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Please fill in your manuscript title.	ROV Teleoperation based on Sensory Augmentation and Digital Twins

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Abstract

Abstract submissions should be formatted into four (4) specific paragraphs:

1. **Objectives/Scope:** Please list the proposed paper's objectives and scope. (25-75 words)

   ROV operations are mainly performed via a traditional control kiosk and data feedback methods, such as the use of joysticks and camera view displays equipped on a surface vessel. This traditional setup requires significant personnel on board (POB) time and imposes high requirements for personnel training. This paper proposes a virtual reality (VR) based haptic-visual ROV teleoperation system that can substantially simplify ROV teleoperation and enhance the remote operator's situational awareness.

2. **Methods, Procedures, Process:** Briefly explain your overall approach, including your methods, procedures, and process. (75-100 words)

   This study leverages the recent development in Mixed Reality (MR) technologies, sensory augmentation, sensing technologies, and closed-loop control, to visualize and render complex underwater environmental data in an intuitive and immersive way. The raw sensor data will be processed with physics engine systems, and rendered as a high-fidelity digital twin model in game engines. Certain features will be visualized and displayed via VR headset, whereas others will be manifested as haptic and tactile cues via our haptic feedback systems. We applied a simulation approach to test the developed system.

3. **Results, Observations, Conclusions:** Please describe the results, observations, and conclusions of the proposed paper. (100-200 words)

   With our developed system, high-fidelity subsea environment is reconstructed based on the sensor data collected from an ROV including the bathymetric, hydrodynamic, visual, and vehicle navigational measurements. Specifically, the vehicle is equipped with a navigation sensor system for real-time state estimation, acoustic Doppler current profiler for far-field flow measurement, and a bio-inspired artificial literal-line hydrodynamic sensor system for near-field small-scale hydrodynamics. Optimized game engine rendering algorithms then visualize key environmental features as augmented user interface elements in a VR headset, such as color-coded vectors, to indicate environmental impact to the performance and function of the ROV. In addition, augmenting environmental feedback such as hydrodynamic forces are translated into patterned haptic stimulus via a haptic suit for indicating drifting possibilities in near field. To enable an intuitive control of ROV locomotion and lower the training barrier, a series of functions are also developed for human body motion capture and hand gesture recognition. Human body motion parameters are then mapped into ROV locomotion commands via closed-loop controls. As such, the operator can use their bodies and hand gestures for ROV control, whereby perceiving the environmental changes via haptic and augmented user interface.

4. **Novel/Additive Information:** Please explain how this paper will present novel (new) or additive information to the existing body of literature that can be of benefit to and/or add to the state of knowledge in the petroleum industry. (25-75 words)

   ROVs are widely used in subsea exploration and intervention tasks, playing a critical role in offshore inspection, installation, and maintenance activities. The innovative ROV teleoperation feedback and control system will lower the barrier for ROV pilot jobs.

Introduction

Subsea engineering plays a vital role in offshore energy, aquaculture, sustainability, disaster preparedness, seafloor mining and cabling, and maritime transport (Casey 2020; McLean et al. 2004; McNutt 2002). Currently, remotely operated vehicles (ROV) have been widely used in subsea engineering and the ROV market is expected to continue growing in the foreseeable future (Brun 2012; WBOC 2021). However, the current ROV operation usually involves long personnel on board (POB) time and a high mental load during the operation, making it a highly specialized task with an obvious barrier to broader participation. A fundamental problem of ROV operations is the lack of effective control feedback and teleoperation system to meet the unique challenges of subsea environment. For example, camera view displays cannot fully convey the complex subsea environmental information to the human operator, such as the 3D space information and dynamic internal currents and can be easily influenced by the low visibility. Human operators often lose sense of orientation due to subsea currents if without effective assistance from the system, which can impact subsea manipulation, installation, maintenance, and stabilization operations. Such an inability to directly sense underwater hydrodynamic features can break the feedback loop for proper and safe ROV control actions, resulting in an induced perceptual-motor malfunction (Finney 2015).

To resolve the control problems in ROV operation, this paper proposes a sensory augmentation teleoperation system based on Virtual Reality (VR) and a haptic simulator. A realistic subsea environment with hydrodynamic force features is reconstructed in VR based on the sensor data collected from a ROV. Then, two kinds of feedback modes are enabled, including augmented visual feedback (such as colored vectors) for far field environmental features, and patterned haptic feedback for the near field features. Human operators can intuitively sense environment conditions, such as flow directions and intensity, and operate the ROV for different tasks with a relatively low cognitive load. To verify the effectiveness of the proposed sensory augmentation system, a pilot study was performed with 30 participants in a VR simulator. The remainder of this paper introduces the background, the experiment, and the results.

