ARTICLE

Enhancing Subsea ROV Operations: A Survey of Operator Challenges, Essential Skills, and Novel Teleoperation Technologies

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ABSTRACT

The utilization of remote operated vehicles (ROVs) has become essential across various subsea industries, such as oil and gas exploration and offshore wind energy, yet significant challenges remain in achieving effective human-ROV interaction. Despite advancements, ROV operations are hindered by complex control systems, high physical and cognitive demands on pilots, and a lack of sensory feedback mechanisms that fully convey the underwater environment's dynamics. This study addresses these gaps by surveying ROV pilots and industry stakeholders to identify prevalent operational challenges, essential skills, and perspectives on integrating novel teleoperation technologies, including mixed reality and haptic feedback. Findings reveal a strong industry interest in technologies that enhance situational awareness and ease control demands, although concerns remain regarding practical integration and operator fatigue. By highlighting the critical skills required and potential benefits of human-centered augmentation systems, this study provides insights to inform future ergonomic designs, training frameworks, and technology development aimed at advancing safe and effective ROV teleoperation.

Keywords: ROV, survey, competence, haptics, mixed reality

Introduction

Remote operated vehicles (ROVs) have become indispensable in various subsea operations, supporting a range of industries from oil and gas exploration to the construction and maintenance of offshore wind farms and scientific research. The global ROV market has seen substantial growth, driven by the rapidly decreasing cost of deployment and improved versatility of these systems. Emerging engineering applications, particularly in challenging subsea environments, will benefit from the broader utilization of ROVs through enhanced agility, safety, and endurance (Xia et al., 2022). However, despite these advancements, the field of ROV operation remains highly specialized, with significant barriers to employment due to the extensive professional preparation required in related disciplines such as ocean sciences, naval architecture, and marine engineering. Most ROV-related jobs require professional preparation (ocean sciences, naval architecture, marine engineering, and diving knowledge), which takes many years of training (Ge et al., 2012). The existing ROV service workforce consists of marine engineers, professional divers, and robot service providers.

Therefore, the demand for skilled ROV operators is projected to increase dramatically. However, the harsh subsea conditions and the complexity of ROV controls pose major challenges for the future workforce (Xia et al., 2022). The existing control systems, primarily based on live video from onboard cameras, often fail to convey the complex dynamics of the subsea environment, such as internal currents, low visibility, and unexpected marine events (Voldsund, 2023). Addressing these challenges requires reevaluating human-robot interaction (HRI) methods to improve the intuitiveness and efficacy of ROV pilots. For example, multisensory feedback, which includes visual, auditory, and haptic sensations, has been recognized in the literature as a potent augmentation for robot teleoperation, significantly enhancing motor performance (Zhou et al., 2023; Zhu et al., 2022). However, the transferability of this knowledge to subsea ROV operations, with their unique and alien environmental characteristics, remains underexplored.

For the need of better ROV HRI system design, a complete understanding of the requisite skill sets and competencies for effective ROV operation is necessary. Currently, there is a notable lack of comprehensive data on the specific technical and soft skills that enhance operational proficiency and safety. Furthermore, there is insufficient insight into industry practitioners' perspectives on current training practices and workforce development for ROV pilots, which are crucial for informing future educational and training frameworks. Additionally, as technological advancements continue to reshape operational landscapes, the potential integration of advanced teleoperation technologies, such as mixed reality (MR) and haptic control systems, offers a promising avenue to revolutionize ROV teleoperation and support ships (Sapp, 2023; Xia et al., 2023). However, there exists a significant gap in understanding the industry's reception to and the potential impact of these innovative systems. These technologies promise to enhance the intuitiveness and responsiveness of control systems, potentially reducing operator fatigue and improving mission outcomes. Yet, their practical application and acceptance within the industry remain largely unexplored.

