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PAPER

Head-Up Display System for Closed Circuit Rebreathers With Antimagnetic Wireless Data Transmission

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ABSTRACT

Rebreather divers use LED-based head-up displays (HUD) as a primary display and warning device for the partial pressure of O_2 in the breathing loop. Such devices are usually mounted on the mouthpiece of the rebreather in the field of vision of the diver. LED-based HUDs are simple devices and can be designed so that they are easy to understand but have limited information content. Few alphanumeric or graphical screen-based HUDs have been developed in the past. Connecting such a device to a rebreather requires cable links, which divers dislike, and increases the risk of entanglement. State-of-the-art wireless data transmission uses ultrasonic waves or low-frequency electromagnetic waves; the former is not silent, and the latter achieves only very low data transmission rates of a few bytes per second and does not meet the antimagnetic standards required by military divers. The present paper describes a novel HUD system that incorporates a simple LED-based primary HUD along with an advanced secondary head-up diving computer with a micro organic LED screen. An optical infrared data transmission system is used to transmit all rebreather relevant data from the primary to the secondary device. One prototype of the system was manufactured and successfully tested in the laboratory according to relevant European standards as well as during several dives in fresh and sea water.
Keywords: head-up display, near eye display rebreather, wireless underwater data transmission

Introduction

Head-up displays (HUDs), or near-eye displays, are mounted directly in close vicinity to the user's eye. In this position, they are always in the field of vision allowing the user to read the display without tilting the head or moving an arm to bring a wrist-worn device into the field of vision. HUDs are currently a hot topic in the media as well as in scientific journals. These discussions focus on the impact they may have on individuals and the society, especially when individuals are continuously updated with e-mails and social media alerts. Google glass, for instance, is expected to come out later this year (Ackerman, 2013).

Near-eye displays have already been used in professional and military applications for several years, providing the user data about current position, speed, and heading. Displays with a graphical interface may also include a map. These displays provide a hands-free solution and update the user with data in real time, which may be a strategic advantage in professional and military applications.

Recreational divers usually choose where and when they dive. They normally select dive sites with good visibility and are often led by a guide. In general, they do not perform dives in which they will be required to be continuously updated with navigational data. The need for information is different for professional and military divers, especially for Explosives Ordnance Disposal (EOD), Special Forces, and rescue divers. These divers are expected to dive in the worst conditions. They commonly face visibility close to zero (silt out), where reading a traditional wrist-worn diving computer (DC) may be impossible. In order to follow a predefined profile and course, divers have to be updated continuously with information about heading and depth, along with information relevant to their breathing apparatus, such as tank pressure and breathing gas composition.

EOD divers use electronically controlled closed circuit rebreathers (ECCRs) as a standard breathing apparatus. In contrast to open circuit systems, most of the time, a failure of such systems is not obvious, and the diver has to rely on electronics and sensors rather than subjective perception. The most critical parameter in an ECCR is the partial pressure of O_2 (pO_2) inside the breathing loop. Failure of the O_2 sensors may quickly lead to a pO_2 above 1.6 bar or below 0.14 bar, a breathing mixture, which is no longer life sustaining. Failure of the pO_2 sensors is believed to be one of the major causes of rebreather fatalities (Vann et al., 2007). Therefore, most modern rebreathers are equipped with an HUD as a primary warning device consisting of one or more LEDs. It is placed on the mouthpiece of the rebreather in a position where it is always in the field of vision of the diver. However, such LED-based systems have limited information content since LEDs may only be switched on or off. More information can be communicated by using blinking and coded sequences; however, the downside of increased information is increased complexity. HUDs must be easy and clear to understand since incorrect breathing gas mixtures, or failure of the rebreather, may influence the mental readiness of the diver.

State-of-the-Art Alphanumeric HUDs for Diving

HUDs with alphanumeric displays for divers do already exist: The commercially available CompuMask (Aeris) and the DataMask (Oceanic) are recreational DCs, which are fully integrated into a traditional diving mask. They are based on a liquid crystal display together with an optical system. These HUDs are based on a closed-system design, and therefore, no add-ons are possible. Although the Data Mask is well designed, it is only available in one size, limiting its use.

Gallagher (1999) and Belcher et al. (2003) developed head-mounted displays for EOD missions. These displays are larger and more expensive to produce, have high power consumption, and require cable connections. Designed and manufactured as military equipment, they are not available to recreational divers.

Previously, we mounted a graphical display with an optical system directly to the mouthpiece of a rebreather (Koss & Sieber, 2011a; Figures 3 and 4). With a carefully positioned device, good visualization of standard dive data was achieved. However, mouthpiece movements resulted in optical misalignments where the display (partially) moved out of sight. Later, we achieved excellent results using the display with a full face mask; in this case, the device was mechanically fixed in a desirable position relative to the eyes.

