

Human Body Motion and Hand Gesture Control for Remotely Operated Vehicle (ROV) Teleoperation

Pengxiang Xia¹, Hengxu You², Tianyu Zhou³, Jing Du, Ph.D., M.ASCE⁴

¹Ph.D. Student, Informatics, Cobots and Intelligent Construction (ICIC) Lab, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611; e-mail: xia.p@ufl.edu

² Ph.D. Student, Informatics, Cobots and Intelligent Construction (ICIC) Lab, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611; e-mail: you.h@ufl.edu

³ Ph.D. Student, Informatics, Cobots and Intelligent Construction (ICIC) Lab, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611; e-mail: ye.yang@ufl.edu

⁴Associate Professor, Informatics, Cobots and Intelligent Construction (ICIC) Lab, Department of Civil and Coastal Engineering, Univ. of Florida, Gainesville, FL 32611 (corresponding author); Email: eric.du@essie.ufl.edu

ABSTRACT

Remotely Operated Vehicles (ROV) are widely used in subsea navigation and operation tasks. Currently, ROV operations are primarily conducted through traditional control kiosks and feedback methods, with the camera display and joysticks control on a surface vessel. This kind of control method resulted in an extremely high training barrier. The marine and offshore sectors are dominated by male workers due to the harsh working conditions. Besides, subsea engineering also poses strict requirements on age, because of the mental and physical load of certain tasks. Therefore, this paper proposes a human body motion and hand gesture control method in Virtual Reality (VR) for ROV teleoperation, aiming to lower the training barrier, improve the work condition, and reduce mental load during the tasks. Specifically, human body motion parameters, mainly motion and orientation, are recorded in VR and mapped with ROV locomotion control via closed-loop control. A series of scripts are developed to recognize human gestures as functional control, such as light on/off or ROV up/down control. Finally, a configuration UI panel is designed for personnel adjustment. A case study was also presented to verify the effectiveness of the system. With this control system, the operator could teleoperate ROV in a more comfortable and safer environment in a more intuitive manner.

INTRODUCTION

Subsea engineering is under great development in offshore energy, aquaculture, sustainability, disaster preparedness, seafloor mining and cabling, and maritime transport (Casey 2020; McLean et al. 2004; McNutt 2002), due to the large area of unexplored ocean and ocean floor that provide great resources (Baird 2005). Remotely operated vehicles (ROVs), is an effective tool for subsea exploration and operations for decades (Kennedy et al. 2019). Currently, ROV operation is a highly specialized area with a high training barrier to broader participation. Most ROV-related jobs require strict professional preparation (ocean sciences, mechanical engineering, and diving knowledge) that takes many years of training. Besides, subsea operation tasks usually require for long time focus on operation with high mental load, and the work procedure of ROV operation (long time operation on the vessel above ocean) makes the work environment even harsh. All these factors make it even harder for the future subsea workforce to utilize or team up with underwater ROVs.

To solve these problems, this paper proposes a Virtual Reality (VR) based teleoperation method, with multi feedback system and body motion & hand gesture control system, aiming to enhance human perception of ROV work environment and develop a more intuitive close-loop control-feedback system to reduce the training barrier in current subsea engineering. A multi feedback system was applied to provide sufficient environmental hydrodynamic information, i.e., subsea currents information (Xia et al. 2022; Xia et al. 2023). Besides, a body motion and hand gesture control method was developed to make operators react to feedback intuitively with their natural body motions. Besides, a configuration panel was provided to operators for adjust haptic feedback sensitivity and body motion control sensitivity to their most preferred values. A case study was performed the effectiveness of the system. The result showed that operators could teleoperate the ROV in a more intuitive manner with higher control precision and lower workload, which may help to reduce training barriers in the future.

