Comparative assessment of human machine interfaces for ROV guidance with different levels of secondary visual workload

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***Abstract*— Majority of ROVs are underwater vehicles with relatively slow dynamics virtually providing a ROV pilot extra time to perform other tasks, such as inspections and arm operation. However, with many tasks performed simultaneously with flying, the relevant information is typically dispersed on a number of screens overloading the pilot's visual channel. Surprisingly, there is very little research examining the unique human-factors problems associated with unmanned underwater vehicles. Use of audio display has been suggested as a means to reduce visual workload, to enhance situation awareness, and mitigate the visual and cognitive demands of contemporary ROV operations. Our research investigate the effects of secondary visual tasks on operators workload and performance using standard visual navigation interface, augmented reality visual interface and audio interface. All experiments were performed on the state-of-the-art, real-time ROV simulator developed by Mobile & Marine Robotics Research Centre, University of Limerick and augmented reality system developed by Laboratory for Underwater Systems and Technologies, University of Zagreb. As expected, the results show that in no-load conditions visual guidance is better than the guidance-by-sound. By contrast, the effects of secondary visual load affect operators' performance. The use of augmented reality paradigm and especially hearing, in the form of the auditory display, emerges as an important advantage. Improvement depends on a level of experience in using auditory guidance system. Practice has a major effect on performance, bringing us to the conclusion that there is a more room for improvement in using auditory interface.**

I. Introduction

The term remotely operated vehicle or ROV, in the maritime world, refers to a Unmanned Underwater Vehicle that is remotely operated by a human operator from the surface. The ROV is directly connected to the user interface through the umbilical cable (or tether) that transmits the power and communication.

A contemporary ROV control room is stuffed with screens presenting everything from video streaming from multiple cameras to various data acquired from multiple ROV subsystems. The information is exclusively presented visually. The pilot is often required to perform multiple tasks simultaneously e.g. piloting, inspection, search and therefore enormous quantity of information [1], dispersed on different screens may easily overload the ROV pilots' visual channel and prevent them from perceiving all important information related to the particular task. In ROV applications these issues, i.e. dispersion of relevant information, overloading of visual channel and operator multitasking, are recognized as a significant problem often resulting in failed missions or even mishaps. Surprisingly, there is very little research examining the unique human factors problems associated with unmanned underwater vehicles [2], [3].

Augmented Reality (AR) is a technology which, combining a real-world scene with a virtual elements, change the way we receive information. All the relevant information that exists can suddenly become part of our decision making process. It embodies not only a usual (ordinary) visual blending of real and virtual worlds, but it can also merge capabilities of other human senses i.e. hearing or touch, unloading the operators' visual channel and benefiting from additional advantages specific to that human sense.

Humans use auditory modality for development and maintenance of situation awareness in natural environments. We are able to determine the location of a sound source anywhere in the 360-degree space around us (even for those that are out of our field of view), monitor events at multiple locations simultaneously and to switch our focus of attention between sound sources at will [4]. Exploiting these human abilities it is reasonable to expect that operators situational awareness can be improved using spatial sound interface/display.

To authors' knowledge, there are not comprehensive studies that compare performance of visual, AR or audio guidance methods. The aim of this paper is to compare, based on objective measures, ROV path following performance using different HMI's: standard visual-navigation display, AR visual display and AR auditory display. We hypothesize that performance of visual navigation (standard or AR) for no or low workload scenarios will be superior to the audio navigation. The reasons for that are: spatial acuity of the visual channel is much better than that of the auditory channel [5], and humans use vision on a permanent basis for navigation, we are very well trained for visual navigation. We also hypothesize that applying additional visual and cognitive load the advantage of using AR paradigm and especially hearing, in a form of the auditory display shall come to the light.

The objective of this paper is to present comparative test and analyze effectiveness of the different HMIs used. Hence, section 2 describes the methodology and a simulation platform used in the paper. Next, experimental results are provided in Section 3 and are discussed. Finally, a set of conclusions are provided.