Literature Review

ROV for subsea operations

ROV is a type of tethered underwater vehicle designed for underwater intervention, exploration, equipment installation and data collection (Brun 2012; NOAA 2021; Patiris 2015). ROVs can be classified as education class, inspection class and work class (Wang et al. 2019) based on the main designed functionalities, while can also be categorized as micro class (100m, 5kg), mini class (300m, 10kg), light work class (2000m, 100kg) and heavy work class (3000m, 300kg) (Patiris 2015) based on working depth and payloads. Although varying in capabilities and sensors carried on, all types of ROVs have basic capabilities of maneuverability along more than one principal axis and state estimation. Usually, pilots work on the vessel with the 2D live video captured by ROV-equipped camera. However, such 2D video could not provide sufficient information about ocean waves and currents, and low visibility could undermine the human perception of the workspace (Chemisky et al. 2021; Li et al. 2019). Besides, complex and high-turbidity currents can significantly influence ROV's self-stabilization and cause disorientation in subsea exploration (Lawrance and Hollinger 2018). For example, drifting is a prevailing issue in ROV navigation. Currents can push the ROV away from its original route (Lu et al. 1997), and high-turbidity currents can also bring an extreme burden on subsea installations and maintenance (Gupta and Paul 2018). The drifting rate caused by subsea currents can be several kilometers per hour sometimes (Chutia et al. 2017).

Currently, more efforts are made on autonomous algorithms for ROV operation. For example, vision-based color correction and tracking algorithm for high depth and low light ecosystems (Arce et al. 2022) was developed in order to tackle the low visibility challenge. Besides, some studies focused on enhancing control precision such as self-stabilization using adaptive nonlinear feedback controller (Tran et al. 2020), disturbance rejection controller to improve maneuvering accuracy (Cao et al. 2020). Simultaneous Localization and Mapping (SLAM) (Meireles et al. 2014) and closed-loop controls based on machine learning (Fang et al. 2019) have also been developed to solve the drifting problem. However, these studies focused too much on ROV autonomy with neglection of human perception. Actually, humans are the commanders and controller of the system, and are responsible for important control actions. Improving ROV algorithms but lack of effort in transferring environmental information to human operations can still undermine control operations in the complex and dynamic subsea environment.

VR-Based Teleoperation and Sensory Augmentation

VR is a tool for rendering realistic virtual scenes and providing rich spatial information (Brooks 1999; Zheng et al. 1998). Recently, increasing studies are focused on VR-based robot teleoperation given the benefits of coupling perception between robots and humans (Chakraborti et al. 2017; Concannon et al. 2019; Zhou et al. 2020). Such a human-robot perception sharing method is extremely helpful in difficult tasks requiring motion planning and interactions between robot and human agents. In subsea engineering, there have been efforts in applying VR teleoperation in underwater capture tasks (Elor et al. 2021) and deep ocean remote control (Martin et al. 2021). Compared to other teleoperation methods, VR has its own benefits as a multisensory augmentation platform. On one hand, VR can render realist virtual scenes with rich 3D spatial information and auditory feedback, and can also be programmed to provide additional visual feedback such as visualizing path optimization plan (Wang and Liu 2021) and novel user interface (UI) for work progress (Safikhani et al. 2020). On the other hand, haptic devices can be integrated with VR to generate haptic feedback in correspondence with the occurring events (Li et al. 2019; Sakagami et al. 2022). The VR-haptic solutions have been widely applied in many applications, i.e., snake robot pipe inspection (Zhu et al. 2022) and tower crane balance control (Zhu et al. 2022). Specifically in ROV teleoperation, additional haptic feedback may significantly enhance human sensation and spatial awareness (Sakagami et al. 2022; Xia et al. 2023). Currently, more efforts have been made to integrate haptic feedback with ROV control systems, including generating an illusional feeling of external force for a kinesthetic perception of the ROV (Amemiya and Maeda 2009), and linear-oscillating actuator using asymmetric drivers to create equivalent pressure signals (Ciriello et al. 2013). However, these preliminary solutions can only generate simple tactile cues without a rich reproduction of the physical interactions or a larger range body coverage, or are not integrated well with VR for immersive visual-haptic feedback. Further studies are still necessary to fully integrate visual-haptic feedback in VR for ROV teleoperation.