LITERATURE REVIEW

Traditional ROV control was based on joystick with live 2D video streaming. Although this method was verified effective in ROV operation, it cannot transit enough environmental information, which resulted in high mental load for operators. Usually, operators needed to face the low visibility in subsea environment (Chemisky et al. 2021; Li et al. 2019). Besides, the complex and high-turbidity currents can significantly influence ROV's self-stabilization or cause disorientation in exploration (Lawrance and Hollinger 2018). Preliminary studies tried to solve these problems by improving autonomous algorithms in trajectory control and stabilization. The main method was to integrate multi kinds of sensory data for precise control. For example, doppler velocity log (DVL), inertial measurement unit (IMU) and short baseline acoustic system (SBL) data could be combined for precise trajectory control (Soylu et al. 2016), while dual-eye vision based system (Lwin et al. 2019) and acoustic-based 3D space underwater positioning system (Pedersen et al. 2019) were used for ROV stability control. Although these autonomous algorithms contributed to enhancing the control precision to some extent, they still remained humans unaware of the working environment. The lack of ability to perceive various subsea environmental features and appropriate control methods can break the critical feedback-control loop for accurate motor actions, resulting in an induced perceptual-motor malfunction (Finney 2015).

In order to enhance the human perception of the ROV workspace, researchers gradually tried to include additional types of feedback, i.e., haptic feedback, to provide more comprehensive environmental information, such as specific hydrodynamic features. For example, the combined pressure and torsion forces could be applied on the user's bodies to produce the illusional feeling of external force incorporated, generating a kinesthetic perception of the ROVs (Amemiya and Maeda 2009). More specifically, a gyro effect haptic actuator was tested to simulate torque feedback even when ungrounded (Shazali 2018) and a linear-oscillating actuator using asymmetric drivers was developed to create equivalent pressure signals, such as pushing or hydrostatic pressure in remote system operations (Ciriello et al. 2013). These efforts were only tested in limited environment with insufficient hydrodynamic features captures. Therefore, a more comprehensive framework was proposed to capture and reproduce multi-levels of hydrodynamic features in VR (Xia et al. 2023), which was able to augment human ability in critical decision-making such as navigation path planning by providing sufficient working environment information.

After developing efficient feedback system, new control system should be designed to fit the features of feedback system. Currently, VR is a widely used platform for robot teleoperation to couple perception and controls between humans and robots (Chakraborti et al. 2017; Concannon

et al. 2019; Zhou et al. 2020). The beneficial of VR in multisensory augmentation has been verified in robotic control such as snake robot control (Zhu et al. 2022) and tower crane balance control (Zhu et al. 2022). In ROV operation, although studies have begun to use VR in different tasks, such as underwater capture tasks (Elor et al. 2021) and deep ocean remote control (Martin et al. 2021), no efficient control method for VR-based ROV operation was proposed. These designs still asked operators to sit there statically with a joystick for operation. Especially when integrating with haptic feedback, sticking to traditional joystick control could still break the critical feedback-control loop. Some new control methods for VR-haptic systems has been proposed, such as innovative haptic balancing controllers (Zhu et al. 2022) or designing efficient control interfaces (Li et al. 2019), and such kind of improvement is necessary for designing new ROV VR-haptic control system.

METHODOLOGY

In order to construct an intuitive close-loop control-feedback system, this paper proposed a VR-haptic body motion and hand gesture control system based on our previous multi-feedback system (Xia et al. 2022; Xia et al. 2023). As demonstrated in **Fig. 1**, the system was constructed in Unity 2022.4.25f version based on our previous systems (Du et al. 2016; Du et al. 2018; Du et al. 2017; Du et al. 2018; Shi et al. 2018). The whole system consisted of the virtual environment system, virtual ROV system and human operator system. The VR environment ensured a high-fidelity ocean wave simulation, subsea light rendering as well as adjustable water color and field of view (FOV) by applying the crest ocean system (Harmonic 2022). Subsea currents areas were designed in the environment, which would physically interact with the virtual ROV system. The virtual sensors of ROV system would capture hydrodynamic features and generate two kinds of feedback, augmented visual feedback and haptic feedback. Feedback signals were then sent to human-equipped devices, HTC VIVE head mounted display (HMD) (VIVE 2022) and bHaptics suit (bHaptics 2022). On the other side, human operators could intuitively react to these occurring feedback events with their natural body motions for control.

