# HMD as a new Tool for Telepresence in Underwater Operations and Closed-Loop Control of ROVs

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***Abstract*—With the recent development of computer graphics and video-gaming, $360^\circ$ cameras and related technologies, Head Mounted Displays (HMDs) are becoming a popular tool to improve the users experience and efficiency. This trend is also connected to the computer technology improvements of the latest years and its price decrease: HMDs are now more performing and, at the same time, commercially accessible to the masses.**

**In this paper a HMD is used to improve the telepresence experience, to increase the situational awareness during underwater operations, and to actively control a Remotely Operated Vehicle (ROV). Although HMDs are already used to actively control the *point of view* of the operator by moving the camera system of vehicles, in this paper they are used to control the vehicle itself, providing a hand-free Human-Machine Interface (HMI). In this way the operator has the possibility of controlling other devices (e.g. a manipulator attached to the ROV) *while* moving the ROV, highly increasing the efficiency of the underwater operations.**

**Three control methods inspired by previous work developed for the classical joystick interface are presented, full-scale experiments and conclusions on the usability of the proposed solution for real off-shore operations are discussed.**

## I. Introduction

A Head (or Helmet) Mounted Display (HMD) is, as the name implies, a device containing one or more displays that is attached to the head (or the helmet) of an operator. Depending by its configuration it can display the same image or different views to the eyes, providing, in the latter case, a stereoscopic view. With the decrease of price of inertial sensors and Micro-Electro-Mechanical Systems (MEMS), most of the HMDs available in the market have integrated inertial sensors to track the user's head attitude in its Degrees Of Freedom (DOFs): roll, pitch and yaw.

Although some prototypes of those devices have their roots back in the 60s, and even if the research on those devices never stopped since, they became highly popular in the commercial market only in the latest years, in connection with the development of the computer technology and of related products: for example HMDs offer a completely new approach to video-gaming, since the user can feel *inside* a virtual world, instead of an external viewer. The HMD sensors allows the user to move his visual perspective inside that virtual world, giving a fully immersive experience. Some producers of flying drones provides the possibility of viewing the cameras on supported HMDs, providing to the user a first-person perspective of the flight. The recently introduced $360^\circ$ cameras, in connection with HMDs, can also provide the possibility of get different views of the vehicle surroundings by moving the head towards the point of interest.

As described in the previous examples, those devices can accomplish different goals depending by the application. In this context it is important to define the following terms [22]:

- **Virtual Reality** (VR): a computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person (e.g. video-gaming applications);
- **Augmented Reality** (AR): a technology that superimposes a computer-generated image on a user's view of the real world (e.g. drones control applications);
- **Telepresence**: the use of virtual reality technology for remote control of machinery or for apparent participation in distant events (e.g. remote vehicles control).

In this paper the telepresence aspect is mainly treated, although augmented reality could have a great impact for the further development of this technology. A recent overview of the aspects of virtual reality in connection with the usage of HMDs is provided in [15].

Notice that, as briefly mentioned above, the idea of using stereoscopy and HMDs to increase the effectiveness of certain teleoperations is not a novel idea. The first related reference can be found, to the knowledge of the authors, in [13], where the feasibility of monocular HMDs for aerospace applications was studied. In this paper is in fact mentioned:

*"The exact nature of the visual displays utilized in a space ship will depend on precisely what operations man is expected to perform [during] a given mission [...]. Nonlinear displays and other relatively novel display characteristics should not be overlooked or neglected in attempting to find an adequate solution to... [such problems]."*

Since then, many others have used such technology for different applications: [14] proposes a first approach to use HMDs for telemanipulation, where the effectiveness of such approach is investigated. The head motion is linked to the motion of cameras on the area where the manipulator is operating, freeing the operator's hands from the need of controlling the cameras orientation. [2] lists possible applications of the HMD technology, spanning between military, space exploration,

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aviation, industrial and medicine applications. [24] and [7] suggest some HMDs prototypes for medical applications. [3] proposes a telepresence system to visit museums, [16] uses a HMD to better operate excavation field robot. Some research is also focused on understanding the problems of motion sickness and nausea given by the prolonged used of HMDs, that can highly impact on the effectiveness and that is one of the main obstacles to a wider employment of this technology, see for example [19], [18] or [4]. [18] is also a good review of the HMD technology in connection with teleoperation. Moreover comparative results with standard interfaces are presented.

In this paper the usage of HMDs is explored with the objective of increasing the telepresence experience and the situational awareness while operating a Remotely Operated Vehicle (ROV); moreover the motion of the vehicle is controlled by the operator (by moving his head) through a HMD.

Notice that a similar work has been done in [18] for land robots, while there exist no similar work published for underwater vehicles, to the best knowledge of the authors. [27] approached this vision from an industrial design point of view, suggesting the possibility of employing HMDs for underwater operations.