System Design

Due to the insufficiency of the current ROV teleoperation system in immersive, intuitive, and effective feedback, this paper proposes a VR-based sensory augmentation system that provides both augmented visual feedback and haptic feedback for a shared perception between the remote ROV system and the human operator. Compared with other VR-based sensory augmentation methods, this paper leverages VR as a data center, which receives sensory data from ROV sensors and generates full body level coverage feedback. The system is developed in Unity 2020.3.35f based on our previous studies (Du et al. 2016; Du et al. 2018; Du et al. 2017; Xia et al. 2022; Xia et al. 2023). As shown in Fig. 1, the system consists of ROV module, virtual operation module, vector field simulator, particle flow simulator, virtual sensor module, and haptic suit module. After receiving the sensory data from ROV, VR processes the data such as flow speed and direction to each module for further feedback generation and control operations. User inputs, as well as hydrodynamic conditions, determine the ROV movements in the simulator. Augmented visual feedback and virtual particle flows for simulating the hydrodynamic interactions are generated based on the particle systems of the physics engine. Particularly, the simulated particle flows can physically interact with the ROV model and hence the virtual sensors can capture the key hydrodynamic features. Finally, the dynamic data is sent to the haptic suit plugin via Python Unity Socket (Siliconifier 2022) and corresponding vibration is generated on the haptic suit.

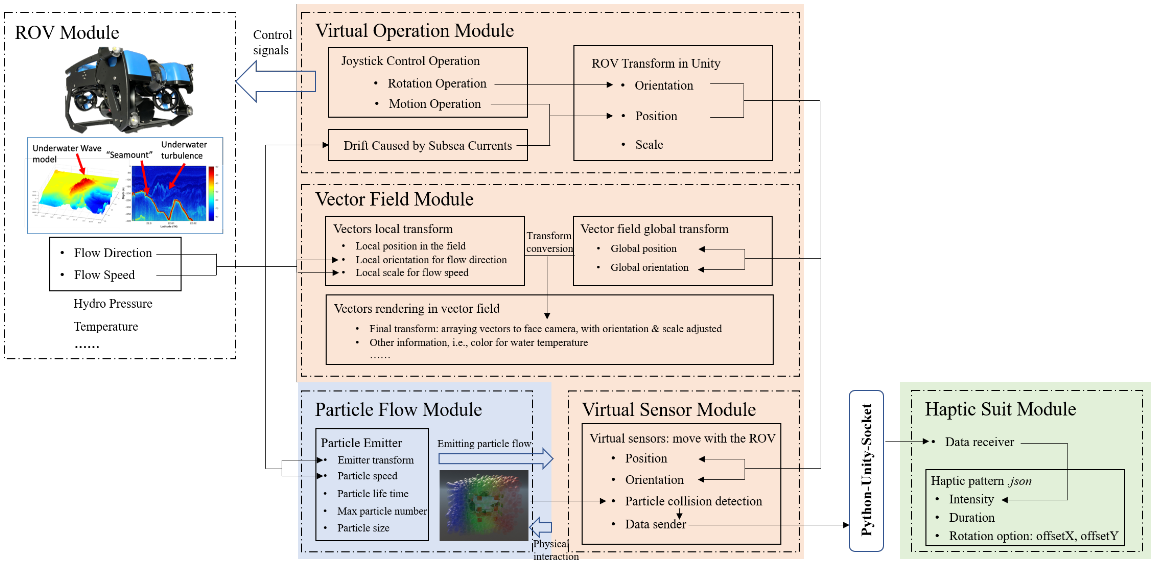

Fig.1 System Architecture

Two feedback modes are included in the system. The VR system reconstructs a realistic subsea environment based on the crest ocean system (Harmonic 2022) to ensure high-fidelity ocean wave simulation, adjustable water color settings and subsea light rendering. Meanwhile, the Unity visual effect graph (VFX) (Unity 2022) is applied to simulate the floating dust that human operators usually rely on for locomotion controls of ROV. Except for the traditional visual feedback, this system also provides a visual augmentation feedback, the vector field (Fig. 2a), to indicate the flow direction and speed. Specifically, after converting the local transform with the global transform of the ROV, all the vectors are arrayed around ROV with the orientation and scale adjusted depending on the pose of the camera. Each arrow in the vector field points to the flow direction with the length as indication of flow speed, i.e., a longer arrow represented a higher flow speed.

