Journal of Computing in Civil Engineering
Human Autonomy Teaming for ROV Shared Control
--Manuscript Draft--

Manuscript Number:	CPENG-5756
Full Title:	Human Autonomy Teaming for ROV Shared Control
Manuscript Region of Origin:	UNITED STATES
Article Type:	Technical Paper
Manuscript Classifications:	Automation and robotics; Human-computer interaction; Visualization and mixed realities
Funding Information:	National Science Foundation (2128895) — Dr. Jing Du
Abstract:	ROV is a widely used subsea vehicle in offshore oil and gas industries to assist in the development and inspection of offshore oil fields, given its agility, safety, and endurance. As the offshore industry and subsea engineering fields advance, the demands on ROV technology, particularly in terms of control accuracy and safety, have been greatly increasing. Traditional methods require ROV operators to be stationed on vessels in challenging conditions, relying on video streams that offer limited spatial information about the ROV working environment. All these factors make conventional joystick controls even harder for novices. This research aims to propose a novel approach to human-autonomy collaboration aiming to diminish the learning and operational burdens on operators. A VR-based sensory augmentation and body motion teleoperation method was applied, which allows operators to teleoperate the ROV in a much more comfortable environment. An interactive user interface was developed to enable seamless engagement with the autonomous system and facilitate dynamic switching between human and autonomous controls. To assess the system, a human subject experiment was conducted to compare the performance of an inspection task between human control, full autonomy, and human autonomy teaming methods. The result indicated that our solution could enhance human understanding of the ROV work status as well as reduce human workload during operation.
Corresponding Author:	Jing Du, Ph.D. University of Florida Gainesville, FL UNITED STATES
Corresponding Author E-Mail:	eric.du@essie.ufl.edu
Order of Authors:	Pengxiang Xia
	Tianyu Zhou, Ph.D.
	Yang Ye
	Jing Du, Ph.D.
Suggested Reviewers:	
Opposed Reviewers:	
Additional Information:	
Question	**Response**
The journal requires that all submissions fall within its aims and scope, explained here. Please explain how your submission fits the journal's aims and scope.	This paper fits well within the scope of the Journal of Computing in Civil Engineering as it presents innovative ideas and advances in computing, specifically in the context of enhancing the operational capabilities of remotely operated vehicles (ROVs) in offshore engineering settings, which is a crucial aspect of civil engineering in oil and gas industries. It encompasses innovations in artificial intelligence and information technology by integrating VR-based sensory augmentation and body motion teleoperation methods, and offering a novel approach to human-autonomy collaboration, thus aligning with the journal's focus on cross-disciplinary areas of

	software and hardware applications. Additionally, the development of an interactive user interface and the implementation of dynamic switching between human and autonomous controls reflect the journal’s interest in computer-aided design systems and strategic computing resource management. The research, therefore, not only contributes valuable insights into the application of advanced computing technologies in civil engineering tasks but also addresses broader implications for enhancing safety and efficiency in the engineering profession.
Papers published in ASCE Journals must make a contribution to the core body of knowledge and to the advancement of the field. Authors must consider how their new knowledge and/or innovations add value to the state of the art and/or state of the practice. Please outline the specific contributions of this research in the comments box.	This research makes a unique contribution to the core body of knowledge in subsea engineering by proposing an innovative approach to human-autonomy collaboration in the operation of remotely operated vehicles (ROVs) within offshore oil and gas industries. The integration of a VR-based sensory augmentation and body motion teleoperation method, coupled with an interactive user interface, not only advances the state of the art in ROV technology and operational capabilities but also elevates the state of practice by enhancing control accuracy and safety. By addressing and resolving the limitations of traditional ROV operation methods, this paper offers a groundbreaking solution, evidenced by empirical assessments, that significantly diminishes operational burdens and augments human understanding of ROV work status, adding substantial value to the fields of civil and subsea engineering.
The flat fee for including color figures in print is $800, regardless of the number of color figures. There is no fee for online only color figures. If you decide to not print figures in color, please ensure that the color figures will also make sense when printed in black-and-white, and remove any reference to color in the text. Only one file is accepted for each figure. Do you intend to pay to include color figures in print? If yes, please indicate which figures in the comments box.	No
Authors are required to attain permission to re-use content, figures, tables, charts, maps, and photographs for which the authors do not hold copyright. Figures created by the authors but previously published under copyright elsewhere may require permission. For more information see http://ascelibrary.org/doi/abs/10.1061/9780784479018.ch03. All permissions must be uploaded as a permission file in PDF format. Are there any required permissions that have not yet been secured? If yes, please explain in the comment box.	No
ASCE does not review manuscripts that are being considered elsewhere to include other ASCE Journals and all conference proceedings (see next question for expanded conference proceeding	No

requirements). Is the article or parts of it being considered for any other publication? If your answer is yes, please explain in the comments box below.	
Is this article or parts of it already published in print or online in any language? ASCE does not review content already published (see next questions for conference papers and posted theses/dissertations). If your answer is yes, please explain in the comments box below.	No
Has this manuscript, in whole or in part, been submitted to a conference?	Yes
ASCE will consider manuscripts based on conference papers if the following requirements are met: • The conference paper must not be under copyright at any other institution. If the paper is under copyright elsewhere, it is the author's responsibility to obtain permission from the copyright holder to submit and publish the paper with ASCE prior to submission. • The conference paper must contain new and expanded information, methodology, interpretation, and conclusions from the conference paper. Whether the conference paper meets these criteria is up to the judgement of the journal's editor. Authors must provide a description of how the journal paper is different from the conference paper. ASCE reserves the right to request a copy of the conference for comparison purposes. • The conference paper must be cited in the submitted journal article. By submitting your paper, you confirm that the above criteria have been met. In the comment box below, please list the name and date of the conference, and a description of how your manuscript differs from the conference paper. as follow-up to "Has this manuscript, in whole or in part, been submitted to a conference?"	Some of the contents of this paper are based on a paper published as in i3CE conference proceedings. We were invited to extend the paper and submit to this special collection. We confirm that at least 50% of this manuscript are new contents.

ASCE allows submissions of papers that are based on theses and dissertations so long as the paper has been modified to fit the journal page limits, format, and tailored for the audience. ASCE will consider such papers even if the thesis or dissertation has been posted online provided that the degree-granting institution requires that the thesis or dissertation be posted. <p>Is this paper a derivative of a thesis or dissertation posted or about to be posted on the Internet? If yes, please provide the URL or DOI permalink in the comment box below.	No
Each submission to ASCE must stand on its own and represent significant new information, which may include disproving the work of others. While it is acceptable to build upon one's own work or replicate other's work, it is not appropriate to fragment the research to maximize the number of manuscripts or to submit papers that represent very small incremental changes. ASCE may use tools such as CrossCheck, Duplicate Submission Checks, and Google Scholar to verify that submissions are novel. Does the manuscript constitute incremental work (i.e. restating raw data, models, or conclusions from a previously published study)?	No
Authors are expected to present their papers within the page limitations described in <u><i>Publishing in ASCE Journals: A Guide for Authors</u></i>. Technical papers and Case Studies must not exceed 30 double-spaced manuscript pages, including all figures and tables. Technical notes must not exceed 7 double-spaced manuscript pages. Papers that exceed the limits must be justified. Grossly over-length papers may be returned without review. Does this paper exceed the ASCE length limitations? If yes, please provide justification in the comments box below.	No
All authors listed on the manuscript must have contributed to the study and must approve the current version of the manuscript. Are there any authors on the paper that do not meet these criteria? If the answer is yes, please explain in the comments.	No

Was this paper previously declined or withdrawn from this or another ASCE journal? If so, please provide the previous manuscript number and explain what you have changed in this current version in the comments box below. You may upload a separate response to reviewers if your comments are extensive.	No
Companion manuscripts are discouraged as all papers published must be able to stand on their own. Justification must be provided to the editor if an author feels as though the work must be presented in two parts and published simultaneously. There is no guarantee that companions will be reviewed by the same reviewers, which complicates the review process, increases the risk for rejection and potentially lengthens the review time. If this is a companion paper, please indicate the part number and provide the title, authors and manuscript number (if available) for the companion papers along with your detailed justification for the editor in the comments box below. If there is no justification provided, or if there is insufficient justification, the papers will be returned without review.	NA
Is this manuscript being submitted as part of a special collection? You can find active calls for papers for special collections in ASCE Journals here.	Yes
Please list the title of the special collection and the name of the guest editor(s) below. as follow-up to "Is this manuscript being submitted as part of a special collection? You can find active calls for papers for special collections in ASCE Journals here."	Integrated Human Machine Intelligence (IHMI) in Civil Engineering Dr. Changbum “Ryan” Ahn, Seoul National University (cbahn@snu.ac.kr) Dr. Hubo Cai, Purdue University (hubocai@purdue.edu) Dr. Pingbo Tang, Carnegie Mellon University (ptang@andrew.cmu.edu) Dr. Cheng Zhang, Purdue University Northwest (zhan4168@pnw.edu)
When submitting a manuscript, authors must include a section heading titled “Data Availability Statement” before the “Acknowledgments” section or after the “Conclusion." Within the section, authors will include one or more of the following statements, as well as all citations to data, code, or models. You can read more about the Data Availability Statement policy here.	a. Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Please select one or more of the statements below that apply to your manuscript. The statement(s) listed in your manuscript should match those you select in your response to this question. *Note that regardless of your response to this question, all reasonable requests for data from reviewers during the review process must be fulfilled.*	
If there is anything else you wish to communicate to the editor of the journal, please do so in this box.	Thank you!

UNIVERSITY of FLORIDA

Herbert Wertheim College of Engineering
Engineering School of Sustainable Infrastructure & Environment

1949 Stadium Road
460F Weil Hall
Gainesville, FL 32611
Office: (352) 294-6619
Email: eric.du@essie.ufl.edu

September 30, 2023

RE: Submission of technical paper to Special Collection "*Integrated Human Machine Intelligence (IHMI) in Civil Engineering*"

Dear Guest Editors,

Please find our submission of a technical paper titled "***Human Autonomy Teaming for ROV Shared Control***" for the special collection "***Integrated Human Machine Intelligence (IHMI) in Civil Engineering***".

This paper introduces a novel approach to human-autonomy collaboration for remotely operated vehicles (ROVs) used in offshore oil and gas industries, addressing increased demands in control accuracy and safety. The approach employs a VR-based sensory augmentation and body motion teleoperation method, enabling operators to teleoperate the ROV in a more comfortable environment, and features an interactive user interface to facilitate dynamic switching between human and autonomous controls. An experimental assessment revealed that this solution enhances human understanding of the ROV work status and reduces operator workload during operations.

We confirm that this submission contains at least 50% new contents in addition to a conference paper we submitted to ASCE i3CE conference.

We sincerely look forward to the comments.

Sincerely,

Eric Jing Du, Ph.D.
Professor
Department of Civil and Coastal Engineering
Department of Mechanical and Aerospace Engineering (Affiliate)
Department of Industrial and System Engineering (Affiliate)
Herbert Wertheim College of Engineering
University of Florida
460F Weil Hall, 1949 Stadium Road, Gainesville, FL 32611
Secretary, Visualization, Information Modeling, and Simulation (VIMS) Committee, ASCE
Email: eric.du@essie.ufl.edu | Phone: (352) 294-6619 | Fax: (352) 392- 3394
ICIC Lab: https://faculty.eng.ufl.edu/ericdu/

ICIC LAB
Informatics,
Cobots and Intelligent
Construction Lab

Human Autonomy Teaming for ROV Shared Control

Pengxiang Xia[1], Tianyu Zhou, Ph.D.[2], Yang Ye[3], Jing Du, Ph.D., M.ASCE[4]

[1] Ph.D. Candiate, 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] Postdoc Research Associate, Informatics, Cobots and Intelligent Construction (ICIC) Lab, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611; e-mail: zhoutianyu@ufl.edu
[3] Ph.D. Candidate, 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
[4] 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

ROV is a widely used subsea vehicle in offshore oil and gas industries to assist in the development and inspection of offshore oil fields, given its agility, safety, and endurance. As the offshore industry and subsea engineering fields advance, the demands on ROV technology, particularly in terms of control accuracy and safety, have been greatly increasing. Traditional methods require ROV operators to be stationed on vessels in challenging conditions, relying on video streams that offer limited spatial information about the ROV working environment. All these factors make conventional joystick controls even harder for novices. This research aims to propose a novel approach to human-autonomy collaboration aiming to diminish the learning and operational burdens on operators. A VR-based sensory augmentation and body motion teleoperation method was applied, which allows operators to teleoperate the ROV in a much more comfortable environment. An interactive user interface was developed to enable seamless engagement with the autonomous system and facilitate dynamic switching between human and autonomous controls. To assess the system, a human subject experiment was conducted to compare the performance of an inspection task between human control, full autonomy, and human autonomy teaming methods. The result indicated that our solution could enhance human understanding of the ROV work status as well as reduce human workload during operation.

