Enhancement of Underwater Teleoperation using a Pseudo-Haptic Attitude Indicator

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***Abstract*—The use of Remotely Operated Vehicles (ROVs) has seen its use increased significantly, as it presents a tool for present and future exploration of environments which are not suited for human presence. Specifically, the teleoperation of ROVs with diverse sizes and purposes has been used extensively to explore underwater domains. The complexity of teleoperation requires dealing with different stimuli, especially when performing multiple tasks such as sample extraction, exploration, and repair. Furthermore, since controlling the ROV involves a variety of data, information, cooperation, and communication challenges, coordinating these tasks in various contexts can be too challenging and demanding for human perception, even for trained personnel. In this context, one of the main instruments of the pilot is the attitude indicator, which informs the pilot of the orientation of the vehicle. However, it has been documented that a great percentage of flight accidents happen due to this instrument, which might confuse the pilot during stressful tasks. To mitigate this, representing the attitude of the ROV in a more intuitive way and providing a safer teleoperation experience could be achieved by using pseudo-haptic (PH) feedback. PH approaches can be used to provide haptic feedback during teleoperation without the need for haptic devices, which can enhance the pilot's situation and spatial awareness. This work explores and develops several PH techniques to facilitate the link between human awareness and teleoperated vehicles and aims to contribute to a more intuitive experience during teleoperation.**

***Index Terms*—Pseudo-Haptics, Remotely Operated Vehicles, Underwater Teleoperation, Attitude Indicator, Human-Robot Interaction, Situation Awareness, Spatial Disorientation.**

I. INTRODUCTION

In recent years, human beings have been exploring and studying more and more diverse and inhospitable environments. Factors such as extreme temperatures, poor visibility, existence of predators or environmental hazards and high pressure contribute to the harshness and general inaccessibility of sites of exploration and do not accommodate the presence of a human being. Teleoperation of ROVs allows the human to forfeit the risks often involved in these dangerous conditions and explore remote environments.

Teleoperation offers a plethora of applications: ranging from undersea exploration, emergency support, ship repairing, maintenance of ships and harbours [1], extra-planetary exploration, military missions, search and rescue activities, to robotic surgery. Teleoperation in underwater environments can also help simulate space domain conditions, exploring neutral buoyancy [2]. This does not only support human direct interaction in space [3], [4], but could improve ROV teleoperation in space. Also, data collecting capabilities have been highly increased with research of mixed human-robot exploration of space [5].

However, teleoperation can be a challenging task because the operator is remotely located and physically detached from the exploration site. In particular, to successfully navigate, the operator needs to be aware of the robot's attitude (i.e., pitch and roll) which may be easy to reference when there are familiar objects in the remote environment that act as reference points. Be that as it may, if those reference points are absent and the on-board cameras are fixed, operators sometimes find it surprisingly hard to accurately assess the attitude of their robotic vehicles. As a result, the operator's situation and spatial awareness of the remote environment can be compromised and the mission effectiveness can suffer.

This work aims to address the issue of situation and spatial awareness in ROV teleoperation by introducing a novel approach: replacing the standard attitude display with a PH display. Situation Awareness (SA), as defined by Endsley [6], is "a person's perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". The spatial reasoning that underlies situation awareness is determined by the concept of Spatial Awareness (SpA) defined as the ability to perceive and organize spatial information about objects, and understand their relative positions and movements in the workspace [7]. Pseudo-haptic feedback consists on the illusion of haptic perceptions provided without haptic feedback devices in a virtual or remote environment. As defined by Biocca et al. [8], haptic feedback can be provided through "perceptual illusions in which users use sensory cues in one modality to fill in the missing components of perceptual experience." Human vision is usually preferred as a vehicle for PH techniques due to its dominance over other human senses [9]. Replacing the standard display of attitude with a more intuitive, perceptible and immersive display introduced by PHs could improve situation and spatial awareness.

The excess of information that overloads the operators, combined with the difficult and, in some cases, stressful situations of teleoperation, contributes to a loss of situational and spatial awareness and seriously hampers teleoperation. Moreover, not all scientists have experience with teleoperation, so working with a specialized crew may be necessary to accomplish the goals of their study. This kind of cooperation frequently entails a period of rigorous crew testing, training, and adjustment. Integrating PH techniques into teleoperation systems can streamline control interfaces, reducing the learning curve for operators and empowering scientists to conduct autonomous exploration with greater ease and efficiency and less risks of mistakes. Consequently, developing effective and intuitive displays of the orientation of the ROV is essential for enhancing situation and spatial awareness in teleoperation, ultimately improving mission outcomes and enabling exploration in challenging environments.

Concluding, the objectives this work proposes to achieve are:

1: Development of a PH attitude indicator capable of intuitively informing the operator of the attitude of the robot without causing a loss of situational and spatial awareness.
2: Develop and perform a user study to quantitatively and qualitatively assess the situational and spatial awareness provided by the developed attitude indicator by comparing it to a regular attitude indicator.

The remainder of this document is organized as follows: Section II shows the theoretical background and a review of the state of the art; Section III presents the development of the proposed approach; Section IV describes the user study created to support the study's claims; Section V reports and discusses the quantitative and qualitative results of the user study; and finally, Section VI presents the conclusions of this work and suggestions for future work.