In this paper the interest is mainly focused in knowing if this could actually replace the classical joystick control for underwater operations in the future, especially for operations where the employment of the classical joysticks means the need of two operators at the same time. This is relevant because the usage of the HMDs would leave the operator with both the hands free to operate other tools than the vehicle itself; in particular would be possible to control manipulator(s) mounted on the vehicle *while* controlling the vehicle motion. Nowadays those two operations (control of the vehicle and of the manipulator) can only be done by two operators. This results in a challenging situation due to the necessary tasks synchronization: the inputs that one operator give to one system (e.g. the ROV) cannot disregard (and will influence) the inputs that the other operator is giving to the system he is controlling (e.g. the manipulator). This will necessarily cause many small corrections that can make the operations imprecise or slow. A more efficient operation is expected if one operator could control the whole system.

This paper is organizes as following: Section II briefly presents the ROV used for the experiments and its applications, Section III presents the used HMD, Section IV presents the cameras and the stereo-rig mounted on the vehicle. Section V describes the software used to process the HMD images and the interface to the ROV control software. Section VI presents the algorithms that use the HMD attitude output to control the vehicle motion. Section VII shows the experimental results obtained in May 2015 in Trondheimsfjorden, Norway. Finally, Section VIII states the conclusions, possibilities and limitations of this technology and possible further work.

## II. The 30k ROV

### A. Vehicle Description

The 30K ROV is a work class ROV that is powered from and communicates with a surface vessel through a $1000m$ umbilical (Figure 1). All systems needed for operation such as power supply, navigation computers and monitors are fitted inside a control container carried by the aforementioned vessel. It weights $1800\mathrm{Kg}$, and its dimensions are respectively $260, 150, 160\mathrm{cm}$ for length, width and height. Maximum depth rating is $1000\mathrm{m}$. It is propelled by six $3000\mathrm{W}$ thrusters, two horizontal, three vertical and one lateral.

30k is equipped with a 7DOFs hydraulically-powered Raptor manipulator from Kraft Telerobotics connected with a joystick that reproduces its kinematics, provides force feedback and allows for master/slave control of the device.

The sensors payload includes an X-Sens100 IMU, a transponder that communicates with a Kongsber High-Precision Acoustic Positioning (HiPAP) system, a Teledyne RDI Workhorse Doppler Velocity Log (DVL), a Valeport mini Pressure Sensor. For a detailed list of specifications, refer to [26], [9] and [5]. Figure 2 shows the vehicle, the sensors payload and the connections with the control devices.

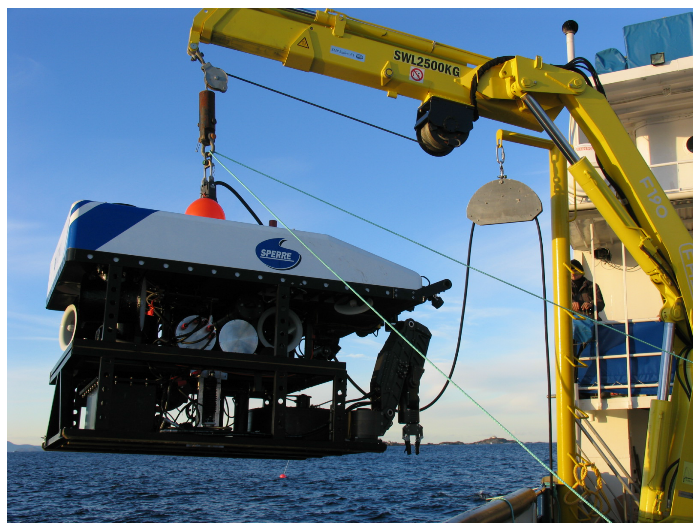


Fig. 1. Sperre 30k work-class ROV in the launch phase.

### B. Standard Operations

The Applied Underwater Robotics Laboratory (AUR-Lab) of NTNU, Norway, operates the vehicle mainly in two different ways depending by the operations needs: for manipulation work, picking operations, sensor deployment operations (and so on) two operators are needed: one controls the vehicle by using the ROV control console provided by the vendor (Figure 2), and the other one controls the manipulator with its joystick. For survey, mapping and exploration missions the automatic DP control system developed at NTNU is preferred, since accuracy and precision of positioning is to be prioritized (refer to [25] for information concerning the control system, to [17] for the AUR-Lab operations).