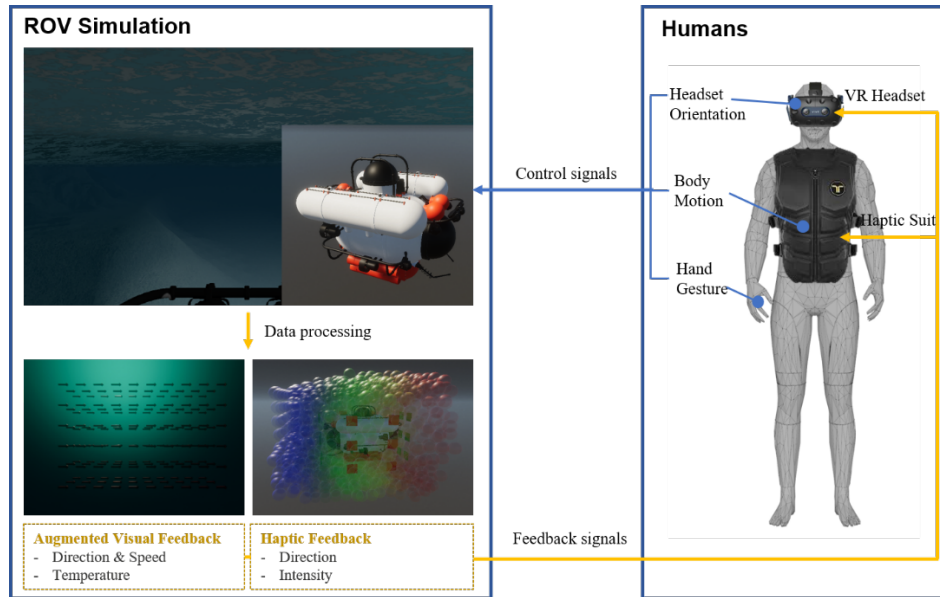


Fig.1 System architecture of VR-Haptic body motion control system.

Specifically, to map human motions with ROV correctly, we developed a series of functions to convert body motion parameters to ROV control signals. In general, ROV rotation was synchronized with head orientation of operator, and human body postures were designed to control the ROV motion, for example, the ROV would move forward when the human operator leaned forward. To realize the unachievable actions for human body motions, such as floating up and down, a hand gesture detection and recognition method was developed with HTC VIVE headset. Besides, this system provided human adjustable parameters such as feedback sensitivity and motion control sensitivity, allowing operators to adjust control parameters to their most preferred values.

As listed above, human body motions were designed to control the ROV motion in the x direction (left and right) and z direction (forward and back) in Unity. The system would create a control center when the system started and the human body motion from the control center was calculated as ROV moving speed, as illustrated in **Eq. 1** and **Eq. 2**, where $\vec{v}_{rov}$ is the movement speed of the ROV, $\vec{d}_{xz}$ is human motion vector in x and z direction plane, $n \in [0, 1]$ is human adjustable motion sensitivity, $\vec{p}_{1,xz}$ and $\vec{p}_{0,xz}$ are current human headset position and control center position in the x and z direction plane respectively. In this system, the maximum ROV motion speed was set to 1.5 m/s. The orientation of the headset was collected and synchronized as ROV rotation as well. Usually, the rotation speed of the human body could be out of the capability of ROVs. Therefore, a restriction was set as the maximum rotation speed, which was 45 °/s in this system. As illustrated in **Eq. 3**, $\vec{\theta}_{rov}$ is the rotation speed of the ROV and $\vec{\theta}_{operator}$ is the rotation speed of the human headset.

$$\vec{v}_{rov} = \min \left(\vec{d}_{xz}, \frac{0.2}{n + 0.1} \right) * 7.5(n + 0.1) \quad \text{Eq. 1}$$

$$\vec{d}_{xz} = \vec{p}_{1,xz} - \vec{p}_{0,xz} \quad \text{Eq. 2}$$

$$\vec{\theta}_{rov} = \min (\vec{\theta}_{operator}, 45) \quad \text{Eq. 3}$$

Finally, a hand gesture detection and recognition method was developed based on OpenXR (VIVE 2023) to capture hand motion from the dual front camera system on HTC VIVE headset and reconstruct located hand models in Unity with precise transform and rotation. In total, four kinds of hand gesture functions were developed by this system, as shown in **Fig. 2**. Specifically, operators could open their left hand in front of the cameras to show ON/OFF the augmented visual feedback, while a similar function was realized on the right hand to show on/off the UI panel, which was used to adjust haptic sensitivity and body motion sensitivity. Meanwhile, operators could use their right index finger to adjust these two kinds of parameters to their most preferred values. Since it was impossible for humans to control the ROV up and down with their body motion, the function was realized by hand gestures as well. Operators could use their thumbs up and down for ROV floating and diving control. The motion speed was decided by **Eq. 4**, where $\vec{v}_{rov,y}$ is the ROV speed on y axis, $\vec{p}_{tip,y}$ and $\vec{p}_{proximal,y}$ are the position on y axis of thumb tip joint and proximal joint respectively, $\vec{p}_{tip}$ is the position of thumb tip joint and $\vec{p}_{proximal}$ is the position of thumb proximal joint.