This study undertakes a comprehensive survey among ROV pilots, manufacturers, and service providers, aiming to bridge critical knowledge gaps identified in the field. The objectives are threefold: to elucidate the prevalent challenges in ROV operations and pinpoint the essential skills and competencies needed for effective performance, to capture industry perspectives on current training and workforce development practices, and to evaluate the acceptance and perceived benefits of MR and haptic technologies in ROV operations. By exploring these areas, the study seeks to contribute to developing more intuitive and effective human-centered augmentation systems for teleoperation, potentially transforming how ROVs are operated in challenging subsea environments.

Literature Review

ROV for Subsea Operations

An ROV is an uncrewed unit designed for underwater observation, survey, inspection, construction, intervention, or other tasks (American Bureau of Shipping [ABS], 2022). It is important to distinguish ROVs, which are actively controlled by a human operator via this tether, from autonomous underwater vehicles, which operate without a tether and follow pre-programmed instructions. While a small number of advanced ROV systems incorporate semi-autonomous functions, the vast majority of operations rely on the direct, real-time control of a pilot. ROVs can be pre-programmed to follow a specific route to view assets or specific areas of concern. An important area of usage is with oil and gas companies and offshore renewable energy projects. They frequently utilize ROVs to assess asset integrity issues, such as identifying structural degradation or product leakage. ROVs are commonly used to inspect thousands of kilometers of pipelines, and the inspection tasks can sometimes be performed 24 h and 7 days (Yu et al., 2019). To perform these tasks, ROVs are equipped with a suite of sensors to provide pilots with the necessary data to navigate and interact with the subsea environment. Standard payloads include multiple high-definition video cameras, imaging sonar (e.g., forward-looking sonar), and navigation sensors such as an ultra-short baseline (USBL) positioning system, a Doppler Velocity Logger (DVL), and depth/pressure sensors. More complex missions may add tooling and specialized scientific sensors. Consequently, ROV operations are often a collaborative effort, where the pilot works alongside a co-pilot or sensor specialist who helps manage the complex data streams (Capocci et al., 2017). ROVs are also commonly equipped with underwater manipulation capabilities, such as one or more manipulator arms (robotic arms). The trend towards smaller, all-electric vehicles has led to a proliferation of lightweight electric manipulators, meaning that even small inspection-class ROVs often carry cutters or grabbers for intervention tasks. They are capable of heavy operation work, like subsea maintenance for oil and gas industries and the ocean science community (Hudson et al., 2005).

The standard teleoperation paradigm for ROVs has traditionally relied on pilots interpreting primary video feeds from the vehicle's onboard cameras. This vision-centric control method, however, provides insufficient sensory data for robust piloting, particularly in the challenging subsea domain. Environmental factors such as low visibility and high turbidity significantly impair the operator's situational awareness, while conventional 2-D video fails to convey critical hydrodynamic forces like ocean currents (Chemisky et al., 2021; Li et al., 2019). This creates a perceptual gap between the operator's understanding and the vehicle's true state in its environment, which can disrupt the sensorimotor control loop and degrade performance (Finney, 2015). The problem becomes especially acute during tasks that demand precise station-keeping for inspection or maintenance, as unseen currents can destabilize the vehicle and compromise the mission (Cao et al., 2020; Li et al., 2019).

In response to these challenges, much of the recent academic literature has concentrated on enhancing the ROV's autonomous capabilities through advanced algorithms. Significant efforts have focused on developing adaptive nonlinear controllers for self-stabilization (Tran et al., 2020), disturbance rejection controllers to improve maneuvering accuracy (Cao et al., 2020), and sophisticated vision-based algorithms for color correction in deep, low-light conditions (Arce et al., 2022). While these system-level improvements are valuable for mitigating environmental effects on the vehicle, they largely overlook the human in the loop. With comparatively less attention paid to advancing the human-robot interface, a critical bottleneck remains. Improving vehicle-side algorithms without simultaneously enhancing the pilot's ability to perceive and interact with the remote environment will continue to limit operational effectiveness in complex and dynamic subsea settings. We need a better understanding of the challenges faced by ROV pilots, and the advanced technologies that might benefit ROV control interface design, to build a more effective ROV HRI control system.