II. BACKGROUND AND RELATED WORK

A. Situation Awareness

Situation awareness has been extensively researched and serves as a basis for performance in a wide range of fields, such as teleoperation, driving, air traffic control, military operations, education, and train dispatching [10]. SA encompasses a comprehension of the states of the environment, its critical factors, elements and sources and can be divided into three levels: 1) Perception of the dynamics of relevant elements of the environment; 2) Comprehension of the current situation by understanding the significance of the relevant elements, particularly when integrated together in relation to the operator's goals; 3) Projection of the future status supplied by knowledge of the status and dynamics of the relevant elements and comprehension of the current situation. It is the ability to understand what will happen with the system in the near future. Higher levels of SA (2 and 3) are particularly critical to effective functioning in complex environments, such as the cockpit, and allow people to function in a timely and effective manner, even during very complex and challenging tasks [11].

B. Spatial Disorientation

Spatial Disorientation (SD) can be formally defined as an ”erroneous sense of one's position and motion relative to the plane of the earth's surface,” [12]. SD is a result of perceptual errors attributed in part to the inefficient presentation of synthetic orientation cues by the attitude indicator in poor visual conditions [13]. As a result, SD has long been linked to aviation accidents, and attempts to reduce its impact have not kept up with the risk it poses to pilots [14] [15] [16]. Research has shown that improvements in the design of the attitude indicator can help mitigate instrumentation as a factor in the onset of SD [13].

C. Attitude Indicator

The Attitude Indicator (AI), originally called the Artificial Horizon Indicator, is a primary flight instrument used in aviation to provide pilots with essential information about the orientation of an aircraft with respect to the earth's horizon. The instrument, as can be seen on figure 1, visually represents the aircraft's pitch and roll attitudes in relation to the horizon, aiding pilots in maintaining proper control and orientation during flight. However, to help mitigate SD, it is necessary to provide the pilot with the most intuitive and effective AI possible [17].

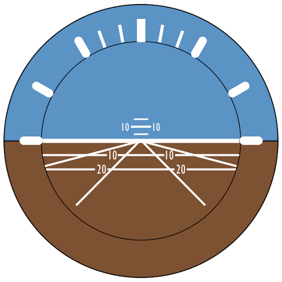


Fig. 1. Example of a standard attitude indicator.

D. Development of Attitude Indicators

Since 1945, numerous research have attempted to answer the broad question of whether AI format would be more natural to understand and compatible with when displaying the aircraft's attitude on head-down instruments [18]. For example, when comparing standard MA and MH displays involving recovery tasks in a PC-based simulator authors recommended that the format of the attitude indicator be reevaluated, even for new uses like remotely piloted aircraft control [18]. More intuitive icon displays have been shown to hasten the initial correction and reduce the number of roll reversal error in spite of the traditional HUD decreasing the total recovery time [19]. Extended horizon display, hybrid concepts, display size and scale have also been studied [13] [20]. Color shading and color patterns were also shown to be the most effective visual signals to integrate into a background attitude indicator [21].

E. Haptics

Haptic sensations allow humans to manipulate and perceive a physical object. This perception makes it possible for humans to understand and feel the material and surface properties of manipulated objects, with one example being weighing an object [22]. In order to perceive haptic sensations, haptic display requires the user to be supplied with physical stimuli using force feedback devices. These devices emulate real sensations of physical objects or environments such as texture, roughness, weight, force or heat.

In the context of teleoperation of robots, haptic feedback is essential to human engagement with remote or virtual environments once they bridge the physical gap between the operator and the remote robotic system. It is successful in providing a more immersive and effective means of control, resulting in reduced latency effects, safer operations, improved manipulation or increased operator efficiency. However, rich and comprehensive haptic feedback is difficult to deliver because of issues with hardware size, application-specific needs, cost and naturalness [23].

F. Pseudo-Haptics

Lécuyer [24] introduced pseudo-haptic feedback as a tool to simulate haptic sensations when interacting with virtual environments. Virtual objects and their properties are perceived through visual feedback and by interacting with the virtual environment. By distorting this visual feedback, one's perception of the object or the environment can be manipulated. Because there is no need for a haptic feedback device, pseudo-haptics enable a more convenient approach when tackling immersivity on remote operation, while maintaining lower costs, fewer hardware needs and better mobility [25]. Many PH feedback techniques have been investigated, such as: stiffness and mass using the C/D ratio (relation between users input control and displayed response) [26]; friction, gravity or viscosity in the movement of a cube [24]; torque [27]; simulating shape properties and manipulating users' perception of a real object [28]; mixed haptic and pseudo-haptic perception of force [29]; compliance in medical teleoperation [30].

III. PSEUDO-HAPTIC ARTIFACT

This section introduces the pseudo-haptic attitude indicator artifact, which was a product of various iterations of concept discussion and design by members of the MEROP research group [31], in the context of enhancing mobile robot teleoperation through improved multimodal interfaces. This concept aimed to improve SA and to reduce SD on teleoperators by improving the intuitiveness of the standard representation of attitude with recourse to PH technology.

A. Artifact Requirements

The requirements of the PH AI that was developed are as follows:

1) The AI should be able to effectively inform the teleoperator of the current orientation of the robot, in pitch and roll;

2) The PH feedback should be clear, intuitive and easy to understand in order to avoid compromising mental or physical workload during teleoperation.

