemical oxygen sensors, whose output signal is proportional to the partial pressure of O_2, are used as sensing elements. In a mCCR the diver reads the pO_2 from a display (Baran, U., Frost, A.J., 2004) and if needed adds O_2 manually. In an eCCR this regulation task is usually performed with a microcontroller and a solenoid valve.

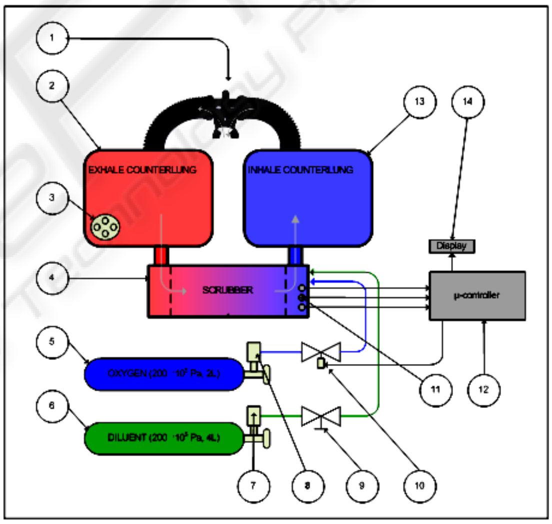

Figure 2: Schematics eCCR (1: mouthpiece, 2: exhale counterlung, 3: overpressure valve, 4: scrubber, 5: oxygen tank, 6: diluent tank, 7,8: pressure regulators, 9: manual diluent vlave, 10: solenoid, 11: pO_2 sensors, 12 µ-processor, 13: inhale counterlung, 14: display).

The regulation of the pO_2 inside the loop depends on the pO2 sensor signal. Unfortunately these electrochemical sensors are not reliable components and have a short life time of approximately 1 year in use. Typical problems that may occur are:

- non linearity
- current limitation (the output signal of the sensor is limited above a certain pO2)
- sensor failure

The consequence of a sensor failure may be a deviation of the pO_2 inside the loop, wich can be life threatening.

State of the art method to solve this problem is to use three pO_2 sensors instead of one (Deas, R.A., Evtukhov, M.V., 2003). If one sensor signal differs from the others, the sensor signal is "voted out" (voting algorithm) (Parker, M., 2005). Sensors of the same production lot and the same age often show the same failures at the same time. **Problems that occur because of wrong but similar sensor signals of at least two sensors can still not be detected because the voting algorithm will not work in this case as "voting" does not offer a real sensor signal validation.**

Another weak point in commercial available eCCR systems is the oxygen injection. Usually a solenoid valve is deployed for this task. Failures that may appear are that either the valve does not open anymore (defect in the solenoid or the electronics) or that it is stuck open (for example because of dirt). A valve that is stuck open will allow a free flow of O_2 that will lead in a short period of time to a life threatening pO_2 inside the loop. A solution, that can be found in eCCR for military applications is to use multiple solenoids for redundancy. In fact in recreational rebreathers this is still not state of the art.

The present paper describes a eCCR controller, that allows on the one hand a true sensor signal validation and on the other hand is equipped with a novel sensorized oxygen injection mechanism, that, in case of a failure, does not allow an O_2 free flow and enables reliable failure detection.

This eCCR controller enabled the development of a small and lightweight eCCR prototype for recreational proposes. It will be detailed in the section results.

2 METHODS

2.1 pO_2 Sensor Signal Validation

As described above, the state of the art voting algorithm does not provide a real sensor signal validation as it is based just on a comparison of the output signals of the sensors. A novel sensor signal validation procedure was developed to confront this problem.

The principle is based on injection of a gas with a known pO_2 in front of the pO_2 sensor membrane. With the help of another solenoid, gas from the diluent tank can be injected directly in front of the membrane of the oxygen sensors. With an orifice of 140 µm diameter the maximum flow is restricted to 2 bar l / min. Within an injection time of 5 s the pO_2 sensor signals should drop to the value corresponding to the pO_2 of the injected gas, which is given by the O_2 percentage of the diluent gas and the ambient pressure. A comparison of the sensor signal and the calculated reference signal allows then a reliable sensor signal validation and failure detection.

