Diver's Full Face Mask Head-Up Display System Using Waveguide Optical Display Technology

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Abstract — Military, public safety and science divers conduct operations in what can be one of the most inhospitable environments on the planet characterized by extreme temperature, pressure, and extremely poor visibility. Handheld displays and gauges can be virtually useless in an environment frequently characterized by zero visibility, and this has been a serious limitation to underwater manned diving operations [1].

Waveguide optical display technology has the potential to radically transform diver visual display systems by enabling the diver's face mask itself to become a see-through head-up display, similar to something from an Iron Man or Star Trek movie.

Under a recent international government sponsored program, the Naval Surface Warfare Center-Panama City Division (NSWC PCD) developed a concept prototype binocular see-through head-up display inside a diver's full face mask using waveguide optical display technology.

This paper will describe diver visual display systems, waveguide optical display technology, development of the concept prototype, results of diver evaluations, and recommendations for follow-on research and development.

Keywords—*waveguide, optics, see through, diving, visibility*

I. Introduction

Military, public safety and science divers routinely conduct operations in an environment of extremely poor visibility. During these underwater operations – whether underwater construction, maritime security, search and rescue, or scientific research – divers have a critical need to view life support, communication, navigation, and other sensor data in real time regardless of the ambient visibility conditions. Handheld displays and gauges can be virtually useless in an environment characterized by zero visibility, and this has been a serious limitation to underwater manned diving operations [1].

II. DIVER VISUAL DISPLAY SYSTEMS

Naval Surface Warfare Center Panama City Division (NSWC PCD) is the US Navy's leading laboratory for research, development, testing, evaluation, and technology transition of diver visual display systems; with unique facilities for rapid prototyping and manufacturing, human systems integration and extreme environment testing. Along with NSWC PCD, the Naval Experimental Diving Unit (NEDU), and Naval Diving and Salvage Training Center (NDSTC) are co-located tenant commands at the Naval Support Activity Panama City (NSA PC).

A diver operating underwater with a dive mask in zero visibility presents a unique challenge. Near-to-eye (NTE) display systems incorporating micro display technology and the associated optics provide a workable solution in zero visibility environments [4].

NSWC PCD developed several NTE display systems for divers, including the Integrated Diver Display Mask and the Combat Diver Display Mask which integrate micro displays and custom designed optical systems into a dive mask frame, providing clear visual access to basic life support information (Fig 1).

Fig.1. Combat Diver Display Mask

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The Binocular Mask-Mounted Display integrates two color micro displays with custom optical system into a binocular housing that provides high resolution color sensor data imagery (Fig 2).

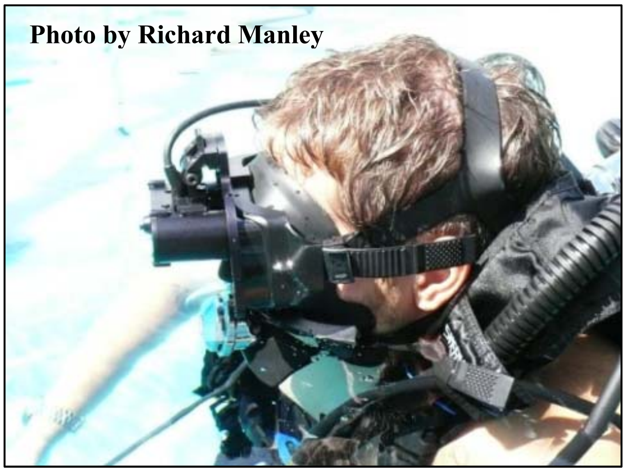

Fig.2. Binocular Mask-Mounted Display

While these systems have greatly improved diver operational capability, mission effectiveness, and safety; they still have significant limitations. Occluding the diver's normal field-of-view (FOV) and having to switch back and forth between multiple displays to access life support, navigation, and sonar data adds significant task loading, and can greatly increases the likelihood of errors.

An ideal diver's display system should have the capability to provide all types of data – alpha numeric, graphics, and high resolution video – as well as provide for ease of switching between data types. The system should be low volume, lightweight, and streamlined; have a low power requirement, and provide a large FOV while allowing the diver to maintain situational awareness. An ideal implementation of these requirements would be a see-through head-up display (HUD) capability directly integrated into the diver's face mask. Emerging waveguide optical display technology has the potential to provide this capability for divers by enabling the diver's face mask itself to become a true see-through head-up display.