II. Methodology and resources

The nature of the experiments requires substantial number of experiments and test operators (subjects). The necessity of conducting the high cost in-field experiments was avoided by the use of the real-time ROV simulator expanded with visual and audio AR system. The ROV simulator was developed at the Mobile & Marine Robotics Research Centre (MMRRC),

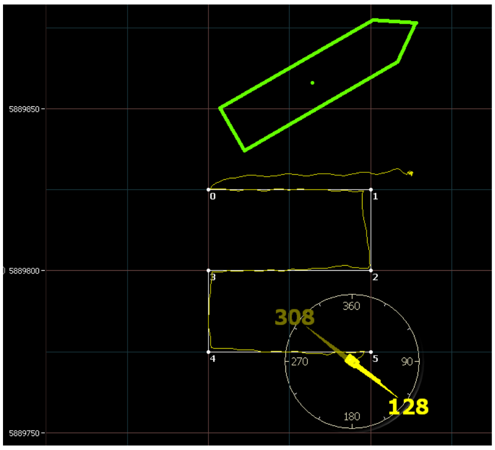

Fig. 1. Example of the Mission Layout for the Path Following Experiment

University of Limerick, Ireland while AR system was developed at the Laboratory of Underwater System and Technologies, University of Zagreb, Croatia. The experimental platform and its components are described below.

A. ROV simulator and communication framework

Multi Purpose Platform Technologies for Subsea Operations (MPPT Ring) is a set of assistive tools developed in the MMRRC. It comprises simulation, modelling, control and visualisation tools, [6]. Part of our interest, usually used to effectively train ROV pilots, is a high-level simulator. The simulator presents navigation data via typical navigation screen used for ROV operations (Figure 1). It also provides position, orientation and feedback data from ROV sensors, needed by the AR system to accurately generate virtual environment. Medium used for data transfer is the Mission Oriented Operating Suite (MOOS) which provides a framework for inter-process communication, [7]. AR system can be easily reattached from the simulator to the real ROV system. In that case accuracy and reliability of ROV localisation is crucial for the proper performance of the AR system. Underwater localisation is by no means a trivial task and was investigated by many scientists, [8], [9].

B. Guidance

Path following refers to the problem of forcing a vehicle to converge to and follow a desired spatial path, without any temporal specifications [10]. Applying control algorithms in a form of a appropriate guidance laws provides method suitable for path following or trajectory tracking. The guidance system generate reference for the yaw rate controller (human operator) which is responsible for controlling the direction of the velocity. Path following is ensured by proper steering laws as long as vehicle speed exist. Consequently, the control objective is to track the motion of a target that moves along a predefined path and it is given by:

$$\lim_{t \to \infty} (p(t) - p_D(t)) = 0 \tag{1}$$

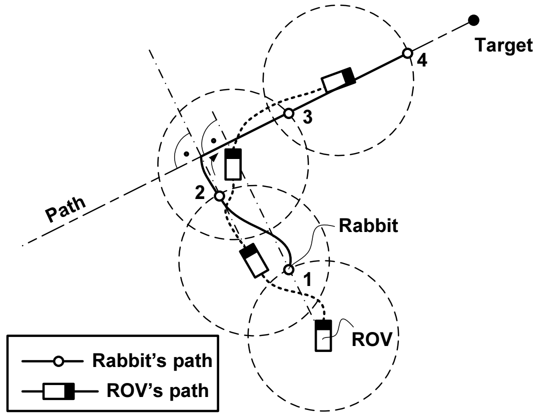

Fig. 2. Positioning of a dynamic virtual target (rabbit), relative to the ROV

where $p(t)$ represents actual ROV position and $p_D(t)$ desired ROV position. For path-following purposes, desired ROV position $p_D(t)$ is actually ROV's direct projection onto the path. It means that only cross-track error $e(t)$ is relevant and control objective can be rewritten as follows:

$$\lim_{t \to \infty} (e(t)) = 0 \tag{2}$$

Number of guidance laws are developed to ensure stabilization of $e(t)$ to the origin. In our work we have chosen the method used in ship motion control systems [11] which is known as enclosure-based steering.