The PH AI went through several iterations before the final improvement of the artifact on Unity, having been done in group by members of the MEROP research group. With the aforementioned artifact requirements in mind, the first stages of the PH AI design can be seen on figures 2 and 3, where the behaviour and principles of the AI were explored. Figure 2 shows the principle of the PH technique that used the visual effect of the gravity pull to represent the orientation change of the box; the liquid (represented by the red shape) settles on the top right corner, indicating the pull of gravity and that the object suffered a 135 rotation, counter-clockwise. Figure 3 exemplifies this behaviour more clearly on a three dimensional view, where the dark-blue colour represents the top of the liquid and the direction from where gravity is pulling. The red arrows also show this direction. A shift in orientation of the liquid - represented by the dark blue top - is now more relatable to a real scenario, and thus more visually apparent.

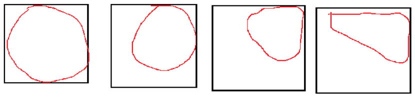


Fig. 2. First stage of the development of the PH AI Artifact.

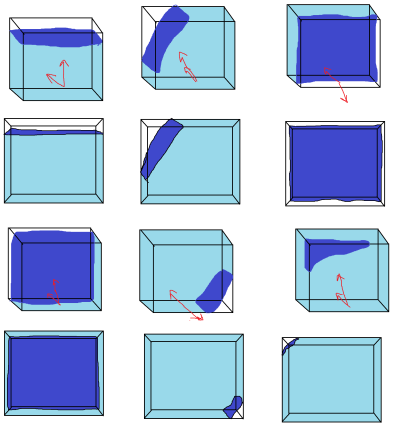


Fig. 3. Second stage of the development of the PH AI Artifact.

B. Features Integration and Development

The basic principle of behaviour of this artifact consists on the movement of a liquid in a recipient that experiences some change in orientation, as could be seen on the first iterations of the artifact. The liquid is encapsulated in a box container, and emits several particles that provide clues about the orientation, as can be seen on figure 4. This section discusses the selection of features and their development.

1) ***Liquid****:* The main component of the PH AI is the pink liquid encapsulated in a closed recipient. The operation behind the liquid obeys a very simple rule: it behaves similarly to

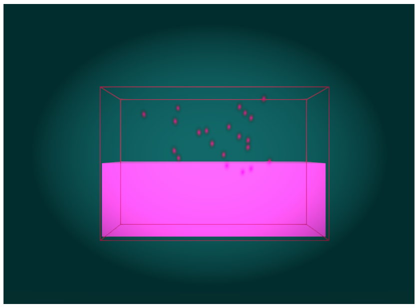


Fig. 4. Artifact with all the PH features integrated.

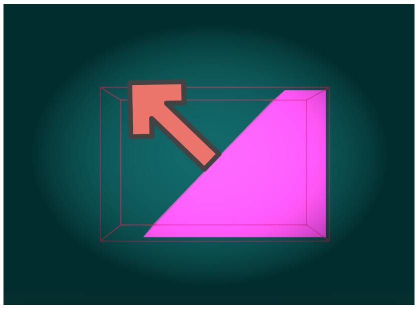


Fig. 5. Example of the liquid behaviour when rotation to the left (negative roll) is applied. The arrow symbolizes the ”sky” reference.

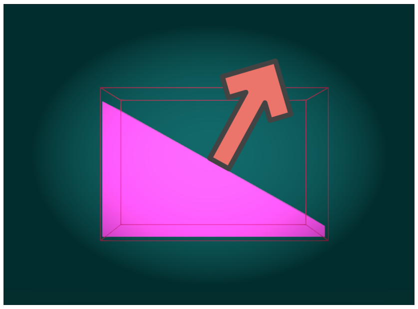


Fig. 6. Example of the liquid behaviour when rotation to the right (positive roll) is applied. The arrow symbolizes the ”sky” reference.

water in a bottle or cubic recipient when rotated or given different orientations. This fulfills the main requirement in the design of the AI: to effectively provide the teleoperator with the orientation of the robot. To meet the second requirement proposed before, the behaviour of this component: 1) uses gravity as a reference, providing an intuitive and natural reference for the orientation of the box; 2) relies upon human innate sense of spatial awareness and visual cues to quickly convey the orientation of the object; 3) uses the common experience in daily life of the concept of liquids settling at the bottom of a container, making it easier for individuals to understand, adapt and predict the orientation of objects based on the behavior of the liquid within.

In the artifact, two axes of rotation are represented, similarly to standard AI. If the liquid moves to one side of the box, it indicates a change in the roll angle. For example, as seen on figure 5, if the liquid moves to the right side of the box, it suggests a roll to the left. Conversely, if it moves to the left side, it suggests a roll to the right, seen on figure 6.

If the liquid moves toward the front or back of the box, it represents changes in pitch angle. For instance, if the liquid moves to the front, it informs the teleoperator of a negative pitch. If it moves to the back, it suggests a positive pitch. This behaviour is exemplified on figures 7 and 8.

However, if there is no discernible difference between positive and negative pitches, one might confuse whether the liquid is inclined toward the point of view or toward the back of the indicator. Therefore, the AI uses different colours to represent the top of the liquid for different pitches, as can be seen on figures 8 and 9.

This component was designed using the shader graph tool from Unity. The construction of the shader is done by performing multiple operations to the position of the liquid. First, the input roll and pitch rotations are added to the liquid. This allows the liquid to rotate in respect to the attitude given to it by the teloperator - which symbolizes the rotation of the robot. Next, the liquid is limited to only half of the bound box container, in order for its rotation to be perceptible. For this, a step is applied to limit the top half from appearing on the shader. Lastly, the colour of the shader is applied.