Figure 3a shows an enhanced version of the sensor signal validation apparatus, where it is not only possible to inject diluent gas in front of the sensor membrane but also pure O_2, to test the sensor for current limitation and linearity at preferable a depth between 6 and 10m. It has to be remarked that due to the small flow of just 2 bar l / min, the functionality of the rebreather is not negatively affected.

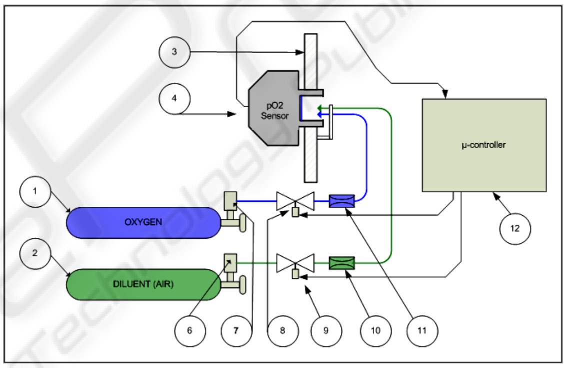

Figure 3a: The principle schematics of our true pO_2 sensor signal validation (1: oxygen tank, 2: diluent tank, 3: sensor support, 4: pO_2 sensor, 6,7: pressure regulators, 8,9: solenoids, 10,11: flow restriction orifices, 12 microcontroller).

2.2 Safe O_2 Injection

The metabolized O_2 has to be replaced by fresh O_2 from the tank. Therefore usually in eCCR a solenoid is controlled by a microcontroller as schematically displayed in figure 2. To confront the problems like a stuck solenoid valve, we invented a novel pO2 injection mechanism, displayed schematically in figure 3b.

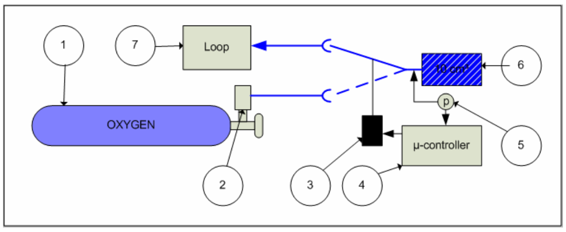

Figure 3b: Safe O_2 Injection.

O_2 is supplied from an oxygen tank (figure 3b). The pressure is then reduced with a oxygen compatible standard SCUBA fist stage (2) to a intermediate pressure of 10 bar over ambient. Instead of the state of the art 2/2 solenoid used for oxygen injection, a 2/3 version (3) is deployed. When powered though the microcontroller (4), the reservoir (6) is filled with 0,1 bar l O_2. When the solenoid is switched off, the gas in the reservoir is injected into the loop (7). To monitor the injection and detect reliably a failure, a pressure sensor is integrated (5) (the pressure of the successfully filled reservoir should be like the intermediate pressure 10 bar over ambient).

A failure of the solenoid (stuck open or closed) will not result in a free flow of O_2. A second benefit is that due to the design with a reservoir every O_2 injection will provide exactly 0,1 bar l of O_2. This allows an easy calculation of the O_2 metabolism of the diver.

2.3 Electronics - Hardware

As core component of the electronics the 8 Bit RISC microcontroller ATMEGA 32 from ATMEL () was chosen (32kByte flash ROM, 2 kByte RAM). A 4x20 characters display is connected via SPI bus (EA DIP 204-4, www.lcd-module.de). To enable a detailed post dive analysis a slot for SD memory cards was integrated in the set up. Three N-FET NDS355 serve as solenoid drivers.

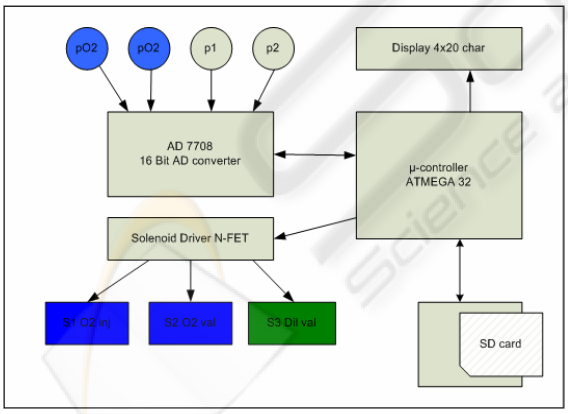

Figure 4: Electronics.