III. WAVEGUIDE OPTICAL DISPLAY TECHNOLOGY [2]

Waveguide optical displays couple images from a micro display into a *waveguide*, translates the images through a series of internal reflections finally exiting toward the eye. This provides a magnified, see-through virtual display image at a specific distance in front of the viewer. These systems use a number of different optical approaches including diffractive, holographic, polarized, and reflective optics.

Diffractive waveguides use deep slanted diffraction gratings to couple optically collimated (magnified) light from the micro display into the waveguide; then exit to the eye through another set of diffraction gratings. These gratings are fairly expensive to manufacture, and have an intrinsically small field-of-view (Fig 3).

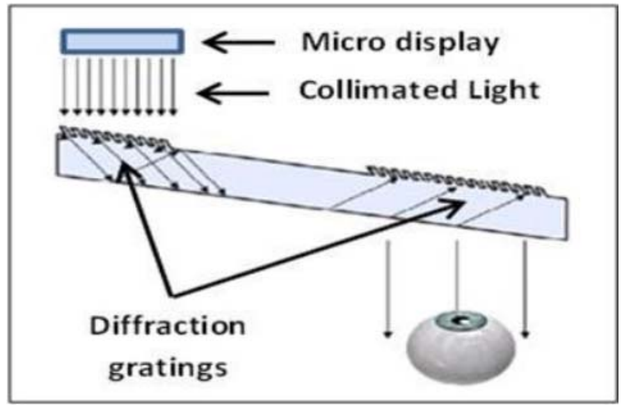

Fig.3. Diffractive Waveguide

Holographic waveguides reflect specific wavelengths of optically collimated light from a micro display at a certain angle relative to an embedded hologram. Holographic waveguides have a limited field-of-view due to light losses through the embedded holograms. Since each holographic element can reflect only one wavelength of light, three individual holograms per holographic element are required - Red, Green, and Blue respectively – to provide full color transmission capability (Fig 4).

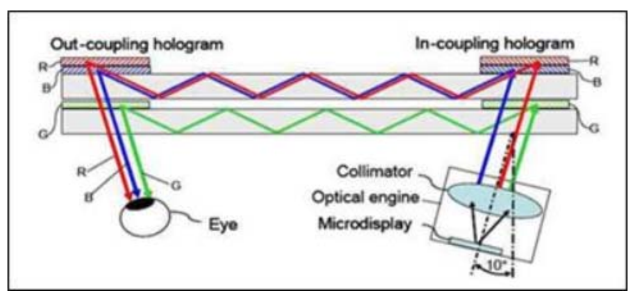

Fig.4. Holographic Waveguide

Polarized waveguides use multi-layer coatings with embedded polarized reflectors to couple the micro display image into the waveguide and extract the light towards the eye (Fig 5).

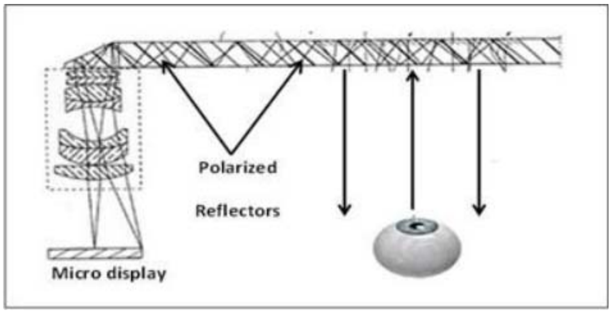

Fig.5. Polarized Waveguide

The polarized coatings must be deposited on a glass substrate since plastic is not yet compatible with this process. Polarized waveguides typically require very high brightness level micro displays due to significant light losses. This type of waveguide technology is produced by *Lumus Ltd,* and is used in several consumer and military products (Fig 6).

Fig.6. Lumus DK-40 Prototype

Reflective Waveguides use an off-axis projection micro display and semi-reflective curved mirrors to optically couple collimated light from the micro display into the waveguide (Fig 7).

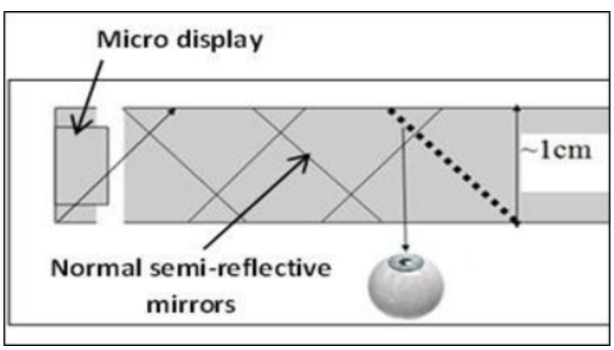

Fig.7. Reflective Waveguide

Reflective systems tend to be more power efficient since there is no light loss due to polarization, grating, or holographic effects. Reflective wave guides can be manufactured from glass; such as Google Glass (Fig 8), or molded plastic; such as the Optinvent ORA-S (Fig 9).