KEYWORDS: ROV; Virtual Reality; human autonomy teaming

INTRODUCTION

Subsea engineering has been rapidly developing for decades, driven largely by the escalating demand for offshore energy and resources (Casey 2020). The most widely used tool for subsea engineering is Remotely Operated Vehicle (ROV). It is vital for multiple ocean exploration purposes such as inspection, installation and maintenance (Azis et al. 2012), due to its agility, safety, and endurance. Provided the rapid expansion of the ROV market and the growing needs for subsea engineering (Li et al. 2018; WBOC 2021), there is a foreseeable shortage of ROV operators in the near future. However, current ROV control system is still at a primary level, with operators stationed on the vessels, maneuvering through joysticks and reliant on limited 2D camera view (BlueRobotics 2021; Patiris 2015). On one hand, operators need to work in uncomfortable environments, and cannot receive sufficient information for better control, such as water conditions (Xia et al. 2023). On the other hand, it requires tremendous training to master the coordination between feedback and joystick actions, which remains the ROV operator a highly specialized profession with high training barriers to broader participation (Institute 2018; Oceaneering 2022). Furthermore, the long-time subsea operations also place significant cognitive load on the ROV pilots.

To mitigate these challenges, researchers have initially turned to autonomous solutions, such as simultaneous localization and mapping (SLAM) for ROV navigation (Meireles et al. 2014;

Vargas et al. 2021), self-stabilization with adaptive nonlinear feedback controller (Tran et al. 2020), and machine learning methods (Amundsen et al. 2021). However, achieving precise underwater ROV operations solely via full autonomy remains extremely difficult due to the inherent challenges associated with underwater environments (Antonelli and Antonelli 2014; Trslic et al. 2020). Unlike terrestrial robots that can be outfitted with an array of high-quality sensors, ROVs are somewhat limited. The low visibility in the underwater environment restricted the effective visual range for cameras (Lachaud et al. 2018; Xia et al. 2022), and LiDAR is not widely equipped either. Furthermore, specific subsea tasks, like inspections, deeply rely on human insight and experiential judgment for decision-making. Although these studies contributed a lot to automated navigation, current artificial intelligent technology cannot qualify such complex decision making for dynamic trajectory planning. At the same time, recognizing these autonomy constraints, some researchers began to use mixed reality (Elor et al. 2021) and sensory augmentation technologies (Shazali 2018; Xia et al. 2023) to assist human-centered operation. These studies incorporate virtual reality and haptic devices to enhance human perception of the working environment, which increases the control precision but makes the workload and mental load even higher.

Therefore, this study proposed a new human autonomy teaming (HAT) framework by integrating autonomy algorithms, Virtual Reality (VR) and sensory augmentation methods. Human operators are responsible for autonomy allocation and decision making, while autonomous algorithms can assist in position estimation and autonomous navigation. An interactive user interface was developed in VR to enable seamless engagement with the autonomous system and facilitate dynamic switching between human and autonomous controls. The teleoperation system allowed operators to work in a more comfortable environment. Human operators could use their natural body motions for ROV control, which is verified to greatly reduce learning barriers for ROV operation. A human-subject experiment was conducted to verify the effectiveness of the system. The result indicated that with autonomy assistance and appropriate human autonomy teaming design, operators could benefit from lower workload and mental load and also keep a great performance in inspection tasks.

LITERATURE REVIEW

Autonomy for ROV Operations

ROVs are underwater devices designed for a range of tasks including inspection, exploration, and installation, maintenance and data collection for subsea engineering (Brun 2012; Patiris 2015). In terms of operational depth and payloads, ROVs can categorized into the micro class (100m, 5kg) mini-class (300m, 10kg), light work class (2000m, 100kg) and heavy work class (3000m, 300kg) (Patiris 2015). Regardless of their specific designs, standard features of ROVs include multi-axial mobility, state estimation, and data transmission via umbilical cables or additional wireless means (Song et al. 2020). Different classes of ROVs vary in functionality, capability and cost. Compared to commonly used ground robots, ROV operators are facing much more unique environmental complexities, including unpredictable water flows, reduced visibility due to light scarcity and water murkiness, radio frequency limitations, fluctuating temperatures and pressures, and potential biofouling risks (Lachaud et al. 2018; Nitonye et al. 2021; Xia et al. 2022). Additionally, they face operational threats such as umbilical cable snags, impacts, communication breakdowns, elongated control response times, and disturbances from aquatic life and electrical issues (Walker et al. 2020; Yang et al. 2020). Despite the challenges inherent in ROV operations, the control and feedback mechanisms remain in a primary level. Operators are often stationed on vessels, maneuvering the ROV through joysticks and relying solely on 2D camera visuals (NOAA 2021; Patiris 2015). This control method necessitates intensive training to establish a robust connection between the visual inputs and appropriate control responses (Oceaneering 2022). As a result, a pilot shortage exists in offshore industries due to the great entry barriers to operate the ROV.

To tackle problems related to the harsh environment of ROV workplaces and reduce the learning curve for ROV pilots, many existing efforts are made in autonomous algorithms as similarly seen in other intelligent systems (Schjølberg and Utne 2015). The basic and most common method is to enhance Kalman filter for better state estimation and trajectory control, such as the extended state-based Kalman filter (ESKF)-based model predictive control (MPC) to incorporate external disturbances and measurement noises into navigation trajectory (Long et al. 2022; Long et al. 2021). For high level autonomy and better estimation, additional data source is necessary. Some studies tried to integrate the ROV-equipped camera data for better autonomy control, such as the embedded markers and vision-based localization data system(Zaman and Mardiyanto 2021), and dual-eye vision-based docking system (Lwin et al. 2019). These methods addressed the autonomy localization and docking problem to some extent for near-shore operations. However, as introduced above, the low visibility in the deep ocean makes the cameras less reliable. In that case, more sensor data is necessary to keep high precision trajectory planning, e.g., doppler velocity log (DVL), inertial measurement unit (IMU) and short baseline acoustic system (SBL), for precisive trajectory estimation and prediction (Soylu et al. 2016), which might not be acceptable for small-scale ROVs. In addition, human knowledge and experience can be critical for some inspection and navigation planning tasks (Xia et al. 2022), which cannot be solved by current artificial intelligence system. In general, curent studies greatly addressed the problems of position estimation and simple automated navigation, but human operators can still be necessary for dynamic decision making.

Sensory Augmentation for ROV Operations

As introduced above, despite the advancement made in ROV autonomy, there is a recognition of the irreplaceable value of human operators to deal with uncertainties in the subsea environment. Currently, the complex and dynamic subsea environment, the limited human operator ability to process and react to these dynamics, and the lack of user-friendly control methods for ROV teleoperation, bring great burdens to operators. Relying solely on 2D camera view with joystick control, operators need tremendous training to build the correct feed-control loop. This can disrupt the critical feedback-control loop necessary for precise motor actions during ROV operations and lead to perceptual-motor malfunctions (Finney 2015). Therefore, in addition to the efforts on autonomy, more and more researchers tried to enhance human perception by applying sensory augmentation methods for better human control precision. In general, two kinds of sensory augmentation, visual augmentation and haptic augmentation, are used in current human-centered ROV teleoperation methods.

For visual augmentation, VR is a popular interface that simulates realistic environments, offering users a depth of spatial information (Brooks 1999; Zheng et al. 1998). When incorporated into robot teleoperation, VR can help to build a tighter integration of human and robot, for better perceptions and controls (Concannon et al. 2019; Zhou et al. 2020). This can also benefit in improving motion planning and interactions during complicated tasks demanding both human and robotic insights (Williams et al. 2019). Therefore, a great number of studies have explored the merits of applying VR in ROV teleoperations across diverse assignments, such as underwater capture tasks (Elor et al. 2021), deep ocean remote control (Martin et al. 2021) and VR device based teleoperation methods (Sapp 2023; Xia et al. 2023). These initial trials verified the effectiveness and efficiency of VR for ROV control system. Especially, it is widely believed that the greatest benefit of VR is providing semantically rich visual cues (Khadhraoui et al. 2016), which could greatly enhance human spatial awareness that is critical for complex subsea tasks (Chellali and Baizid 2011).

However, visual cue is not the only feedback human relies on for sensorimotor control. Humans usually make sense of the consequence of the initiated action multimodal sensory feedback, such as the visual, auditory, and somatosensory (tactile and proprioceptive) cues (Kirsch and Kunde 2013; Shadlen and Newsome 1996; Wood et al. 2013). The motor planning and feedback loop is broken when the perceptual ability is affected, such as the missing haptic stimulation in most existing VR-based systems (Ye et al. 2022). The importance of haptic feedback has been recognized in ground robot teleoperation studies. Recently, more and more studies have verified the effectiveness of haptic feedback for various ground robots, such as snake robots (Zhu et al. 2022), robotic arms (Zhou et al. 2023), and tower cranes (Zhu et al. 2022). As for haptic stimulation in ROV controls, there is also a lot of information that cannot be clearly transmitted via visual feedback, i.e., flow conditions. In this case, haptotactile signals can be used to enhance the human perception of motion and status of ROV. Early efforts included using one-dimensional haptic simulation (such as pressure or torsion forces) to produce the illusional proprioception and kinesthetic perception of the ROVs (Amemiya and Maeda 2009). Later, linear-oscillating actuators using asymmetric drivers are used to simulate hydrostatic pressure in remote ROV systems (Ciriello et al. 2013). Advanced status sensors, such as gyroscope sensors, are used to provide dynamic data to drive haptic actuators to simulate torque feedback (Shazali 2018). Further, in order to provide more immersive full-body level haptic feedback, haptic suit is involved to simulate the feeling of water for better understanding of flow conditions (Xia et al. 2023). Till now, human perception and control precision can be significantly improved with the advancements of visual and haptic sensory augmentation methods in ROV teleoperation methods.

Human Autonomy Teaming

In general, autonomy plays a vital role in augmenting human ability via automatic navigation, data collection and environment modeling (Mader et al. 2016; Rakha and Gorodetsky 2018) but it lacks decision-making ability, while human-centric methods enhance human perception and control precision but increase workload and mental load during long-time operation. Given the advancements of current technology, it is time to push conventional joystick control systems to a higher level of autonomy (LOA) (Skeete 2018), which requires a better human autonomy teaming (HAT) strategy (Lyons et al. 2021). HAT enables autonomy agents to work together with human operators, where complementary strengths of humans and autonomous systems are melded to enhance team performance (Lyons et al. 2021; O'Neill et al. 2022). The term "HAT" emerged in the mid-2010s, marking a shift in focus from full autonomy to collaborative autonomy. One of the strengths of HAT is its adaptability in dynamic and complex environments. Such environments often pose challenges that neither humans nor autonomous systems can address independently, i.e., it is observed enhanced performance in drone navigation when pilots collaborate with autonomous agents, leveraging the human's cognitive flexibility and the machine's computational prowess (Simpson 2021). For ROV operation, it is a common scene that operators need to deal with complex underwater environment, such as low visibility and dynamic subsea currents. HAT could be an effective method to enhance control performance as well as reduce human workload.

Several factors are deciding the efficiency of HAT system. The first factor is autonomy allocation, also called task or function allocation (Abbass 2019; Rahman et al. 2016; Roth et al. 2019). The tasks should be assigned to human or robot agents based on their capability (Abbass

2019; Rahman et al. 2016). Specifically, for ROV operation, autonomy is more precise in state estimation and navigation, while human operator is better in route plan and decision making. Besides, an effective user interface (UI) is also important. Research has demonstrated that interfaces promoting bi-directional communication between humans and autonomous agents boost team efficiency (Calhoun et al. 2018). Transparent systems that explain their reasoning can further augment this relationship (Chen et al. 2016; Felzmann et al. 2019). Thirdly, a recurring theme in HAT literature is the trust. The reliability and predictability of an autonomous system significantly influence human trust (McNeese et al. 2021). It is noted that trust calibration, ensuring neither too much nor too little trust, is paramount for optimal team performance (Schaefer et al. 2019). Finally, cognitive models play an instrumental role in HAT, simulating human cognitive processes to facilitate smooth interactions. By understanding how humans think, feel, and decide, these models allow autonomous systems to predict human behavior and adjust their actions accordingly, ensuring seamless cooperation (Demir et al. 2018). There are also studies trying to adjust UI elements by tracking human cognitive load (Zhou et al. 2023). In this study, we focused on the two most basic factor for HAT design, autonomy allocation and UI design. This study aimed to propose an HAT framework for ROV teleoperation based on automation and sensory augmentation methods. It is expected to enhance the team performance as well as reduce human workload and the carrier barriers of ROV pilots.