Following the rebreather display, we developed a technical DC with Trimix (helium, nitrogen, and oxygen breathing gas mixture) capabilities. As an add-on to the primary wrist-worn DC, an HUD was developed. Basically, this HUD showed an identical copy of the screen of the primary DC. As such, it had no microprocessor and was not able to work as a standalone unit without the primary DC. This device featured a unique optical design: The optical path of the system consisted of a solid Polymethylmethacrylat block, which was glued directly onto the visor of a diving mask. The prisma-shaped lens, which is mounted inside the mask, produces a virtual image equivalent to viewing a 400 × 200 mm^2 display at a comfortable reading distance of 1 m. More detailed information can be found in our previous work from 2011 (Koss & Sieber, 2011a, 2011b). In general, the system worked well, but mounting the device on a mask turned out to be difficult; once glued onto the visor, the position could no longer be adjusted. Divers also found the cable between the HUD and the primary DC handset disturbing and irritating, especially with rebreathers. Two cable connections were required, one from the DC to the rebreather and another from the computer to the diver's mask.

In our previous work (Sieber et al., 2012), a new HUD system for full face masks was described. Commercially available "AGA style" full face masks were retrofitted with a port into which an HUD was introduced directly in front of the user's eye. To adjust the device, it was possible to rotate the HUD as well as to move it horizontally (left or right).

Several HUD solutions were presented in the past; however, there is no stand-alone device that is specifically developed for a rebreather and can work without a separate handset or controller unit. U.S. Navy EOD divers currently use the MK16 rebreather. These devices are equipped with a simple LED-based HUD. In contrast to LED-based HUDs, graphical or alphanumerical displays have the big advantage of being able to display a large quantity of information but may be more difficult to understand than a simple "red light" warning HUD. Therefore, in a meeting with representatives of the U.S. Navy, it was speculated that the ideal solution could consist of a two-component HUD system. This would include a simple LED-based primary HUD, located on the rebreather mouthpiece, and a secondary mask worn organic LED (OLED) screen-based HUD, combining the advantages of both HUD design concepts. Ideally, rebreather and dive data should be transmitted to the secondary HUD via a wireless link in order to avoid a disturbing cable link (Koss & Sieber, 2011b). Rather than containing just a simple display, the mask worn device should preferably be a complete computer incorporating a microcontroller, pressure sensor, memory, and tilt-compensated compass—all features that one can also find in an advanced DC. Moreover, the device should also have sufficient processing power to perform decompression calculations in real time. The head-up DC (HUDC) should be a standalone unit with an integrated power supply, preferably rechargeable, and without any cable connections. Another important feature would be a tilt-compensated compass, which should provide heading information on the HUDC directly in the line of sight, facilitating easier navigation. To the best of our knowledge, no commercially available HUDs with an integrated compass exist today.

The current paper details the results of a first feasibility study, which focused on two goals:

- Research and development of a wireless transmission technology for the transmission of rebreather data from the mouthpiece to a mask worn device, with data transmission rates of at least 1 kBit/s. Additionally, a simple mouthpiece worn LED HUD will be developed. This technology should be able to pass antimagnetic requirements due to its intended use by EOD divers.
- Development of a standalone HUDC with a 32-bit microcontroller, digital pressure sensor, wireless interface, tilt-compensated compass, high-contrast OLED screen, rechargeable battery, and Universal Serial Bus (USB) port.

Methods

Concept

The idea of the current project is a dual HUD, consisting of a primary LED-based HUD, located on the rebreather mouthpiece, and a secondary sophisticated HUDC with an integrated OLED micro screen. While the positioning of the primary LED-based HUD was obvious and well proven in the past by many rebreather manufactures, one of the main questions remaining was where to mount the secondary HUD. Approaches from the past showed that HUDs mounted on the mask are easy to read. The optical path split design (Koss & Sieber, 2011b) was a good approach, especially when it comes to water and pressure resistance, but the inability to adjust the position was a disadvantage. A potential solution would be a one-piece HUD, mounted on a support from the frame of the mask, where the support could be designed in a way that enables easy tilting and rotation of the device.

The concept is displayed in Figure 1. The primary HUD sits on the mouthpiece of the rebreather and is connected to it via a cable, which can be routed along a breathing hose, so it does not disturb the diver. A secondary HUDC is mounted with a ball joint on the frame of a diving mask. In addition to the adjustment of the HUDC, the ball joint allows it to be tilted up and removed from the line of site completely when it is not required.

After discussions with EOD divers, it became clear that a cable link to a mask-mounted device will not likely be accepted by divers as it increases the risk of entanglement. Divers would favor a wireless solution.