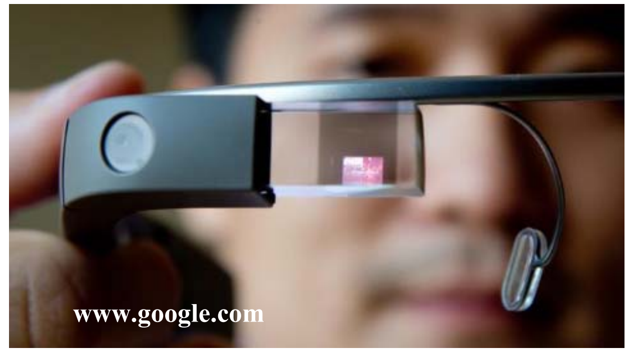

Fig.8. Google Glass

Fig.9. Optinvent ORA-S

IV. CONCEPT PROTOTYPE DEVELOPMENT

Under a government sponsored international program, NSWC PCD was tasked to research emerging waveguide optical display technology, build a concept prototype binocular see-through head-up display inside a diver's full face mask, and conduct user evaluations in a controlled, representative mission environment.

Full Face Mask Platform

The full facemask platform selected was the standard US Navy MK-20 FFM, commercial Interspiro Divator MK II (Fig 10). This is the most widely used full facemask for diving in the US military, as well as among the public safety and scientific diving communities.

Fig.10. US Navy MK-20 FFM

Polarized Waveguide Display Technology

Based on technical maturity, performance, price, availability, and integration potential; NSWC PCD selected the OE-32 Module manufactured by Lumus Ltd (Rehovet, IS) as the waveguide optical display platform for the project (Fig 11). The OE-32 uses a high-brightness 1280 x 720 pixel LCoS color micro display. The waveguide consists of a thin 1.6mm lens designed for a 22mm eye relief, which displays a 40 degree diagonal FOV image. The module accepts a standard video signal input.

Fig.11. OE-32 Optical Module

Electronics and Sensors

The OE-32 Modules are embedded into the left and right sides of the US Navy MK-20 FFM faceplate, and the left and right side electronics housings. Depth sensor, electronic compass, custom electronics boards, LEDs, and batteries are integrated into the housings. A Gumstix microprocessor using embedded Linux controls the system functions. The system is powered by two (2) replaceable CR 123 lithium-ion batteries that provide power for approximately 1-hour.

Optical Integration

<u>Binocular Alignment</u>

To simplify the system it was desirable to achieve binocular image alignment with the waveguide lenses installed in a fixed position. This was accomplished by using an interpupilary distance (IPD) of ~65mm to accommodate 95% of users [3] and initially installing the modules perpendicular to the diver's line of site. Each module was then simultaneously rotated outward from the perpendicular plane until a binocular image converged in the direct line-of-site at a specific focal distance (Fig 12).

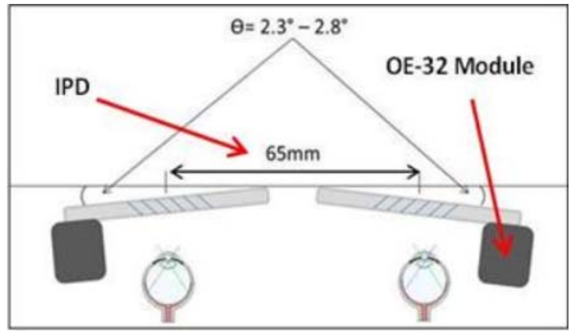

Fig.12. Binocular Alignment Design

A tilt, or convergence angle between 2.3 and 2.8 degrees was used which set the binocular focal plane distance at approximately 8ft in front of the diver. The resultant FOV was 25 degrees. This decreased FOV as compared to the 40 degree FOV for the basic OE-32 module was due to the binocular installation at a larger eye relief distance within the facemask. Two OE-32 modules, one left side and one right side, were then embedded into the sides of the US Navy MK-20 FFM faceplate and IPD spacing and alignment held in place with a polycarbonate alignment clip.

Water vapor condensation (fogging) on the waveguide lens caused significant blurring and obstruction of the image. However, the diver's inhalation cycle pulls airflow across the inside faceplate area which reduces mask fogging. The OE-32 modules were integrated inside the mask with a space between the waveguide lens and mask faceplate to allow airflow to reduce fogging on the waveguide lens as well.