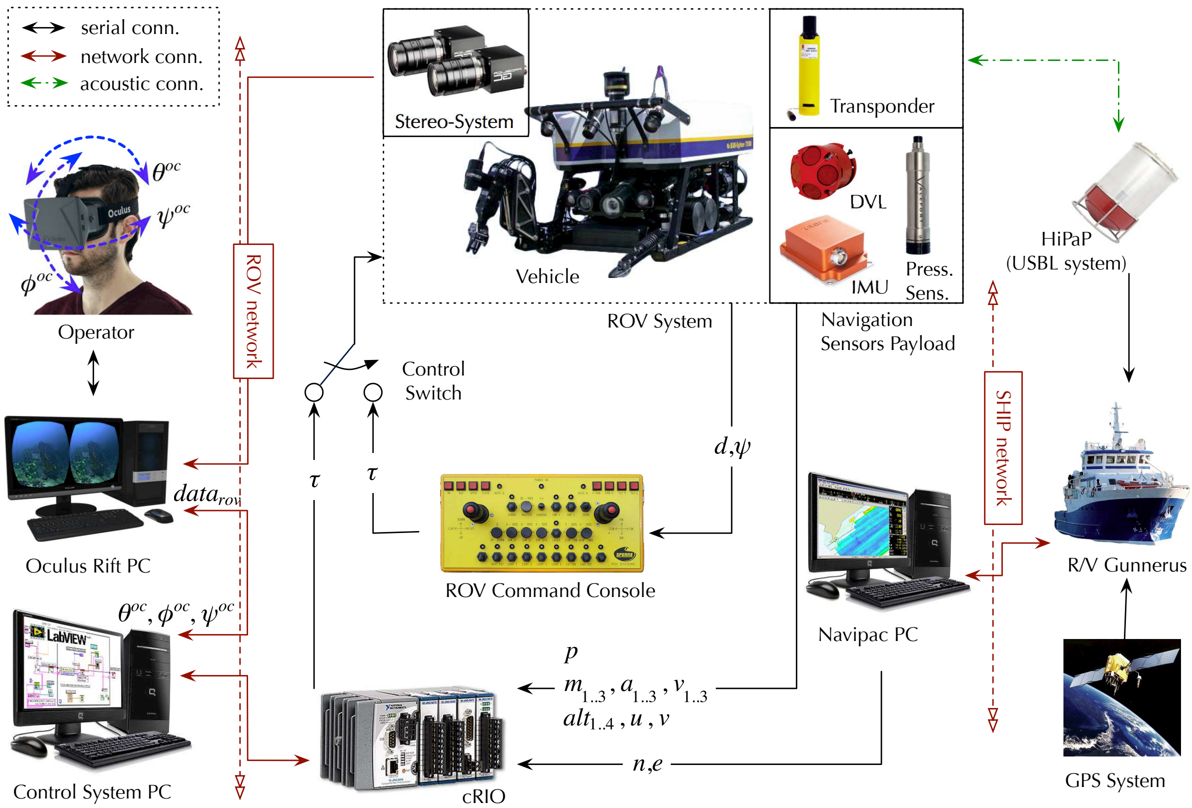


Fig. 2. Main hardware components and connections. Black, red and green lines represent respectively serial, network and acoustic connections. The main sensors payload and signal flow is represented. In the left part the connection between the OR, the OR PC and the DP Control System PC is shown, together with the exchanged information.

## III. Oculus Rift

The HMD used in this work is the Oculus Rift (OR) DK2, shown in Figure 3. It is one of the most known HMD systems, but it is still only available as a developer kit. The consumer edition is believed to be released in 2016. The Oculus Rift has a magnetometer, accelerometer and gyroscope for tracking head attitude at a high refresh rate since its mainly designed for VR applications, where the ability to look around in a virtual world is essential. In addition to the attitude information, it is possible to measure the relative position of the device in space through an external infrared tracker that also increases the accuracy of the attitude measurements. More information about the hardware can be found in [1].

Although this device has been considered to increase the telepresence with vehicles like aerial drones, or to simulate the presence in fictional 3D scenarios (for videogames purposes), to the knowledge of the authors it has never been used for the active control of ROVs before.

Fig. 3. The Oculus Rift is the HMD chosen for increasing the telepresence experience and to actively control the ROV 30k.

## IV. Stereo-Vision System

The ROV is equipped with two Allied Vision GC1380C that provide images at a resolution of $1360 \times 1024$ pixels at a frame rate of 20.2fps; higher frame rate could be achieved by reducing the resolution of the cameras [29]. In this experiment reduced the resolution to obtain 30fps. Those cameras are fitted in underwater camera casings and mounted on a stereo-rig. The images are sent to the OR to provide a stereoscopic view of the underwater environment. Although this settings was experimental, from the first tests the operator got a much more *immersive* experience, given the real 3D view feeling. In further work more work should be done to find the optimal camera positioning to get the best view experience. Notice that this stereo-rig has been used by AUR-Lab also for the construction of underwater photogrammetry models [20].

## V. SOFTWARE

Two computers are used to run all the softwares needed for the operations. One computer is focused on the user interface, OR image rendering and camera processing. The second computer is used for the real-time control of the ROV [25]. The system architecture is shown in Figure 2.

### A. Oculus Rift computer

The software developed for stereoscopic capture and visualization consists of three independent threads, which runs in parallel after the initialization process. The main reason for the parallel processing is due to different time frames for each independent process. Two external libraries were used, OpenCV and PvAPI, [21] and [23] respectively.

One thread is responsible to queue and capture the frames for both cameras using the PvAPI library. The cameras were sampled in 30Hz to avoid performance issues. Both images where queued as soon as the most recent frame was captured, increasing efficiency.

The second thread is responsible for the communication with the OR. The OR is instantiated in a singleton, while data such as readings for the accelerometers were stored on a shared memory. In this thread the last images captured by the cameras are rendered directly in the OR, with the corresponding camera for each eye. It is a common practice to have the rendering thread running between 60Hz and 75Hz to avoid motion sickness. The software was based on the examples presented in [8].