Challenges Faced by ROV Pilots

The operation of ROVs in subsea environments necessitates a complex interplay of technical skills and ergonomic considerations, which if not optimized, can significantly hinder operator performance and lead to safety risks. Ergonomically, the design of ROV control stations often fails to align with the best practices recommended for human-computer interaction, leading to operator discomfort and potential long-term musculoskeletal problems. Previous studies indicate workers experience high-risk musculoskeletal disorders due to awkward postures, excessive force, and repetition, often resulting from limited working areas and prolonged standing periods (Abdullah et al., 2024; M. Noor & Raja Ghazilla, 2020). These ergonomic challenges reduce operational efficiency and elevate the likelihood of chronic health issues among pilots, emphasizing the need for ergonomic enhancements in control station designs.

In addition to ergonomic issues, ROV pilots face challenges stemming from the complexity of control interfaces. Traditional ROV systems often employ a multifaceted array of controls and feedback mechanisms that require extensive training and high concentration levels, potentially overwhelming pilots, particularly under time-sensitive or stressful conditions. A study on the cognitive workload of ROV pilots found that their performance during complex sample collection in unpredictable environments was enhanced when they were supported by a teammate providing an additional viewpoint (Blitch, 2017). This suggests that non-intuitive controls can significantly increase the risk of errors during critical tasks. The cognitive demands are further compounded by the necessity to monitor multiple information streams simultaneously, including live video feeds, sonar data, and navigational charts, which can lead to high mental workload and fatigue. While pilots rely heavily on crucial non-visual tools like SONAR, USBL, and DVL to supplement their spatial awareness in low-visibility conditions, the cognitive challenge of integrating these disparate data streams remains significant. Research by Tang et al. assessed the mental workload of trainee pilots of remotely operated aircraft, which underscores that cognitive overload is a common issue, particularly during complex maneuvers or emergency scenarios (Tang et al., 2022).

The remote nature of ROV operations often isolates the operator from direct environmental cues, exacerbating the difficulty of maintaining spatial orientation and situational awareness. A study examined work-related stress and its impact on performance and safety among professionals in high-stress environments, indicating that isolation and lack of direct environmental interaction can lead to increased stress and compromised decision-making (Cahill et al., 2020). Moreover, this effect is further amplified by the solely reliance on visual feedback, which often fails to convey the full spectrum of environmental dynamics (Xia et al., 2022). The challenge is to provide ROV pilots with comprehensive sensory feedback to enhance perception and interaction with the subsea environment. Innovative human augmentation technologies such as augmented reality and virtual reality (VR) interfaces that incorporate real-time multi-sensory feedback could potentially address these issues (Sapp, 2023; Xia et al., 2023).

Human Augmentation Techniques for ROV Operations

The challenges in subsea ROV operations, characterized by complex, dynamic environments and the inherent limitations in human operator capabilities to process and react to these dynamics, underscore the necessity for advanced HRI methods. The reliance on 2-D camera views and joystick controls demands extensive training and disrupts the critical feedback-control loop necessary for precise motor actions, often leading to perceptual-motor malfunctions (Finney, 2015). In recent years, human augmentation techniques have been proposed to support difficult ROV operations. A popular example is with MR. Its ability to render realistic scenes and provide rich spatial information makes it particularly suitable for enhancing robot teleoperation (Zhou et al., 2020; Zhu et al., 2022). Literature underscores the potential of MR in bridging the perceptual and control gaps between humans and robots, facilitating improved planning and execution of complex tasks that require both robotic precision and human cognition (Macciò et al., 2022).

