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Development of a graphical head-up display (HUD) for rebreather diving

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Abstract

Head-up displays (HUDs) are mounted in the field-of-view in close proximity to the eye. The present work describes the development of HUDs for rebreather diving. The developed HUDs feature a micro-screen instead of LED-based systems found in nearly all existing available commercial units. Two mouthpiece-mounted prototypes were developed. However, this approach turned out to be impractical and a better solution was found with mounting the HUD directly onto the diver's mask. A split optical path, where the HUD is glued to the visor, and a small lens located inside the diving mask were key features enabling a compact and lightweight design while, at the same time, withstanding pressure and water ingress.

Keywords: head mounted display (HMD), head-up display (HUD), diving computer, rebreather

1. Introduction

Rebreathers are diving apparatus where the diver breathes from a closed breathing loop. Exhaled gas is recycled, with carbon dioxide (CO_2) being chemically filtered and metabolised oxygen (O_2) being substituted with fresh O_2. In closed-circuit rebreathers a number of O_2 sensors, for example, three per unit for redundancy (Sieber and Pyle, 2010), measure the partial pressure of O_2 (pO_2) inside the breathing loop. In closed-circuit rebreathers the pO_2 is kept within safe limits of 0.16–1.6bar (National Oceanic and Atmospheric Administration, 2011) through monitored O_2 injection. For control (manual closed-circuit rebreathers) and/or safety (electronic closed-circuit rebreathers) reasons the diver needs to continuously monitor the pO_2 on one or, for redundancy, more dedicated handsets. However, in this way the pO_2 is only checked in intervals.

In state-of-the-art closed-circuit rebreathers systems pO_2 monitoring is additionally supported by head-up displays (HUDs) mounted in close proximity to the eye in the diver's field-of-view. The HUD enables hands-free monitoring, so that the user becomes aware of problems with the pO_2 value more quickly. At present, these HUDs consist of relatively basic displays comprising one or more light emitting diodes (LEDs), which are encapsulated in a small support typically mounted on the mouthpiece of a rebreather. Some systems only indicate whether or not the measurements are within safe pO_2 limits, while more sophisticated systems use LEDs with blinking codes to display the value of pO_2. However, the coded displays require fast and correct interpretation, which may be difficult if the diver is under any form of stress and will also require enhanced diver training. It is possible that if the diver can see at a glance a numerical display of the exact pO_2 value in the field-of-view, then that might result in faster reactions to any developing situation.

Gallagher (1999) and Belcher et al. (2003) developed HUDs for rebreathers with integrated video displays that could be used for displaying dive-relevant data such as the pO_2 being inhaled. However, these HUDs were designed for military missions, such as countermine diving, and were not available for civilian applications. Other designs that display data underwater in the diver's field-of-view have been developed and are currently available to all diving sectors, and include the DataMask HUD from Oceanic and the CompuMask HUD from Aeris.

These are diving masks with an integrated recreational diving computer, including a display that shows numeric data and icons/symbols. Currently, these mask-based systems support only open-circuit diving with air or O_2 enriched air (Nitrox) with up to 50% O_2. They do not support breathing gases used in technical diving, like Nitrox up to 100% O_2 or Trimix (O_2, helium and nitrogen), and PO_2 sensors for rebreathers cannot be interfaced to current versions of these HUDs. An additional disadvantage of the DataMask and CompuMask is that they are offered in only one size, so they may not fit all users.

This paper presents the design process to create a HUD for rebreather divers that addressed the problems described and that:

- was capable of displaying dive-relevant data like pO_2, depth, time and decompression obligations;
- had mixed gas capability (including Trimix);
- had inputs for three pO_2 sensors;
- was readable for divers of all age groups with a wide range of sight capabilities;
- could present interpretive dive data in an easy-to-read format;
- was usable with any existing rebreather; and
- was water and pressure resistant up to 300m depth.

2. Design methodology

The initial idea was to develop a mouthpiece-mounted HUD for rebreathers that had a miniaturised screen instead of basic LEDs. For the display the resolution had to fit the criteria of achieving an overall small design with a small viewing area and low power consumption, so both organic LEDs (OLEDs) and liquid crystal displays (LCDs) were considered. Diving computers usually have transflective LCD screens that are only readable with sufficient illumination from ambient light or a backlight. In contrast to a typical diving computer, a HUD display is mounted in a housing shielded from ambient light. Since LCDs require an active backlight, OLEDs were chosen as they do not need backlighting and have a higher dark room contrast which results in improved readability (Bass et al., 2010). Three suitable OLEDs were identified as possible components, and their specifications are given in Table 1.