$$\vec{v}_{rov.y} = \frac{p_{tip.y} - p_{proximal.y}}{|\vec{p}_{tip} - \vec{p}_{proximal}|} * 1.5 \quad \text{Eq. 4}$$

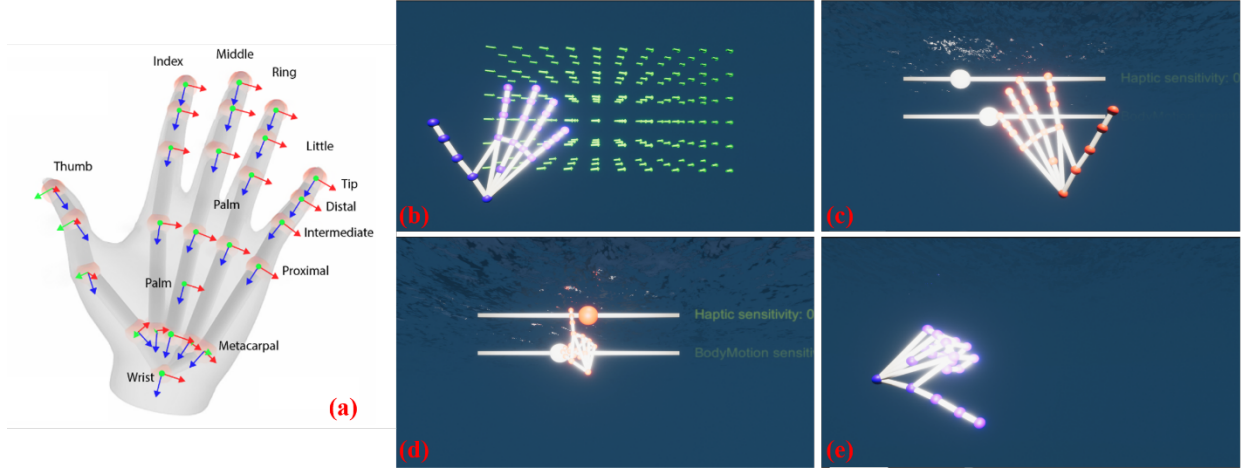


Fig.2 Hand gesture recognition examples. (a) Names of hand joints. (b) Control of showing on/off augmented visual feedback. (c) Control of showing on/off sensitivity UI panel. (d) Adjusting sensitivities. (e) Up/down control of ROV motion.

CASE STUDY

To verify the effectiveness of the control and feedback system, a case study was performed to compare the performance difference between traditional joystick control and our body motion control system. Participants were asked to control the ROV in VR to follow a ball, and were asked to keep relatively closed to the target ball and maintain a similar trajectory. We compared the average deviation to the target ball and Dynamic Time Warping (DTW) (Müller 2007) results for two trajectories. Besides, the NASA Task Load Index (TLX) (Index 1990) survey was used to analyze participants' workload during the experiment. In total, we recruited 30 participants for the case study, which consisted of 19 males and 11 females respectively and all the participants were aged from 18 years old to 42 years old (mean=26.3, std=4.38).

As shown in **Fig. 3**, the line represented the target ball's trajectory and the point cloud indicated the distribution of participants' trajectories. The average deviation (m) per frame ($0.01s$) in the joystick condition and body motion condition were 7.426m and 3.926m respectively, while the average DTW trajectory similarities were 472.736 and 291.146. Specific results were demonstrated in **Fig. 4**. Significant difference could be observed between the joystick condition and the body motion control condition ($p = 0.001$). Similarly, for the DTW similarities, significant difference could be observed between the joystick condition and the body motion control condition ($p = 0.013$). Besides, participants showed a higher overall workload in the NASA TLX survey in the joystick condition compared to the body motion control condition ($p = 0.0058$). In general, the joystick control method was not that intuitive for participants, especially for those who lack related control experience. On the contrary, the body motion control method was based on natural body interaction and participants could easily adapt to it even if they were total novices for ROV

operations, so operators could maintain a relatively better performance with our proposed system. Besides, operators significantly felt a lower workload with body motion control compared to the joystick control method.