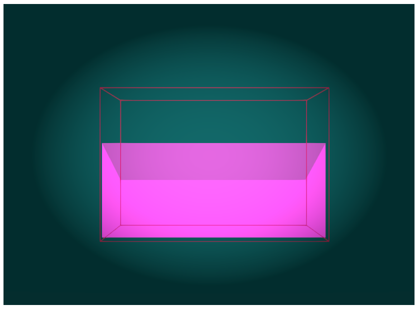


Fig. 7. Example of the liquid behaviour when negative pitch is applied.

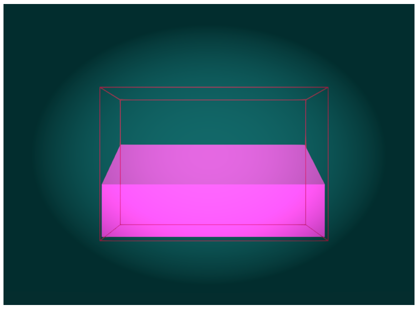


Fig. 8. Example of the liquid behaviour when positive pitch is applied.

*2) **Particle System**:*

The particle system (PS) is the component that complements the liquid representation of the orientation. This component generates particles that float out of the liquid and towards what can be referenced as the ”sky”. The combination of the PS with the liquid can enhance visual clarity by providing multiple visual cues and the teleoperator can interpret the attitude information not only from the liquid’s orientation but also from the direction of particle movement.

The direction in which the particles float serves as an indicator of the ”upward” direction or the opposite of gravity,

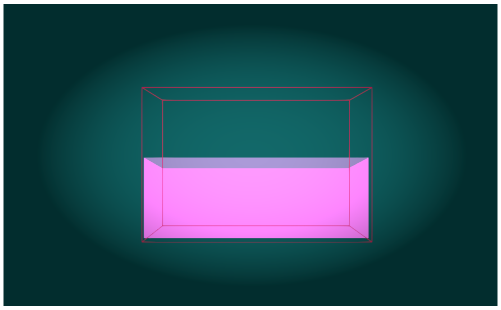


Fig. 9. Example of the new colour of the liquid representing the bottom.

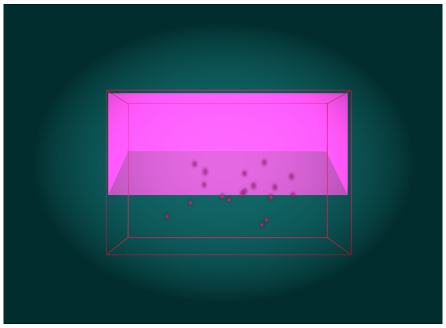


Fig. 10. Example of the particle behaviour when 180º of roll is applied.

TABLE I
PROPERTIES OF PS MAIN MODULE

Value	Description
1.9 s	Length of time the system runs
Enabled	System restarts after duration time, repeating the cycle
0 s	Delay in seconds before emission of particles
9 s	Initial lifetime for particles
0.3	Initial speed of each particle
0.4	Initial speed of each particle
0	Initial rotation angle of each particle
EC1EA2 (Pink)	Initial color of each particle
30	Maximum number of particles
3	Number of particles emitted per second
0	Number of particles emitted per distance unit

as can be seen on figure 10. If the particles consistently move in a particular direction, it visually reinforces the orientation of the system. The floating particles also create a dynamic and evolving visual representation of the system's behavior, since they can observe not only the current orientation, but also the rate of change.

The PS was created using the same name component from Unity, comprised of several modules that provide control over different aspects of the particle behavior. Particles are individual visual elements that collectively form the effect and can have properties like size, color, rotation, lifetime, speed, delay in seconds before emission and their maximum number. These flow from a source of particles named emitter, where it defines where particles are emitted from and can be a point, line, or a shape.

The number of particles that coexist in the PS was carefully tuned using the aforementioned parameters. A balance was achieved as too many particles being displayed leads to an excess of information, which results in confusion. The effective number of particles seen on the artifact was 25, as the combination of particle lifetime and speed allowed only for 24 particles to exist at the same time. The chosen shape for the emitter was a cone, where the emitted particles diverge in proportion to their distance to the cone's center line. The angle was adjusted, as an angle of zero represented a cone, and an angle of 90º represented a flat disk. The radius was also adjusted and the arc was defined as 360º to emit particles all around the cone. The emission was chosen to randomly generate particles around the previously defined arc. Table I shows all the chosen values for the properties.

TABLE II
PROPERTIES OF PS SHAPE MODULE

Value	Description
Cone	Shape of the volume that emits particles
5.16	Angle of the cone
1.08	Radius of the cone
360	Particles are spawned around the arc
Random	How particles are spawned around the arc

A box shape was also considered for the emitter, where the particles move in the emitter object's forward direction. However, the divergence of particles provided by the cone shape were preferred because: 1) they enhanced the center of mass of the liquid system by flowing in an outward motion and could improve the overall intuitiveness of the artifact; 2) they did this in a better way than a simple PS flowing out of the box in just one direction. This PS was attached the liquid component and then the modular parameters were adjusted to achieve the desired visual effect. The Triggers module was also added, where it was specified that particles would disappear upon reaching the top of the liquid container. This ensured that the trail of particles was not too long, which leads to confusion due to the teleoperator not clearly distinguishing changes in orientation - the ”history” of particles would be too long for the teleoperator to clearly assess the current orientation. The chosen values for the Shape Module properties are shown in figure II.

