VR-Based Haptic Simulator for Subsea Robot Teleoperations

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ABSTRACT

Subsea engineering operations heavily rely on remotely operated vehicles (ROV), and the performance depends on the seamless interaction between ROV and the human operator. Due to the dynamics of subsea environments such as the uncertainty of turbulence, affected visibility, and the interference with subsea ecosystems, control of subsea ROV is challenging for human operators who have never exposed to such an environment. Even with the tremendous amount of practice, the human operator can easily misjudge the situation and make wrong decisions in subsea operations. This research proposes an intuitive human-robot collaboration method based on mixed reality system (VR/AR). To explore the potentials of utilizing a mixed reality system to accomplish ROV control, a haptic suit is combined with VR goggles to bring an immersive subsea environment to the operator. A comprehensive physics model is first transferred to VR equipment, depicting a detailed underwater environment including turbulence and interaction with ambient objects. Then the haptic suit executes the corresponding pressure signals to the operator's body in real-time. The feedback signals from haptic suit provide the human operator with realistic sensation of subsea situations peripheral to the robot. This immersive virtual environment ensures ROV operators of real-time awareness of the proximity conditions and prediction of changes. As a result, a less-trained human operator can pilot the ROV based on his/her intuition and experience to maximize the performance and avoid potential mistakes.

INTRODUCTION

According to the National Oceanic and Atmospheric Administration (NOAA), about 95% of the world's oceans and 99% of the ocean floor are unexplored (Baird 2005). Augmenting human abilities in subsea engineering, such as offshore construction and inspection (e.g., floating cities and offshore wind farms) and subsea exploration and operations (e.g., offshore mining, subsea cables, and energy harvesting), provides a historic opportunity for the new economic growth and scientific discoveries. Subsea infrastructure is also critical to tackling the unprecedented challenge of the climate crisis - various disaster models project a 45-87% increase of severe hurricanes in the next three decades in the US coastal areas (Knutson et al. 2013), threatening more than 30% of the US population (Census 2019). There is an urgent need to seek for the versatile, high efficiency, low risk-cost subsea engineering solutions.

For decades, subsea exploration and operations have been mostly carried out with the help of Remotely Operated Vehicles, or ROV (Kennedy et al. 2019). A typical ROV system consist of a submersible vehicle, a surface control unit and a tether management system (Salgado-Jimenez et al. 2010). Technicians from above sea level can take control of the whole system to accomplish complex tasks with the help of live video streaming (Zhang et al. 2017). Subsea engineering operations benefit from ROVs because of their agility, safety, endurance and cost savings (Li et al. 2019). But the teleoperation of ROV can be very challenging and risky due to the mismatch between the subsea workplaces and the daily experience of the human operator. The complexity of subsea environment, such as the rapidly varying internal currents, low visibility, unexpected contacts with marine lives, may all undermine the stability of the ROV, or the stabilization controls (Khadhraoui et al. 2016). Although nowadays most ROVs are equipped with a certain level of self-stabilization and self-navigation functions (Fossen 2011), for complex engineering tasks, human controls are still often needed. Human sensorimotor control relies on multimodal sensory feedback, such as the visual and somatosensory cues, to make sense of the consequence of any initiated action(Wood et al. 2013). In ROV teleoperations, the lack of human ability to perceive various subsea environmental and spatial features, such as the inability to directly sense water flows and pressure changes, can break the loop between motor action and feedback, leading to an induced *perceptual-motor malfunction* (Finney 2015). Although in practice these parameters can be collected and displayed via monitor screens, it requires a significant training effort to comprehend and react in a timely manner. Even a highly experienced operator can make mistakes when exposed to an unfamiliar environment, especially in high stress or tired mental situations. There is an urgent need to grant ROV operators the ability to see, to hear and to feel the system with multisensory capacity in an intuitive way.

To mitigate the perceptual-motor malfunction and reduce training needs in ROV teleoperations*,* we propose a virtual telepresence system based on VR and a sensory augmentation simulator. The remainder of this paper introduces the background and the system design.