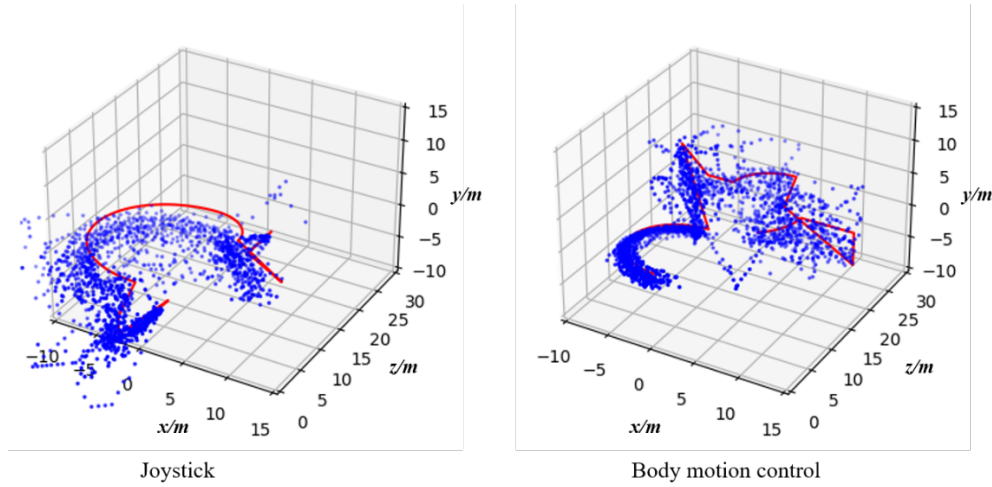


Fig.3 Target ball's trajectory and distribution of human operators' control trajectories.

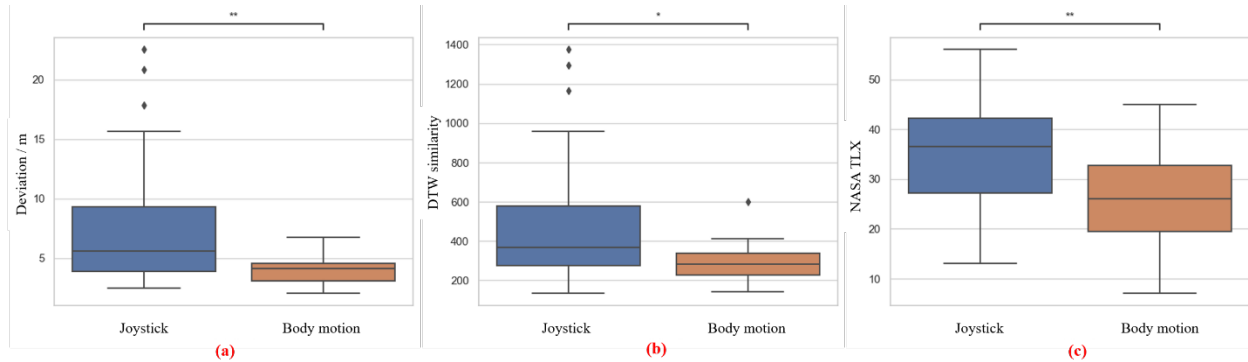


Fig.4 Results of case study: (a) Average deviation; (b) DTW trajectory similarities; (c) NASA TLX survey

DISCUSSION AND CONCLUSION

Currently, ROV control mainly relies on traditional control kiosks and feedback methods, which result in high work load, long training process, and uncomfortable working environment. This paper proposed a VR-haptic body motion control-feedback system for future ROV teleoperation, aiming to provide a more intuitive control-feedback system to reduce training barrier of ROV operation. In this system, human operators could react to the occurring events with their natural body motions and hand gestures to control the ROVs. A case study with 30 subjects was performed to verify the effectiveness of the system. The result showed that our proposed system could help in enhance performance while reduce the workload of ROV operation. There were some limitations that needed to be improved in the future as well. For example, there was not a maturely

designed UI in this experiment for the sensitivity parameters control. Some participants complained that the UI was hard to recognize in the 3D space. A better UI design should be taken into consideration in future applications.