Display A had a resolution beyond the design requirements, had competitive power consumption and was the smallest, but this display was not selected because of limited availability and price. Display B compared with display C had lower power consumption and was smaller. For both displays B and C, resolutions of different data layouts were trialled.

Darroch et al. (2005) suggests using at least 6 pixel high fonts for reading text on hand-held devices and this threshold appeared also applicable for the HUD. Two different font sets, 8 and 16 pixels, for data of different importance were generated using GLCD Font Creator (Pocket MicroTechnics) and used to test out different layouts. With a 64 × 48 pixel resolution and a 8 pixel font, all data could be arranged on display B but this left little space to insert separation lines between data or increase the font height of more important data. On a window with 128 × 64 pixel resolution, this was possible on display C and, therefore, it was chosen for the HUD design.

When the display was mounted as planned on the mouthpiece of the rebreather, it was located at the typical distance of about 10cm from the diver's eye. From around 40 to 50 years of age, people usually cannot focus at that distance (Brueckner et al., 1987), hence an optical system had to be introduced to enable focusing at such a near distance. A convex lens placed between the eye and the display is the simplest optical system to create a virtual image (of the display) at a comfortable reading distance (see Fig 1).

Equations 1 and 2 (Bass et al., 2010) show the relation between the focal length (f) of the lens; the distance (x) between lens and display; the distance (x') between lens and virtual display; the display width (w); and the width of the virtual image (w'). For a constant virtual distance (x') and decreasing focal length (f), the object comes closer (x) to the lens, which is an advantage in HUD design where miniaturisation is a main objective.

$$\frac{1}{f} = \frac{1}{x} + \frac{1}{x'} \qquad (1)$$

$$\frac{x}{x'} = \frac{w}{w'} \qquad (2)$$

Table 1: Selection of micro displays suitable for the HUD application

Display	**A**	**B**	**C**
Product no.	ME3204	DD-6448BE-2A	DD-12864WE-1A
Manufacturer	MicroEmissive Displays	Densitron	Densitron
Display format (pixel)	320 x 240	64 x 48	128 x 64
Viewing area (mm)	4.8 x 3.6	13 x 10	22 x 11
Overall dimension (mm)	9.8 (15.5)* x 13.65	18.5 x 18.1	26.7 x 19.3
Typical power consumption (mW)	50**	16***	59***
Dark room contrast (CR)	>1:1000	>1:100	>1:100

*Width of the display itself (and width of the flexible circuit connector)
**Typical operating conditions, display digital video (standard BT.656)
***Typical operating conditions, 50% display turned on, step up converter efficiency 85%

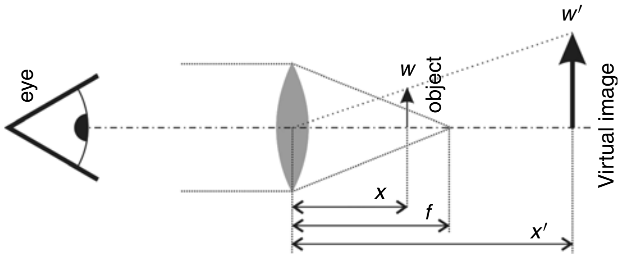

Fig 1: Viewing of a near-eye object through a convex lens

However, the virtual image size also increases with shorter focal length. To see the entire virtual image of an object from a given distance to the lens, a certain lens diameter is required. Shorter focal length and greater image size needs a greater lens diameter, hence larger objects (displays), as well as the resulting greater minimal lens dimensions, are disadvantages for miniaturisation. A compromise for these opposites was required for the HUD design.

In HUD designs for military divers, Gallagher (1999) chose a virtual viewing distance (x') of 25cm. However, presbyopia, which occurs in the natural course of aging (Rutstein and Daum, 1998), reduces the ability to focus on near objects, and from around the age of 40 to 50 years, many normal-sighted people can no longer focus at 25cm distance (Brueckner et al., 1987).