Finally, the communication with the control computer is held by the last thread. The OR attitude is sent to the control computer trough a UDP protocol, at $5\text{Hz}$ , which is interpreted according to the selected control algorithm (speed control, position control, etc). Also, the bidirectional communication enables the possibility to display critical data on the headset (such as depth, distance to target, heading, etc). This introduces a certain level of *Augmented Reality* to the user experience; in the authors opinion improving the impact of the Augmented Reality experience with more complex and elaborated information can increase widely the situational awareness. This would increase widely, in turn, the efficiency of the mission.

### B. Control computer

The second computer is responsible for the DP control system. It runs on an independent PC in order to increase the reliability as well as ensuring that no HMI-related thread would interrupt the communication with the ROV.

The DP system is developed using LabView, on its Graphical User Interface (GUI) it is possible to enable, disable the HMD control, and chose the different HMD control methods. If the communication with HMD is lost, the operator can take control of the vehicle using the joystick.

The DP system runs a Kalman Filter for sensor fusion and state estimation, a nonlinear PID controller, signal processing, thrust allocation algorithms and so on. Details can be found in [25], [9], [11], [6] and references therein.

## VI. OCULUS RIFT CONTROL METHODS

The Oculus Rift IMU output is given as an input to a guidance system, which goal is to produce a feasible desired state for the control system. In particular the goal is to associate the three possible rotations of the head with the changes of three DOFs of the vehicle. Recalling that an ROV can freely move in space through its 6 DOFs: $\boldsymbol{\eta} = [\ x \quad y \quad z \quad \phi \quad \theta \quad \psi\ ]$, the goals is to control $x$ (surge) with a forward and backward motion of the head, $y$ (sway) with a sideways motion of the head and $\psi$ (way) rotating the head left and right. It is here necessary to say that $\phi$ and $\theta$ are passively stable [25], hence don't require active control, and $z$ is controlled independently by an altitude or depth controller, dependently by the requirements of the specific mission [9]. Consequently, the control of $\phi$, $\theta$ and $z$ will not be treated in the following.

### A. Oculus Rift Variables

The selected guidance system is based on the one developed for the joystick interface in [10] and produces a direct thrust or a *oculus rift* velocity reference $\boldsymbol{\nu}^{oc}$ from which desired *vehicle* position and speed $\boldsymbol{\eta}_d$ and $\boldsymbol{\nu}_d$ are calculated, depending by the selected control method.

The normalized head angle measured by the OR attitude sensors are (see the link between the variable and the head rotation in the top left corner of Figure 2):

$$\overline{\boldsymbol{\Theta}^{oc}} = \left[\ \overline{\phi^{oc}} \quad \overline{\theta^{oc}} \quad \overline{\psi^{oc}}\ \right] \tag{1}$$

where $\overline{\phi^{oc}}, \overline{\theta^{oc}}, \overline{\psi^{oc}} \in [-1, 1]$ are respectively the OR roll, pitch and yaw. The normalization is done to have common and defined limits for the angle ranges.

Experimental tests suggested that is beneficial to introduce a saturation and a dead zone when considering the OR output vector $\boldsymbol{\Theta}^{oc}$. The saturation helps the operator not to bend his head over the comfort limit, while the dead zone allows the operator to rapidly find the zero head position without inducing oscillations in the process. The OR roll and pitch angles are saturated at $30°$, while yaw is saturated at $45°$. The dead zone is constrained to $5°$ around the zero position.

### B. Direct Thrust Control

The simplest OR control is a feed-forward force control. This turns operators head movements directly into thrust commands and involves no feedback terms, the following control law is employed:

$$\boldsymbol{\tau} = \boldsymbol{K}_{oc}^{\tau} \boldsymbol{T}_{oc}^{b} \overline{\boldsymbol{\Theta}^{oc}} \tag{2}$$

where $\boldsymbol{K}_{oc}^{\tau}$ is defined so that the maximum output will correspond to the maximum available thrust:

$$\boldsymbol{K}_{oc}^{\tau} = \text{diag}\ \left[ X_{\max} \quad Y_{\max} \quad 0 \quad 0 \quad 0 \quad N_{\max}\ \right] \tag{3}$$

where $X_{\max}$, $Y_{\max}$ and $N_{\max}$ are respectively the maximum available thrust in surge, sway and yaw. $\boldsymbol{T}_{oc}^{b}$ is the transformation matrix that links the OR reference frame to the ROV body frame:

$$\boldsymbol{T}_{oc}^{b} = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{4}$$

Notice that the minus sign in the transformation matrix is necessary to obtain the expected ROV motion given a certain head rotation. For example it is expected for the ROV to move forward when the head is bended forward. In the following tests the $\boldsymbol{T}_{oc}^{b} = \boldsymbol{I}$, where $\boldsymbol{I}$ is the identity matrix. Finally $\boldsymbol{\tau}$ is the 4 elements thrust vector, that specifies a thrust value for every *controllable* DOF.