RELAED WORKS: VR-BASED SENSORY AUGMENTATION

VR for human-robot collaboration (HRC) has presented benefits of pairing humans and robots cognitively (Chakraborti et al. 2017). It can result in a better planning of behaviors and interactions in difficult tasks that require both robotic and human intelligence (Williams et al. 2019). VR simulation provides a direct visualization of robot actions and the surrounding workplaces, and thus lowers the communication barriers (Kaminka 2013). Recently, it is also noted that VR can serve as the basis for sensory augmentation, i.e., providing visual, auditory and haptic cues associated with an intended action, to improve motor performance (e.g., (Sugiyama and Liew 2017; Zhou et al. 2020; Zhu et al. 2021). Especially, haptic devices combined with a VR simulation can generate vibration and pressure onto the user's body in correspondence with the occurring events (Tian et al. 2014, 2017). These tactile signals can be used as feedback cue sign for the human operator's sensation to help understand motion and status of the remote ROV. The feedback signal can be produced by actuators in a variety of types to mimic featured situations. Linear-oscillating actuator uses asymmetric drivers can create equivalent pressure signal (Ciriello et al. 2013), such as pushing or hydrostatic pressure. A gyro effect haptic actuator can simulate torque feedback even when ungrounded (Shazali 2018). The combined pressure and torsion forces applied on the user's body can produce illusional felling of external force and incorporated buy the user's proprioceptors and as a result generating kinesthetic perception of the ROV (Amemiya and Maeda 2009). Other devices can generate force feedback through electrical muscle stimulation (Ishikawa et al. 2015), which can provide a sense of motion. But intensive usage of haptic device may result in perceptual fatigue (Coren 2003). So, an evaluation system for monitoring the mental behavior and stress level of the user is also necessary especially for the prolonged operation.

VR-BASED HAPTIC SIMULATOR FOR ROV

This paper presents the design of a system that combines the VR environment and a whole-body haptic device to augment human operator's ability in ROV teleoperations. The system consists of four main components: (1) A ROV-based sensor network for subsea environmental data collection; (2) Subsea environmental modeling and visualization; (3) ROS-VR data transfer infrastructure; and (4) VR-based haptic simulator. Figure 1 illustrates the system architecture.

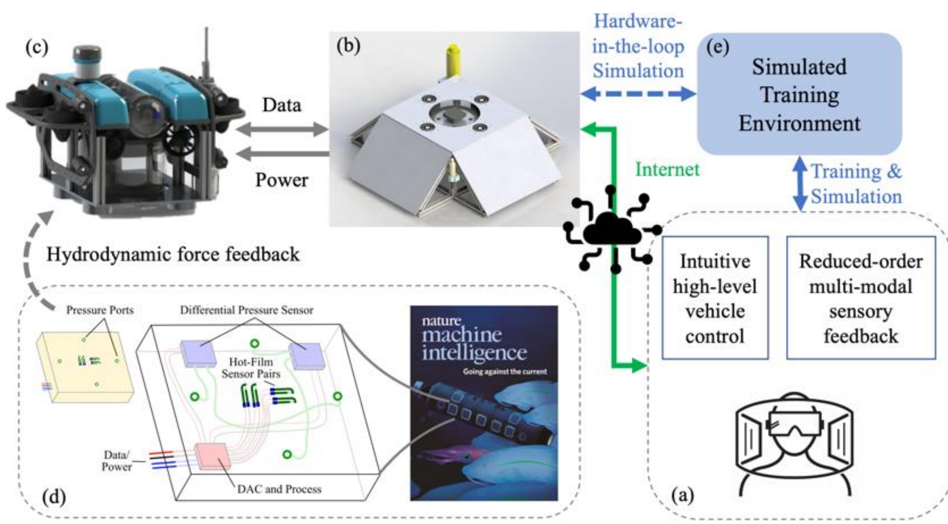

Figure 1. Proposed ROV teleoperation system. (a) VR sensory simulator. (b) Subsea docking station acting as remote nexus points for cabled power and network communication to the robot. (c) Modular ROV system. (d) Bioinspired flow sensing system to provide real-time hydrodynamic force sensing. (e) A simulated training environment.