For the haptic feedback, a particle flow and virtual sensory system is applied to simulate the hydrodynamic conditions and generate corresponding feedback. ROV sensory data is usually spatially and temporally sparse with low refresh rate, which is not sufficient to generate comprehensive full-body coverage haptic feedback. Therefore, a particle system is used to generate continuous flows based on the sensory data, and then the particle flow could physically interact with a large number of virtual sensors distributed around the ROV model (Fig. 2b). The virtual sensors are mapped with haptic suit to trigger all the 40 vibrators (Fig. 2c). The system supports up to 800 particles, 2Hz feedback refresh rate with 24 virtual sensors mapped to 40 vibrators on haptic suit.

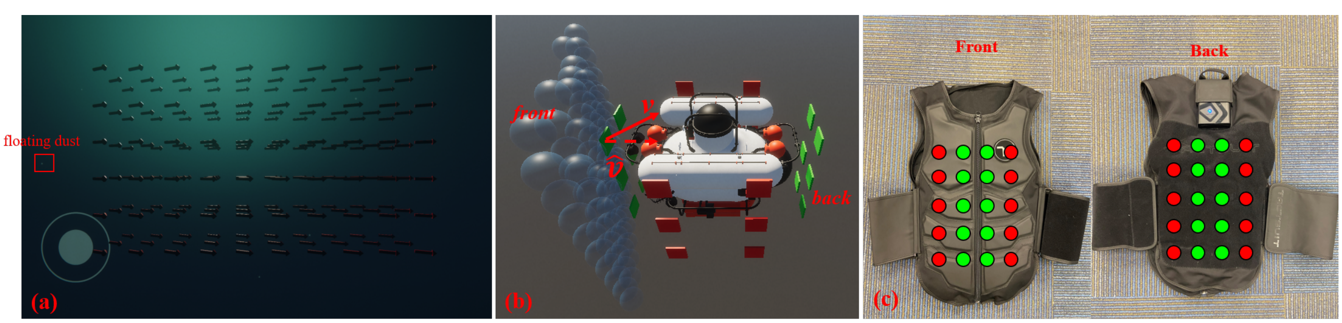

Fig.2 Feedback system. (a) Visual Feedback. (b) Particle flow with virtual sensors. (c) Vibrators map on the haptic suit.

Specifically, when particles collide with any virtual sensor, the sum of normal momentum is calculated as the representation of the flow intensity, as illustrated in Eq. 1, where m_i is the mass of particle i, $\hat{v}_i$ is the normal vector of the velocity of particle i, which is the projection of speed perpendicular to the contact surface. Since mass difference is neglected in the system because the hydrodynamic features are manifested as the pressure gradient, the mass m is equally set to 1.0 in practice. Each virtual sensor collects particle data when a collision happens and generates the flow intensity individually.

$$M_{sensor} = \sum m_i * \hat{v}_i \qquad \textbf{Eq. 1}$$

After obtaining the flow intensity, a conversion function will be applied to discount the larger raw data to a range of 0 to 1cm/s^2 for vibration intensity by Eq. 2, where M_{sensor} represents the flow intensity sent by the sensors calculated in Eq. 1, and I is the final vibration intensity on the haptic suit. Then, the intensity array with 24 values is sent to the Python terminal via the Python-Unity-Socket (Siliconifier 2022) to trigger the haptic suit. With this system being well designed, operators can clearly feel the changes in the strength and direction of the water flow with their body sensation.

$$I = \frac{e^{0.33*M_{sensor}} - 1}{e^{0.33*M_{sensor}} + 1} \qquad \textbf{Eq. 2}$$

Human-Subject Experiment and Results

In order to verify the effectiveness of the sensory augmentation method, a human-subject experiment was designed to evaluate human performance with the proposed system in the straight-line navigation with the drifting issues causing by subsea currents. The task was to keep straight-line navigation with five checkpoints and 10 subsea current zones along the way. The total distance was 90 meters and the average ROV navigating speed was set to 1 m/s. The estimated finishing time for each condition without any delay was 1.5 minutes. The difficulty of the task was gradually increased along the navigation, with a longer distance more subsea current zones to arrive at the next checkpoint. Each participant was asked to finish the task twice with and without multi-feedback system. We analyzed the ROV trajectory, the number of checkpoints reached, and average deviation to evaluate the overall performance in terms of the straight-line deviation. Besides, the pupillary size was used for cognitive load analysis. As the literature indicates, pupillary diameter and eye blink rate are closely related to cognitive load and mental fatigue levels (Ye et al. 2022). Finally, participants were asked to finish two surveys after each trial, including NASA task load index (NASA-TLX) (Index 1990) for the workload level evaluation and a Trust Scale survey (Merritt 2011) for trust level analysis. As shown in Table 1, 30 subjects participated, aging from 19 years old to 37 years old (mean=25.2, std=4.06), including 18 males and 12 females. Among all, most were from engineering majors (25 or 86.7%) while a small portion of participants (5 or 16.7%) were recruited from non-engineering majors.