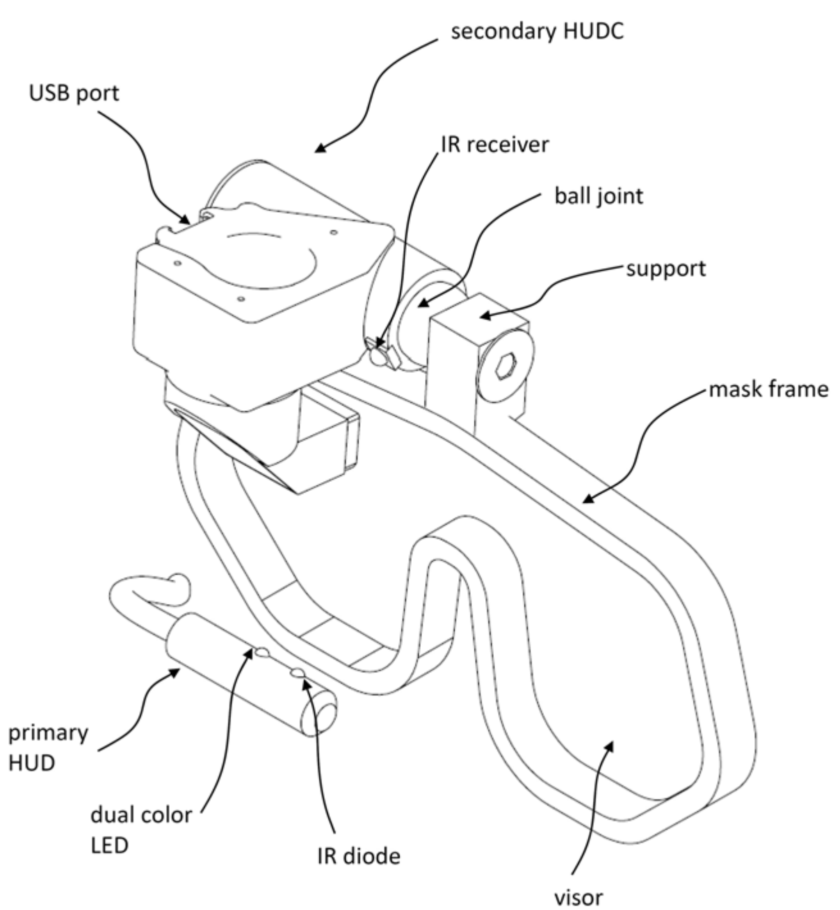
Wireless Data Transmission to the HUDC

Wireless systems used in SCUBA diving are based on electromagnetic data transmission with a low-frequency carrier (5–32 KHz). For instance, the DMR01 (Dynatron, Switzerland) (Mock & Voellm, 1992) is a low-cost, low-power digital receiver for underwater wireless data transmission used in popular DCs from Uwatec, Switzerland. Electromagnetic carrier frequencies from 5 to 32 kHz allow only low data transmission rates of a few bytes per second. This is sufficient to transmit simple data, such as tank pressure, but not adequate for all of the essential data from a rebreather with an update rate of 1–2 Hz. Another disadvantage of such systems is their magnetic signature, which does not allow their use during EOD missions.

An alternative underwater wireless data transmission could be Bluetooth or ZigBee-based devices, but with a 2.5-GHz carrier; the maximum transmission distance in sea water is limited to a few centimeters (Lloret et al., 2012). Acoustic modems based on ultrasound are suitable for underwater data transmission; however, as stealth and silence is of utmost importance for EOD and Special Forces divers, in general, such data transmission is also not acceptable. Optical data transmission fulfills antimagnetic requirements and is silent, but it requires a free line of sight between the transmitter and the receiver. In the case of an HUD, this line of sight can be achieved by placing the transmitter on the mouthpiece and the receiver directly above the secondary HUDC. The required transmitting distance

FIGURE 1

The primary HUD is located on the mouthpiece, and the secondary HUD is located on the frame of the diving mask. The primary HUD transmits data via an IR link.



(a few centimeters) is relatively short, which permits the use of infrared (IR) optical data transmission. Although the absorbance of IR light in water is of magnitudes higher than that of light with a shorter wavelength, such as blue (Pope & Fry, 1997), this remains a viable method of transmission.

Transmission Protocols

A variety of IR data transmission protocols exist. Before Bluetooth became available, the Infrared Data Association (IrDA) protocol (Knutsen & Brown, 2004) was popular for point-to-point wireless data transmission between handheld devices like cell phones or PDAs and a personal computer. IrDA hardware is still available, but the complete implementation of IrDA requires a substantial software effort; in particular, the IrDA stack (required for pairing, handshaking, and controlling the data transmission) consisting of multiple layers has to be implemented. Other disadvantages of IrDA are the relatively short transmission range and its high sensitivity to external disturbances. While IrDA allows data rates of up to 1 GBit/s, the required data bandwidth for the rebreather is, at maximum, only a few hundred bits per second.