Imagine a circle with radius $r > 0$ (rabbit distance) enclosing ROV $p(t)$. The circle intersects the line (path) at two points. The steering law generated by enclosure-based steering strategy says that vehicles velocity vector has to be directed toward the intersection point that corresponds to the desired direction of travel, [12]. If cross-track error $e(t)$ is greater than the rabbit distance, circle and path do not intersect, and virtual target is positioned at the point on the circle closest to path, guiding the operator straight towards the path, as illustrated in Figure 2. The enclosure-based steering with rabbit distance of 10 meters ensures optimal path following performance using auditory display as shown in our previous work [13].

Guidance law defines position of the single virtual target in space. Operators task is to track the target as good as possible. Based on it's angular perception, operator orients the vehicle towards the virtual target. We can say that in order to achieve efficient path following and satisfy steering law, good (low bias and high resolution) perception in the neighbourhood of zero azimuth is essential. Azimuth perception in the remaining areas does not need to be that good but it still needs to preserve the feeling of ROV dynamic i.e. target position (left forward, right), direction of turning (towards or away from the target) and approximate rate of turn.

In order to experimentally evaluate HMI performance, the objective function defined by integral square measures of weighted tracking error and control effort (vehicles input forces and torques) is introduced [14].

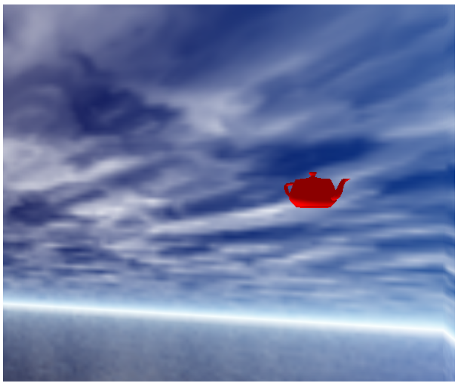

Fig. 3. Example of the Visual AR interface

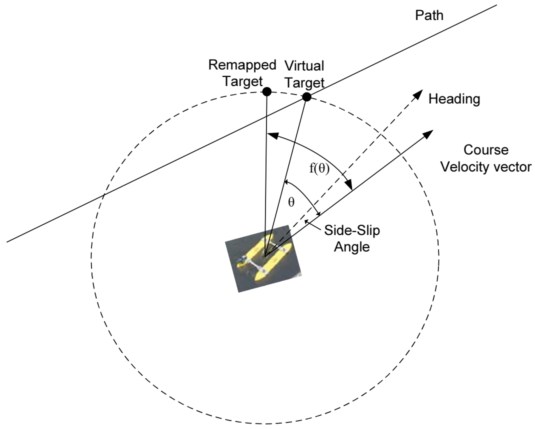

Fig. 4. Virtual target remapping using supernormal azimuth localisation cues. Original azimuth θ is remmaped to $f(\theta)$

$$minPi = \int_0^T \left(e(t)^T \cdot Q \cdot e(t) + \tau(t)^T \cdot P \cdot \tau(t)\right) \,\mathrm{d}t \tag{3}$$

$P > 0$ and $Q \geq 0$ are the weighting matrices, e is cross-track error and $\tau = [\tau_x \ \tau_n]^T$ is a control effort vector consisting of forward force and yaw torque. The best performance corresponds to the minimal performance index.

C. AR system

Visual AR display presents virtual target to the operator as shown in figure 3. Position of the virtual target is a reference, generated by path following algorithm. It is assumed that cognitive load for simple target tracking is lower then for the navigation using standard "Nav" display (Figure 1), where based on users perception of ROV position, orientation and desired path, operator guides the vehicle according to its own, "natural" guidance law.

On the other hand, Audio AR display presents the target to the operator over headphones helping him to navigate ROV towards the virtual target position. Generally, audio interface can present verbal or non-verbal information about data. But due to fact that "...spatial virtual sound, processed at direct perceptual levels, have lower load during navigation than verbal commands, which require cognitive mediation" [15], we propose audio display which supports non-verbal spatial sound cues.