Table 1. Background information of participants (n=30)

Category	Item	Number	Percentage
Gender	Male	18	60.00%
	Female	12	40.00%
Age	Under 20	1	3.33%
	20 to 29	24	80.00%
	Above 30	5	16.67%
College Major	Engineering	25	83.3%
	Non-Engineering	5	16.7%

The performance results are shown in Fig.3. Participants could more easily localize themselves and better resist the drift effect with additional feedback provided. These subjects performed well on all indicators with our system. The trajectories pattern was more concentrated in the straight-line in the multi-feedback condition compared to the control condition (Fig. 3a). The Wilcoxon test (HAYES 2021) showed that there was a significant difference in the numbers of checkpoints reached between two conditions ($p < 0.0001$). Similarly, a great difference was observed in the average deviation as well. Participants could keep a significant lower deviation in the multi-feedback condition compared to the control condition ($p < 0.0001$), where the average deviation (m) per navigated distance (m) were 7.739m and 2.282m for two conditions respectively. Besides, there was significant difference in cognitive load depending on whether additional feedback was provided. Usually, higher pupil diameters represent higher cognitive load in the experiments. The result showed that participants had higher average pupil diameters during the experiment if no additional feedback provided ($p = 0.0021$), where the average was 4.13mm for control condition and 4.00mm for multi-feedback condition. In general, participants could perform much better in control with lower cognitive if additional feedback was provided to indicate flow conditions.

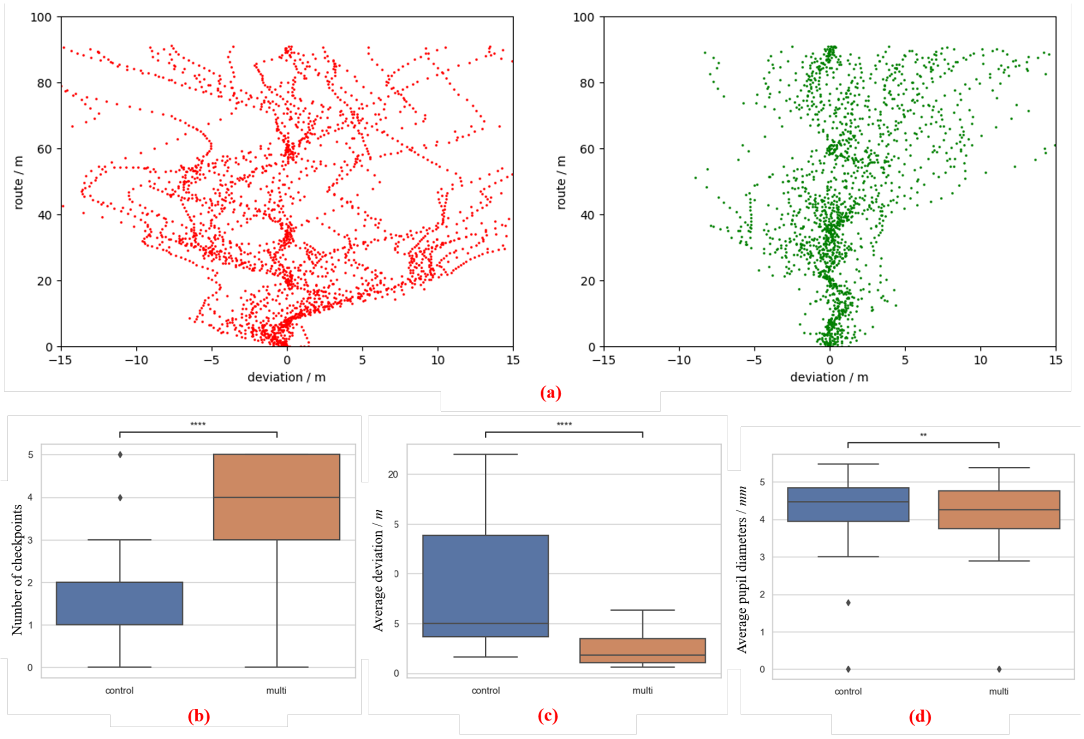

Fig.3 Performance analysis results for two conditions. (a) Trajectories patterns. (b) Number of checkpoints reached. (c) Average deviation. (d) Average pupil diameters.