Finally, to meet the purpose of the PS component in the AI, it was necessary that the particles would always flow towards the ”sky” reference when the AI was rotated, which was programmed using a script.

IV. USER STUDY

A. Design

To investigate the viability and performance of the PH AI artifact to improve situation awareness in teleoperation, twenty unpaid individuals, seven female and thirteen male, aged between 21 and 29 with an average age of 23,55 years (with a standard deviation $\sigma = 1,86$), volunteered to participate in the user study detailed in this section. None of the participants possessed prior knowledge of PH, the user study or its objectives. In the user study, participants had to perform attitude recovery tasks in a simulated underwater teleoperation of a virtual robot subjected to a random orientation. The point of view of the participants was similar to that of a featureless underwater scenario of teleoperation. During this study the participants were aided by two different attitude indicators that resulted in two different conditions:

C: Control attitude indicator with moving-horizon;
PH: PH attitude indicator.

A western referential attitude indicator was adapted to the Unity Engine by a member of the MEROP group, also in the context of ROV teleoperation, which served as the control condition and can be seen on figure 11. Each participant performed 10 trials per condition, a total of 20 trials per participant and could start with a random AI. Before starting the test, participants answered several questions regarding their familiarity with joystick controllers, underwater diving, attitude indicators and teleoperation. Additionally, a questionnaire was also conveyed to the participants after each trial. These questions provided the user study with qualitative feedback regarding participants' confidence, perception, frustration, mental and physical workloads for each trial.

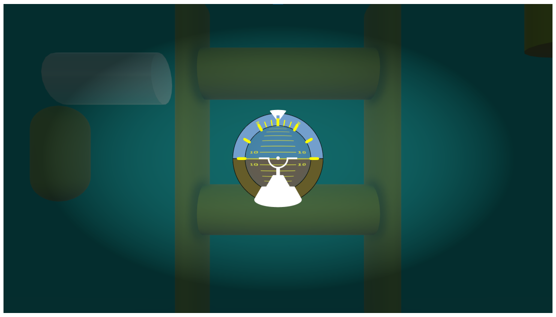


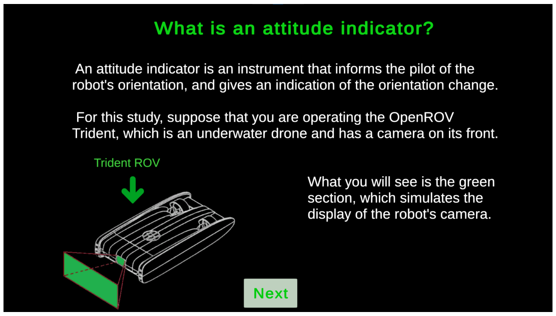
Fig. 11. Standard western referential attitude indicator used for control.

B. Apparatus

*1) **Teleoperation Station**:* During the user study, participants sat at the desk that had the setup for the teleoperation station, wore noise cancelling headphones and were alone in the room. The interface developed for the administration of the study was displayed through one screen. Regarding the controls of the virtual robot, present on figure 12, test subjects utilized an XBOX gamepad to perform the trials - the controls of the gamepad in the virtual environment were explained by the study administrator beyond any doubts - and a mouse to answer the demographic and trial questionnaires.

Fig. 12. Gamepad controls for the User Study.

*2) **Test Virtual Environment**:* An application-specific interface was developed to provide instructions to participants, displayed in slides as seen on figure 13, host the virtual teleoperation environment, demographic and post-trial questionnaires. Furthermore, the application was responsible for collecting trial data, and several scripts were honed to ensure the smoothness of each trial and to generate the virtual environment.



What is an attitude indicator?

An attitude indicator is an instrument that informs the pilot of the robot's orientation, and gives an indication of the orientation change.

For this study, suppose that you are operating the OpenROV Trident, which is an underwater drone and has a camera on its front.

What you will see is the green section, which simulates the display of the robot's camera.

Fig. 13. Example of a slide from the introduction of the user study.

To generate the random orientation for each trial, the interval [-180, 180] was divided into 72 possible angles with a step of 5º, which was decided as the minimum noticeable change in orientation. Additionally, to avoid trivial trials, a dead zone of 10º in each axis of rotation (pitch and roll) was added, as can be seen of figure 14.

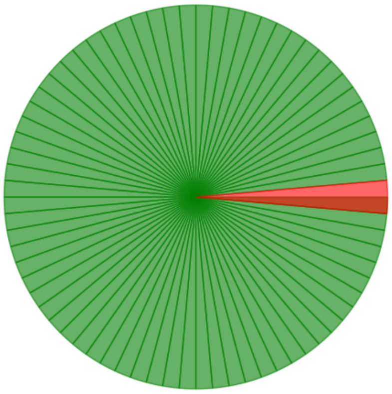


Fig. 14. Separation of the whole 360º into 72 angles with a step of 5º (in green) and a dead zone of 10º (in red).

C. Procedure

*1) **Instructions, Consent and Demographic Questionnaire**:* Participants were introduced to the test and presented with written instructions regarding the testing environment and controls. Written information concerning the mechanism of attitude indicators was also presented. After reading the instructions of the study, participants signed the consent form and answered a demographic questionnaire, regarding experience with AIs, teleoperation, underwater diving and joysticks.