METHODOLOGY

System Architecture

This study aimed to propose a HAT framework for ROV teleoperation based on sensory augmentation and autonomous algorithms. As demonstrated in **Fig. 1**, the system consists of ROV module, VR digital twin module, human-centered feedback and control module, autonomy module, and UI. The sensor data collected by ROV could be transmitted to Unity via ROS # (Bischoff 2021), a web socket data transfer method, to build a realistic digital twin in VR. Compared to the general VR system, this method rebuilt not only the environment objects but also hydrodynamic features and physical interactions in the VR environment. A high-fidelity underwater hydrodynamic simulation, subsea light rendering as well as adjustable water texture and field of view (FOV) were ensured by applying the crest ocean system API (Harmonic 2022). The hydrodynamic information was used to generate full-body coverage haptic feedback, and augmented visual feedback was rendered in VR as well. Similarly, the same information was sent to the autonomy module for auto-navigation. In general, humans were responsible for decision making and target selection, while autonomy agents were used for state estimation and navigation in our design. Human operators could switch control between human mode, stable mode and auto mode based on needs, and assign navigation goals for autonomous algorithms. Finally, the control actions were sent back to ROV via ROS#.

INSERT FIG.1 HERE

For ROV module, camera and acoustic doppler current profile (ADCP) (Guerrero et al. 2012) or pressure sensors are necessary to capture the hydrodynamic features. Based on the size of ROV and task requirements, some extension functions can be integrated, such as 3D reconstruction and localization. Our previous studies have developed the pipeline to convert complex point cloud models to Unity objects and reconstruct the realistic VR scene by using machine learning (Zhou et al. 2020). This method could significantly reduce the data amount and increase the conversion speed. Besides, there are also some developed methods for GPS synchronization (Mack 2015) with VR for better localization and teamwork. These methods extended the potential of VR as a multi-sources platform for complex industry applications. This paper does not focus on 3D modeling and localization methods for ROV. Sensory augmentation, task allocation, and UI design will be mainly introduced in the following sections.

Sensory Augmentation and Haptomotor Control

The sensory augmentation and haptomotor control system was designed to provide immersive control-feedback loop for human operators. The conventional joystick control method restricted human perception of the working environment, broke the precise control-feedback loop, and increased career barriers. Provided with multi-sensory feedback, human operators could gain more immersive environmental information, and interact with their most natural body motions as in the real world, which could significantly reduce the learning barrier. Previous studies have verified its effectiveness in navigation and stabilization tasks (Xia et al. 2023; Xia et al. 2023). In this research, we adjusted the system to fit the features of the VR system and human-autonomy interaction needs. As shown in **Fig. 2**, two kinds of feedback were generated on human-equipped devices, including visual augmentation on HTC VIVE headset (VIVE 2022) and haptic feelings on bHaptics TactSuit X40 (bHaptics 2022). Operators could use their natural body actions to react to these sensory cues. A series of functional control was designed on VR controllers, which was detail introduced in the User Interface section. Packaged human control signals were then sent to real ROV and converted to thruster-based control signals.

INSERT FIG.2 HERE

For visual augmentation, this system provided a vector field with arrayed arrows indicating the flow speed and directions. Each arrow pointed to the flow direction in that area, and the length of the arrow represented the flow speed, i.e., a shorter arrow represented a smaller flow speed. On the other hand, haptic feedback was designed to simulate the feeling of water flushing human bodies. To convert single sensor data to full-body covered haptic feelings with 40 units on the haptic suit, a particle flow and virtual sensor system was designed to simulate the hydrodynamic forces in the VR digital twin. This data augmentation process was necessary to enhance the spatially and temporally sparse sensor data to high refresh rate and dense simulation data. Specifically, a particle flow was generated based on the received sensor data from ROV. The dense particle flow with hundreds of particles could physically interact with the virtual ROV in realistic way. A total of 24 virtual sensors were distributed around the ROV model, which received the collision data from the particle flow. These virtual sensors were mapped with 40 real units on the haptic suit, and therefore a full-body coverage body feeling could be generated.

At the same time, operators could use their natural body motions in reaction to the occurring events, such as strong turbulence, based on sensory feelings. This kind of natural reaction does not require high-level mental processing. Specifically, the ROV control parameters, such as motion and orientation control signals, were driven by human body motions, including head rotation and body postures. The local rotation of the human body read from the headset was sent to control the pitch, roll and yaw of the ROV. Besides, human body postures were designed to control the ROV's horizontal motion, such as that the ROV would move forward when the human operator leaned forward. For those unachievable actions for humans, such as raising up and sinking down vertically, the control signals were read from the VR controller trackpad. To be noted, the position-based control signals cannot be directly used in thruster-based ROV control. After data from Unity was received through ROS#, a data conversion process was necessary in ROS. Here as an example, we used a mini-class ROV, BlueROV2 (BlueRobotics 2021), which was equipped with six thrusters. For motion control signals, a scaled motion control signal from Unity, $\boldsymbol{P_v} = [\boldsymbol{v_{rov.x}}, \boldsymbol{v_{rov.y}}, \boldsymbol{v_{rov.z}}]^{\boldsymbol{T}}$, can be directly converted to thruster control signals via **Eq. 1** and **Eq. 2**, where $\boldsymbol{v_{rov.x}}$, $\boldsymbol{v_{rov.y}}$, and $\boldsymbol{v_{rov.z}}$ are control signals in Unity coordinate, $\boldsymbol{P_v}$ is the control signal from the operator in Unity, $\boldsymbol{P_{v.rov}}$ is control signals for ROV, ${}^{\boldsymbol{ROS}}_{\boldsymbol{Unity}}\boldsymbol{T}$ is the transformation matrix from Unity to ROS, and ${}^{\boldsymbol{ROV}}_{\boldsymbol{ROS}}\boldsymbol{T}$ is the transformation matrix from ROS to ROV.

$$\begin{bmatrix} P_{v.rov} \\ 1 \end{bmatrix} = {}^{ROS}_{Unity}T \; {}^{ROV}_{ROS}T \begin{bmatrix} P_v \\ 1 \end{bmatrix} \qquad \textbf{Eq. 1}$$

$$con = \begin{bmatrix} -P_{v.rov}(1) + P_{v.rov}(2) \\ -P_{v.rov}(1) - P_{v.rov}(2) \\ P_{v.rov}(1) - P_{v.rov}(2) \\ P_{v.rov}(1) + P_{v.rov}(2) \\ P_{v.rov}(3) \\ P_{v.rov}(3) \end{bmatrix} \qquad \textbf{Eq. 2}$$

As for rotation control, similarly, after converting rotation data $\boldsymbol{P_{\theta,rov}}$ in Unity coordinate to correct format $\boldsymbol{P_{\theta,rov}}$ in the ROS coordinate illustrated in **Eq. 3**, a PD controller was then used to adjust ROV posture smoothly by comparing ROV current orientation with target human head orientation.

$$\begin{bmatrix} \boldsymbol{P_{\theta,rov}} \\ \boldsymbol{1} \end{bmatrix} = {}^{\boldsymbol{ROS}}_{\boldsymbol{Unity}}\boldsymbol{T} \begin{bmatrix} \boldsymbol{P_\theta} \\ \boldsymbol{1} \end{bmatrix} \qquad \textbf{Eq. 3}$$

Autonomy Control

Based on the capability and size of ROV, many kinds of autonomy methods, such as PID controller, SLAM and machine learning methods, can be applied. In this study, we only focused on inspection used mini-class ROV. The sensors equipped and computation ability cannot support high-cost methods. Therefore, a basic Kalman Filter and PID controller was used for the auto navigation system.

There are two control modes for autonomy, stable mode and auto mode. **Fig.3** illustrated the system scheme for Kalman Filter PID controller, where PID controller was used for ROV motion control and Kalman Filter was used to eliminate measurement error for precise state estimation. After the target position was assigned by human operators, the target position and ROV estimated state were sent to PID controller to generate the control signals towards the target in VR. The generated control signals, IMU sensor data, and ADCP flow data were then sent to Kalman Filter. The Kalman Filter would calibrate the predicted data and sensor data to filter the noise and estimate current state. The updated state data was then sent back to PID controller again for the next frame control signal calculation. Specifically, parameters were set as $\boldsymbol{K_p = 1.55}$, $\boldsymbol{K_i = 0.05}$, and $\boldsymbol{K_d = 0.74}$ in current design. The PID parameters could be adjusted to optimized values by the particle swarm optimization (PSO) algorithm (Marini and Walczak 2015) based on the real application needs. For stable mode, the target position was always set as the current state. As mentioned above, the position-based control signals should be sent to ROV via ROS# and converted to thruster-based control signals.

INSERT FIG.3 HERE

User Interface

To seamlessly integrate human and robot agents, a better user interface design is necessary. Currently, there are two main challenges for VR User interface design. Firstly, it should be decided how to switch control between humans and autonomy agents. Usually, it can be human-decided or autonomy-decided, corresponding to different levels of autonomy. Secondly, ROV is needed to be operated in a 3D space, which required a special design for target assignment. Conventional VR UI design could only deal with 2D plane operation, which cannot fit the features of ROV teleoperation. Additionally, sensory augmentation and haptomotor-driven control system was designed to reduce human mental load during operation and learning barriers. The UI design should not be too complex to require too much training process.

Given the human-centered control system we used, a human-decided switch control design was used in this system. All the functional control was allocated on VR controllers. For better understanding, the left-hand controller was used for human mode control and the right-hand controller was designed for auto mode-related functions. As listed in Table 1, the left controller trigger, grip and trackpad were designed for human control, entering the stable mode, and up & down control respectively. On the other hand, the right-hand controller was mainly designed for target selection for autonomy navigation, specifically including confirm current selection, cancel current selection and up & down selection for 3D space navigation.

INSERT TABLE 1 HERE

To enable 3D navigation, we further developed the traditional mini-map UI for depth selection. As shown in **Fig. 4**, operators could first select the target position in the *xz* plane (**Fig. 4a**) in the stable mode. After pushing the right-controller trigger button for confirmation, the mini-map would rotate and the system entered the depth selection phase (**Fig. 4b**). Operators could further use the trackpad to adjust the depth and push the trigger button for confirmation (**Fig. 4c**). Then the system would enter auto mode and the ROV would automatedly navigate to the target point. Even in the auto mode, the orientation of ROV was synchronized with human operators. This aimed to provide operators with immersive spatial information for their decision-making. For example, operators might decide to change the target when observing accidents or strong turbulences. The system would return to stable mode when the ROV arrived at the target position.

INSERT FIG.4 HERE

Although the mini-map system could provide depth selection, there could still be problems for novices. For those who were familiar with the VR mini-map system, they could easily adapt. But for novices, especially for those who were weak in spatial ability and recognition (McGee 1979), tremendous training was necessary to build the connection between the mini-map and the real-world directions. In order to reduce the learning barriers for novices and take advantage of VR, we also developed an egocentric target selection method (Masnadi et al. 2022), with which human operators could behave as in the real world without too much mental process. As shown in **Fig. 5**, operators could use their right-hand controller to point to the target in the *xz* plane. Then similarly, enter the depth selection mode and adjust depth with trackpad on controller. There were three lines located at 5m, 10m, and 30m for reference of distance. In general, mini-map system provided a global view with more specific state estimation information, while egocentric system was easier to access with lower training barriers.

INSERT FIG.5 HERE

Human Subject Experiment Design

In order to verify the effectiveness of this task allocation method and HAT system, a human subject experiment was conducted with three conditions, fully autonomy condition, human control condition, and human autonomy condition. As shown in **Fig. 6**, participants were required to finish a subsea pipeline inspection task, starting from a start point, planning the route based on flow conditions, and returning to the start point to end the experiment. In total, there are three different kinds of flow settings in the experiment. Each participant would start with a random flow setting and need to plan their route appropriately for the shortest inspection time, based on the sensory information they received. For autonomy condition, current ROV autonomy system could only follow the predefined route without the ability to dynamically plan the route based on environmental conditions.

INSERT FIG.6 HERE

Before the experiment started, each participant would sign the consent form and begin with a training session to familiarize themselves with the system, including VR and haptic device, control functions, as well as the procedure of the experiment. After that, human subjects were asked to finish two conditions, human control condition and human autonomy condition. At the same time, the fully autonomy condition experiment would be conducted with the same inspection task. The system recorded the ROV's trajectories as well as the time to finish the inspection task. As said above, a random flow setting would be selected at the beginning of each trial. This is aimed to eliminate the learning effect. The three flow settings had been calibrated to have the similar shortest finishing time. The distribution of three flow settings and the best navigation route were plotted in **Fig. 7**.