The survey analysis result was shown in Fig. 4. Participants felt much easier to finish the task with our system and trusted the proposed system more. The NASA-TLX is a widely used, subjective, multidimensional assessment tool that rates perceived workload in assessment of a task (Index 1990). In this experiment, participants rated much lower in NASA TLX if multi-feedback system was provided ($p = 0.0006$). On the other hand, participants rated higher in trust scale survey with multi-feedback system ($p < 0.0001$). The result indicated that our system could significantly reduce operators' workload in similar tasks, and operators can trust the system more since more environmental information could be transited to humans with our system.

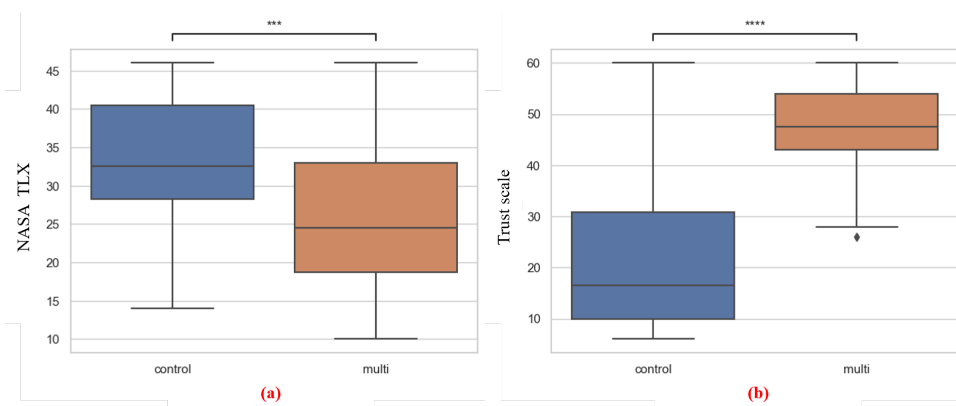

Fig.4 Surveys results for two conditions. (a) NASA TLX. (b) Trust scale survey.

In conclusion, the experiment results revealed the potential benefits of integrating sensory augmentation methods in current ROV control systems. The results verified that with sensory augmentation feedback to indicate hydrodynamic conditions in the proximity, the performance and perception results of ROV operators could be significantly improved in ROV navigation operations and the anti-drifting operations.

Conclusions

Subsea engineering is highly dependent on ROVs. At present, traditional control kiosks and feedback methods can not deal with the complexity of the subsea environment, including dynamic internal currents, low visibility, and unexpected contact with marine lives. This paper proposes a sensory augmentation method to enhance the ROV operator's perception through novel feedback methods, simulating the hydrodynamic features of the surrounding subsea environment as augmented visual feedback and haptic feedback in the VR environment for ROV teleoperation. The case study result showed that with sensory augmentation methods, human operators' performance was significantly improved. Besides, operators had both lower workload and cognitive load during the operation, and they preferred to trust the system more if more feedback information provided.

In conclusion, with the urgent need for subsea engineering, new human-robot interaction designs are necessary to enhance the human sensation of the ROV working environment. The proposed new method of ROV feedback and controls is expected to help advance a booming subsea engineering industry that requires a strong integration between human intelligence and robots to tackle environmental complexity and task dynamics. Without losing the generalizability, this method is expected to enable a much closer human-ROV collaboration for subsea inspection and survey, i.e., the maneuver and navigation controls of remote ROVs for sensor data collection and scanning of vessels and subsea structure inspection in offshore zones. It can make the key tasks easier, including navigation (localization and state estimation), control (path planning and maneuvering through complex environments) and perception (for robot position control and the inspection task) with lower work and cognitive load but higher trust for the system. Besides, this method is also strongly positioned for better accessibility and inclusion. It aims to lower the career barrier for a traditionally highly professional area. The sensory augmentation method for robotic control may help mitigate the age and gender requirement, promoting career longevity. The new technology may also help salvage the careers of experienced workers who have suffered from career injuries, such as diving diseases.

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