Mechanical Design

The mechanical design layout is shown in Fig 13. Electronics housings were manufactured from an epoxy-resin material using a rapid prototyping stereo-lithography process. The battery compartment cap is made from machined naval brass. LEDs are embedded into the lower left and right side of the housings. All housings and electronics are sealed against pressure using a black polyurethane potting compound; the exceptions being the battery compartment to allow swap out of batteries, and the Gumstix processor board compartment to allow access for software updates and re-programming. These compartments use standard O-ring seals. The system is designed and manufactured for use in water to a depth of 30 feet. Three custom designed buttons are employed – one for the battery compartment to turn the system ON/OFF; and two for the Gumstix processor compartment to control other system functions.

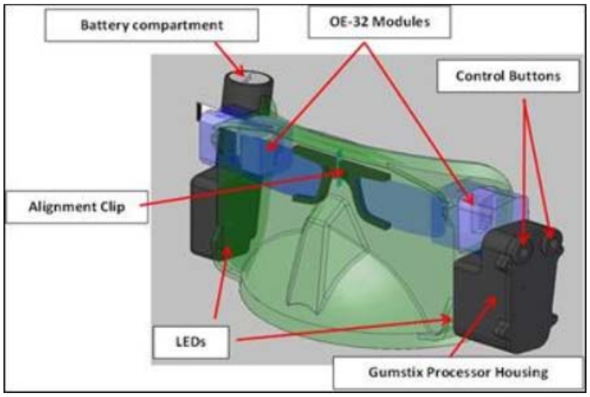

Fig.13. Prototype Mechanical Design Layout

Data Display Screens and Modes

Two types of display screens were developed; one for underwater navigation data and a second for closed circuit rebreather (CCR) data.

Navigation Mode

Data provided to the diver on the navigation screens includes real-time magnetic compass heading, depth, and time from the embedded sensors. The diver can turn the display ON/OFF; adjust between three brightness levels, use the timer function (Start/Stop/Rest), and the NAV-LOK function. When the NAV-LOK button is pressed, the current compass heading is "boxed" and the LEDs are illuminated to allow the diver to use multiple cues for conducting underwater navigation (Fig 14).

Fig.14. Navigation Display Screen

Closed Circuit Rebreather (CCR) Mode

Data provided on the CCR display screen includes depth, maximum depth, and dive time from the embedded sensors. *Simulated* voltage data for oxygen sensors and partial pressure of oxygen (PPO2) is also provided (Fig 15). The LEDs are used to flash warning cues. The diver can turn the display ON/OFF, and adjust between three brightness levels.

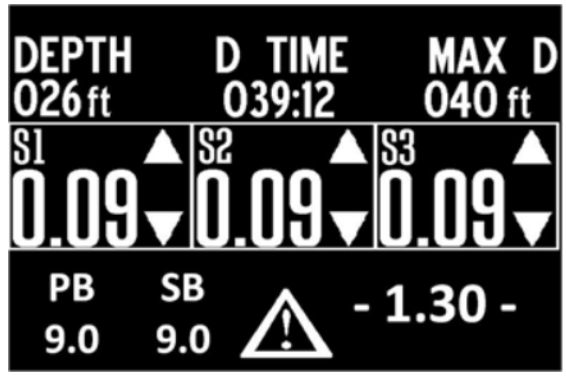

Fig.15. Closed Circuit Rebreather Screen

V. USER EVALUATIONS

Eight (8) joint service military divers conducted in-water evaluations in 2013 at the Naval Diving and Salvage Training Center (NDSTC), and the Navy Experimental Diving Unit (NEDU) in Panama City, Florida using the prototype mask (Fig 16) with open circuit SCUBA, and conducted underwater navigation, and underwater mine countermeasures (UMCM) response exercises.

Fig.16. FFM-HUD Prototype

The purpose of these evaluations was for military divers to provide qualitative input regarding the utility and feasibility of using a see-through type of head-up display for actual diving missions.

Underwater Navigation Exercise

Divers conducted a 500 yard underwater navigation swim from their starting point using the NAV-LOK function and one of the navigation screens. Upon reaching the target the diver surfaced, switched to the other navigation screen, set a reciprocal heading using the NAV-LOK function, and conducted a return underwater navigation swim back to the starting point (Fig 17).

Fig.17. UW Navigation Exercise

Underwater Mine Countermeasures (UMCM) Response Exercise (Fig 18)

Divers used the CCR display screen, descended to the bottom, and navigated to an inert mine shape using the Navy's AN/PQS-2A sonar where they conducted a UMCM response exercise; then egressed back to the starting point and surfaced.