IR systems commonly found in the remote controls of home entertainment systems present an additional and simpler option. These systems use a variety of methods for coding, for example, phase coding, pulse distance coding, or pulse length coding (Vishay, 2013). Although these codes are simple to implement, when it comes to transmitting several tens of bytes, it would be more favorable to use a preexisting hardware interface for the microcontroller. Instead of using software coding, it is possible to use the Universal Asynchronous Receiver/Transmitter (USART) interface at a suitable baud rate, in particular, the USART TX signal, to switch on and off a 36-kHz signal, which is then driving the IR diode. An ATxmega32A4 processor (Atmel) was chosen for the primary HUD. One of the internal timers is configured to generate a 36-kHz pulse width modulator (PWM) signal with a duty cycle of 10%. The output of the USART interface is configured as logic “and” with the PWM output signal and then further used to directly drive the IR diode.

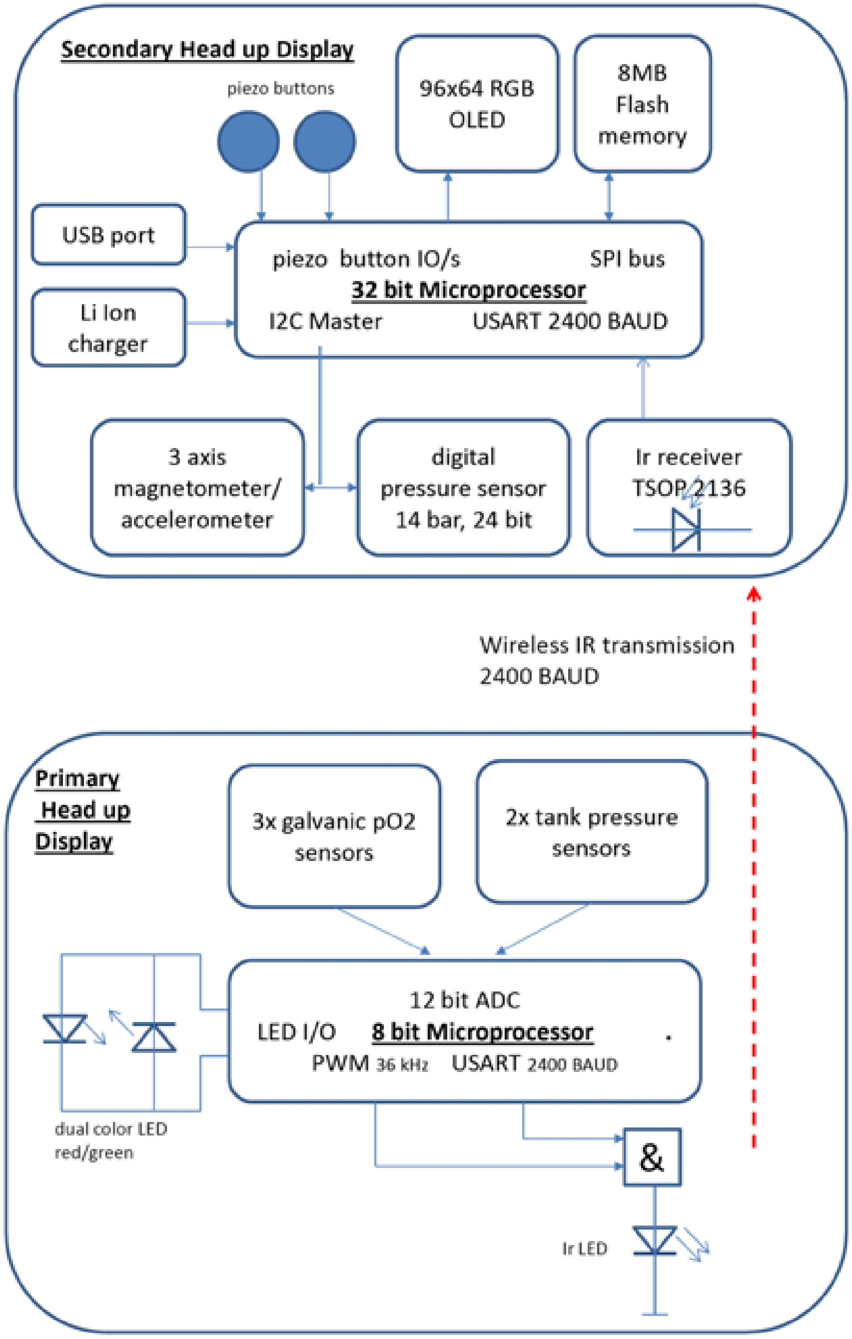
Demodulation of the signal is simple; the output of a suitable integrated demodulation circuit (TSOP 2136, Vishay) can be connected directly to the USART Rx pin of the AVR32 (Atmel) microcontroller of the secondary HUDC. The baud rate of the transmitter has to be carefully selected in order to match the specification of the receiver for minimum and maximum pulse length. When using a 36-kHz receiver, 2,400 bits/s is a suitable data transmission rate. If higher data rates are required, one may use a 450-kHz receiver and transmit with 19,200 bit/s; however, these receivers are difficult to find on the market.