*2) **Practice Sessions**:* Each participant performed two practice sessions during the full test session, one before each round of 10 trials per AI. Practice sessions had a minimum of 2 minutes and allowed participants to understand the controls of the ROV and the stable position of the AI, which was the goal of every recovery task trial. This session guaranteed visual features to serve as points of reference to help participants locate themselves spatially.

3) ***Trials:*** To start the trial, the test subject pressed the button on screen ”Start Trial”, generating a random orientation for the robot and enabling the control of the robot. The stable position was previously defined as the robot having no pitch or roll, and during the trials the participants had to orientate the robot to the previously defined stable position. When the participant thought this position was achieved through his perception of the attitude indicator, a key was pressed to finish the trial.

4) ***Post-Trial Questionnaires:*** After each trial, the participants answered a qualitative questionnaire to assess confidence, perception, frustration, mental and physical workloads. Each user had to answer these questions in a range from 1 to 10.

5) ***Resting Period:*** After completing 10 trials, the participants had a resting period in which they could leave the teleoperation station and move around the room. The resting period had a minimum of 5 minutes and preceded the practice session for the following AI.

6) ***Attitude Indicator Preference:*** Following the completion of the 20 trials and corresponding questionnaires, each participant was asked to provide feedback on both attitude indicators, comparing them and their preferred attitude indicator.

The duration of the full user study was, on average, 50 minutes. Each user study would depend on resting time,

D. Metrics

The metrics of the user study can be classified as: quantitative data provided by the trials performed by the users and qualitative data provided by the post-trial questionnaires (confidence, perception, frustration, mental and physical workloads). The quantitative metrics are defined as follows:

1) ***Trial Time:*** Trial time was defined as the total time in seconds between the start of the trial (when the user pressed ”Start Test”) and the moment that the user pressed the button to finish the trial.

2) ***Input Time:*** Input time was defined as the time in seconds between the start of the trial and the moment the user started maneuvering the robot.

3) ***Pitch and roll difference:*** As mentioned before in this chapter, the only changes in orientation were applied to the pitch and roll components of the orientation of the robot. The pitch and roll difference represent the difference in degrees between the final orientation and the objective orientation, represented by 0º.

4) ***Joystick distance:*** The position of the right joystick, which controlled the orientation of the robot, was defined as a point inside the unit circle. To rotate the robot in the virtual environment, test subjects moved the joystick. Every time the joystick is moved, the corresponding coordinates inside the circle unit are updated. Using these known coordinates, the euclidean distance between the two consecutive positions of the joystick is calculated. The sum of the distances represented the total analogue distance traversed by the right joystick per trial.

V. RESULTS AND DISCUSSION

A. Quantitative Results

The quantitative results of the user study were analysed using a RM MANOVA statistical analysis to: 1) understand how and if the conditions of the user study (factors) influenced the metrics; 2) if the metrics had any influence on one another. This helped clarify the existence of interactions amongst variables.

The data followed a multivariate normal distribution and did not violate Mauchly’s Test of Sphericity, which are essential assumptions that underpin the validity of the RM MANOVA analysis. A significance lower than 0.05 was obtained on univariate tests, which identifies a significant statistical difference between both conditions on all metrics. A Bonferroni correction - used when several dependent or independent statistical tests are being performed simultaneously - was also applied to prevent results from incorrectly appearing to be statistically significant. The results of this analysis are present on table III, where the negative values of average differences indicate higher scores for the C condition. Input time was not influenced by the condition nor the gender, as no statistically significant interactions were observed.

TABLE III
PAIRWISE COMPARISON RESULTS BETWEEN CONDITIONS ON RM MANOVA.

Metric	**Avg. difference (C-PH)**	**Z**	**p-value**
Trial Time (s)	$-10,587$	$13,769$	$< 0,001$
Joystick Movement	$-78,110$	$5,701$	$0,018$
Pitch Difference (º)	$-3,041$	$5,940$	$0,016$
Roll Difference (º)	$-3,009$	$4,305$	$0,039$

TABLE IV
MEAN AND STANDARD DEVIATION FOR EACH METRIC UNDER DIFFERENT CONDITIONS

Metric	**Control (C)**	**Pseudo-Haptic (PH)**
Roll Difference	1.28 ± 9.95	4.29 ± 21.59
Pitch Difference	2.73 ± 9.60	5.77 ± 14.49
Joystick Movement	646.01 ± 370.80	724.12 ± 396.23
Trial Time	53.03 ± 30.28	63.62 ± 32.78

Then, multiple RM ANCOVA statistical analyses were performed but found no relevant statistically significant interactions between single metrics and demographic data.

B. Quantitative Discussion

The experimental results of the user study show that the precision of participants using the PH AI had an average difference of approximately 3° on pitch difference and roll difference, when compared to the C AI. This value, despite being lower than the 5° (considered to be the smallest noticeable change in orientation), shows that the lack of reference influenced this difference in precision. Given that this was a precision orientated task, the lack of reference directly influenced the performance of the PH AI.

The lack of reference could have a direct impact on other results as well, for example the joystick movement. Longer joystick movements can be a result of the corrections applied when trying to achieve the final stable position of the trial. Alternatively, longer movements may be a result of bias within participants that had already previous knowledge of AI, leading to correct assessments to where perform the joystick movements or adjustments and resulting in shorter joystick movements and also shorter trial times.