ROV Sensor Network for Environmental Data Collection. We propose an artificial skin, a distributed sensor system that allows a flexible add-on sensor package for subsea environmental data collection (Figure 1d). It uses an array of paired differential pressure sensors mounted on electronics boards. The boards are embedded in elastomers with hardware that allow them to connect to the 3D printed scaffolding, or the custom shell. These sensor modules distribute throughout the custom shell designed to fit to the surface of the ROVs to collect sensing signals including temperature, pressure, and shear stress. Vision-based data will also be used for 3D reconstruction and extraction of the region of interest based on our prior studies (Liu et al. 2021). In addition, there is no existing underwater robotic infrastructure that supports 24/7 operation of the system. Therefore the system includes a subsea robotic resident system based on a docking station design that can be deployed for long terms and tasked remotely from a remote station on land (Song et al. 2020), which utilizes power and communication interfaces available from existing cabled subsea observatories or inter-continental telecommunication infrastructure (Wallen et al. 2019). The ROV is connected to a docking station (Figure 1b) through cabled systems for reliability in power and data transfer, and the docking station is connected to remote a human operator via Internet. The bioinspired flow sensing system (Figure 1d) is integrated with the vehicle to provide in-situ hydrodynamic force measurements. In addition, a simulated training environment (Figure 1e) can be added to this system to enable fast training of new operators, pre-mission evaluation of operation plans.

Subsea Environment Modeling and Visualization. The proposed ROV teleoperation system requires real-time modeling and visualization for "making sense" of the dynamic, dangerous and underexplored subsea workplaces. It needs to address the challenges of both data sparsity and data overload that could happen and equally destructive in the effort of modeling subsea workplace. We design a hierarchal process to model subsea workplaces: (i) For modeling environment in the close proximity to the ROV, we will apply the robot-carried sensors to infer the turbidity, pressure, and temperature with hydrodynamic numerical simulation. The idea is to estimate workplace characteristics within a small radius (<3m) centered around the underwater robot. (ii) For modeling the bigger range of the workplaces, we propose to relate the surface roughness information with hydrodynamic processes in the water column. The model will be based on the physical principles (conservation laws). The low-dimensional model approximate will be implemented using the Deep Convolutional Generative Adversarial Network (DCGAN) (Brunton et al. 2020). Then a 3D model will be built in VR, with renderings adjusted to subsea workplace condition. The scene contains necessary construction objects and a ROV, which can be used to interact with the surroundings. The first-person view of the pilot is also adjusted to a common ROV's camera view. To control the ROV and visualize the mounted camera, the VR environment is transferred into a stereoscopic head-mounted display (HTC VIVE) (Candeloro et al. 2016).

ROS-VR Data Transfer Infrastructure. The ROV-operator interaction requires seamless data transfer between the Robot Operating System (ROS) and the Unity environment for VR and the sensory simulator. It also requires a fast (ideally, real-time) rendering of the environment. A ROS-Unity infrastructure developed by us (Zhou et al. 2020) is employed to transfer data between robot and operator system for seamless controls. The system features two functions: converting VR user actions or haptic device data to robotic dynamics and rebuilding the 3D scene in VR based on point cloud data from the remote robot. Rosbridge is used to provide a JSON API for transferring data between ROS and Unity. ROS server converts robotic dynamics data into JSON messages via rosbridge and publishes it or receives JSON message from Internet and converts it to ROS message. We grant the ROS server and Unity's WebSocket the same IP address, so that the ROS server can publish the processed topics to the ROS platform, and the Unity can subscribe to all topics on ROS platforms through ROS#.