Primary HUD Design

Figure 2 displays the overall electronic system layout. The core element

FIGURE 2

Electronic layout of the HUD system.



of the primary HUD is an 8-bit, low-power, ATxmega32 processor. This processor was chosen for four reasons:

- The 10-channel internal 12-bit analog-to-digital converter (ADC) with programmable amplification allows the readout of galvanic O_2 sensors, as well as analog low-cost tank pressure sensors, without any additional analog circuitry.
- The internal clock of the processor is calibrated; thus, no external crystal is required.
- Atmel's pico power technology allows an ultralow standby current of 0.7 µA, allowing a substantial reduction of the overall power consumption.
- The I/O (input/output) can be configured in many ways, including the hardware logic, "and" especially useful for the IR transmission.

One 4.2-V rechargeable Li Ion battery is used to power the circuit. Up to three O_2 sensor cells can be connected to the internal ADC through an 8-pin waterproof connector. This connector also allows access to the circuit programming interface and serves as a port to recharge the Li Ion battery. One I/O pin and a ground are used as water contact to switch on the primary HUD. Short-circuiting the contacts directly after startup enables the calibration mode.

Using IR remote control hardware, data transmitted are unidirectional. The primary HUD is programmed to transmit data via USART two times per second. The data are organized in a struct and include the pO_2 of three galvanic O_2 sensors, mV reading of the sensors, and tank pressures with a resolution of 0.1 bar (range: 0–300 bar). After the primary HUD is switched on, it sends an additional struct containing the serial number of the microcontroller, the software version, and all calibration data (mV readings of the O_2 sensors in O_2, ADC offset of the tank pressure sensors at 0 bar, and ADC readings at 200 bar tank pressure). An 8-bit checksum is included as the last 8-bit entry in each struct in order to detect transmission errors. Each struct consists of 24 bytes in total, and one transmission takes approximately 100 ms. In order not to block the processor during the transmission, the direct memory access is used to send the data for the USART interface, so the microcontroller is free to process other tasks during the transmission of data.

Secondary HUDC Design

Rather than using an 8-bit microprocessor, as found in the primary HUD, an advanced 32-bit processor was selected. The main reason for this is that this processor also permits the calculation of modern and mathematically advanced decompression models in real time; otherwise, simplifications are required to calculate similar decompression schedules on an 8-bit processor (Kuch et al., 2011). The main specifications of the selected 32-bit AT32UC3B0256 processor include

- 256-kByte flash ram
- 32-kByte ram
- 10-bit ADC
- 1.8-V core voltage
- USB connector, including USB host
- direct memory access for serial peripheral interface (SPI), USART, and I2C
- event control system
- 12- to 66-MHz clock

One drawback of using microcontrollers with different architectures as in this case is the different endian signedness, which has to be taken into account when transmitting data from the 8-bit to the 32-bit microprocessor of more than 1 byte in size (e.g., float, double, etc.). A 96 × 64 pixel OLED display is connected to the microprocessor via the SPI and operates at 12 MHz. A step-up converter generates the required OLED drive voltage of 14 V. A 64-Mbit flash memory is incorporated to store dive relevant data, which are organized in a file allocation table (FAT) 16-file format. Once the microcontroller is connected to a USB bus, the internal memory is recognized as mass storage memory, similar to a memory stick, and dive data can be read with file browsers like Windows Explorer. Depth is measured with a 24-bit digital pressure sensor (MS5803-14, Measurement Specialties, Switzerland). Data are read out via I2C interface two times per second. The conversion time of the sensor at its highest resolution is 10 ms. A digital three-axis magnetometer/accelerometer is connected to the microprocessor via I2C bus as well. It is used to calculate tilt and roll angles as well as the compass heading (ST Microelectronics, 2010). As in the primary HUD, a rechargeable Li Ion battery (type 16340) is included. An integrated charger circuit (MAX1555, Maxim IC) allows charging of the battery via USB in approximately 8 h. Two piezo discs are used as input buttons and are bonded to the inside of the polycarbonate housing with cyanacrylate glue. Pressing on the polycarbonate housing slightly deflects the piezo discs, generating a small voltage, which is sufficient to trigger an external interrupt on an I/O pin of the microprocessor. Except for one parallel load resistor of 1 MΩ, no additional analog signal conditioning circuits are necessary to interface the piezo discs. All of the electronic components are placed on a four-layer board with overall dimensions of 26×26 mm^2.