For the sensor signal processing the 16 Bit AD7708 (figure 5) analog to digital converter from Analog Devices is connected via SPI bus to the microcontroller. Its high resolution and the programmable input stage allows directly connecting the pO2 sensors (electrochemical pO2 sensors used in rebreathers have a typical output signal of approximately 8-13 mV @ 0,21 bar pO2). Two Motorola MPX5999 pressure sensors are used to measure on the one hand the ambient pressure (there the negative pressure port is closed) and on the other hand the differential pressure of the reservoir to ambient.

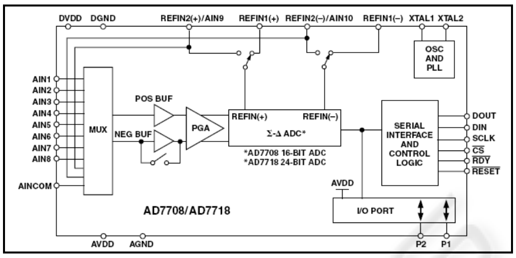

Figure 5: Analog Devices AD 7708.

Two low drop voltage regulators from Texas Instruments are used to provide 5V for the microprocessor, the display, the AD converter and the pressure sensors and 3,3V for the operation of the SD memory card.

Figure 6: Scrubber and scrubber head with solenoids, pressure sensors and two pO2 sensors (Analytical Industries, PSR 11-39-MD2).

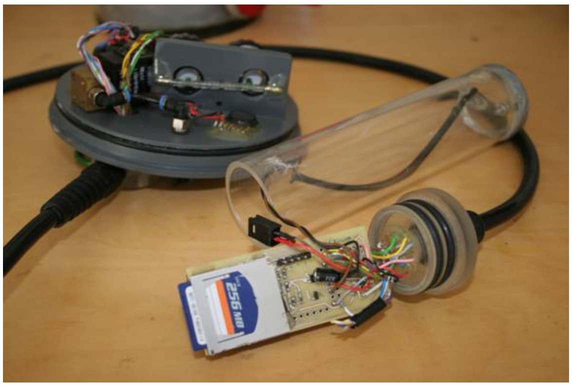

Figure 7: Electronics with the SD card slot and the lexan housing depth rated to 120 m.

2.4 Software

As programming platform the ATMEL AVR Studio 4 together with the free of charge GNU C compiler WinAVR (http://winavr.sourceforge.net/) was used under Windows XP.

The pO_2 control loop is designed in a way to keep the pO_2 inside the loop constant at 1,3 bar at a depth greater than 16 m. In the range between the surface and 16 m the pO_2 is increasing linear from 0,5 bar on the surface to 1,3 bar in 16m (compare figure 9 A and 9 B).

Error messages are created if a pO_2 sensor signal is outside the limits, the sensor signals differs more than 0,01 bar from each other, the battery voltage is below 6,5V and if the calculated O_2 metabolism of the diver is less than 0,3 or more than 3 bar l / min.

Every 120 seconds the sensor signal validation procedure with diluent as validation gas is carried out which results in the spikes in the readings of the pO_2 sensors (figure 9B, 10C). During the validation cycle the calculated O_2 in % has to drop to a value less than 25% (figure 9C and 9D). If not, an alarm signal is generated.

Optionally at a depth between 6 and 10 m once a dive the pO_2 sensors are checked for linearity and current limitation by injection of pure O_2 in front of the sensor membrane.

For the pre dive preparations the system can perform automatically a negative pressure test, a positive pressure test and the pO_2 sensor calibration.

All sensor data are stored on SD card in spreadsheet format. FAT 16 or FAT 32 formatted SD memory cards can be used. For each dive a new file is created. Additionally data like battery voltage, oxygen injection, oxygen consumption and error messages are stored.

3 RESULTS

This novel device with its true sensor signal validation and the safe oxygen injection is the key component of our eCCR prototype with the following specifications:

- Outer dimension: 45x25x18 cm³
- Scrubber: 1,5 kg
- Max depth: 50m
- 1 oxygen tank: 1,5 l, 200 bar
- 1 diluent tank: 1,5 l, 200 bar
- total weight: 12 kg
- maximum dive time: 180 min

After the dive the SD card can be read out with every PC equipped with a memory card reader and visualized with suitable programs like Microsoft EXCEL Figure 9 shows data of a test dive with 45 min duration to a maximum depth of 22m.