### C. Speed Reference

In this case, the change of the OR variables is mapped to a desired OR velocity $\boldsymbol{\nu}^{oc}$ that is the input to a reference model. A mapping is needed to associate the DOFs in the OR reference system to the body frame DOFs of the vehicle:

$$\boldsymbol{\nu}^{oc} = \boldsymbol{K}_{oc}^{\nu} \boldsymbol{T}_{oc}^{b} \overline{\boldsymbol{\Theta}^{oc}} \quad (5)$$

where $\boldsymbol{K}_{oc}^{\nu}$ is a diagonal scaling matrix for velocity:

$$\boldsymbol{K}_{oc}^{\nu} = \text{diag} \begin{bmatrix} K_u & K_v & 0 & 0 & 0 & K_r \end{bmatrix} \quad (6)$$

The implemented reference model is a second-order low-pass filter (see, for instance, [12] for an in-depth description of the model):

$$\begin{aligned} \dot{\boldsymbol{\eta}}_d &= \boldsymbol{J}(\psi_d)\boldsymbol{\nu}_d \\ \ddot{\boldsymbol{\nu}}_d + 2\boldsymbol{\Delta}\boldsymbol{\Omega}\dot{\boldsymbol{\nu}}_d + \boldsymbol{\Omega}\boldsymbol{\nu}_d &= \boldsymbol{\Omega}^2\boldsymbol{\nu}^{oc} \end{aligned} \quad (7)$$

$\boldsymbol{\Delta}$ and $\boldsymbol{\Omega}$ represents the damping and natural frequency parameters for every DOF and should be set so that the reference model would produce a feasible output for the vehicle. In [28] the values used for those parameters are extensively reported. Notice that the $\boldsymbol{\nu}^{oc}$ produced by (5) is given to the second equation in (7) to produce a *vehicle* desired velocity $\boldsymbol{\nu}_d$. This is then transformed in the desired position with the first equation of (7), that is a coordinate transformation to the NED frame described by the matrix $\boldsymbol{J}(\psi_d)$.

### D. Position and Velocity control

For the closed loop control of the ROV, a nonlinear PID control law is implemented. This algorithm can work in two modes: position and velocity reference control. For the position control the following algorithm is used:

$$\boldsymbol{\tau} = -\boldsymbol{J}^T(\hat{\boldsymbol{\eta}}) \left( \boldsymbol{K}_p \tilde{\boldsymbol{\eta}} + \boldsymbol{K}_i \int_0^t \tilde{\boldsymbol{\eta}} d\boldsymbol{\tau} \right) + \boldsymbol{K}_d \tilde{\boldsymbol{\nu}} \quad (8)$$

where $\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta}_d - \hat{\boldsymbol{\eta}}$ is the control error defined as the difference between the desired and estimated state vector. $\boldsymbol{K}_p$, $\boldsymbol{K}_i$, $\boldsymbol{K}_d$ are proper tuning matrices to be chosen dependently by the vehicles characteristics and the expected convergence performance. If the velocity control is chosen, the force elements corresponding to surge and sway are changed into:

$$\begin{aligned} X &= -K_{p,u}(u - u_d) - K_{i,u} \textstyle\int_0^t (u - u_d) d\tau \\ Y &= -K_{p,v}(v - v_d) - K_{i,v} \textstyle\int_0^t (v - v_d) d\tau \end{aligned} \quad (9)$$

where $u$ and $v$ are the surge and sway speeds. For the integral effect of both controllers, an anti wind-up algorithm is implemented in the following way:

$$\boldsymbol{\tau}_i = \left( \boldsymbol{K}_i - \boldsymbol{K}_{\text{anti},i}(\text{sat}(\boldsymbol{\tau}_i) - \boldsymbol{\tau}_i) \right) \int_0^T \bar{\boldsymbol{\eta}}(t) d\boldsymbol{\tau} \quad (10)$$

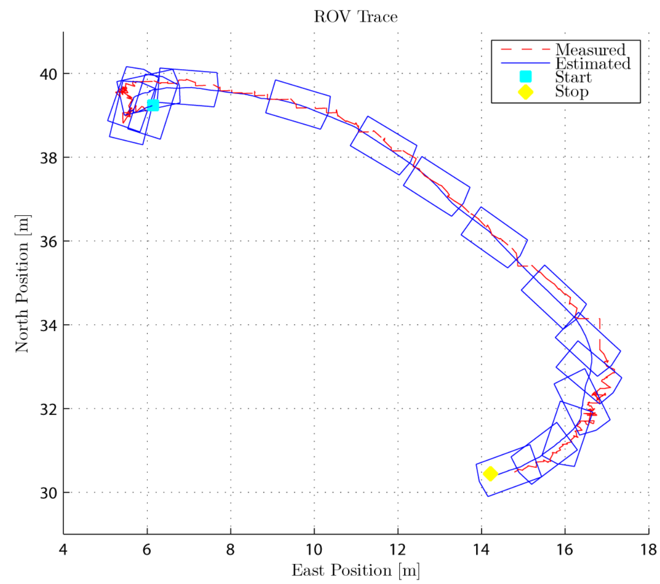


Fig. 4. Force control is used to push 30k on a straight line, ending with a turn. Although this method is more responsible, it is more challenging to obtain a smooth response.