Optical Design

A typical HUD for diving is mounted in close vicinity (5–10 cm) from the diver's eye. A person with normal eyesight cannot focus on such short distances; thus, an optical system has to be introduced. In its simplest form, it consists of a single convex lens placed between the screen and the eye.

The smallest passive OLED screens available in small quantities have a diagonal of 0.6–1 inch. A single convex lens is magnifying the screen, which causes distortions of the image. In a previous paper, we described a two-lens system consisting of a concave lens and a convex lens. In this arrangement, an optical magnification of approximately 1 was achieved, which delivered good results in terms of readability. However, the lenses had a diameter, which was small compared to the OLED screen resulting in a small optical aperture. This caused a high loss of brightness, which made it difficult to read the display on the surface in bright sun.

The optical design of the secondary HUDC is detailed in Figure 3. It uses two lenses as well, but in contrast to our earlier system (Sieber et al., 2012), the concave lens, which is placed in 10-mm distance of the OLED, has a much larger diameter resulting in a brighter HUDC. The eyepiece is formed from a computer numerical control (CNC) machined plano-convex lens with a focal length of 45 mm. The plane side is in contact with water. Between the two lenses, a single-surface stainless steel mirror is placed to fold the optical path and reduce the overall dimensions. To be able to estimate the pressure resistance, a finite element analysis was done. The first prototypes of the housing, designed in SolidWorks 2011 (Dassault Systèmes), were CNC milled from black PVC (Figure 4).

Assembly

The optical parts were bonded to the PVC housing with ultraviolet curable glue. Before the lenses were inserted, the cavity inside the HUD was flushed with dry and clean air from a SCUBA tank to avoid water

FIGURE 3

The optical path of the secondary HUD consists of two lenses and a single surface mirror.

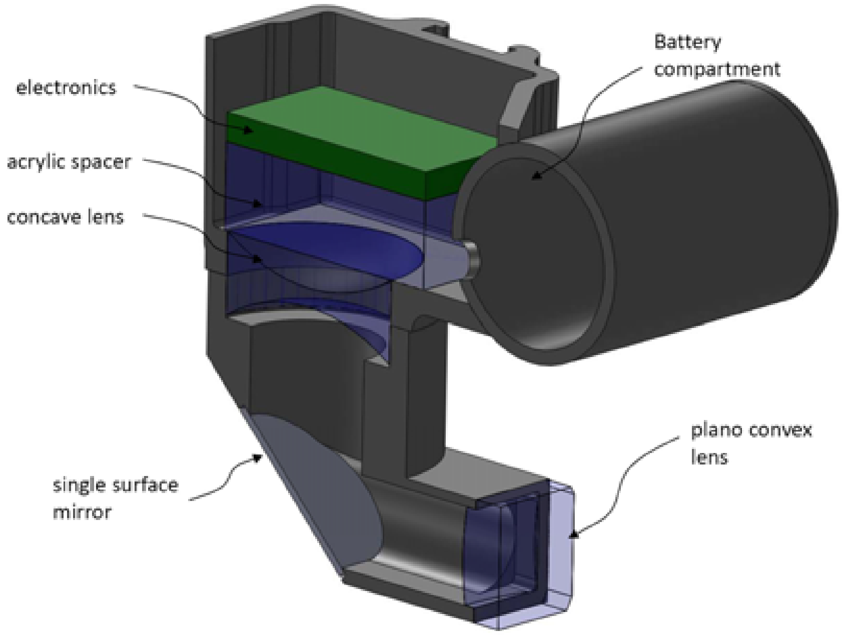


FIGURE 4

The primary HUD features two tank pressure sensors and can be connected to three galvanic pO_2 sensors.

condensation on the front lens during cold water diving. The electronic compartment was encapsulated in black polyurethane.

Software Development for the Primary HUD

The primary HUD reads up to three pO_2 sensors and two tank pressure sensors with a sampling rate of 1 Hz. Data are transmitted via an IR link at 2,400 bit/s. To reduce the overall power consumption of the primary HUD, the ATXmeage remains in sleep mode as long as the device is out of the water. In order to detect an immersion, there are two water contacts at the side of the housing. One is connected to the ground, while the other one is connected to an I/O pin of the microcontroller. As soon as they are electrically connected (e.g., by water), an external interrupt is triggered, and the microprocessor wakes up. After a short initialization routine, which among other things initializes all the sensors, the program enters its normal operation mode. Ten seconds after leaving the water, detected again by the water contacts, the program sets the microprocessor back into sleep mode.