INSERT FIG.7 HERE

After each experiment trial, participants were asked to finish two surveys, including a NASA-TLX survey (Hart 2006) for the workload level estimate, and a user experience survey to measure the perceived benefits of the control system. The user experience survey asked about participants' overall preference, fatigue, concentration, feeling of system complexity, and confidence in decision making. Finally, a demographic survey was conducted after the experiment, to collect information about gender, age, college majors, and experience with VR. All results were analyzed with the Wilcoxon tests as preliminary analysis found that data did not satisfy the normality assumption (Cuzick 1985).

RESULT

Participants

In total, 28 college students were recruited for the human subject experiment. The demographic information was shown in **Table 2**. Participants were aged from 20 years old to 32 years old (mean = 26.43, std = 3.07), including 17 males and 11 females respectively. As for college majors, 21 participants were from engineering majors (75%) such as Civil Engineering and Computer Science, and 7 participants (25%) were recruited from non-engineering majors such as Geography and Biology. Despite the difference in gender, age and educational background, all participants were trained to be familiar with VR devices and control system to finish the experiment.

INSERT TABLE 2 HERE

Experiment Performance

Firstly, we recorded the ROV's trajectory under three conditions, with a data capture rate of 60Hz. These distinct conditions are illustrated in **Fig. 8**, where each group exhibits different trajectory patterns. For the autonomy condition (**Fig. 8a**), it was observed autonomous algorithms consistently produced ROV trajectories characterized by remarkable stability. Consequently, the trajectories in this condition appeared more concentrated and shorter when compared to the other conditions. However, it's important to note that these autonomous systems lacked the capability to dynamically adjust their route plans in response to varying flow conditions. Conversely, for the human condition (**Fig. 8b**), the trajectories were more scattered, which might be caused by the limitations of human operators in terms of spatial recognition and precise control. However, human operators exhibited the ability to adaptively modify route plans in accordance with changing flow conditions. This kind of dynamic decision-making capability proves to be critical in real ROV operations, particularly when navigating complex subsea environments characterized by dynamic currents and unforeseen incidents. When the autonomy system was integrated with human control (**Fig .8c**), it was observed that the strengths of both approaches were retained, leading to enhanced performance. The trajectory pattern of this condition exhibited a degree of concentration when compared to human control alone. Besides, this approach effectively leveraged the decision-making capabilities of human operators to adapt route plans based on dynamic flow conditions, further enhancing the ROV's performance.

INSERT FIG.8 HERE

The analysis of task finishing time also verified the effectiveness of human-autonomy teaming approach. **Fig. 9** showed the average task finishing time of three conditions, with 210.12s for autonomy condition, 180.09s for human condition, and 147.86s for human autonomy condition. The Wilcoxon test showed a significant difference in task finishing time between autonomy condition and human autonomy condition ($p < 0.0001$), between the human condition and human autonomy condition ($p < 0.0001$) and between the autonomy condition and human condition ($p = 0.019$). In general, autonomy system was more capable of precise state estimation and position control if appropriate sensor data was provided, but it lacked of intelligence to deal with dynamic events. On the contrary, human operators were excellent in planning based on their previous knowledge and experience. This result further proved that an appropriate human autonomy teaming design could significantly enhance group performance compared to relying on humans or autonomy only, by integrating the precise control ability of autonomous algorithms and the dynamic decision making ability of human operators.

INSERT FIG.9 HERE

More interestingly, it was found that participants occasionally intervened in the autonomy process within the HAT framework under some circumstances. To delve deeper into the motivation behind this behavior and to inform future HAT system design, we highlighted the trajectory data by labeling the human control process, as shown in **Fig 10**. In general, it is observed that operators might switch control under two conditions. Firstly, operators might take control when they were close enough to see the targets. While the precise rationale behind this behavior remains unclear, we assumed the possibility of psychological factors influencing their decisions. Besides, it was noted that a number of operators chose to take when navigating around hilly terrain, opting for a direct, upward over-the-hill trajectory to reach the next target, while the autonomy system was designed to follow a circumferential route around the hills. Actually, in the experimental setup, no significant discrepancy in terms of total distance covered or time taken was observed between these two routes. The operators' choice to intervene, perhaps rooted in their intuition that a direct path should be swifter, highlighted a crucial aspect of autonomous systems: the necessity for operators to comprehend the intentions of the ROV. As introduced earlier, information transparency could be important within the HAT design, as it sustains human comprehension and trust in autonomous agents. The insufficient transparency in our current design suggests further improvement and investigation in subsequent studies.

INSERT FIG.10 HERE

Survey Result

To further investigate how HAT method influenced human perception and work experience, participants were asked to finish a NASA TLX survey and answer user experience questions, including the preference of the control method (preference), overall fatigue level during the whole operation process (fatigue), perceived concentration on the tasks (concentration), perceived complexity of the control methods (complexity), and confidence in decision making and route planning (confidence). Participants were asked to finish the surveys after each experiment trial. All the questions were ranked from 0 to 10.

As shown in **Fig. 11**, participants showed an overall lower perceived workload in the sum value of NASA TLX survey ($p < 0.0001$) in the HAT condition compared to human control only. Similarly, participants also showed higher preference ($p < 0.0001$), lower fatigue level ($p < 0.0001$), lower perceived complexity ($p = 0.0009$), and higher confidence in control ($p < 0.0001$) in the HAT condition. There was no significant difference in the perceived concentration ($p = 0.89$) during the operation. The fatigue and high mental load have always been critical problems for ROV pilots, especially for long-term navigation and inspection. Our survey findings showed the potential of a well-designed HAT system in mitigating these challenges. Specifically, it becomes evident that an appropriately designed HAT system can effectively reduce human fatigue and perceived workload, and simplify the control interface. The reason might be that a competent HAT system design can allocate a portion of the human workload, consequently leading to a substantial reduction in human fatigue. Besides, additional information provided by the autonomy system could assist in the human decision making process, which enhanced their confidence when planning the route in the experiment.

INSERT FIG.11 HERE

DISCUSSION

This research tried to design a HAT strategy for ROV teleoperation based on sensory augmentation technology and autonomy technology. In our design, the autonomy system was responsible for position estimation and trajectory control and human operators concentrated on route plan and dynamic decision making. A human subject experiment was conducted to compare the performance difference between human control only, autonomy control only and human autonomy system in subsea pipeline inspection tasks. The results preliminary revealed the effectiveness of HAT method in reducing human workload, fatigue level, perceived difficulty in control and enhancing human confidence in making decisions. However, there are still some further research problems to be resolved.

First of all, it's important to note that our study exclusively employed a basic Kalman filter and PID controller for the design of the mini-class ROV autonomy system. In contrast, larger-scale ROVs equipped with high-fidelity sensors like sonar and underwater LiDAR could offer an opportunity to implement more advanced technologies, including machine learning (ML), for more precise trajectory control. Furthermore, additional functionalities like collision avoidance and scenario reconstruction could be integrated if the computational capacity of larger ROVs allows.

The utilization of these advanced technologies holds the potential to significantly enhance the synergy between human operators and ROVs, consequently augmenting the level of automation (LOA) and its impact on human operators. On the other hand, as discussed in the result section, human operators might opt to take control if it is hard for them to comprehend the intentions of the ROV. This study did not delve extensively into the domain of system transparency. Our preliminary findings suggested that a transparent system capable of explaining its decision-making processes might further enhance this human-ROV relationship. Subsequent research endeavors could prioritize investigating how transparency influences human decision-making within the HAT system.

CONCLUSION

In this study, we designed and evaluated a human autonomous teaming (HAT) system for mini-class remotely operated vehicles (ROVs) used in teleoperation scenarios. The system utilized a combination of Kalman filters and PID controllers to enhance the capabilities of autonomous systems while providing an intuitive user interface (UI) with a mini-map and an egocentric target selection system to facilitate human interaction. This system enabled human operators with the ability to dynamically assign complex decision-making and route planning objectives while delegating the responsibility for state estimation and trajectory control to the ROV. A human-subject experiment was conducted to evaluate the effectiveness of this system, including three conditions: human control only, autonomous control only, and the HAT condition. The experiment focused on a pipeline inspection task with different subsea current settings. The results obtained through the combined analysis clearly demonstrated the superior performance of participants operating under HAT conditions. Subjects not only demonstrated excellent task performance but also provided favorable feedback in the post-task survey. Specifically, participants reported significantly lower perceived workload, denoting reduced cognitive and physical burdens. Higher confidence in decision making during task execution was observed, affirming the value of the HAT system's seamless synergy between human expertise and autonomous capabilities. Notably, participants reported lower levels of fatigue, which has long been a challenge in ROV teleoperation. Moreover, perceived operation complexity was substantially reduced, enhancing the overall user experience.

In summary, this study preliminarily proved the transformative potential of the HAT system in mini-class ROV teleoperation. The innovative integration of human decision-making with autonomous functionality not only enhanced task performance but also addressed critical concerns related to operator fatigue and task complexity. This research was expected to encourage more studies further exploring the application of HAT systems in similar operational contexts. In addition, this study also suggested further researched topics based on experiment results, including better autonomy system design involving more high-fidelity sensor data and transparency design. Future investigations may also delve deeper into the system's adaptability and scalability in various real-world scenarios, further solidifying its significance in the domain of ROV teleoperation.

DATA AVAILABILITY

All data, models, or code generated or used during the study are available from the corresponding author by request.

ACKNOWLEDGEMENTS

This material is supported by the National Science Foundation (NSF) under grant 2128895. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not reflect the views of the NSF.

REFERENCE

Abbass, H. A. (2019). "Social integration of artificial intelligence: functions, automation allocation logic and human-autonomy trust." *Cognitive Computation*, 11(2), 159-171.

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), 1-8.

Amundsen, H. B., Caharija, W., and Pettersen, K. Y. (2021). "Autonomous ROV inspections of aquaculture net pens using DVL." *IEEE Journal of Oceanic Engineering*, 47(1), 1-19.

Antonelli, G., and Antonelli, G. (2014). *Underwater robots*, Springer.

Azis, F., Aras, M., Rashid, M., Othman, M., and Abdullah, S. (2012). "Problem identification for underwater remotely operated vehicle (ROV): A case study." *Procedia Engineering*, 41, 554-560.

bHaptics (2022). "TactSuit X40." <https://www.bhaptics.com/tactsuit/tactsuit-x40>. (July 8th, 2022).

Bischoff, M. (2021). "ros-sharp." <https://github.com/siemens/ros-sharp>. (May 9th, 2023).

BlueRobotics (2021). "BlueROV2 Operation." <https://bluerobotics.com/learn/bluerov2-operation/>. (December 7th, 2021).

Brooks, F. P. (1999). "What's real about virtual reality?" *IEEE Computer graphics and applications*, 19(6), 16-27.

Brun, L. (2012). "ROV/AUV trends: market and technology." *Marine Technology Reporter*, 5(7), 48-51.

Calhoun, G. L., Ruff, H. A., Behymer, K. J., and Frost, E. M. (2018). "Human-autonomy teaming interface design considerations for multi-unmanned vehicle control." *Theoretical issues in ergonomics science*, 19(3), 321-352.

Casey, J. (2020). "Drawing the line: could the subsea industry turn away from oil and gas." <https://www.offshore-technology.com/features/drawing-the-line-could-the-subsea-industry-turn-away-from-oil-and-gas/>. (May 4th, 2023).

Chellali, R., and Baizid, K. "What maps and what displays for remote situation awareness and rov localization?" *Proc., Human Interface and the Management of Information. Interacting with Information: Symposium on Human Interface 2011, Held as Part of HCI International 2011, Orlando, FL, USA, July 9-14, 2011, Proceedings, Part II*, Springer, 364-372.

Chen, J. Y., Barnes, M. J., Selkowitz, A. R., Stowers, K., Lakhmani, S. G., and Kasdaglis, N. "Human-autonomy teaming and agent transparency." *Proc., Companion Publication of the 21st International Conference on Intelligent User Interfaces*, 28-31.

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.

Demir, M., Cooke, N. J., and Amazeen, P. G. (2018). "A conceptual model of team dynamical behaviors and performance in human-autonomy teaming." *Cognitive Systems Research*, 52, 497-507.

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.

Felzmann, H., Fosch-Villaronga, E., Lutz, C., and Tamo-Larrieux, A. (2019). "Robots and transparency: The multiple dimensions of transparency in the context of robot technologies." *IEEE Robotics & Automation Magazine*, 26(2), 71-78.

Finney, G. R. (2015). "Perceptual-motor dysfunction." *Continuum: Lifelong Learning in Neurology*, 21(3), 678-689.