$\boldsymbol{K}_{\text{anti}}$ is the anti-windup tuning matrix. All the numerical values for the tuning matrices that have been used in the experiments reported here can be found in [28]. Notice that with those control methods external forces or disturbances (like the tether drag and current forces) are automatically taken care by the DP system [10], this leaves the operator with the only duty of controlling the vehicle motion.

## VII. Experimental Results

The experiments aimed to test the OR control methods. The ROV has been steered with the OR providing the inputs to the three algorithms and the state of the ROV has been logged. Some results are showed and commented in the following. It is difficult to quantitatively compare the performance of the algorithms, since the experiments have been done in full scale in a unstructured environment. The main objective, at this stage, is to evaluate the usability of the methods and the operator feedback while controlling the ROV with them.

### A. Motion Tests

Three results concerning the three control methods are shown: Figure 4, 5 and 6 show respectively the results for tests related to force, velocity and position control. Force control is used to move the vehicle on a line, ending with a right turn. Velocity control is used to move the vehicle forward on a straight line. Position control is used to move the ROV on a square path, notice that the heading is easily kept stable and constant nevertheless the change in the other DOFs.

Although force control is more responsive, due to the absence of a reference model, the operator reported an higher difficulty of controlling the motion of the vehicle in a smooth way. Following a straight line has been easier with the other

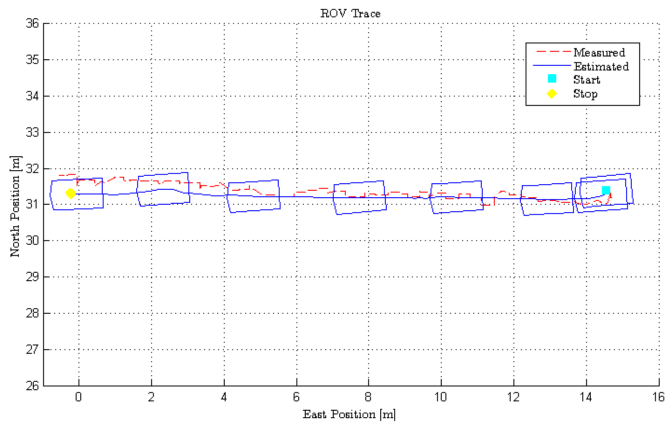


Fig. 5. Velocity control is used to run a straight line. Here the velocity is successfully kept constant along the line.

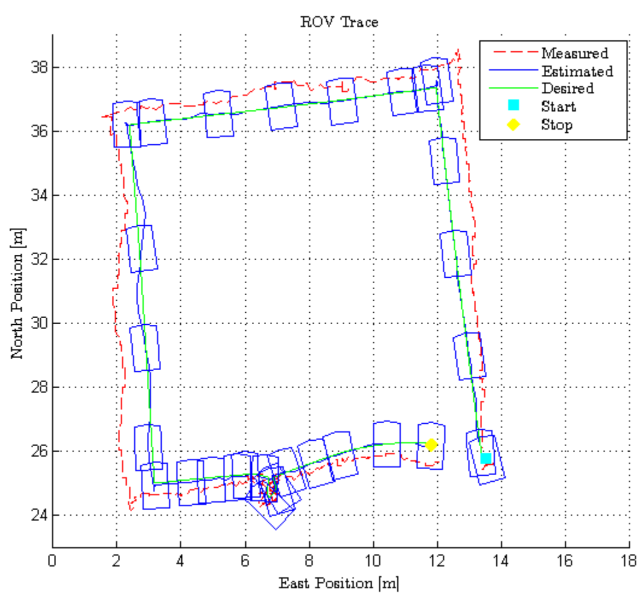


Fig. 6. In this result the operator is moving the vehicle in position control. It is possible to notice that, although the operator does not have a full map representation superimposed on the OR screen, he is able to perform a square with quite high precision, keeping constant heading along all the path.

control functions. In particular it is possible to see how accurate was the motion along the square path, using the position control.

## B. Inspection Tests

In the authors opinion, HMDs are definitely suitable for inspection works, in particular it allows to move around an Object Of Interest (OOI) keeping the focus on the object by slightly changing the heading and moving sideways at the same time. In Figure 7 a small object is inspected by the operator, while the ROV is moved in a small circle around it.

Another test has been done with the purpose of inspecting a bigger object of interest, i.e. Hercules wreck, a tugboat