Laramee and Ware (2002) chose a virtual distance of 1.0m for their HUDs that present data in an overlay format to the real-world image. Since it is also a distance at which a diver usually focuses, for the HUD design, a virtual image distance (in air) of 1.0m was chosen. This resulted, after correction by the refractive index of water ($n_{water} = 1.33$ and $n_{AIR} = 1.0$), in a virtual distance of approximately 1.3m in water (Equation 3).

$$x_1 \times n_1 = x_2 * n_2 \tag{3}$$

For lenses with focal lengths ranging from 50–100mm, a lens with a focal length of 67mm gave an optimum balance of short focal length and a small required lens diameter (that increases with magnification). According to Equation 4 (Bass et al., 2010), a 22mm-wide display at a distance of 10cm (when not using a lens) provides a 12.5° horizontal field-of-view (FOV). The same 22mm (w) wide display placed 64mm (x) behind a lens with a focal length of 67mm (f) appeared 345mm (w') wide at a virtual distance of 1.0m (x'), which gave a 19.6° horizontal field-of-view (FOV).

$$FOV = 2 \times arctan\left(\frac{viewing\ width/2}{viewing\ distance}\right) \tag{4}$$

The system design for use in water followed the prototype concept of Gallagher (1999), which was to enclose an optical path (including the display) in a pressure- and water-resistant tube. The electronics and battery were also arranged in the tube; the minimal inner diameter of the tube was 33mm as defined by the dimensions of the display. The required tube length was defined by the required optical path between display and lens (64mm), with additional space requirements for the electronics and other mechanical issues. The electronic printed circuit board was placed below the optical path, and the battery was placed behind the display (Fig 2). The final design arrangement dictated an aluminium tube with an outer diameter of 40mm, a 3mm wall and an overall length (including required caps) of 95mm.

The front cap of the tube was the lens. The focal length of the lens in water was defined not only by the optical refractive index of the lens material and the lens surface curvatures, but also by the refractive index of the surrounding media. Because a plane lens surface does not contribute to the focal length of the lens, a plano-convex lens, with a focal length of 67mm and an optically active curved surface inside the tube, was used. The lens was machined to fit the tube with a lathe and glued into the tube using epoxy resin (Loctite 3430 A&B).

Testing of the device showed good readability of the display. However, the cylindrical device with a diameter of 40mm positioned close to the diving mask occluded a large area of the diver's field-of-view. To minimise this effect a new inner tube diameter (22mm) was selected for the second prototype. Similar to the first prototype, the front cap was a lens with a focal length of 67mm, and the same electronics and display were included, but, because of the reduced tube size, these were arranged outside, behind and below the tube. The display was directly bonded onto a transparent back cap (polymethyl methacrylate) for the tube.

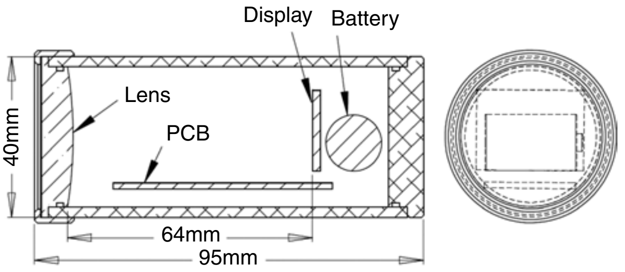

Fig 2: Mechanical design schematics of the first HUD prototype

The optical path (a pressure-resistant assembly of lens, stainless-steel tube and transparent back cap) and the display, together with all other required components, were integrated into a non-pressure-resistant housing. For water resistance, the display and electronic components were encapsulated in silicon gel (Wacker SilGel® 612 A/B). Finally, a pressure-resistant battery housing was added to the design (see Fig 3). In order to avoid vignetting, the display layout was changed in a way that no data was shown in the corners.

The prototype was tested under real diving conditions (see Fig 4). The occluded area-of-view was sufficiently reduced. However, during mouthpiece movements caused, for example, by water drag or head movements, the displayed data moved partly out of sight. The mask, when partly flooded, also hindered the view on the display (although this was not such an issue for full-face masks in similar tests).