Guerrero, M., Rüther, N., and Szupiany, R. (2012). "Laboratory validation of acoustic Doppler current profiler (ADCP) techniques for suspended sediment investigations." *Flow Measurement and Instrumentation*, 23(1), 40-48.

Harmonic, W. (2022). "Crest Ocean System HDRP." <https://assetstore.unity.com/packages/tools/particles-effects/crest-ocean-system-hdrp-164158#description>. (July 5th, 2022).

Hart, S. G. "NASA-task load index (NASA-TLX); 20 years later." *Proc., Proceedings of the human factors and ergonomics society annual meeting*, Sage publications Sage CA: Los Angeles, CA, 904-908.

Institute, I. D. (2018). "ROV Pilots and Technicians." <https://www.idicharleston.edu/rov-pilots-technicians/>. (May 5th, 2023).

Khadhraoui, A., Beji, L., Otmane, S., and Abichou, A. (2016). "Stabilizing control and human scale simulation of a submarine ROV navigation." *Ocean Engineering*, 114, 66-78.

Kirsch, W., and Kunde, W. (2013). "Moving further moves things further away in visual perception: Position-based movement planning affects distance judgments." *Experimental Brain Research*, 226(3), 431-440.

Lachaud, E., Monbeig, Y., Nolleau, P., Hardy, A., Thompson, M., and Lardeux, M. "Opportunities and Challenges of Remote Operating a ROV Embarked on a USV." *Proc., Offshore Technology Conference*, OnePetro.

Li, B., Moridian, B., and Mahmoudian, N. "Autonomous Oil Spill Detection: Mission Planning for ASVs and AUVs with Static Recharging." *Proc., OCEANS 2018 MTS/IEEE Charleston*, IEEE, 1-5.

Long, C., Hu, M., Qin, X., and Bian, Y. (2022). "Hierarchical trajectory tracking control for ROVs subject to disturbances and parametric uncertainties." *Ocean Engineering*, 266, 112733.

Long, C., Qin, X., Bian, Y., and Hu, M. (2021). "Trajectory tracking control of ROVs considering external disturbances and measurement noises using ESKF-based MPC." *Ocean Engineering*, 241, 109991.

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.

Lyons, J. B., Sycara, K., Lewis, M., and Capiola, A. (2021). "Human–autonomy teaming: Definitions, debates, and directions." *Frontiers in Psychology*, 12, 589585.

Mack, E. (2015). "Improved GPS could untether VR and revolutionize geolocation." <https://newatlas.com/super-accurate-gps/37422/>. (August 25th, 2023).

Mader, D., Blaskow, R., Westfeld, P., and Weller, C. (2016). "POTENTIAL OF UAV-BASED LASER SCANNER AND MULTISPECTRAL CAMERA DATA IN BUILDING INSPECTION." *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 41.

Marini, F., and Walczak, B. (2015). "Particle swarm optimization (PSO). A tutorial." *Chemometrics and Intelligent Laboratory Systems*, 149, 153-165.

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.

Masnadi, S., Pfeil, K., Sera-Josef, J.-V. T., and LaViola, J. "Effects of field of view on egocentric distance perception in virtual reality." *Proc., Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 1-10.

McGee, M. G. (1979). "Human spatial abilities: psychometric studies and environmental, genetic, hormonal, and neurological influences." *Psychological bulletin*, 86(5), 889.

McNeese, N. J., Demir, M., Chiou, E. K., and Cooke, N. J. (2021). "Trust and team performance in human–autonomy teaming." *International Journal of Electronic Commerce*, 25(1), 51-72.

Meireles, M., Lourenço, R., Dias, A., Almeida, J. M., Silva, H., and Martins, A. "Real time visual SLAM for underwater robotic inspection." *Proc., 2014 Oceans-St. John's*, IEEE, 1-5.

Nitonye, S., Adumene, S., Orji, C. U., and Effiong Udo, A. (2021). "Operational failure assessment of Remotely Operated Vehicle (ROV) in harsh offshore environments." *Pomorstvo*, 35(2), 275-286.

NOAA (2021). "What is an ROV?", <https://oceanexplorer.noaa.gov/facts/rov.html>. (December 3rd, 2021).

O'Neill, T., McNeese, N., Barron, A., and Schelble, B. (2022). "Human–autonomy teaming: A review and analysis of the empirical literature." *Human factors*, 64(5), 904-938.

Oceaneering (2022). "ROV Personnel and Training." (October 26th, 2022).

Patiris, I. (2015). "ROV, Remote Operated Vehicle." <https://www.theseus.fi/bitstream/handle/10024/86911/Ioannis_Patiris.pdf?sequence=1>. (May 5th, 2023).

Rahman, S. M., Liao, Z., Jiang, L., and Wang, Y. "A regret-based autonomy allocation scheme for human-robot shared vision systems in collaborative assembly in manufacturing." *Proc., 2016 IEEE International Conference on Automation Science and Engineering (CASE)*, IEEE, 897-902.

Rakha, T., and Gorodetsky, A. (2018). "Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones." *Automation in Construction*, 93, 252-264.

Roth, E. M., Sushereba, C., Militello, L. G., Diiulio, J., and Ernst, K. (2019). "Function allocation considerations in the era of human autonomy teaming." *Journal of Cognitive Engineering and Decision Making*, 13(4), 199-220.

Sapp, C. "Enhanced ROV Performance Using AR/VR HUDs." *Proc., Offshore Technology Conference*, OTC, D031S041R008.

Schaefer, K. E., Hill, S. G., and Jentsch, F. G. "Trust in human-autonomy teaming: A review of trust research from the us army research laboratory robotics collaborative technology alliance." *Proc., Advances in Human Factors in Robots and Unmanned Systems: Proceedings of the AHFE 2018 International Conference on Human Factors in Robots and*

Unmanned Systems, July 21-25, 2018, Loews Sapphire Falls Resort at Universal Studios, Orlando, Florida, USA 9, Springer, 102-114.

Schjølberg, I., and Utne, I. B. (2015). "Towards autonomy in ROV operations." *IFAC-PapersOnLine*, 48(2), 183-188.

Shadlen, M. N., and Newsome, W. T. (1996). "Motion perception: seeing and deciding." *Proceedings of the national academy of sciences*, 93(2), 628-633.

Shazali, S. M. "Development of handheld haptics device for driving system of unmanned underwater vehicles." *Proc., MATEC Web of Conferences*, EDP Sciences, 06033.

Simpson, T. "Real-time drone surveillance system for violent crowd behavior unmanned aircraft system (uas)–human autonomy teaming (hat)." *Proc., 2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, IEEE, 1-9.

Skeete, J.-P. (2018). "Level 5 autonomy: The new face of disruption in road transport." *Technological Forecasting and Social Change*, 134, 22-34.

Song, Z., Marburg, A., and Manalang, D. (2020). "Resident Subsea Robotic Systems: A Review." *Marine Technology Society Journal*, 54(5), 21-31.

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.

Tran, N.-H., Le, M.-C., Ton, T.-P., and Tran, T.-P. "ROV Stabilization Using an Adaptive Nonlinear Feedback Controller." *Proc., International Conference on Green Technology and Sustainable Development*, Springer, 144-155.

Trslic, P., Rossi, M., Robinson, L., O'Donnel, C. W., Weir, A., Coleman, J., Riordan, J., Omerdic, E., Dooly, G., and Toal, D. (2020). "Vision based autonomous docking for work class ROVs." *Ocean Engineering*, 196, 106840.

Vargas, E., Scona, R., Willners, J. S., Luczynski, T., Cao, Y., Wang, S., and Petillot, Y. R. "Robust Underwater Visual SLAM Fusing Acoustic Sensing." *Proc., 2021 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, 2140-2146.

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).

Walker, K. L., Stokes, A. A., Kiprakis, A., and Giorgio-Serchi, F. "Impact of thruster dynamics on the feasibility of ROV station keeping in waves." *Proc., Global Oceans 2020: Singapore–US Gulf Coast*, IEEE, 1-7.

WBOC (2021). "Underwater ROV Market Size is expected to grow at a CAGR of 8.5% During 2021-2026 with Top Countries Data." <https://www.wboc.com/story/44099670/underwater-rov-market-size-is-expected-to-grow-at-a-cagr-of-85-during-2021-2026-with-top-countries-data>.

Williams, T., Szafir, D., Chakraborti, T., and Phillips, E. "Virtual, augmented, and mixed reality for human-robot interaction (vam-hri)." *Proc., 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, IEEE, 671-672.

Wood, G., Vine, S. J., and Wilson, M. R. (2013). "The impact of visual illusions on perception, action planning, and motor performance." *Attention, Perception, & Psychophysics*, 75(5), 830-834.

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, 1-12.

Xia, P., Xu, F., Song, Z., Li, S., and Du, J. (2023). "Sensory augmentation for subsea robot teleoperation." *Computers in Industry*, 145, 103836.

Xia, P., Xu, F., Zhou, T., and Du, J. (2022). "Benchmarking human versus robot performance in emergency structural inspection." *Journal of Construction Engineering and Management*, 148(8), 04022070.

Xia, P., You, H., and Du, J. (2023). "Visual-haptic feedback for ROV subsea navigation control." *Automation in Construction*, 154, 104987.

Xia, P., You, H., Ye, Y., and Du, J. (2023). "ROV teleoperation via human body motion mapping: Design and experiment." *Computers in Industry*, 150, 103959.

Yang, X., Utne, I. B., Sandøy, S. S., Ramos, M. A., and Rokseth, B. (2020). "A systems-theoretic approach to hazard identification of marine systems with dynamic autonomy." *Ocean Engineering*, 217, 107930.

Ye, Y., Shi, Y., Lee, Y., Burks, G., Srinivasan, D., and Du, J. "Exoskeleton training through haptic sensation transfer in immersive virtual environment." *Proc., Construction Research Congress 2022*, 560-569.

Zaman, M. Q., and Mardiyanto, R. (2021). "Development of marker detection method for estimating angle and distance of underwater remotely operated vehicle to buoyant boat." *International Journal of Advances in Intelligent Informatics*, 7(3), 249-267.

Zheng, J., Chan, K., and Gibson, I. (1998). "Virtual reality." *Ieee Potentials*, 17(2), 20-23.

Zhou, T., Xia, P., Ye, Y., and Du, E. (2023). "Embodied Robot Teleoperation based on High-Fidelity Visual-Haptic Simulator: Pipe Fitting Example." *Journal of Construction Engineering and Management*.

Zhou, T., Xia, P., Zhu, Q., and Du, J. (2023). "Cognition-driven navigation assistive system for emergency indoor wayfinding (CogDNA): proof of concept and evidence." *Safety science*, 162, 106100.

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.

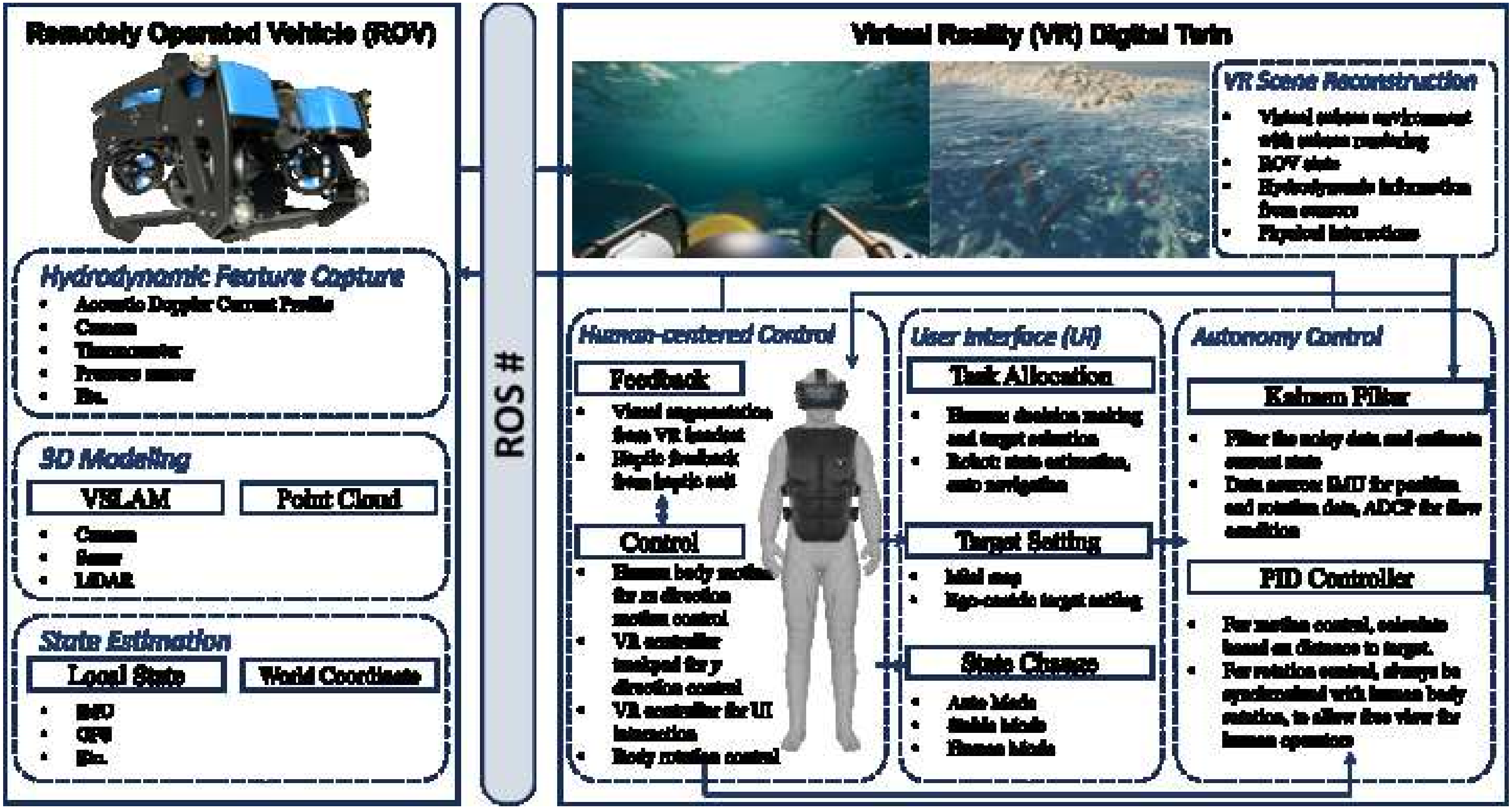
Table 1. Functional control on VR controller