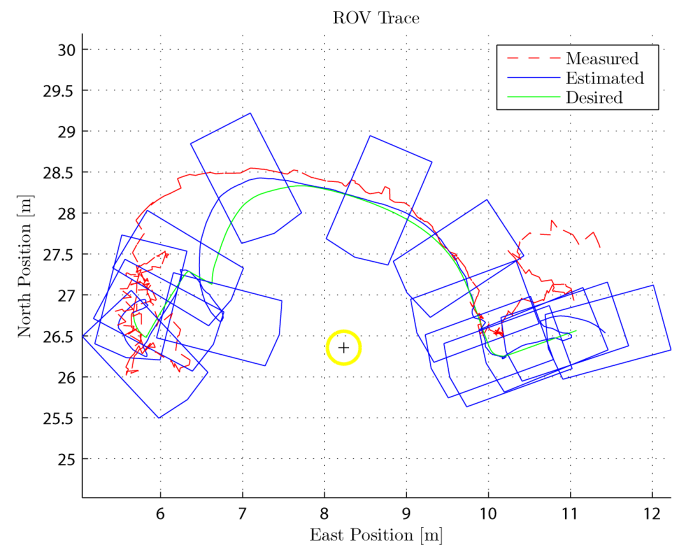


Fig. 7. Position control is used to inspect an object (a bottle on the sea bottom). It is clear that the operator manages to slowly tilt his head in such a way that the OOI is always kept in the field of view of the cameras.

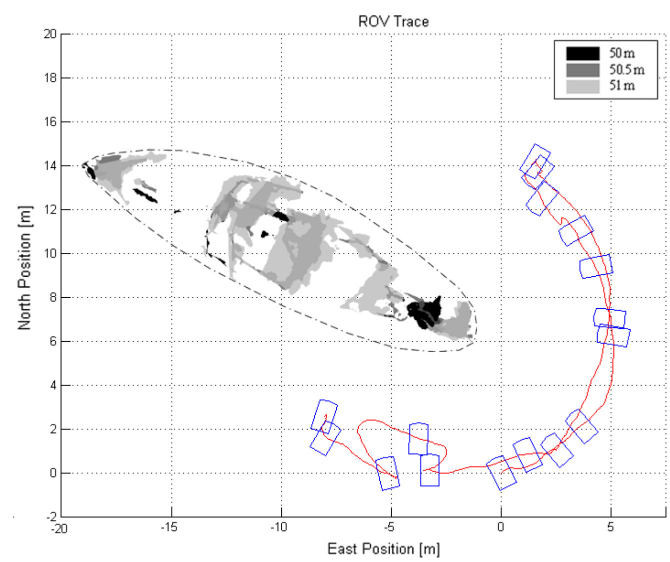


Fig. 8. 30k is inspecting the stern of the Hercules wreck. 3 layers of the photogrammetry model of the wreck are also drawn. The full photogrammetry model is presented in [20]. The ROV is kept stable at 50m depth

that sank in the Trondheimsfjorden in 1957. It is possible to see from Figure 8 how the position control allows smooth inspection maneuvers, making it easy to constantly look at the object of interest. In this case the ROV has been moved sideways while the operator was inspecting the stern of the boat. The stereoscopic view allows to have a great immersive feeling for the operator.

## C. Manipulation Tests

Having the possibility of controlling the vehicle with his head, the operator can use his hands to operate the manipulator (Figure 9). This gives him control over the whole system. In


Fig. 9. The HMD allows the operator to have full control over the whole system, without having to rely on a second operator.

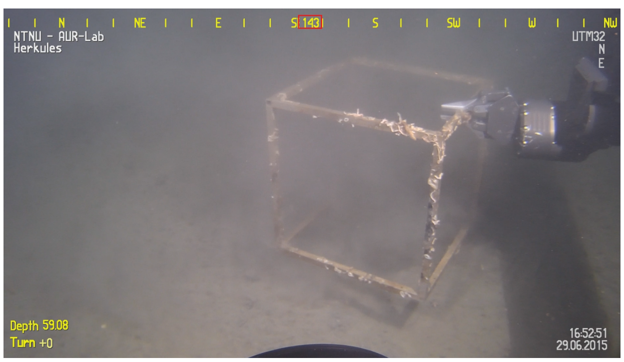


Fig. 10. Here the moment when the box is grabbed is shown: the ROV is kept stable with the HMD and the manipulator is actuated using the joystick depicted in Figure 9.

the reported test a box frame (Figure 10) have been grabbed by the operator, while the ROV was kept stable through the OR. In further work comparative examples will be presented to quantitatively show the effectiveness of this method over the classical joystick method with two operators [14]. Here it is possible to qualitatively report that the operation has been executed with high efficiency: the operator was able to slowly approach the object, adjust the position of the vehicle so that the manipulator could easily grab it, extend the manipulator while repositioning the vehicle so that the object could have been actually reached, grab the object and move to another position to replace it.

## VIII. Conclusion and Further Work

In this paper a HMD system is proposed in order to increase the efficiency of Remotely Operated Vehicles teleoperations and telepresence by augmenting the situational awareness. Moreover the HMD has been used as an interface device for closed-loop control of the ROV, providing to the operator the possibility of having full control on the whole underwater system. The HMD interface gave satisfactory results, showed by the experimental results discussed above. Those suggest that there is space for further improvements that could let this HMI become highly beneficial for real offshore operations, improving their efficiency. In particular the augmented reality is a key to improve the situational awareness of the operator even more. A systematic set of tests that would involve more operators and comparative results against standard control interfaces will be presented in further work. Introduction of more advanced guidance methods is also considered.

## Acknowledgment

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## References

[1] Oculus rift developer forum. https://developer.oculus.com/. Accessed: 2015-07-20.