Trial times for the PH AI took, on average, approximately 10.6° more than its comparison and may be linked to the lack of reference. As mentioned before, as the lack of reference might have resulted in longer joystick movements, it could also have impacted trial times in the same way. By performing many adjustments due to uncertainty of the correct final attitude, one would also take up more time, leading to longer trial times. Alternatively, longer trial times can also be a result of the strategy that many participants reported. When using the PH AI, the strategy used by participants was to initially understand the orientation of the robot based on the information provided by the indicator, and then to start the movement. This had a cost of taking some extra seconds before starting the movement. When using the C AI, participants started the recovery task movements even before understanding the orientation.

C. *Qualitative Results*

A Wilcoxon signed-rank test showed that there was a statistically significant difference on all qualitative post-trial metrics depending on the type of AI used, and these results are shown on table V. Negative scores, positive scores and draws from the Wilcoxon signed-rank test are reported on table VI and should be interpreted as: negative scores mean that the metric score on the PH condition was lower that that of C condition, a draw means that metric scores are equal and positive scores mean that PH score is higher than C score.

As explained previously, confidence, perception, frustration, mental workload and physical workload were evaluated in a range from 1 to 10 (for example, respectively: 1: no confidence on final attitude, weak perception or no mental workload; 10: very confident on final attitude, strong perception or very high mental workload).

TABLE V
VALUES OF THE WILCOXON SIGNED-RANK TEST FOR THE QUALITATIVE METRICS.

Qualitative Metric	**Z value**	**p-value**
Level of Confidence	-6.604	< 0.001
Level of Perception	-5.771	< 0.001
Level of Frustration	-4.508	< 0.001
Level of Mental Workload	-6.319	< 0.001
Level of Physical Workload	-4.183	< 0.001

TABLE VI
RESULTS OF THE WILCOXON SIGNED-RANK TEST FOR THE QUALITATIVE METRICS.

Qualitative Metric	**Negative**	**Positive**	**Draw**
Level of Confidence	46.5%	9.0%	44.5%
Level of Perception	20.0%	48.0%	32.0%
Level of Frustration	19.5%	46.5%	34.0%
Level of Mental Workload	15.5%	52.0%	32.5%
Level of Physical Workload	14.5%	32.0%	53.5%

D. *Qualitative Discussion*

Results show that confidence scored higher on the C AI, which is in agreement with the comments of most participants. Most participants felt that the lack of a scale or a grid on the PH AI induced in them a feeling of ambiguity when orientating the robot to the stable position, hence the much higher values of confidence on the C AI.

The results also show that the PH AI registered higher values for frustration, mental workload and physical workload, showing a clear disadvantage in terms of mental workload, with 52% of participants feeling mentally more challenged than with the C AI. However, 53.5% of participants felt that physical workload was equal for both indicators, as can be seen by the higher percentage of draws on the results of physical workload on the Wilcoxon signed-rank test on table VI. The physical strain of using the joystick to orientate the virtual robot - as 20 trials could have a physical toll on test subjects - could be the reason why most participants felt that physical workload was equal for both indicators.

Frustration results were also higher for the PH AI, with $46,5\%$ of participants being more frustrated than with the C AI. However, after interviewing some subjects post-trials, some of the participants were frustrated with the rotation movement only updating when the position of the joystick was reset. This insufficient drag could lead the robot to move for a couple of seconds without stopping, due to the excessive force applied with the joystick. It is possible that: 1) the rotation of the PH liquid due to this excessive force could aggravate the frustration and workloads felt by participants; 2) frustration, physical and mental workloads declined as participants got used to the movement.

Perception is the only result that does not follow the trend set by the other results. Despite registering longer times per trial, longer joystick movements, higher frustration, mental workload and physical workload values, the PH AI rates higher on perception among participants than the C AI. Although this is not in agreement with other results, one can also refer to the comments of the participants regarding their strategies when using the PH AI: many participants mentioned taking some time to understand the orientation of the robot in the beginning of the trial, and then using the first assessment to stabilize the robot. Instead of trying to maneuver the robot without visualizing the orientation, participants felt that as soon as the orientation was understood and perceived, the recovery movement would be easier. This explains the longer trial times obtained and shows why the perception metric rates higher than the C AI when other metrics do not.

The results of the final question about AI preference, the results were equal. It might be argued that user preference for

AI may have less to do with the speed, accuracy, workload balance and joystick navigated distance, and more to do with how the user perceives the ROV attitude and the intuitiveness that the AI offers, as well as the impact on their spatial awareness. This is a direct consequence of their improved experience, which users prefer over the conventional alternative of attitude representation even though it yields (for the time being) lower results.

E. Participant Comments

Participants were asked if they could justify this choice and to compare both AIs. The various comments made by different test subjects is detailed below:

*1) **More intuitive**:* Participants found that the PH AI took some time to get used to, but once understood, found it more intuitive and sensitive to movement. It was also reported that simple rotations were very easy to understand and the movement required to fulfill the objective was also easier to grasp. Instead of experimenting with the rotation axes during the recovery task, participants reported taking some time to understand the rotation according to the PH AI display and then rotating it.

*2) **Moving both axes simultaneously**:* Moving both axes of rotation simultaneously when maneuvering the PH AI and moving one axis at a time when using the Control AI was reported by almost all participants. Participant number 20 said that he ”only thought of balancing one variable - the liquid - instead of thinking about pitch and roll”.