In the context of ROV teleoperation, MR emerges as a pivotal technology to lower entry barriers and enhance the integration of human inputs in real-time operations. Research has explored MR's utility in diverse ROV operations, from deep ocean remote control to intricate underwater capture tasks, revealing significant improvements in task performance and operator situational awareness (Mack, 2015; Sapp, 2023). MR systems can be programmed to deliver enhanced visual feedback beyond traditional video streaming, offering International Unit designs that map work progress and optimize navigational paths, thereby improving the efficiency and safety of operations (Lee et al., 2022). Another emerging technique for augmentation human capability in ROV operations is the haptic feedback. This multimodal approach is crucial for improving motor performance and ensuring robust control in complex environments (Lathan & Tracey, 2002; Sugiyama & Liew, 2017). Haptic devices can generate tactile stimuli such as vibrations and force feedback, corresponding to real-time environmental interactions, enhancing the operator's perception of the subsea conditions (Nagano et al., 2020; Shazali, 2018). Early implementations in ROV controls have demonstrated the utility of simulating hydrodynamic conditions through haptic feedback, thereby improving spatial awareness and navigational accuracy. Notable efforts include the system to simulate kinesthetic feedback through pressure and torsion forces (Amemiya & Maeda, 2009) as well as linear-oscillating actuators to create realistic pressure signals (Ciriello et al., 2013). These preliminary implementations have verified the potential benefits and effectiveness to apply augmentation technologies in ROV operations. Now is the time to gather insights from professional ROV practitioners on the feasibility and acceptance of implementing these technologies in actual ROV operations.

Methodology

This study employed a systematic survey design to gather insights into the challenges and opportunities associated with ROV operations, the requisite skillsets and competencies, and the potential impacts of advanced human-computer interaction technologies like VR and haptics. The methodology consisted of several key phases designed to ensure comprehensive coverage of the relevant topics and reliable data collection from industry professionals.

Survey Design

The development of the survey instrument was a multi-stage process that began with a workshop involving domain experts from academia and the ROV industry. The aim was to leverage both scholarly literature and practical experience to compile an extensive list of potential survey questions that would cover various aspects of ROV operations, including ergonomic challenges, control system interfaces, training adequacy, and the perception of new technologies like MR systems. Following this initial compilation, an iterative process was conducted with the research team to refine and streamline the questions. This refinement process focused on ensuring clarity, relevance, and conciseness of the survey items while maintaining comprehensive coverage of all critical topics. The goal was to limit the survey completion time to approximately 15 min to maximize response rates and minimize respondent fatigue.

The final survey instrument included 48 questions based on four themes: demographics, challenges for pilots and human resources (HR), requisite skillsets and competencies, and the impacts of integrating novel technologies (please refer to the Appendix for all the survey questions). The list of skills and competencies was derived from a job analysis of 275 postings on LinkedIn for the position of underwater ROV operator that reported the range of knowledge areas, skills, abilities, and other desired characteristics. The most commonly occurring characteristics were converted into statements that participants rated individually based on their perception of importance. For example, “Understanding of ROV mechanical and electronic systems” (knowledge area), “Proficiency in navigation and control systems of ROV” (technical skill), “Clear communication skills” (social skill), “Physical fitness and stamina.” (physical abilities), and “Creative problem-solving skills” (process skills).

Participant Recruitment and Data Collection

The final survey was distributed electronically to a targeted group of participants consisting of 142 ROV service companies and individual users, with 40 complete respondents. These participants were selected from a list provided by the ABS, which ensured that the respondents were credible and currently active in the field. The survey was administered online, allowing for a broad geographic reach and ease of participation for respondents. This mode of delivery was also conducive to a quick turnaround in data collection, which was essential for timely analysis and reporting.

The survey collected data on various demographic factors including the roles of the respondents (e.g., ROV manufacturers, service providers, pilots, and end users from industries such as oil and gas), their years of experience in the field, and optional personal information such as age, gender, and educational background. These demographic details are crucial for analyzing the responses in the context of participants’ expertise and experience levels.