[2] Head-mounted electronic device permits viewing of two images at once. *Electrical Engineering*, 81(6):483–484, June 1962.

[3] A. Agah, R. Walker, and R. Ziemer. A mobile camera robotic system controlled via a head mounted display for telepresence. In *Systems, Man, and Cybernetics, 1998. 1998 IEEE International Conference on*, volume 4, pages 3526–3531 vol.4, Oct 1998.

[4] H.L. Alexander. Experiments in teleoperator and autonomous control of space robotic vehicles. In *American Control Conference, 1991*, pages 1474–1477, June 1991.

[5] V. Berg. Development and commisioning of a dp system for rov sf 30k. Master's thesis, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2012.

[6] M. Candeloro, A.J. Sørensen, S. Longhi, and F. Dukan. Observers for dynamic positioning of rovs with experimental results. In *9th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC)*, volume 1, pages 85–90, September 19-21 2012.

[7] I.S. Cardenas and J.H. Kim. Advanced technique for tele-operated surgery using an intelligent head-mount display system. In *Biomedical Engineering Conference (SBEC), 2013 29th Southern*, pages 143–144, May 2013.

[8] B.A. Davis, K. Bryla, and P.A. Benton. *Oculus Rift in Action*. Manning Publications Co., 2015.

[9] F. Dukan. *ROV Motion Control Systems*. PhD thesis, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2014.

[10] F. Dukan and A.J. Sørensen. Joystick in closed-loop control of rovs with experimental results. *3rd IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV)*, pages 293–300, 2012.

[11] D. Fernandes. *An Output Feedback Motion Control System for ROVs*. PhD thesis, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2015.

[12] T.I. Fossen. *Handbook of Marine Craft Hydrodynamics and Motion Control*. John Wiley and Sons, UK, 2011.

[13] R.J. Hall and J.W. Miller. Feasibility study for a monocular head-mounted display. *Hughes Aircraft Company, Special Technical Document SD 60-70*, 1960.

[14] W.S. Kim, A. Liu, K. Matsunaga, and L. Stark. A helmet mounted display for telerobotics. In *Compcon Spring '88. Thirty-Third IEEE Computer Society International Conference, Digest of Papers*, pages 543–547, Feb 1988.

[15] K. Kiyokawa. Trends and vision of head mounted display in augmented reality. In *Ubiquitous Virtual Reality (ISUVR), 2012 International Symposium on*, pages 14–17, Aug 2012.
[16] Q.H. Le, K.T. Park, Y.M. Jeong, and S.Y. Yang. A study on remote control system integrated intuitive vision system for field robot using head tracker system. In *Control, Automation and Systems (ICCAS), 2014 14th International Conference on*, pages 326–330, Oct 2014.
[17] M. Ludvigsen, P. Lågstad, T. Thorsnes, Ø. Ødegård, R.E. Hansen, M. Candeloro, A.J. Sørensen, S.M. Nornes, G. Johnsen, and C. Malmquist. Underwater vehicles for environmental management in coastal areas. In *Oceans15 MTS/IEEE Genova*, May 18-21 2015.
[18] H. Martins, I. Oakley, and R. Ventura. Design and evaluation of a head-mounted display for immersive 3d teleoperation of field robots. *Robotica*, FirstView:1–20, 5 2014.
[19] M.E. Morphew, J.R. Shively, and D. Case. Proceedings of spie - the international society for optical engineering. In *American Control Conference, 1991*, September 2004.
[20] S. M. Nornes, M. Ludvigsen, Ø. Ødegård, and A.J. Sørensen. Underwater photogrammetric mapping of an intact standing steel wreck with rov. In *4th IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV)*, April 28-30 2015.
[21] OpenCV. Opencv library refefrence. http://docs.opencv.org, June 2015.
[22] Oxford University Press. Oxford dictionaries. http://www.oxforddictionaries.com/definition/english/, August 2015.
[23] PvAPI. Pvapi legacy software from allied vision. http://www.alliedvision.com/en/support/software-downloads.html, June 2015.
[24] E. Schneider, K. Bartl, T. Dera, S. Bardins, G. Boning, P. Wagner, and T. Brandt. Gaze-aligned head-mounted camera with pan, tilt, and roll motion control for medical documentation and teaching applications. In *Systems, Man and Cybernetics, 2006. SMC '06. IEEE International Conference on*, volume 1, pages 327–331, Oct 2006.
[25] A.J. Sørensen, F. Dukan, M. Ludvigsen, D. Fernandes, and M. Candeloro. Development of dynamic positioning and tracking system for the rov minerva, 2012.
[26] Sperre. 30k specifications. http://sperre-as.com/produkter/rov/systemer/sub-fighter-30k, August 2015.
[27] S. Surn. Interaction design in a 4d sea map. Master's thesis, Department of Production Design, Norwegian University of Science and Technology, Trondheim, Norway, June, 2015.
[28] E. Valle. Marine telepresence system. Master's thesis, Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, 2015.
[29] Allied Vision. Prosilica gc1380. http://www.alliedvision.com/en/products/cameras/detail/1380.html, August 2015.