Relative sound source position in relationship to the ROVs frame of reference is obtained in terms of ROV orientation, ROV position and target position. Spatial perception involves an egocentric frame of reference; measurements and orientation of visual/sound images are given from the observer/listeners position. Spatial position of the virtual target is determined by perceived distance, azimuth and elevation angles of the target. Virtual observer/listener is positioned on top of the vehicle in a vehicle flow frame of reference, oriented in a direction of the vehicles velocity vector.

The normal human auditory localisation system has relatively good resolution in azimuth for most kinds of signals in the neighborhood of zero azimuth but it has poor resolution in elevation [16], and in distance [17]. For the guidance applications, even for azimuthal resolution in the neighbourhood of zero azimuth, where is the best, better resolution is desirable. This raises the question of whether it might be possible to design processing for operator that enhance the effective resolution artificially. In command/control applications, the primary goal is to convey unambiguous information to the human operator without incurring increased response bias [5]. In a [17], it is pointed out that it should be possible to improve performance by synthesizing intentionally distorted "supernormal" localization cues even if the result is "unnatural". Approaches for creating supernormal auditory localization cues include simulating localization cues from a larger-than-normal head or remapping the normal localization cues to create regions of supernormal spatial acuity. Our supernormal azimuth localization cues were created by remapping the azimuth position of the sound source according to 4, maintaining the same distance and elevation [18], see Figure 4. .

$$f_k(\theta) = \frac{1}{2} arctan[\frac{2K \cdot sin(2\theta)}{1 - K^2 + (1 + K^2)cos(2\theta)}] \tag{4}$$

For $K > 1$ this transformation provides better-than-normal resolution in the frontal region ($\theta = 0$) but reduce resolution on the side ($\theta = \pm\pi/2$). For $K < 1$, the opposite occurs. Our previous research [13] shows that $k = 3$ ensures improved resolution in the frontal region, preserving the feeling of ROV dynamic, direction and rate of turn.

Virtual Auditory Display is a headphone-based system in which localisation cues are generated by the inexpensive (free) spatial sound application FMOD Ex API [19]. The FMOD Ex is an audio engine developed primarily for game and multimedia developers, musicians and audio engineers. The application supports generalized Head-Related Transfer Functions (HRTFs) [20], [4] to simulate the normal auditory localization cues and provide spatial audio perception. Display thus presents spatial sounds in a 3D audio environment, with each sound being spatialized to seem as if it were

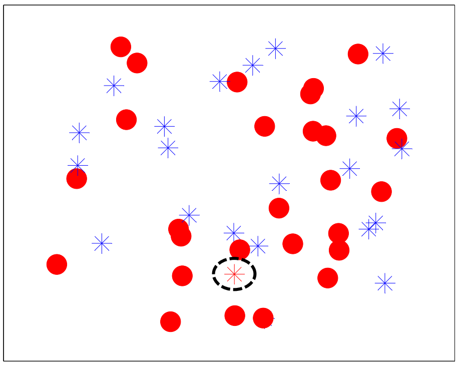

Fig. 5. Secondary visual task with 50 object, 2 colours and 2 shapes. The task is to determine weather the red asterisks is present on the screen.

located at the corresponding real-world location. FMOD is able to spatialize these sounds by tracking the target's and listener's location, momentary orientation and velocity.

Certain types of sounds would lead to more effective navigation, largely because listeners could more easily localize them. This would favor broadband sounds such as noise bursts and complex tones [21], [20], [22]. Non-speech beacons are generally preferred over speech beacons and a continuous operation of a beacon preferred over a pulsed operation [23]. As a result, virtual sound source used for an AR auditory display is a pink noise amplitude-modulated at 10Hz.