Results

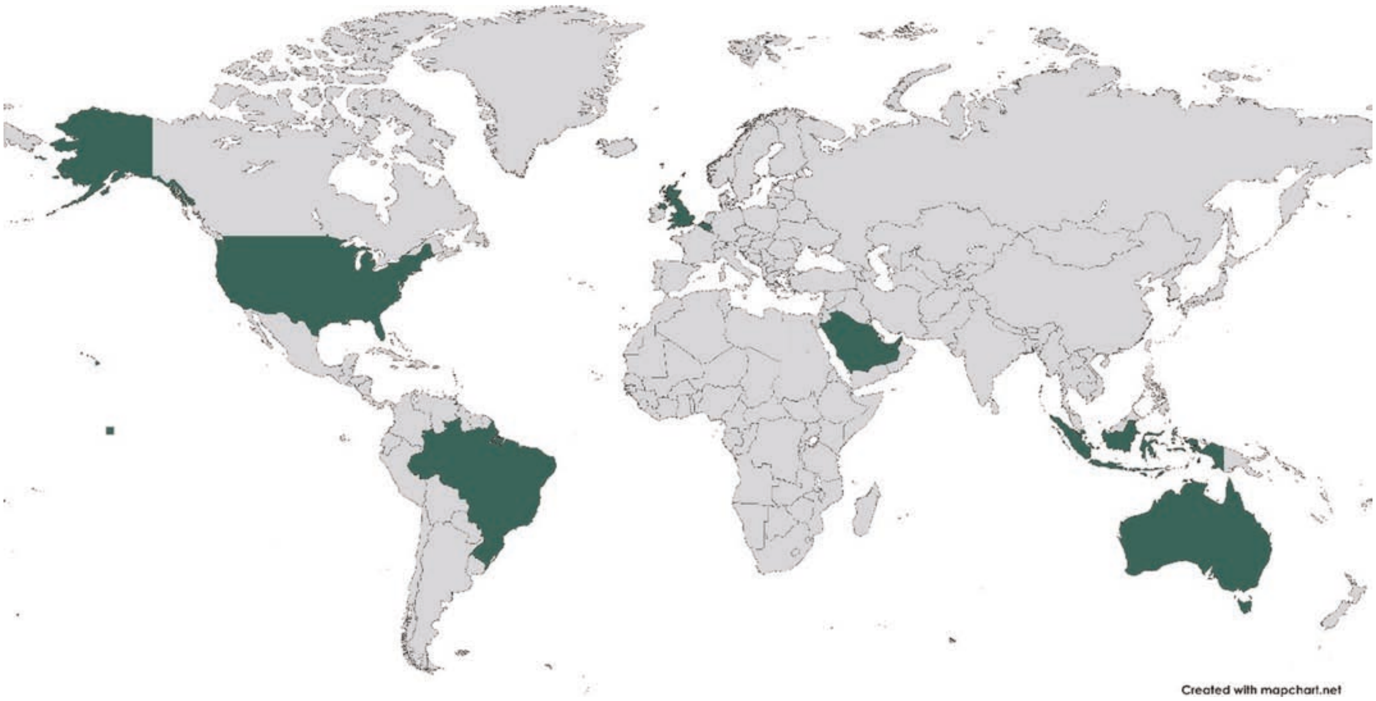
The survey results highlight the essential skillsets and competencies required for effective operation of ROVs. Respondents were asked to rate the importance of various skillsets on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The findings presented below provide insight into the perceived importance of these skills for ROV pilots.

Demographic Analysis

The demographic characteristics of the survey respondents reveal a diverse and global representation of the ROV industry. The majority of participants were from the USA (27.5%) and the United Kingdom (10%), with additional representation from countries such as Indonesia, Australia, the United Arab Emirates, Singapore, Brazil, and others. See Figure 1 for a map of respondents. This diverse geographic representation underscores the broad applicability of the survey findings and highlights the international nature of the ROV industry. The participants predominantly held roles as

FIGURE 1

Locations of survey respondents.



ROV service providers (47.5%), frontline ROV pilots (20%), and others (32.5% including those who did not release the role), indicating strong representation from professionals involved directly in ROV operations and service delivery. Fewer respondents identified as ROV manufacturers or service users.