During normal operation, a bicolored LED informs the diver about the current status of the rebreather. To keep it simple, we limited the number of different blinking codes to four.

1. Green blinking, 500 ms on, 0.5 Hz: Everything is ok—the program runs, and all sensor values are within predefined limits.
2. Red blinking, 500 ms on, 0.5 Hz: Tells the diver to check the pO_2 —at least one of the oxygen sensors reads a pO_2 below 0.3 bar or above 1.5 bar.
3. Red blinking, 500 ms on, 1 Hz: Tells the diver that the pO_2 has reached a critical value—at least one of the oxygen sensors reads a pO_2 below 0.15 bar or above 1.6 bar.
4. No blinking: System is either off (which cannot happen under water, as long as the battery is not empty) or there is some sort of system failure.

Additionally, the LED is used to communicate with the diver during calibration.

Since the included tank pressure sensors do not age, we hard-coded the calibration values for these sensors. Unfortunately, this is not possible for the oxygen sensors for two reasons. First, the divers can attach whatever galvanic oxygen sensor they want. Second, the output characteristic of galvanic oxygen sensors changes over their lifetime, which means recalibration will be inevitable.

To make the primary HUD as robust as possible, no buttons were included into the design. However, an input capability is required to initiate a sensor calibration. To solve this issue, a circuit was integrated that measures the resistance between the two wet contacts. Therefore, it is possible to differentiate between conductivity of water and, for instance, a metal. Based on this, a simple switching function was implemented: Within a short timeframe of a few seconds after primary HUD activation, the water contacts can be short circuited with a metal piece to initiate a pO_2 sensor calibration.

Calibration can be carried out either in air or in pure O_2.

Software Development for the Secondary HUDC

Depth Measurement and Decompression Modeling

The ambient pressure and surface pressure are acquired with a 24-bit digital pressure sensor. Pressure to depth conversion is performed according to the European Standard EN13319 where an increase of 1 bar of pressure results in a depth reading of 10 m.

In the first prototype, a Buehlmann ZH-L16C algorithm is implemented (Buehlmann et al., 2002) for decompression calculations. Nitrox (oxygen-enriched gas) and Trimix for open circuit and closed circuit diving are supported. Gradient factors (Baker, 1998) allow a personalized adaptation of the decompression schedule. A desktop software was developed under National Instruments Lab Windows to validate the decompression model against the original implementation from Baker.

Heading Calculation

An electronic compass can be designed from two orthogonally mounted magnetometers (two-axis magnetometer). These magnetometers are used to measure a 2D magnetic vector, which is then used for the heading calculation. It is necessary to hold the magnetometers horizontally, just like a traditional mechanical compass. When diving, where one is moving in a 3D space, typically no horizontal reference is available. Consequently, the compass is usually at least slightly tilted, and a single two-axis magnetometer would produce incorrect heading calculation. In cases of small tilt angles (usually referred to as pitch and roll), compensation can be achieved with a two-axis accelerometer. Since the accelerometer output is subject to gravity, pitch and roll can be calculated directly from the acceleration vector. The angles are then used to calculate a tilt-compensated heading.

This compensation works reasonably well for small tilt angles. The HUDC, however, is mounted in a way that, when the diver adjusts the device by rotating it, a rather large pitch angle results. In such cases, simple compass designs based on two-axis magnetometer and two-axis accelerometer typically fail. Therefore, a three-axial magnetometer and a three-axial compass were integrated into the HUDC. This allows assessment of a true 3D magnetic and acceleration vector, which is then the basis for a tilt-compensated heading calculation (ST Microelectronics, 2010).

Such electronic compasses are subject to interferences and distortions requiring calibration to compensate. Two types of distortions influence the reading of the magnetometer. Hard iron distortions result only in an offset of the magnetic vectors. A calibration routine was implemented, which collects magnetometer readings while the device is randomly rotated in three dimensions by the user. Maximal and minimal readings are collected for each vector and used to calculate offset and gain for each magnetometer axis (Sieber et al., 2012). Soft iron distortions are difficult to compensate; therefore, a careful layout of the electronic circuit was required, where components containing nickel and others were placed in a safe distance of a few millimeters of the magnetometer.