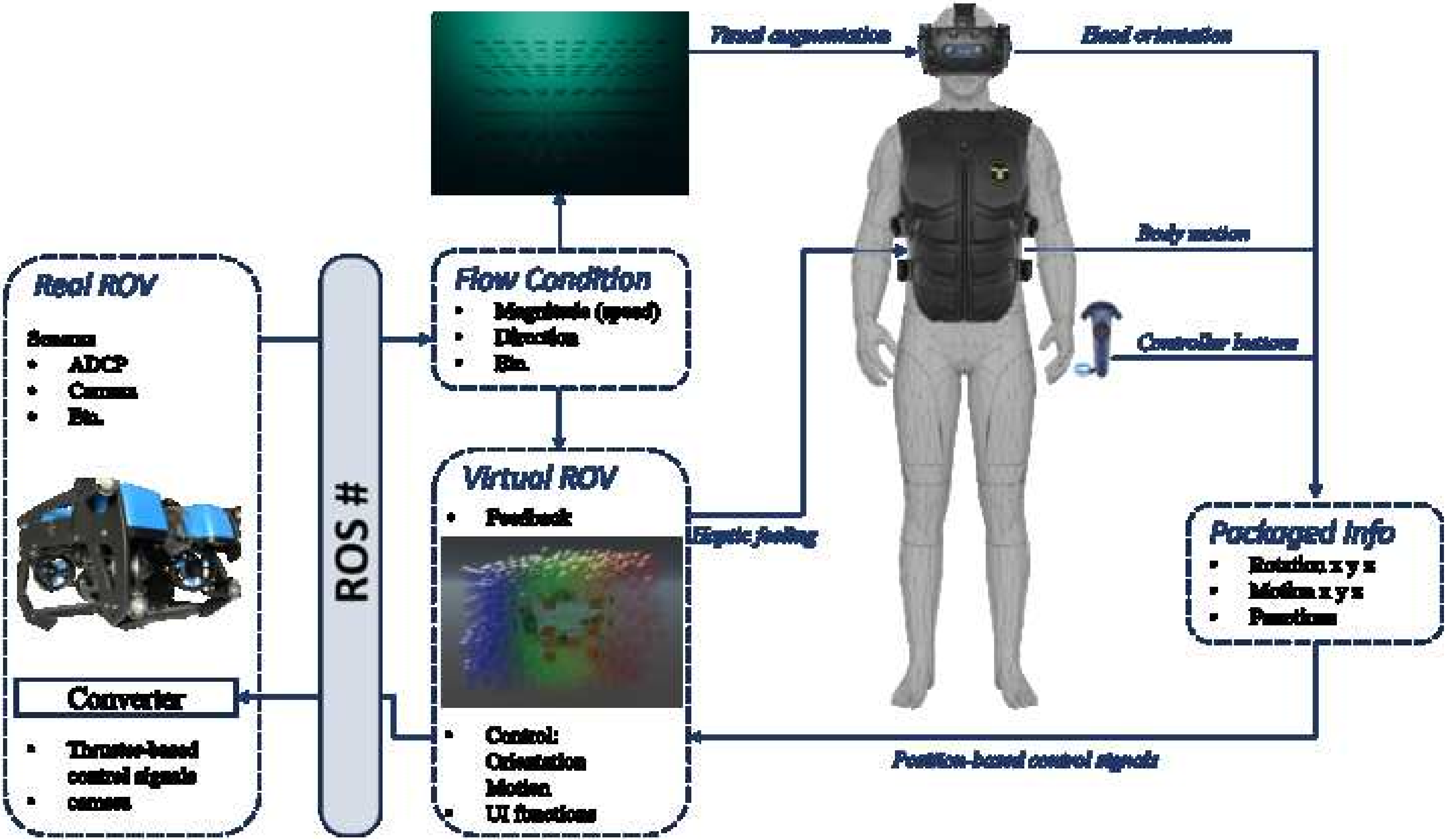
Controller	Button	Function
Left-Hand	Trigger	Hold for human mode
	Grip	Enter stable mode
	Trackpad	UP & down control for human mode
Right-Hand	Trigger	Confirm for selection
	Grip	Cancel current target
	Trackpad	Up & down selection for target position

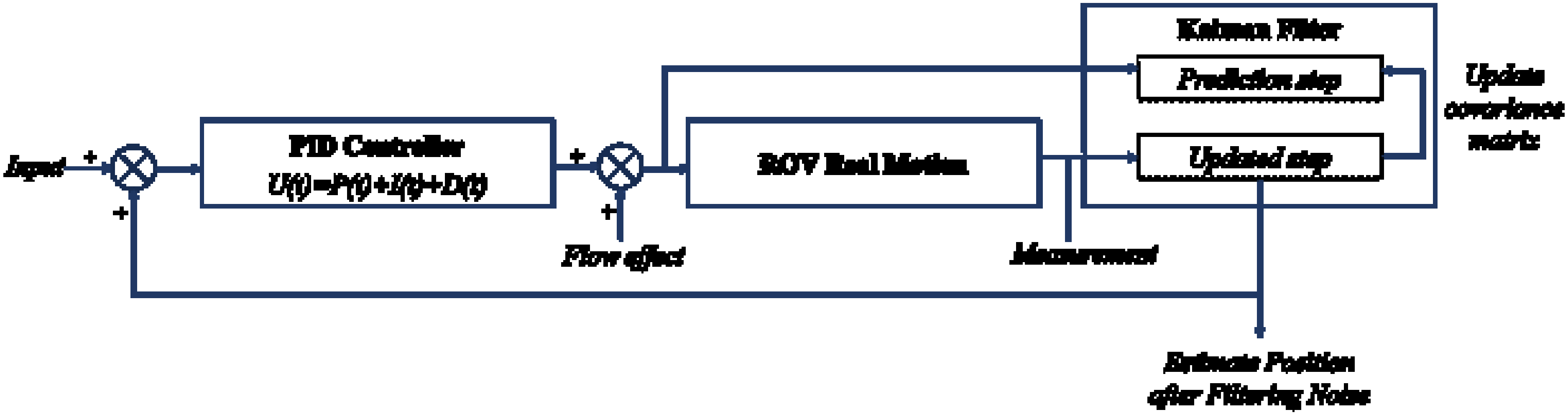
Table 2. Background information of participants (n=30)

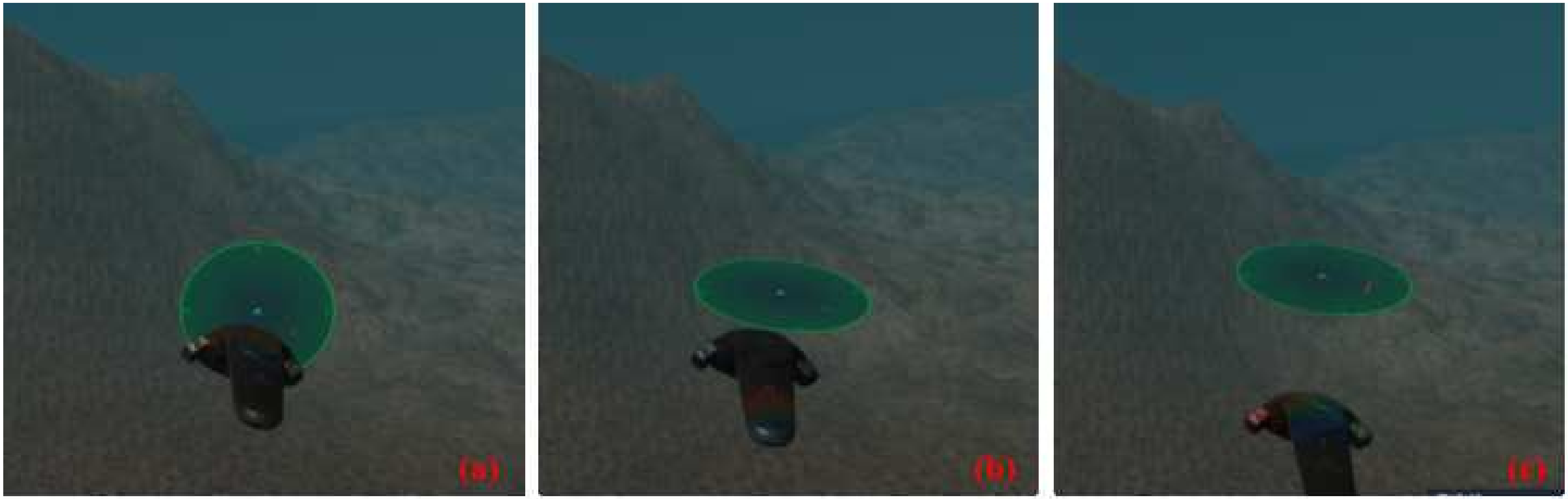
Category	Item	Number	Percentage
Gender	Male	17	60.71%
	Female	11	39.29%
Age	20 to 25	10	35.71%
	26 to 30	14	50.00%
	Above 30	4	14.29%
College Major	Engineering	21	50.00%
	Non-Engineering	7	25.00%