In order to produce a less bulky and lighter HUD that could be attached to a conventional diving mask, a handset was designed that incorporated a microcontroller, pressure sensor, sensor interfaces, battery compartment, LCD screen and waterproof connector to interface pO_2 sensors with the HUD. This reduced the HUD to house just the display and a small interfacing board. The OLED and the required step-up converter were connected with a printed circuit board designed to match the dimensions of the OLED (26.7 × 19.3mm).

For the handset an LCD (EADOGL128-6 from Electronic Assemblies) was selected. It was a monochrome display with the same resolution, a similar communication interface (the serial peripheral interface bus) and a similar command set as the OLED in the HUD; this allowed both displays to be controlled with a similar command set.

The optical paths of the first two prototypes and the HUDs built by Gallagher (1999) were based on pressure-resistant cylinders filled with gas. In order to allow further miniaturisation and optimisation in terms of low weight, a third prototype was developed, where the optical path was designed in an optically clear, non-compressible material such as PMMA. Using this material meant that a pressure-proof housing could be avoided. Integration of optical lenses in a solid acrylic block is not feasible in terms of economic production, thus the optical path was split into two parts: the lens, within air inside the diving mask, and the other part made of an optically clear, non-compressible material (polymethyl methacrylate) outside the diving mask glass, in water.

This design approach had different advantages. PMMA can be easily and economically machined to any form, and the optical path was designed to be rectangular (which matched the display viewing area) which reduced visual occlusion. Moreover, PMMA allowed frameless mounting of the lens, further reducing occlusion of the field-of-view caused by the HUD itself. However, one major drawback of the solid design was that due to the refraction index of the acrylic material of approximately 1.5, the optical path length was increased and, with this, the overall size of the device also increased.

The display was glued directly onto the PMMA with a milled cavity, for correct positioning and to encapsulate the display and electronics in epoxy resin (Loctite 3430 A&B). In the split design it was essential that the two parts of the optical path were correctly aligned and attached in the right angle (α) to the mask glass (see Fig 5).

Several bonding solutions for mounting the lens and HUD on the mask were considered. First the parts were glued using a double-sided adhesive tape (3M VHB 4905 and 4910F). Easy application was possible, however, the tape detached after long

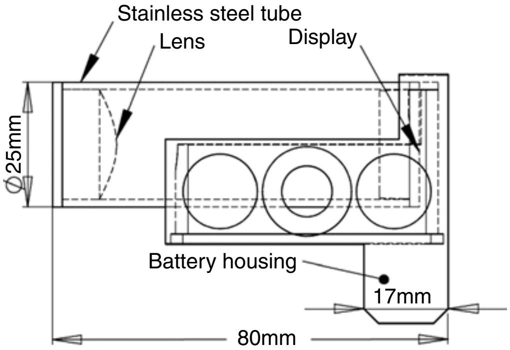

Fig 3: Second prototype mechanics

Fig 4: Second prototype in a test dive

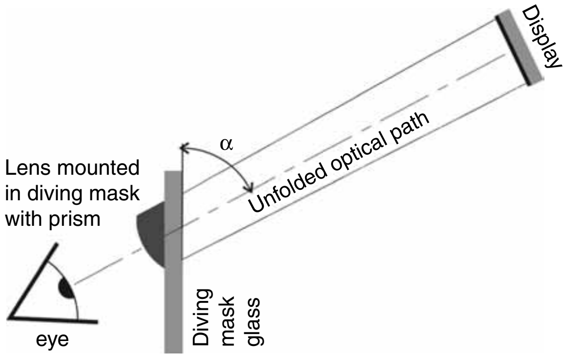

Fig 5: Unfolded optical path and angle (α)

dives. A reliable alternative was found in a silicon adhesive (Dow Corning 3145 RTV MIL-A-46146 adhesive/sealant-clear), even if the gluing process became more complex because of the 12hr curing time.

However, mounting a normal plano-convex lens with the flat side directly onto the visor resulted in chromatic aberration and different geometric distances between lens and the upper and lower edge of the display; it also caused different virtual distances. A special prism-like lens was machined out of a 13mm-thick PMMA lens with a focal length of 67mm. A drawback of the solid design was that the refractive index of PMMA ($n_{PMMA} = 1.49$) increased the required geometric length of the optical path from $x_{AIR} = 64$mm ($n_{AIR} = 1$) to $x_{PMMA} = 95$mm (see Equation 3). However, by folding the outer part of the split design, overall dimensions could be minimised while also producing a compact assembly of mask and HUD (Figs 6 and 7).