Figure 8: One of our eCCR test divers is preparing for a dive with our first prototype.

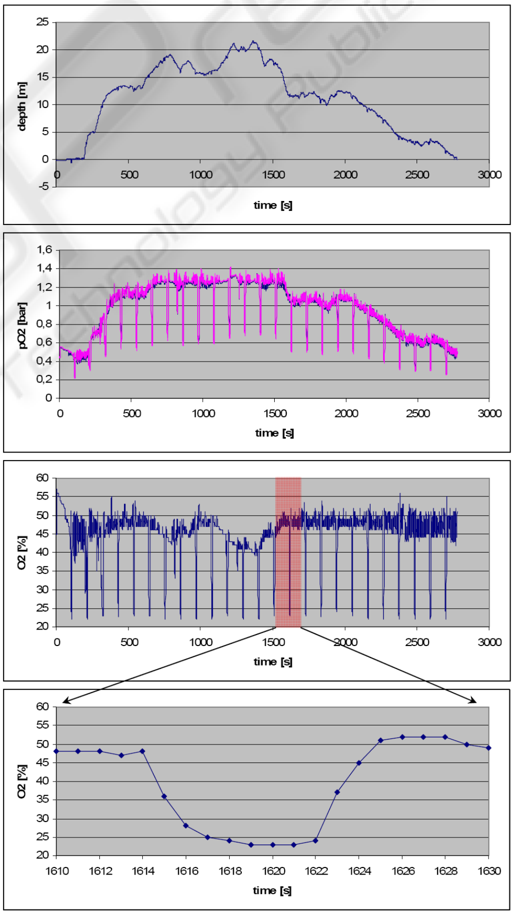

Figure 9: Data of a 45 min test dive in the mediterranian sea to a maximum depth of 22m; A: depth profile; B: pO_2 sensor signals of 2 sensors; C: calculated $\%O_2$; D: one validation cycle.

4 CONCLUSIONS

ECCR have a variety of advantages like:

- silent diving
- no bubbles
- maximized gas efficiency
- warm breathing gas
- humid breathing gas

Disadvantages are that the control of the pO_2 to keep it within life sustaining limits at a constant level depends on sensors which, with a low mean time between failure (MTBF) of less than a year, are prone to fail. State of the art solution is to deploy 3 pO_2 sensors for redundancy. This allows a reliable detection of one sensor failure, but cases, where more than one sensor show the same wrong values cannot be detected, which may lead to a non life sustaining pO_2 inside the loop followed by the death of the diver. A stuck open solenoid is another failure that may occur in a eCCR, resulting in a free flow of O_2, where the pO_2 inside the loop is increasing rapidly, or the case where the solenoid is stuck closed allowing no injection of fresh O_2 inside the loop anymore.

The present paper describes a novel apparatus that combines true sensor signal validation and a reliable sensor failure detection with a safe injection of O_2, where cases like a free flow of O_2 are not possible anymore.

In principle the apparatus can work with just one pO_2 sensor, where in the case of a sensor failure a alarm is given telling the diver to use his separate emergency gas supply in open circuit mode and to abort the dive.

As this system needs just one (or for redundancy two pO_2 sensors, in the case of the failure of one pO_2 sensor, the dive can be continued with the other working one). The costs for the yearly maintenance are dramatically decreased (pO_2 sensors should be changed once a year).

The authors are convinced that the further development of this novel device will lead to a novel kind of diving device for recreational purposes with a dramatically increased safety, low weight of the overall system and independency (180 min maximum dive duration).

5 FUTURE WORK

Near future work will include a further development of the presented electronics, an integration of a second controller for redundancy, a head up display mounted on the mouthpiece with LEDs for status information and a breathing frequency sensor. As the breathing frequency increases with increasing work load (and O_2 metabolism), this parameter allows another cross check giving more safety to the final product.

Typical for electrochemical pO_2 sensors for diving is that at the end of the dive the signal is slightly deviating from the reference signal (during a dive the sensors are very warm and humid gas under high pO_2, factors which present a quite extreme environment – so even if most pO_2 Sensors are temperature compensated changes in the slope of the sensors are not unusual during a dive) Another function that will be implemented in the next firmware release is an advanced sensor signal processing that, in the case of relatively small signal deviations allows a sensor recalibration during the dive (but only if the sensor is still linear, which can be checked with 2 reference gases (O_2 and diluent).

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