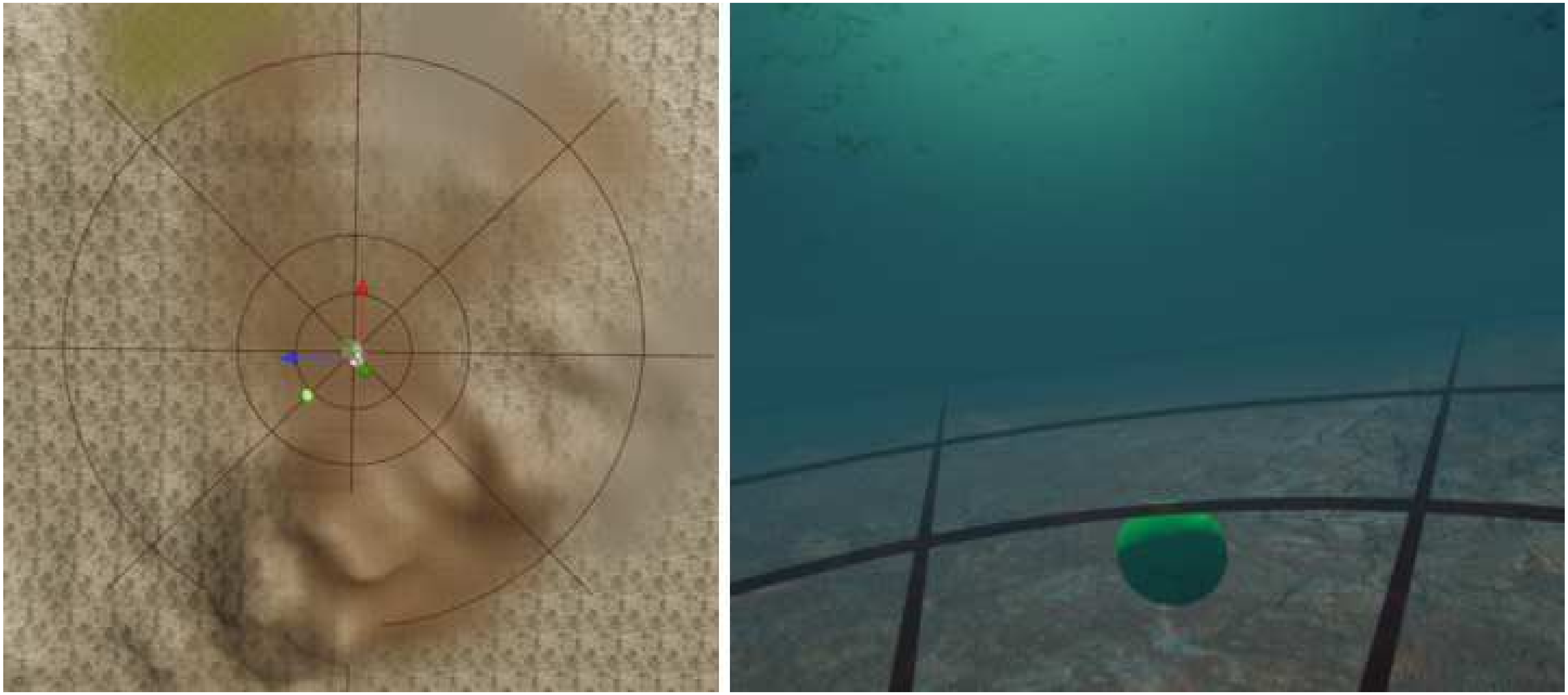
LIST OF TABLES

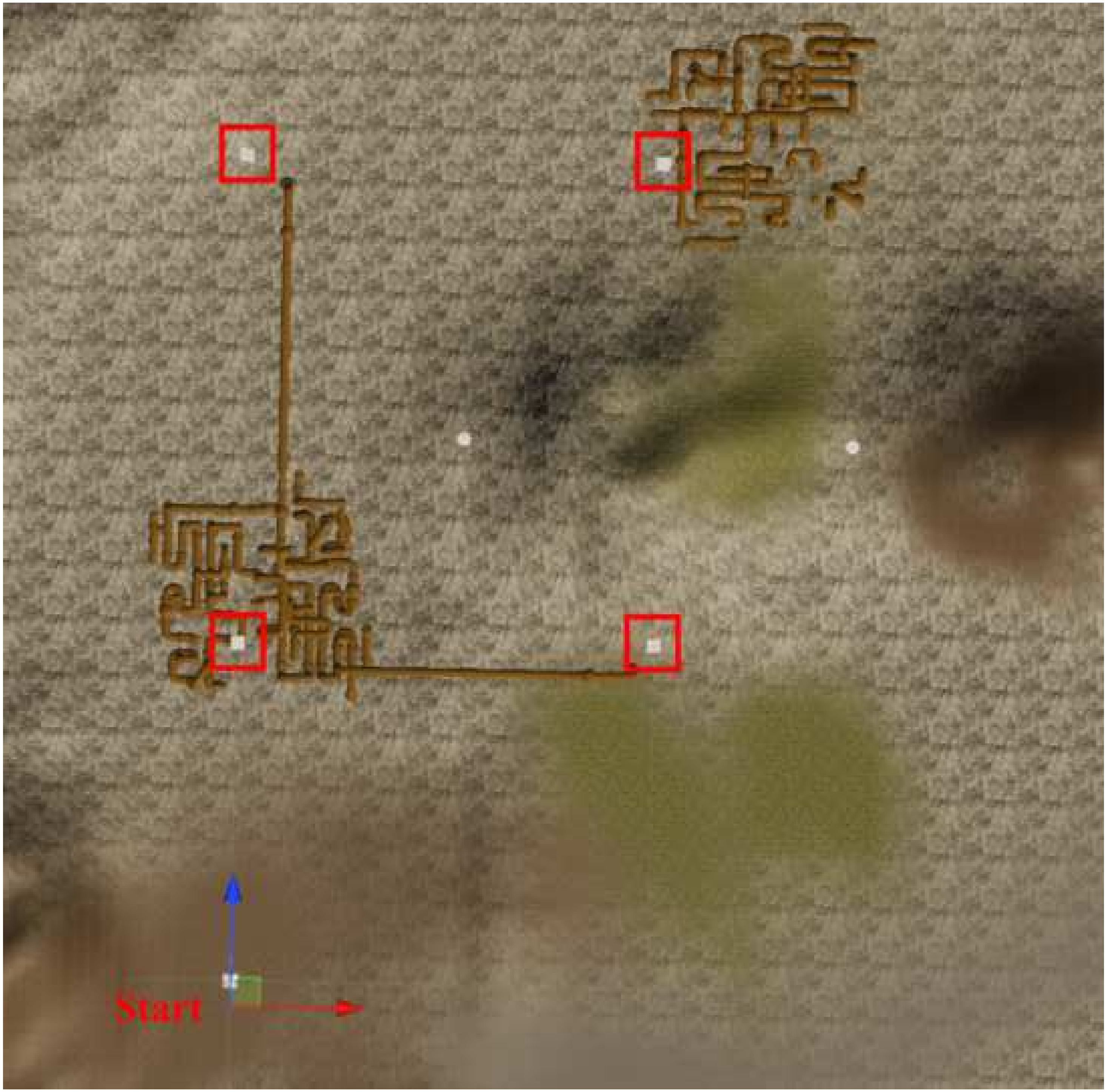

Remotely Operated Vehicle (ROV)
Hydrodynamic Feature Capture
Acoustic Doppler Current Profile
Camera
Thermometer
Pressure sensor
Etc.
3D Modeling
VSLAM
Point Cloud
Camera
Sonar
LiDAR
State Estimation
Local State
World Coordinate
IMU
GPS
Etc.
ROS #
Virtual Reality (VR) Digital Twin
VR Scene Reconstruction
Virtual subsea environment with subsea rendering
ROV state
Hydrodynamic information from sensors
Physical interactions
Human-centered Control
Feedback
Visual augmentation from VR headset
Haptic feedback from haptic suit
Control
Human body motion for xz direction motion control
VR controller touchpad for y direction control
VR controller for UI interaction
Body rotation control
User interface (UI)
Task Allocation
Human: decision making and target selection
Robot: state estimation, auto navigation
Target Setting
Mini map
Ego-centric target setting
State Change
Auto Mode
Stable Mode
Human Mode
Autonomy Control
Kalman Filter
Filter the noisy data and estimate current state
Data source: IMU for position and rotation data, ADCP for flow condition
PID Controller
For motion control, calculate based on distance to target.
For rotation control, always be synchronized with human body rotation, to allow free view for human operator

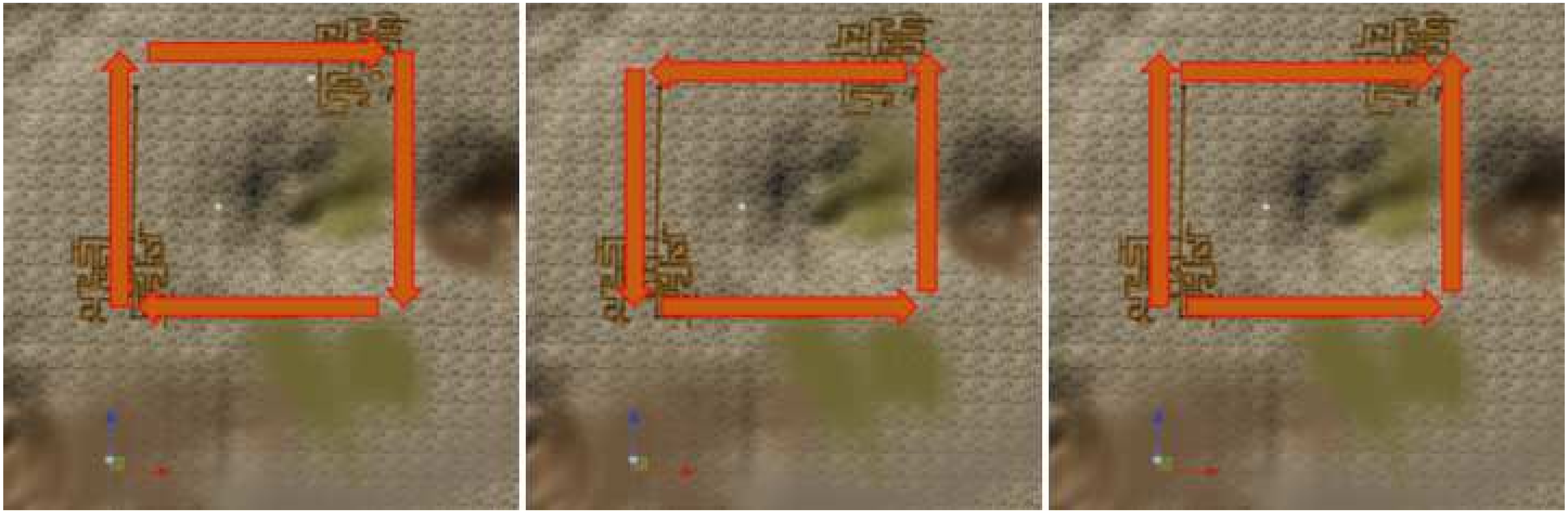

Visual augmentation
Head orientation
Body motion
Controller buttons
Haptic feeling
Position-based control signals
Real ROV
Sensors
ADCP
Camera
Etc.
Converter
Thruster-based control signals
camera
ROS #
Flow Condition
Magnitude (speed)
Direction
Etc.
Virtual ROV
Feedback
Control:
Orientation
Motion
UI functions
Packaged Info
Rotation x y z
Motion x y z
Functions

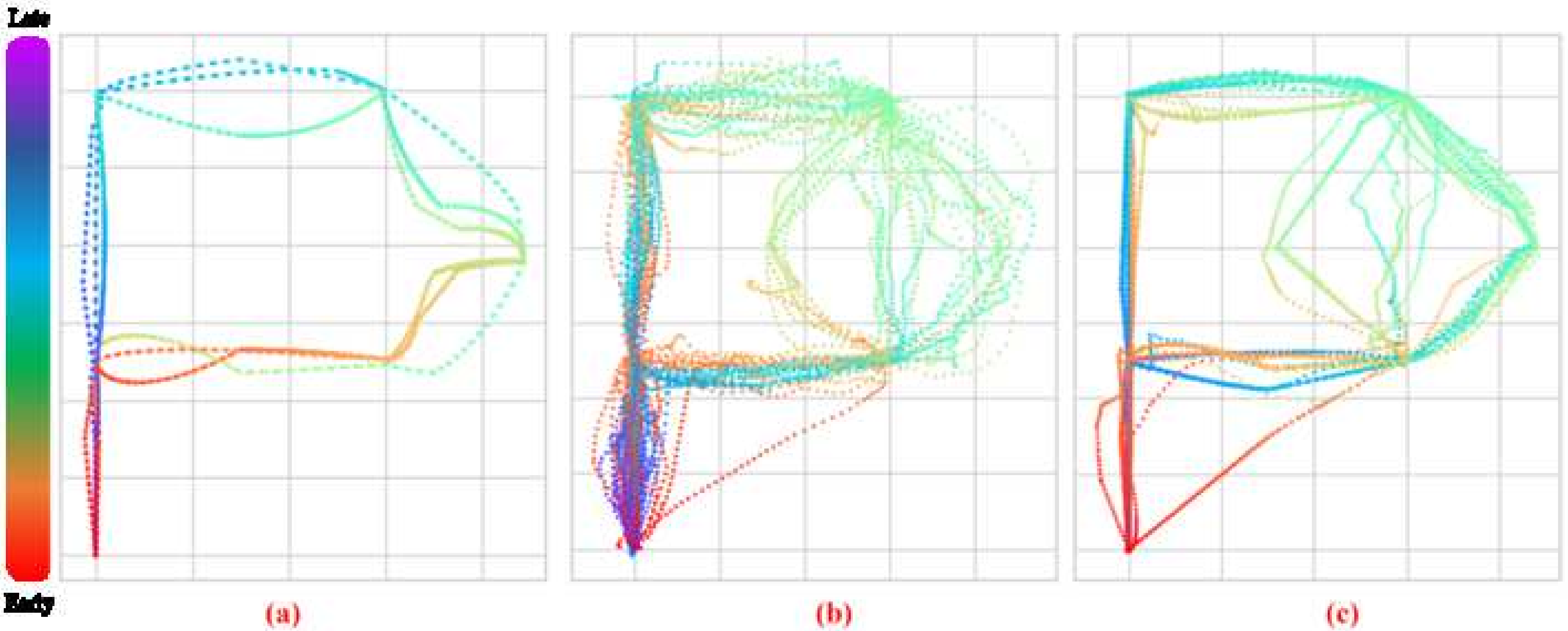

Input
+
+
PID Controller
U(t)=P(t)+I(t)+D(t)
+
+
Flow effect
ROV Real Motion
Measurement
Kalman Filter
Prediction step
Updated step
Update covariance matrix
Estimate Position after Filtering Noise