Figure 2 shows the age and years of experience distribution of the respondents. The respondents demonstrated a wide range of experience in the field, with notable clusters at 8, 12, and 20 years. This diversity in experience levels allows for a comprehensive understanding of industry perspectives, encompassing insights from both seasoned experts and those newer to the field. Most respondents were mid-career professionals, with the majority falling within the age range of 35–54 years. As for the educational background shown in Figure 3, a significant proportion held a bachelor's (35%) or master's (17.5%) degree, suggesting a well-educated workforce capable of managing the technical demands of ROV operations.

ROV Pilot Challenges

Figure 4 shows the result of the responses regarding ROV pilot challenges. The survey results provided insights into the challenges and difficulties faced by ROV pilots. A significant number of respondents agreed on the need for better ergonomic design of the ROV control systems, that the interface and controls of existing ROV systems are not user-friendly, with 44% selecting "somehow agree" and 40% selecting "strongly agree," indicating dissatisfaction with the current user interface. This finding underscores the need for a redesign of ROV interfaces to enhance usability, particularly for those involved in complex underwater operations. The training for current ROV systems was also rated as inadequate by 52% of respondents selecting "somehow agree" and 8% selecting "strongly agree," which suggests that enhanced training programs could mitigate operational challenges and improve efficiency.

Respondents highlighted the mental psychological challenges associated with ROV piloting. A notable number expressed agreement that operating an ROV for long periods leads to a sense of isolation, with 60% selecting "somehow agree" and 16% selecting "strongly agree." Similarly, the remote nature of ROV operations negatively impacts work-life balance, with 40% of respondents selecting "somehow agree" and 16% selecting "strongly agree." These findings suggest that the remote and solitary nature of ROV piloting can have significant effects on the well-being of pilots. Addressing these concerns may involve implementing better support systems or developing more interactive work environments to counteract isolation.

The lack of physical feedback in current ROV systems was another area of concern, with 41.6% selecting "somehow agree" or "strongly agree," and only 29.2% "somehow disagreeing" that there is a lack of physical feedback. The absence of haptic or tactile feedback can contribute to operational mishaps or accidents, highlighting the importance of incorporating enhanced sensory feedback mechanisms to improve control precision and reduce errors.

Overall, the survey findings indicate several critical areas for improvement in current ROV systems, including user interface design, training adequacy, psychological support, physical feedback mechanisms, and ergonomic considerations. Addressing these challenges is essential for enhancing the safety,

FIGURE 2

Age and years of experience of respondents.

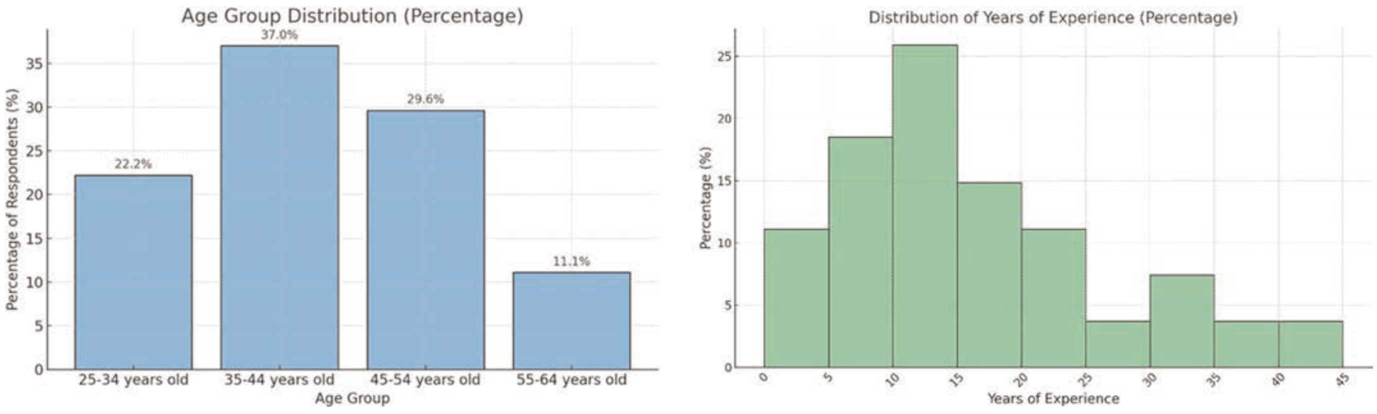


FIGURE 3

Educational background of experience of respondents.