*3) **Lack of reference**:* The control attitude indicator had a reference for pitch and roll and also the pitch axis divided in 2 colours was a big motive of comparison. It affected participant’s notion of accuracy and it was said that this was the decider in the choice of the preferred indicator of the participants. This is obviously something to improve on in the current PH model of an AI, as it should strive for precision during teleoperation.

*4) **Ambiguity**:* Seven participants found the indicator to be ambiguous and were confused on pitch angles of $90°$ or $-90°$.

Only five participants mentioned that the particle system made a big difference, which indicates that it was not used to it’s full potential. I was also said that the colour difference in sphere representing the pitch axis on the C AI was very intuitive (as it reported a negative or positive pitch by using different colours representing the north and south hemispheres), and participant 18 suggested adding something like this to the PH AI in the future, as it can grant more intuitiveness. In spite of choosing the C AI, he suggested that it was beneficial to one’s notion of space to combine both AIs and added that the liquid component should occupy a central position in a future model, due to its importance.

F. Overall Discussion

In conclusion, it is possible that many factors could have influenced the results of the user study. Previous experience with attitude indicators could suggest a bias in terms of performance during the recovery tasks. Higher values for trial times can be explained by the strategies explained by test subjects. Precision values (pitch and roll differences) are a direct result of the lack of reference. Longer joystick movements could be attributed to the low confidence level of participants of the final orientation, which is a direct result of the lack of reference and led to many corrections and adjustments to achieve the stable orientation. Frustration, mental and physical workload values could also be linked to the aforementioned phenomenon and to the perception of the movement of the robot, which could frustrate participants.

These insights and discussion are the results of 400 trials performed by 20 participants and granted a better understanding of how the pseudo-haptic techniques could effectively replace standard features and the effect on subjects. Also, this study had obvious limitations, which should be considered when interpreting these results: 1) it was not possible to fully understand the meaning attributed to the terms ”Frustration” and ”Mental Workload” during the trials as participants could associate any source of frustration or intuition to these metrics; 2) demographic interactions could not be observed due to the reduced number of participants; 3) compromises were made when designing the movement of the virtual robot, as a high fidelity underwater movement could be too abrupt and the purpose of the study defeated. It was decided that a slower movement would be necessary in order to evaluate certain metrics and investigate aspects of the behaviour of the attitude indicator. Future analysis should include a more detailed assessment of the SA of the participants, their spatial reasoning and more demographic data, especially their experience with attitude indicators and teleoperation. In that way, one can start replacing standard features with a new more intuitive display of attitude where the spatial reasoning and situation awareness of the pilots will not be affected during teleoperation.

Lastly, it is important to mention that the standard type of C AI used for the test has been used and refined for many years mainly in the aviation industry whereas the PH AI is the first prototype of its kind: such results are still important and worthy of further investigation, as much about the indicator and the user study can still be improved.

VI. CONCLUSIONS

This work introduced an AI that uses a PH representation of orientation of a ROV, a novelty in the field of teleoperation. To fulfill the first objective of this work, the standard representation of attitude was carefully replaced by PH cues that help display the orientation of the robot through a liquid component, a PS and a bound box. In particular, these clues relied on familiar human knowledge of the behaviour of liquids and of particle systems, acquired through everyday experience, intuition and notion of gravity.

In order to fulfill the second objective of the dissertation, a user study was implemented and conducted to investigate the performance of the attitude indicator and to answer two research questions: (RQ1) ”Can the replacement of attitude feedback with PH features improve the user SA during teleoperation?” and (RQ2) ”Can a PH AI be more effective than a standard MA AI?”.

As to the first research question, it was found that perception of users was rated higher when using the PH AI and their strategy of orientating the robot was possible due to the intuitiveness granted by the replacement of PH features. However, one cannot ignore the ratings of frustration and mental workload: these are, perhaps, a result of the simulation conditions and the joystick use and should be investigated thoroughly in the future. Experimental quantitative results showed that the PH AI was not more effective that the standard MA AI in terms of precision, trial times and traversed joystick distances.

At last, this work showed that it is possible to improve the perception of attitude of subjects during teleoperation, though a more rigorous inspection of the SA is needed. It also showed that the PH AI has room for improvement and potential to represent attitude more effectively than standard instruments by granting an intuitive display. For example, the particle system needs to be tuned in order to accommodate different types of movement (for example, continuous and shorter joystick movements); and markings around the bound box are a mandatory solution to confer precision to the AI, one of its biggest drawbacks.

A. Future Work

Future user studies should gather more demographic information about the participants and evaluate participant SA using a more rigorous methodology. Given the lack of research on this field and the potential of PH feedback, it is suggested the continuation of the investigation of new PH techniques to be integrated in underwater teleoperation or other environments, be it in attitude indicators or on other applications. For example, it would be interesting to investigate how information about the translation of ROV can be conveyed to the pilot using PH clues. Based on the comments of the participants of the user study, the design of PH features in standard devices is advantageous and should be pursued or combined with current devices due to the intuitiveness that PH grants.

Lastly, attitude indicators are predominantly used in airplanes. Most of the information regarding accidents due to misinterpretation attributed to attitude indicators reported in this dissertation comes from flight and pilot records. Because of this, and also because of positive user study participant comments, it is also suggested the investigation of the design of the PH AI for pilots in airplanes.

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