D. Secondary task

A key idea behind the experiments was to vary the visual load systematically. Secondary visual tasks were calibrated in order to induce different levels of visual load. The design of the visual task was based on Treisman's feature integration theory [24] which states that the speed at which a visual target is identified within a display is affected by its visual similarity to other objects in the display. In addition, increasing the number of objects in a display has been shown to increase reaction time to targets, but only when a target object must be recognised by a conjunction of features (e.g. colour and shape). The number and visual characteristics of non-target objects can be used to vary the difficulty of target identification [25].

In our experimental set up, the task was presented on the separate screen from the screen used for navigation. The task was to determine, by selecting "yes" or "no" on the keyboard, whether a target object was present. The difficulty levels were determined by varying the total number of the non-target objects and time available to accomplish the task. In the low-load condition number of all non-target objects was 10 (two different colours and shapes) and time to solve the task was 5 s while in the high-load conditions, number of non-target objects was 100 or available time 2.5 s.

III. Results and Discussion

Participants: a total of 12 students, professors and staff from Laboratory for Underwater Systems and Technologies, Faculty of Electrical Engineering and Computing, University of Zagreb, participated in the experiments. Experiments were performed on a ROV simulator linked via MOOS interface with AR system which presents synthetic spatial visual or acoustic imagery using regular screen or a sound system FMOD and stereo headphones AKG K66.

ROV is controlled manually, using joystick. Ability of the system to simulate different ROVs and apply environmental disturbances such as waves or sea current, was used to create numerous real-life mission scenarios. The ultimate operators goal was to fly the ROV in such a way to overcome the ROV dynamics and environmental disturbances and successfully accomplish the mission as planned, solving the secondary visual task at the same time. Mission results used for analysis consist of: accomplished mission trajectory $p(t)$, control effort $\tau(t)$ and result of the secondary visual task. Mission trajectory combined with the desired path $p_D(t)$ is used to calculate tracking errors $e(t)$. Performance index (equation 3) was then calculated using tracking error and control effort.

Missions are grouped into datasets (DS). Three missions belonging to the same dataset are identical (operator, type of ROV, mission plan, environmental conditions), except for presentation display, visual, visual AR or audio. Within the one dataset, absolute values of all performance index's are scaled by the value of the first performance index, mission accomplished using standard navigation display (5). It allows comparison of corresponding scaled values from different datasets in a way that eliminates the effects of mission specific influences i.e. absolute Pi from longer and shorter mission can not be compared because Pi is affected by the time needed to accomplish the mission. Complete data collection consists of numerous datasets obtained with different operators, types of ROVs, mission plans and environmental conditions.

$$Pi_n^s = Pi_n / Pi_1, \; Pi_n, Pi_1 \in DS_i \tag{5}$$

Where i represents dataset number, n mission index within the dataset and s scaled performance index. Obviously, Pi_1^s is always equal to one. For the sake of analysis, performance index (3) is split into two parts, tracking quality part $Pi_T{}^s$ and control effort part (energy used) $Pi_E{}^s$, scaled according to (5).

$$Pi_{T_n}^s = \int_0^T e_n(t)^T \cdot e_n(t)\, \mathrm{d}t / \int_0^T e_1(t)^T \cdot e_1(t)\, \mathrm{d}t \tag{6}$$

$$Pi_{E_n}^s = \int_0^T \tau_n(t)^T \cdot \tau_n(t)\, \mathrm{d}t / \int_0^T \tau_1(t)^T \cdot \tau_1(t)\, \mathrm{d}t \tag{7}$$

Performance index is given now by:

$$min Pi^s = Q \cdot Pi_T{}^s + P \cdot Pi_E{}^s \tag{8}$$

A. Path following in a no-load conditions

As mentioned earlier the data were collected in three experimental settings: (1) using standard visual Navigation display (NAV), (2) AR visual display and (3) AR auditory display. A common experimental methodology was applied across the different experiments. Participants task was to steer the vehicle along the path with an arbitrary speed profile, while depth was controlled by the auto depth controller. The same scenarios and dependent measures were included in all three experiments, meaning that each participant was asked to navigate the same mission with the same ROV in the same environmental conditions, 3 times in a row with the different navigation interface. The lawn mover type of layout, which is regularly used in a ROV operations, is chosen for the experiments. Desired path consists of number of waypoints connected with straight lines. When the ROV reaches the circle of 3 meters diameter around the way point, virtual target shifts to the next line, example of the mission set up is shown in Figure 1. Missions results are grouped in datasets and scaled according to 5. Performance index is calculated and split in two parts, tracking performance and control effort according to 6, 7 and 8. By putting heavy weight of Q, we prioritize path following quality and vice-versa.