Haptic Simulator. A physics engine NVIDIA PhysX is used to simulate fluid flows and pressure changes in the vicinity of the ROV using a particle-based approach, i.e., the smoothed particle hydrodynamics method (Figure 2). The vectors of particles will be color coded and visualized in a VR headset, as well as driving a haptic suit where 40 vibrators on the upper body will generate haptic cues of different magnitudes of hydrodynamic forces depending on the collisions between the fluid particles and the ROV. The human operator can "see" and "feel" the real-time fluid changes analogous to what most fish are capable of. Particle systems within the Unity game engine is usually used for simulating fluid behavior such as water, flame, smoke. Rendering of the same particle system is adjustable for visual clarity from the scene's camera by using selected shaders. The applied particle system's behavior is calculated by a constraint solver based on position based fluid dynamics (MacKlin et al. 2014; Macklin and Müller 2013). Instead of using smoothed particle hydrodynamics, we propose to use the position-based dynamics because it excels in interactive environments and has a better stability. The applied particle system can be organized and adjusted for various speeds, directions, volumes, and densities. The interaction between particle system and ROV can be recorded as trigger event to signal the haptic suit for interaction.

The proposed simulation can run in a loop shown in Figure 3. ROV and the sensors attached act as the core of the loop, which will interact with simulated peripheral underwater environment and at the same time report to the haptic simulator. The human operator can then interpret the surroundings with tactile haptic feedback and given out motion commands based on his/her perception. At last, the ROV would again interact with surrounding environment and obtain new sensor signal according to its updated state. This closed loop system brings the human operator inside as a participant with active feedback and interaction. Stability of ROV control can be increased as a result. And with real-time feedback, the operator can interpret the whole system faster and be trained effectively.

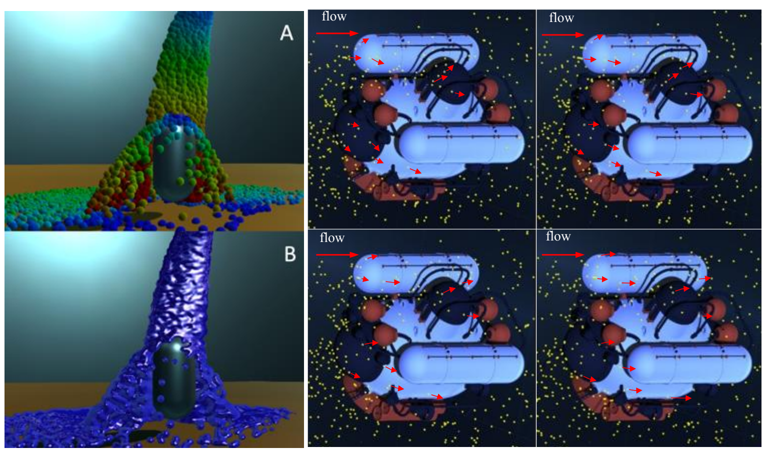

Figure 2. Simulating water flow and pressure changes as particle system. (A) and (B) Particle fluid interacting with object rendered by shaders; (C) Interacting with a ROV model (1 second).

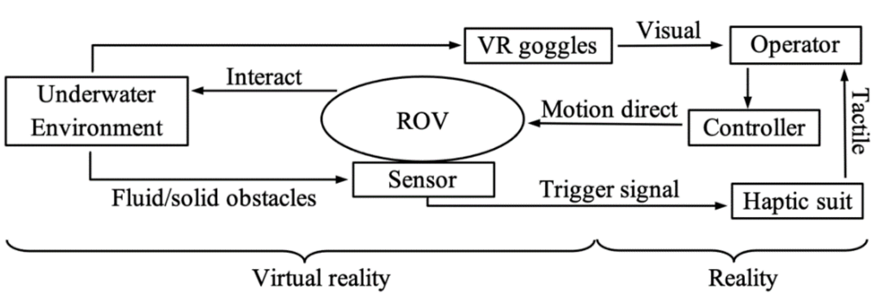

Figure 3. Closed loop ROV control simulation.

By applying position-based particle system, a flow field can be simulated representing real-time underwater condition. The particles are generated from sources with different initial conditions using Unity engine. Each source can contain various numbers of particles, and the shape of emission can also be defined. By tuning direction of particle source and intensity of its emission, complex flow field can be simulated. Figure 2 shows a result from simulated interaction between particles and ROV model over 1 sec of time lapse. Red arrows tracing featured particles flowing along the body showing the change of speed and direction. Tracing particles can be easy with colored rendering, so part of the flow field can be replaced with colored particles for identifying the state of flow for a 3rd person view, but at the same time invisible for the ROV operator.