In conclusion, with the urgent need for subsea engineering, a new teleoperation method is necessary to reduce training barriers. We expect that the proposed VR-haptic close-loop control-feedback system can help advance a booming subsea engineering industry, enable a much closer human-ROV collaboration for subsea inspection and survey, and reduce training barriers and workload for longer work life in subsea engineering. This method is also strongly positioned for better accessibility and inclusion because 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 requirement, promoting career longevity.

REFERENCE

- Amemiya, T., and Maeda, T. (2009). "Directional force sensation by asymmetric oscillation from a double-layer slider-crank mechanism." *Journal of computing and information science in engineering*, 9(1).
- Baird, S. L. (2005). "Deep-Sea Exploration: Earth's Final Frontier." *Technology and Engineering Teacher*, 65(4), 14.
- bHaptics (2022). "TactSuit X40." <<https://www.bhaptics.com/tactsuit/tactsuit-x40>>. (July 8th, 2022).
- Casey, J. (2020). "Drawing the line: could the subsea industry turn away from oil and gas." <<https://www.offshore-technology.com/analysis/drawing-the-line-could-the-subsea-industry-turn-away-from-oil-and-gas/>>. (2022).
- Chakraborti, T., Kambhampati, S., Scheutz, M., and Zhang, Y. (2017). "AI challenges in human-robot cognitive teaming." *arXiv preprint arXiv:1707.04775*.
- Chemisky, B., Menna, F., Nocerino, E., and Drap, P. (2021). "Underwater Survey for Oil and Gas Industry: A Review of Close Range Optical Methods." *Remote Sensing*, 13(14), 2789.
- Ciriello, V. M., Maikala, R. V., and O'Brien, N. V. (2013). "Maximal acceptable torques of six highly repetitive hand-wrist motions for male industrial workers." *Human factors*, 55(2), 309-322.
- Concannon, D., Flynn, R., and Murray, N. "A quality of experience evaluation system and research challenges for networked virtual reality-based teleoperation applications." *Proc., Proceedings of the 11th ACM workshop on immersive mixed and virtual environment systems*, 10-12.
- Du, J., Shi, Y., Mei, C., Quarles, J., and Yan, W. "Communication by interaction: A multiplayer VR environment for building walkthroughs." *Proc., Construction Research Congress 2016*, 2281-2290.
- Du, J., Shi, Y., Zou, Z., and Zhao, D. (2018). "CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users." *Journal of Construction Engineering and Management*, 144(2), 04017109.
- Du, J., Zou, Z., Shi, Y., and Zhao, D. (2017). "Simultaneous data exchange between BIM and VR for collaborative decision making." *Computing in Civil Engineering 2017*, 1-8.
- Du, J., Zou, Z., Shi, Y., and Zhao, D. (2018). "Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making." *Automation in Construction*, 85, 51-64.