Figure 6 shows PI-tracking error part for all 3 interfaces. The scaled PI values in the first column (standard NAV display) of all datasets are equal to 1, because that was the parameter used for scaling, see 5. Because of that, "Standard Visual" column is omitted in all other figures. Tracking performance using visual AR display is negligibly better than using standard display. Assumed lower cognitive load needed for guidance using AR display did not yield any performance improvement. Our conclusion is that operators were able to successfully perceive complex information content at a high rate, associate it with guidance concepts and generate appropriate actions in a no-load scenarios. As expected, tracking performance of the auditory interface is slightly worse ($\approx 20\%$), which can be explained by the fact that spatial resolution of the human hearing channel, although improved, is still inferior. Figure 7 shows that control effort part of the PI for both visual interfaces is almost the same again. Adversely, control effort of the auditory display is better, lower then the one achieved with visual displays. Looks like that interface providing lower spatial resolution does not generate as frequent course "hunting" as display with the better resolution. For lower tracking quality, lower price (effort) is paid.

Finally, figures 8 and 9 show cumulative performance index. In a figure 8 tracking performance is prioritized by putting more weight on tracking part of the PI ($P/Q = 3$). This is the realistic case in a ROV applications where energy is provided through a tether and energy conservation is not a high priority. Second figure presents the case where tracking and effort components are equally weighted. Interestingly, performance using any of experimental interfaces is almost the same.

B. Path following performance with applied secondary visual load

In our second experiment, data were collected using the same experimental settings but operators workload was increased by means of secondary visual task, see II-D. Sec-