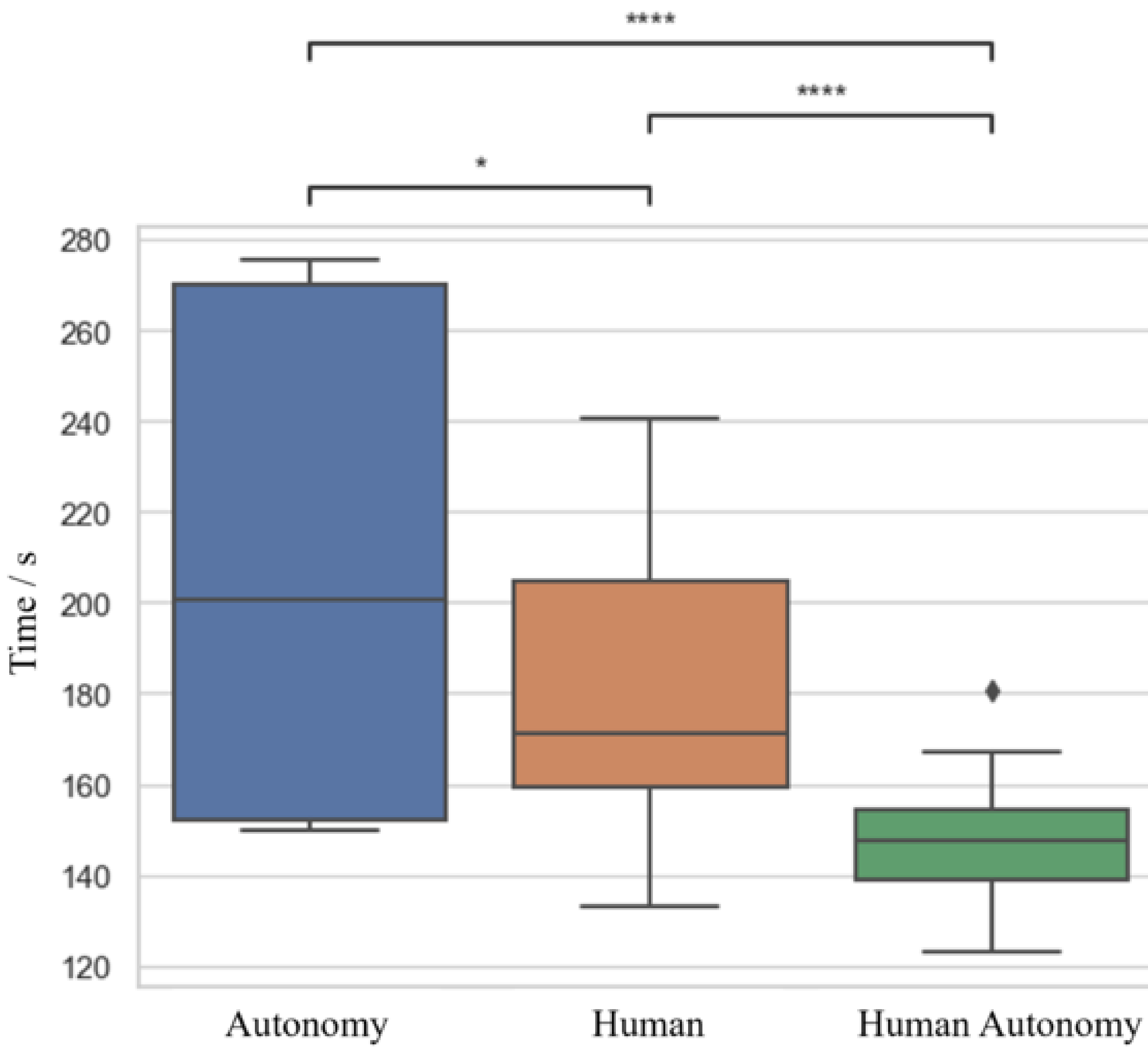

(a)
(b)
(c)

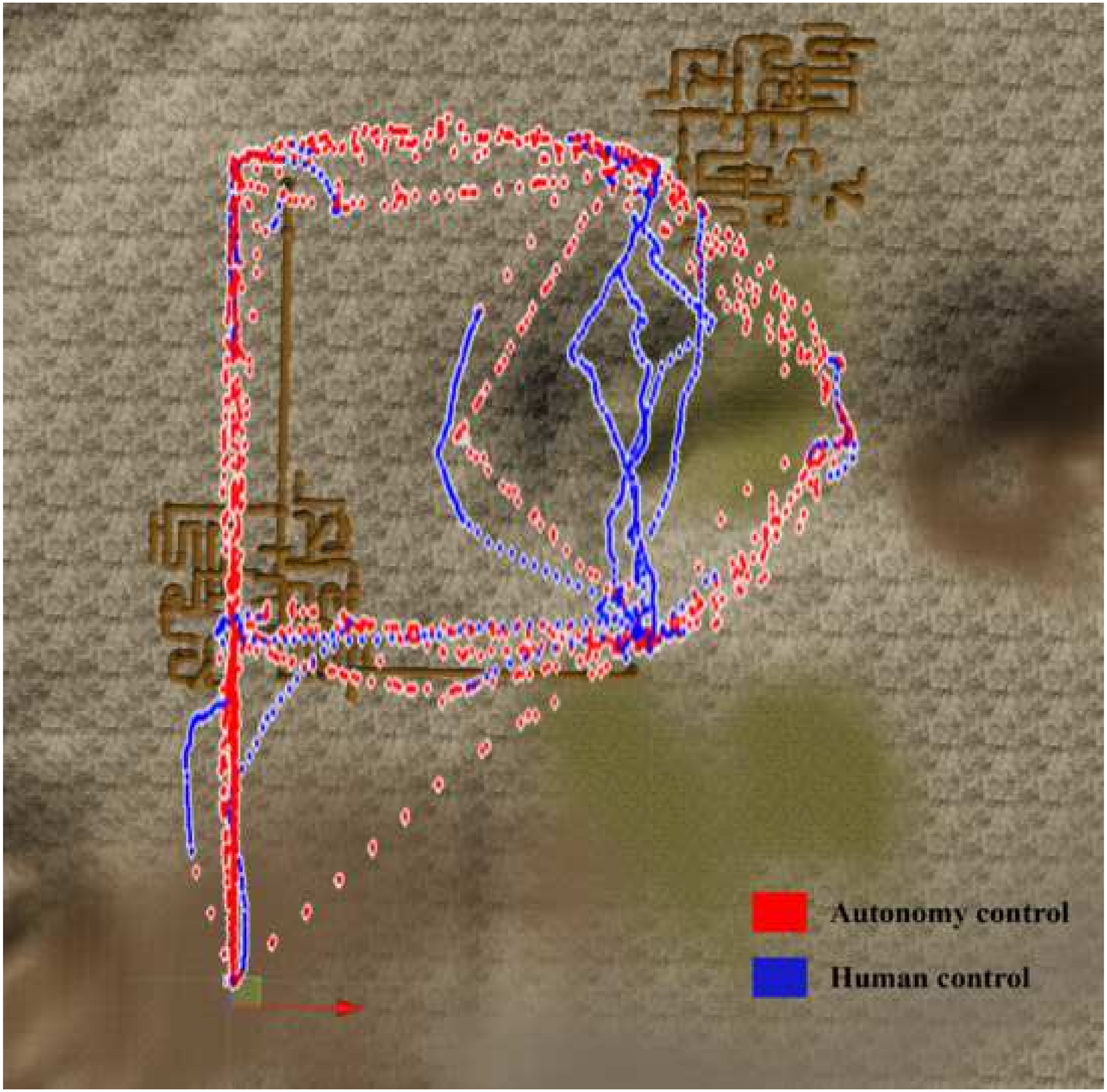


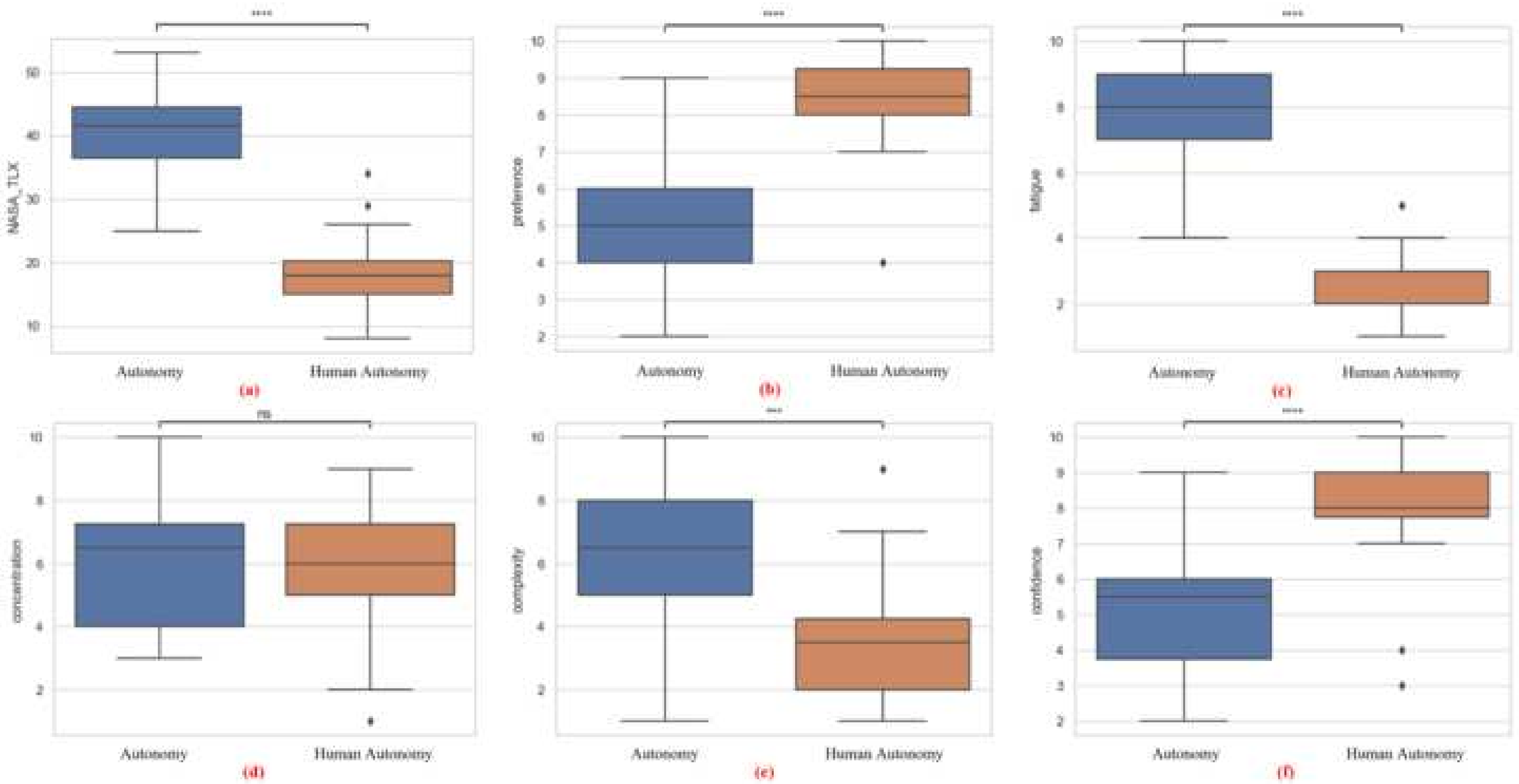

Start




Late
Early
(a)
(b)
(c)


****
****
*
Time / s
280
260
240
220
200
180
160
140
120
Autonomy
Human
Human Autonomy


🟥 Autonomy control
🟦 Human control


****
NASA_TLX
50
40
30
20
10
Autonomy
Human Autonomy
(a)
****
preference
10
9
8
7
6
5
4
3
2
Autonomy
Human Autonomy
(b)
****
fatigue
10
8
6
4
2
Autonomy
Human Autonomy
(c)
ns
concentration
10
8
6
4
2
Autonomy
Human Autonomy
(d)
***
complexity
10
8
6
4
2
Autonomy
Human Autonomy
(e)
****
confidence
10
9
8
7
6
5
4
3
2
Autonomy
Human Autonomy
(f)

LIST OF FIGURES