Fig.18. UMCM Exercise

During this exercise the prototype was programmed to periodically indicate *simulated warning conditions* by flashing the embedded LEDs. The diver noted the warning, and turned on the see-through HUD to assess the specific condition. After assessing the condition, the diver cleared that condition by turning the HUD off and continuing the exercise.

Condensation

During the evaluations it was not uncommon for water droplets to get inside the dive mask during normal donning and doffing procedures. This occasionally resulted in water droplets becoming suspended on the inside of the dive mask faceplate, as well as the waveguide lens (see Fig 19).

Fig.19. Water droplets inside mask

This did cause some limited distortion of the displayed data since a water droplet acts as its own small optical lens. However, it did not cause sufficient distortion to obstruct or significantly degrade the HUD images.

Results

The prototypes were highly rated by the joint service users. All divers stated that the display data remained in-focus during the evaluation exercises, and no mask fogging occurred. Only one (1) diver needed to re-adjust the wearing position of the dive mask during evaluations in order to clearly view the display data. All test divers stated they could use a see-through head-up display dive mask system effectively with other equipment normally associated with military dive missions, and requested additional development of this capability. Detailed comments, suggestions, and specific operational and technical requirements input for a next generation system were also provided.

VI. RECOMMENDATIONS

Waveguide Optical Displays

Since only polarized waveguide displays were used in this initial prototype development, other types of waveguide optical display technologies should be evaluated to determine whether they might provide more viable solutions.

Low Power Micro Displays

Most waveguide-type display systems use very high brightness micro displays with the associated power electronics since they are designed to operate in a high brightness ambient environment. The military diving environment is typically very low light and does not require a high brightness capability. Lower power, lower brightness micro displays should be evaluated to determine whether they can provide acceptable performance in the diving environment.

Angle of Convergence
The typical large viewing screen at a focal distance of several meters is great for a consumer product showing movies and video games, but not for military divers accessing life support, navigation, sonar, and other sensor data. Additional laboratory and in-water testing of different angles of convergence for a binocular system will help determine the optimum image viewing distance for a diver's unique working environment and applications.

3D Display of Data
By using stereoscopic imaging sensors and adjusting the IPD centroid spacing and the angle of convergence; three-dimensional image display of data is possible. This should be developed and tested as it could provide significantly enhanced sonar images, and underwater navigation maps, such as the image shown in Fig 20.

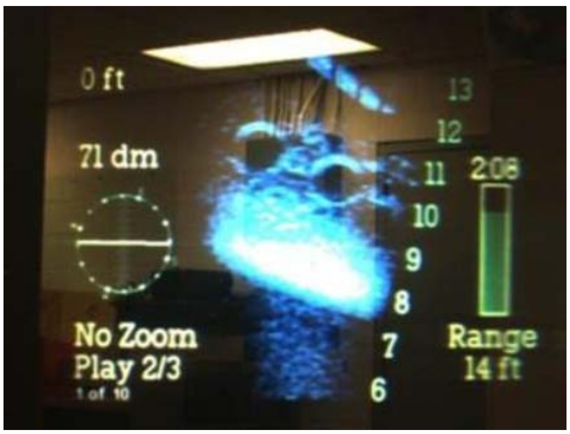

Fig.20. Sonar Image-Navigation Display

VII. REFERENCES

[1] D. Gallagher and R. Dorch 1995, "Diver's head-mounted display", [Underwater Intervention 1995 Conference Proceedings].

[2] K. Mirza and K. Sarayeddine, "Key challenges to affordable see through wearable displays: the missing link for mobile AR mass deployment", [Internal Technical Paper-OPTINVENT S. A.; Rennes, France – 2012].

[3] D. Wagner, J. Birt, M. Snyder, J. Duncanson, "Human factors design guide for acquisition of commercial-off-the-shelf subsystems, non-developmental items, and developmental systems," [1996 National Technical Information Service, Springfield, Virginia].

[4] D. Gallagher and W. Olstad, "Integrated diver display mask system for special diving applications", [21st International Conference on Offshore Mechanics and Arctic Engineering 2002 Conference Proceedings, Oceanology International 2002 Symposium Conference Proceedings].

[5] D. Gallagher, "Diver-based response capability for maritime-port security operations"; [Underwater Intervention Conference 2011 Proceedings; Oceans 2011 Conference Proceedings; Sea Technology magazine article Oct 2012].

[6] R. Manley, D. Gallagher, C. Holmes, W. Hughes, "Mask mounted display design considerations for diver operating environment", [SPIE Defense, Security, and Sensing Conference Proceedings 2011].