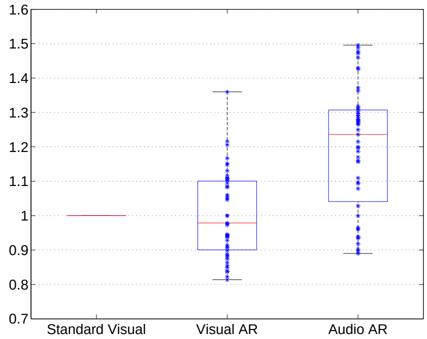

Fig. 6. Performance index - Path tracking quality part

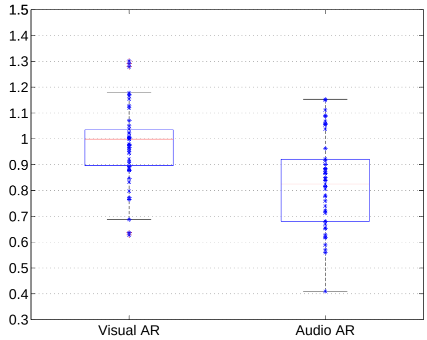

Fig. 7. Performance index - Control effort part

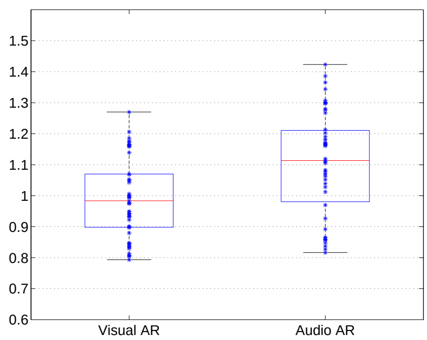

Fig. 8. Performance index - more weight on tracking $P/Q = 3$

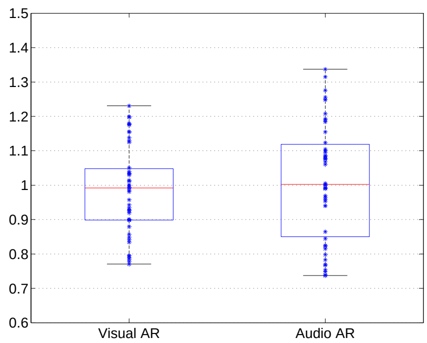

Fig. 9. Performance index - equally weighted, $P/Q = 1$

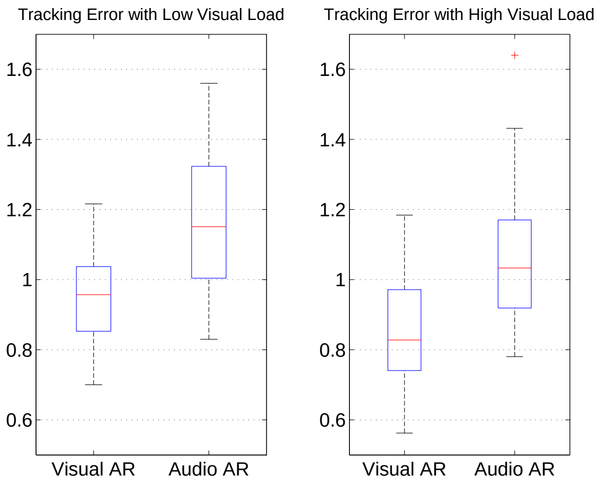

Fig. 10. Performance index - Tracking error part

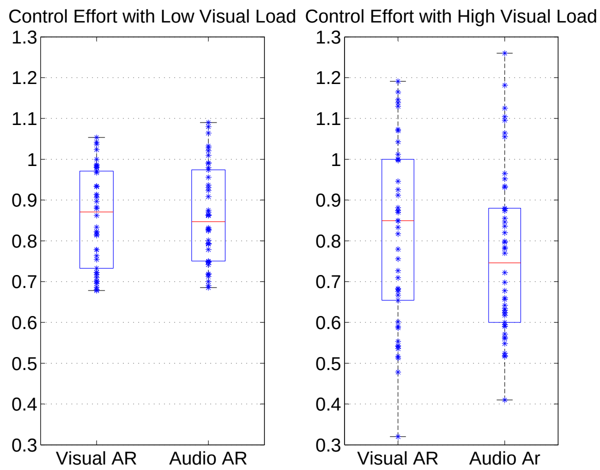

Fig. 11. Performance index - Control effort part

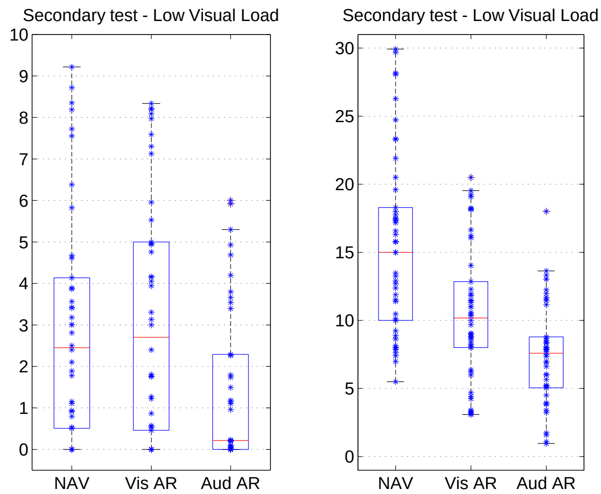

Fig. 12. Results of the Secondary Task (% of incorrect answers)

ondary tasks in a form of low or high load, were presented on a separate screen. Performance index 8, for the purpose of this experiment is extended with the results of the secondary task:

$$minPi^s = Q{\cdot}Pi_T{}^s + P{\cdot}Pi_E{}^s + R{\cdot}ST \tag{9}$$

where, ST represents result of the secondary task, expressed in percentage of the incorrect answers and R is the weighting coefficient of the secondary task.