- Elor, A., Thang, T., Hughes, B. P., Crosby, A., Phung, A., Gonzalez, E., Katija, K., Haddock, S. H., Martin, E. J., and Erwin, B. E. "Catching Jellies in Immersive Virtual Reality: A Comparative Teleoperation Study of ROVs in Underwater Capture Tasks." *Proc., Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, 1-10.
- Finney, G. R. (2015). "Perceptual-motor dysfunction." *Continuum: Lifelong Learning in Neurology*, 21(3), 678-689.
- Harmonic, W. (2022). "Crest Ocean System HDRP." <<https://assetstore.unity.com/packages/tools/particles-effects/crest-ocean-system-hdrp-164158#description>>. (July 5th, 2022).
- Index, L. (1990). "Results of empirical and theoretical research." *Advances in*.
- Kennedy, B. R., Cantwell, K., Malik, M., Kelley, C., Potter, J., Elliott, K., Lobecker, E., Gray, L. M., Sowers, D., and White, M. P. (2019). "The unknown and the unexplored: Insights into the Pacific deep-sea following NOAA CAPSTONE expeditions." *Frontiers in Marine Science*, 6, 480.
- Lawrance, N., and Hollinger, G. A. (2018). "Industry Feedback: Opportunities for Autonomous Monitoring and Intervention in Marine Renewable Energy Arrays."
- Li, X., Chen, G., Chang, Y., and Xu, C. (2019). "Risk-based operation safety analysis during maintenance activities of subsea pipelines." *Process Safety and Environmental Protection*, 122, 247-262.
- Li, Y., Lv, C., and Xue, J. "A novel predictive haptic control interface for automation-to-human takeover of automated vehicles." *Proc., 2019 IEEE Intelligent Vehicles Symposium (IV)*, IEEE, 994-999.
- Lwin, K. N., Myint, M., Yonemori, K., Mukada, N., Kanda, Y., Yanou, A., and Minami, M. (2019). "Dual-Eye Vision-Based Docking Experiment in the Sea for Battery Recharging Application." *SICE Journal of Control, Measurement, and System Integration*, 12(2), 47-55.
- Martin, E. J., Erwin, B., Katija, K., Phung, A., Gonzalez, E., Von Thun, S., Cullen, H., and Haddock, S. H. "A Virtual Reality Video System for Deep Ocean Remotely Operated Vehicles." *Proc., OCEANS 2021: San Diego–Porto*, IEEE, 1-6.
- McLean, C., Manley, J., and Gorell, F. "Ocean exploration: building innovative partnerships in the spirit of discovery." *Proc., Proceedings of the 2004 International Symposium on Underwater Technology (IEEE Cat. No. 04EX869)*, IEEE, 3-6.
- McNutt, M. (2002). "Ocean exploration." *Oceanography*, 15(1), 112-121.
- Müller, M. (2007). "Dynamic time warping." *Information retrieval for music and motion*, 69-84.
- Pedersen, S., Liniger, J., Sørensen, F. F., Schmidt, K., von Benzon, M., and Klemmensen, S. S. (2019). "Stabilization of a roV in three-dimensional space using an underwater acoustic positioning system." *IFAC-PapersOnLine*, 52(17), 117-122.
- Shazali, S. M. "Development of handheld haptics device for driving system of unmanned underwater vehicles." *Proc., MATEC Web of Conferences*, EDP Sciences, 06033.
- Shi, Y., Du, J., Ragan, E., Choi, K., and Ma, S. "Social influence on construction safety behaviors: a multi-user virtual reality experiment." *Proc., Construction Research Congress*, 147-183.
- Soylu, S., Proctor, A. A., Podhorodeski, R. P., Bradley, C., and Buckham, B. J. (2016). "Precise trajectory control for an inspection class ROV." *Ocean Engineering*, 111, 508-523.
- VIVE (2023). "OpenXR for PC VR." <<https://developer.vive.com/resources/openxr/openxr-pcvr/documentation/>>. (January 1st, 2023).

- VIVE, H. (2022). "HTC VIVE VR Devices - Premium VR Experience." <https://www.vive.com/us/?wpsrc=Google%20AdWords&wpcid=16946345271&wpsnetn=g&wpkwn=htc%20vive&wpkmatch=e&wpcrid=594055656895&wpscid=142495177624&wpkwid=kwd-15492340847&gclid=CjwKCAiA76-dBhByEiwAA0_s9V7J5u0MKXvVAFJiaV_8EQ8HT9ZL4ReU_99KFRlqgZWpz9-hjKxcNBoCazwQAvD_BwE>. (December 28th, 2022).
- Xia, P., McSweeney, K., Wen, F., Song, Z., Krieg, M., Li, S., Yu, X., Crippen, K., Adams, J., and Du, E. J. "Virtual Telepresence for the Future of ROV Teleoperations: Opportunities and Challenges." *Proc., SNAME 27th Offshore Symposium*, OnePetro.
- Xia, P., Xu, F., Song, Z., Li, S., and Du, J. (2023). "Sensory augmentation for subsea robot teleoperation." *Computers in Industry*, 145, 103836.
- Zhou, T., Zhu, Q., and Du, J. (2020). "Intuitive robot teleoperation for civil engineering operations with virtual reality and deep learning scene reconstruction." *Advanced Engineering Informatics*, 46, 101170.
- Zhu, Q., Zhou, T., and Du, J. (2022). "Haptics-based force balance controller for tower crane payload sway controls." *Automation in Construction*, 144, 104597.
- Zhu, Q., Zhou, T., and Du, J. (2022). "Upper-body haptic system for snake robot teleoperation in pipelines." *Advanced Engineering Informatics*, 51, 101532.