File System and USB Mode

In predefined time intervals, all dive-relevant data including depth, dive time, tissue tensions, pO_2, tank pressures, and decompression obligations are stored in files in a FAT 16-file system on the internal 64-MBit flash memory. All system-relevant events like startup time and date, user calibrations, or eventual hardware failures are stored in a separate file to achieve a continuous record of operation.

The secondary HUDC can be connected to the USB port of a personal computer or Android mobile phone. The HUDC is recognized as a mass storage device, and the files can be accessed. Additionally, it is also possible to upload a new firmware file, which is automatically updated after switching off the HUDC.

Results

One prototype each of the primary HUD and the secondary HUDC were assembled. These electronics were encapsulated in black polyurethane resin. A ball joint support was machined out of a PVC body and bonded to the frame of a diving mask.

The primary HUD is simple to install. As the input impedance of the three pO_2 channels is 50 kΩ and all three channels are independent from each other, it is possible to connect the HUD sensor interface to preexisting sensor readout hardware. For O_2 and diluent tank pressure readout, the HUD tank pressure sensors are connected to the first stages with off-the-shelf high-pressure hoses.

Initially, the assembled system was tested in an experimental pressure chamber to a maximum depth of 130 msw. After this test was successfully completed, the devices were mounted to an experimental, electronically controlled rebreather. Several in-water tests were carried out to a maximum depth of 10 mfw in an indoor pool and at 30 msw in the Mediterranean Sea (Figure 5). During all the tests, the system worked flawlessly. An inbuilt test program, which checks the cyclic redundancy check of the transmitted data packages, showed that, in the pool, all received data packages were correct. In low visibility (<0.5 m) in a lake, less than 0.1% of the transmitted packages were corrupt.

A group of Special Forces test divers tried the mask during the Experience Week at Grundlsee, Austria (organized by Outer Limits, Austria). All divers reported that the image of the HUDC is clearly readable even when the silt is stirred up. The divers appreciated this true hands-free DC solution, especially when operating scooters or other underwater equipment.

The main specifications of the two devices are summarized below.

Primary HUD:

- Battery: rechargeable Li Ion Battery, 4.2 V, Trustfire 16340
- Power consumption: 10 mA > 2 years in standby mode
- Estimated autonomy: 60 h
- Dual-color LED (red and green)
- IR diode, 950 nm
- Resolution of the pO_2 sensor ADC: 0.1 mV
- Resolution of the tank pressure reading: 0.1 bar

FIGURE 5

Diver with a prototype of the HUD system.

Secondary HUDC:

- Processor: 32 bit, AVR32UC3B256, 12 MHz
- 14-bar ambient pressure sensor, 24 bit
- 64-MBit internal flash memory
- Battery: rechargeable Li Ion Battery, 4.2 V, Trustfire 16340
- Power consumption: 25 mA, 32 µA, standby
- Autonomy: 25 h in diving, 2 years in standby mode
- Compass accuracy: ±2° for tilt angles up to ±45°, ±4° for tilt angles between 45° and 70°
- Size: 52 × 52 × 56 mm^3
- Weight: 91 g including the battery
- Size and distance of the virtual image: approximately 30 × 20 cm^2 in 1-m virtual distance
- Size of the visor: 20 × 16 mm^2

The HUD system was tested according to EN250 and EN13319. Tests were carried out at DEKRA (notified body for personal protective equipment) in Essen, Germany. One concern was if the water absorption of the potting resin (Wevo 552 FL) could affect the function of the device. According to the specifications of the supplier, the water absorption of the potting material is less than 0.16%. In an experiment, an AtXmega processor was encapsulated with the resin and stored in artificial sea water for a period of 2 weeks at room temperature. No changes in functionality or electrical properties of the processor could be observed. The electrical sleep current of the processor before and after the experiment was 0.7 µA; therefore, we concluded that the storage of the potted processor in sea water had no negative effects.

Conclusion

A novel HUD system was developed, which consists of a simple LED primary HUD located on the rebreather mouthpiece and an advanced OLED-based secondary HUDC, which is mounted on the frame of a diving mask. The primary HUD reads three pO_2 sensors and two tank pressure sensors. A dual-color LED serves as a primary diver warning device. All data are transmitted via an IR link to the secondary HUDC, which also serves as a dive computer. Unlike other wireless underwater data transmission methods, the IR link can pass antimagnetic requirements, eliminating the need for cable connections, and is therefore useful for EOD divers. At the same time, it was shown that it is possible to miniaturize the HUDC to such an extent that it can easily be worn on the diver's mask without making the mask bulky.

The primary HUD as a first warning device is very simple to understand. The secondary HUDC presents all dive relevant information, including decompression obligations directionally heading to the diver. These design elements provide a unique advantage, especially in low visibility or "silt out" conditions, where the reading of a wrist-worn DC handset is difficult or even impossible.

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