Figures 10, 11 and 12 show performance results for all three components of the PI. Tracking performance with low secondary load is very similar to the no-load results, meaning that operator using standard NAV display is able to cope with not very requiring load and maintain the same level of path following performance. In a high-load experiment, there is a visible comparative improvement of both AR interfaces. Control effort comparative results (figure 11) for the low-load experiment are also similar to the results of the no-load experiment. In a high-load setup, there is approximately 10% improvement in performance of the AR interfaces but data is more dispersed showing that performances differ significantly from trial to trial. During the low-load experiment rate of error of the secondary task was generally low for all interfaces, as shown in figure 12. Increasing the load, error grows for all interfaces but the most significantly for standard visual interface. The task was on the edge of multitasking capabilities of the test subjects. The best results are achieved using auditory display which can be explained by the fact that operators visual channel was completely free for the secondary visual task.

Figure 13 presents cumulative performance index where all index components are equally weighted. In a low-load experiment there is a small difference between interfaces but the best among equals is visual AR interface. In a high-load experiment, situation is opposite in favor of audio AR interface.

Figure 14 shows comparative performance of all participants using only Audio AR (left graph) versus two participants trained for audio AR interface (right graph). Performance of the trained operators was superior, showing that practice can significantly improve performance in using interfaces we are not trained for, i.e. auditory interface, which is in line with the previous results published in [26].

IV. Conclusions

Results presented in this paper clearly show that there is a rationale for using AR paradigm (visual and audio) for the purpose of ROV navigation. Experimental data confirm our hypothesis that performance of visual navigation (standard or AR) for no-secondary-load scenarios is superior, but it also confirms that under additional visual and cognitive load auditory interface emerges as an important advantage. It was shown that in high-load operational environment unloading the operator yields improved navigation quality. Authors intention is not to suggest that existing type of navigation interface should be replaced, it provides more then just a information needed for guidance i.e. position of the ships or pipelines in the working area, but at contrary, to suggest that AR system could become part of the future, more complex

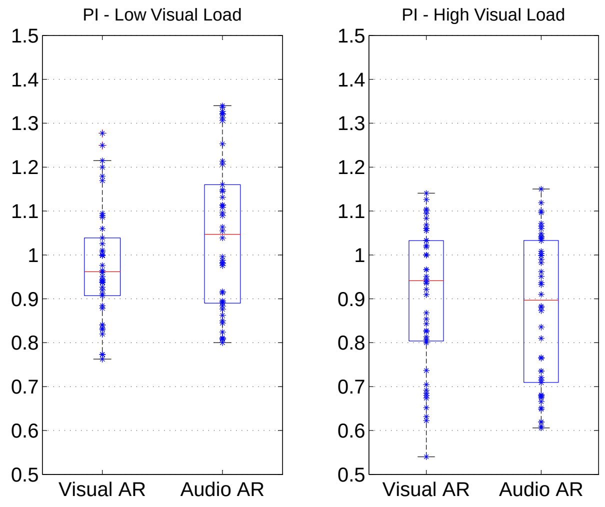

Fig. 13. Performance index - Total with applied secondary visual load

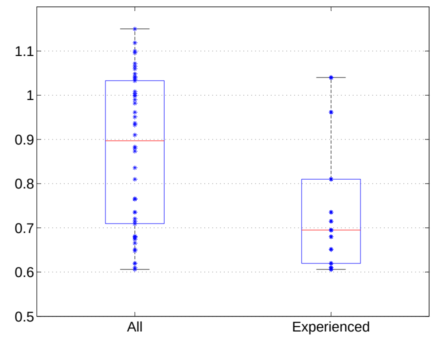

Fig. 14. Performance index of the Audio AR interface. All participants vs 2 participants trained for Audio AR. High load

navigation system. AR can improve overall performance of the ROV operation by reducing visual and cognitive workload and enhancing situation awareness. Results obtained with auditory interface show that practice has a major effect on performance, performance increases with practice, as is often the case with the use of a new interface. There are many possible approaches how to augment our reality for the navigation purposes and this is definitely research area well-worth future work.

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