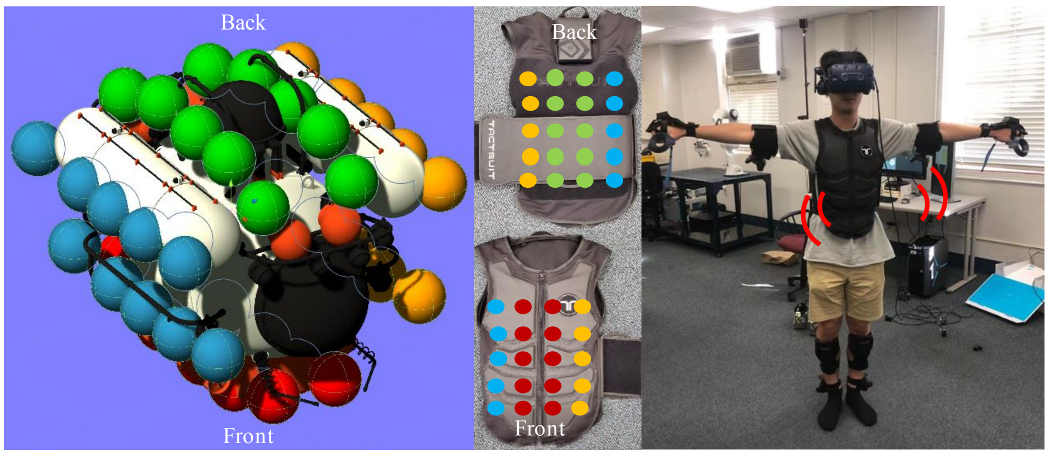

Figure 4. User setup - sphere shaped triggers matching haptic suit feedback points.

Figure 4 illustrates the user setup. Flow field surrounding the ROV can be sensed with trigger objects inside Unity engine. The haptic device features 40 feedback points in total and half of them is in the front while the other half is in the back. As shown in Figure 4, 40 feedback points on the haptic suit will surround the user from 360 degrees. The color rendered balls surrounding ROV model in Figure 4 are 40 trigger objects which can count the amount of particles entering its domain without physical interaction. 40 triggers match the corresponding feedback points on the haptic suit. The feedback will be based on vibration frequency, which is quantified by interactions with particles. The operator can tell the flow rate by sensing intensity of haptic feedback.

CONCLUSIONS

This paper describes the design of an innovative system for the intuitive teleoperation of subsea ROVs with VR and haptic simulation. With the help of position-based fluid simulation, a realistic flow field can be simulated and adjusted to regenerate complex internal currents in subsea workplaces as human-perceivable sensations. This virtual environment unites the human operator inside the system and make him/her an embedded link of the HRC loop. As a result, the human operator can easily sense the state of ROV through visual and haptic feedback and issue adequate control commands in an intuitive way. This will help increase the situational awareness of the human operator, improve training effectiveness of ROV operators, and enable the future civil engineers to enter a subsea era in a safer, less costly way. The future agenda includes testing the system in a simulated subsea inspection task to evaluate the safety and effectiveness. Neurophysiological sensor will be adopted to help assess the functions and performance of the human operator during the mission. It is expected that by integrating the robot control systems with the Unity engine, VR assisted ROV teleoperations can be accomplished in a participatory and inclusive way. With the increasing adoption of VR and haptic methods, the enhanced sensory feedback can help the future civil engineers manage complex underwater tasks with ease. This ROV teleoperation system will ultimately lead to a Robot as a Service (RaaS) model that consists of a cyber-physical unit to facilitate the seamless integration of underwater robots and human operators into a shared cloud environment. We envision that this RaaS model will greatly diversify the subsea workforce and broaden participation in subsea engineering, inspection and scientific discovery.

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