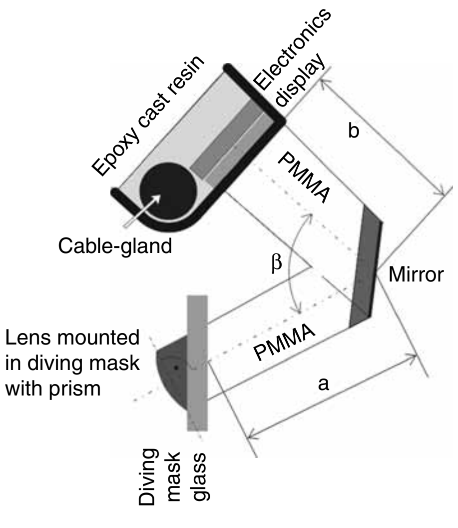

Fig 6: Final HUD design

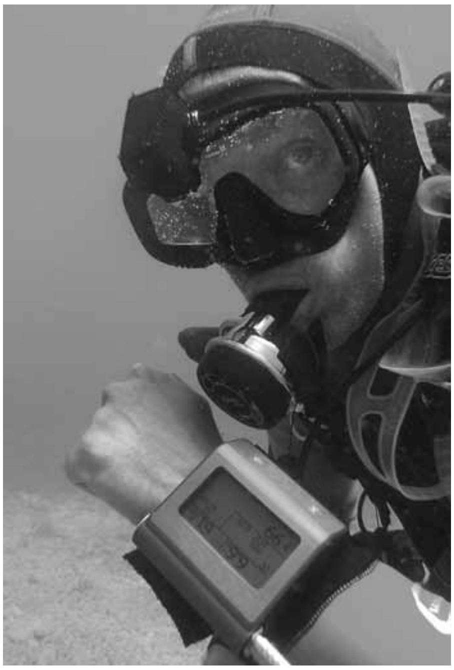

Fig 7: Diver with HUD

The third prototype of a near-eye display could be mounted directly on the visor of a conventional diving mask (Fig 7). This design provided the advantage of having a fixed position of the HUD with respect to the eye. The unit could also be user-mounted, temporarily or permanently.

In combination with the handset (as described earlier) the final HUD unit delivered a display from a complete technical diving computer that supported open-circuit and rebreather diving, with outputs from up to three pO_2 sensors and support for air, Nitrox and Trimix. The HUD was connected to the diving computer via a pressure-resistant cable and connector (ODU, customer specific). The same connector could be used simultaneously to connect a sensor board to read out up to three pO_2 sensors or to connect the dive computer to a PC.

The HUD displayed an exact copy of the handset screen at a virtual distance of 1.0m. The virtual image was 346mm wide, which equals a viewing angle of $FOV = 19.6°$ and showed fonts with a height of 22mm (small font) and 44mm (big font). Pressure resistance tests up to 30bar did not discover any design problems. Test dives were carried out in a 10.5m research pool and in the Mediterranean Sea. The technical data of the HUD are summarised in Table 2.

3. Conclusion

Near-eye head-up displays (HUDs) for rebreather diving were developed. Major advantages of a HUD versus a handset become clear when dive-relevant data have to be continuously monitored, for example for rebreather diving or when precisely following decompression schedules. Hands-free monitoring is

Table 2: Technical HUD data

HUD power consumption	
Max. brightness	12mA@3V battery voltage
Mean brightness	8mA@3V battery voltage
Min. brightness	5mA@3V battery voltage
B × H × L	30 × 40 × 49mm
α	62°
β	60°
a	40.7mm
b	45.0mm
Weight (incl. cable):	120g
Display resolution:	128 × 64 pixel
Virtual image width:	346mm
Virtual image distance:	1000mm
Water and pressure resistance	>30bar

also of special interest when performing underwater activities where both hands are required, such as underwater photography, using underwater propulsion vehicles or working activities. In low visibility and especially 'silt out' situations, where visibility is close to zero, it may become difficult, if not impossible, to read a normal diving computer. In contrast the readability of the HUD, which is directly bonded to the diving mask, is unaffected even in such conditions. This makes the HUD device not only interesting for technical divers exploring caves and wrecks, but also for commercial, rescue and military divers.

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