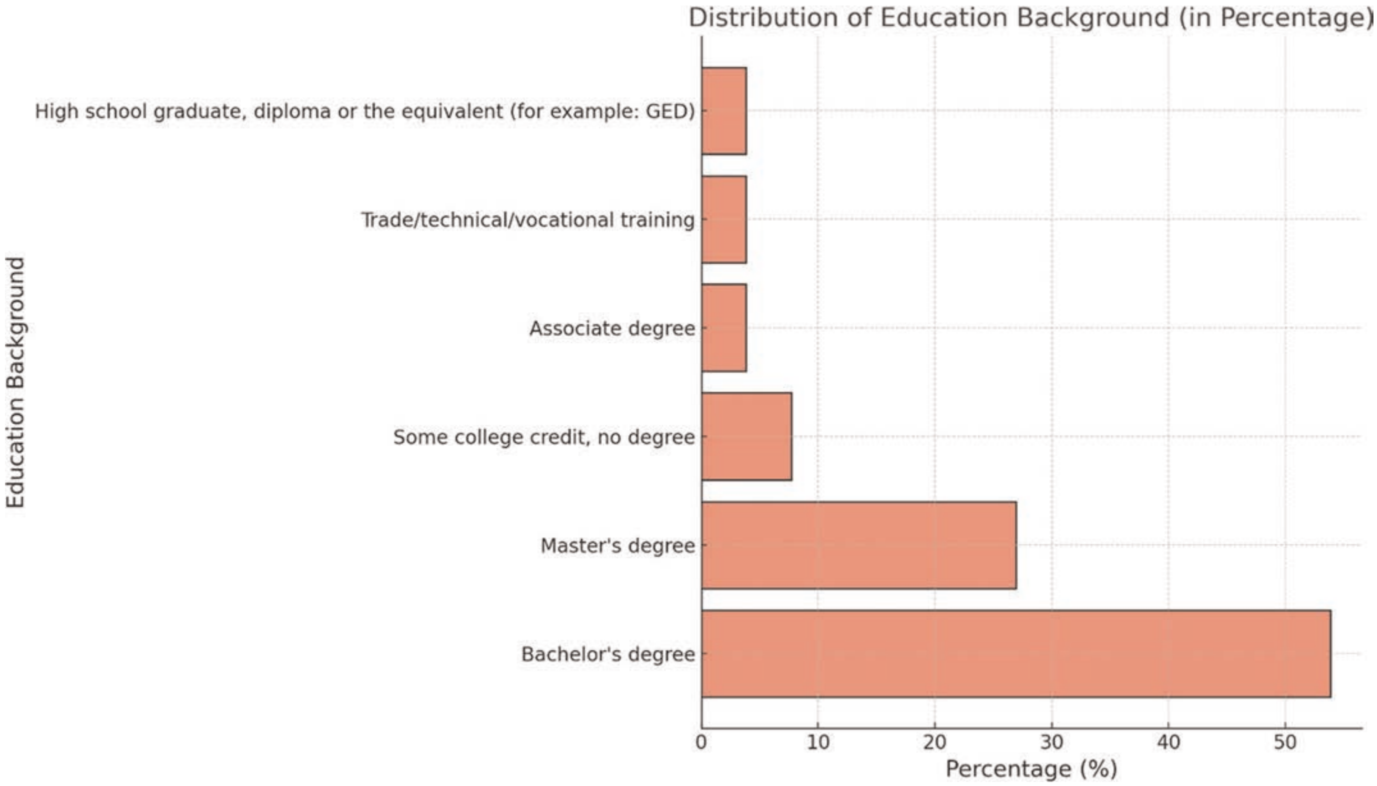
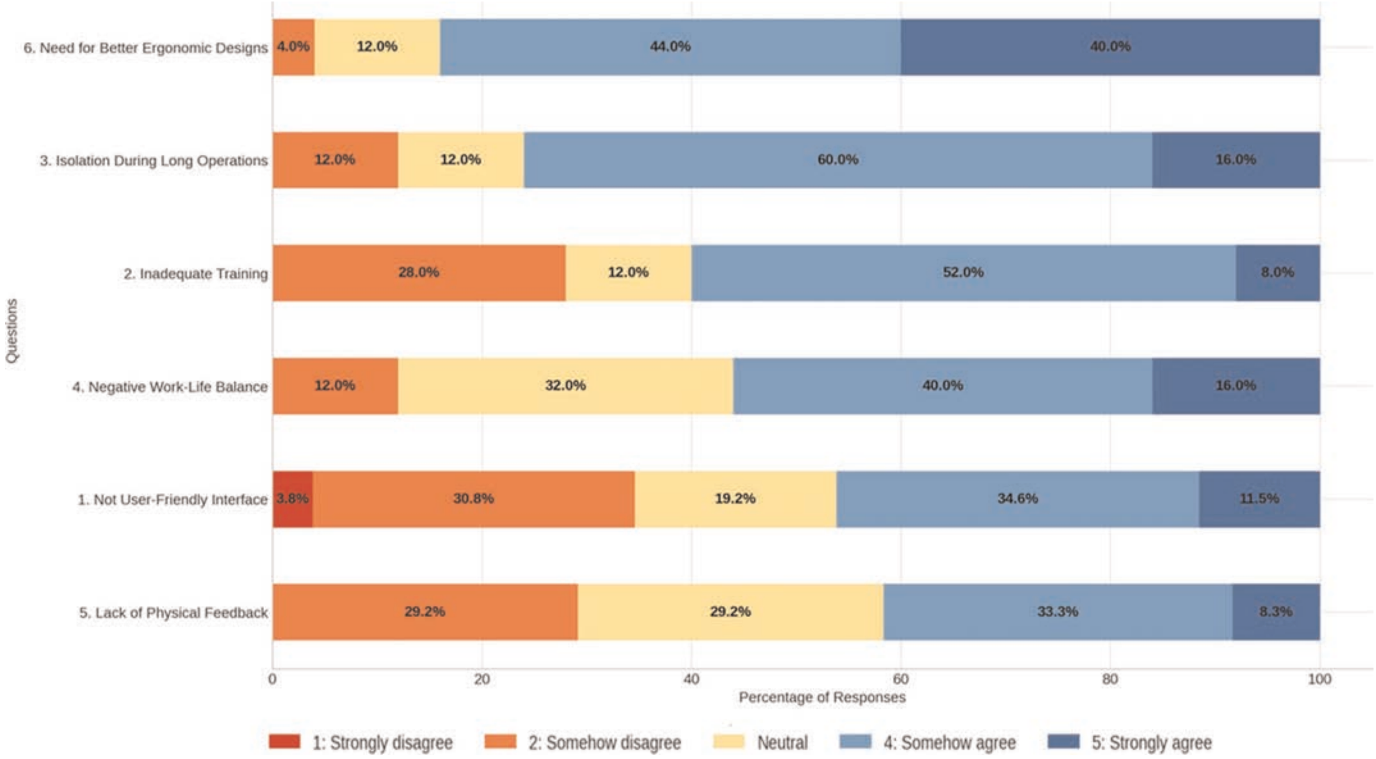


FIGURE 4

Responses regarding ROV pilot challenges.



efficiency, and well-being of ROV pilots. These insights can guide future developments to create more user-friendly, supportive, and effective ROV systems that cater to the needs of their pilots.

ROV HR Challenges

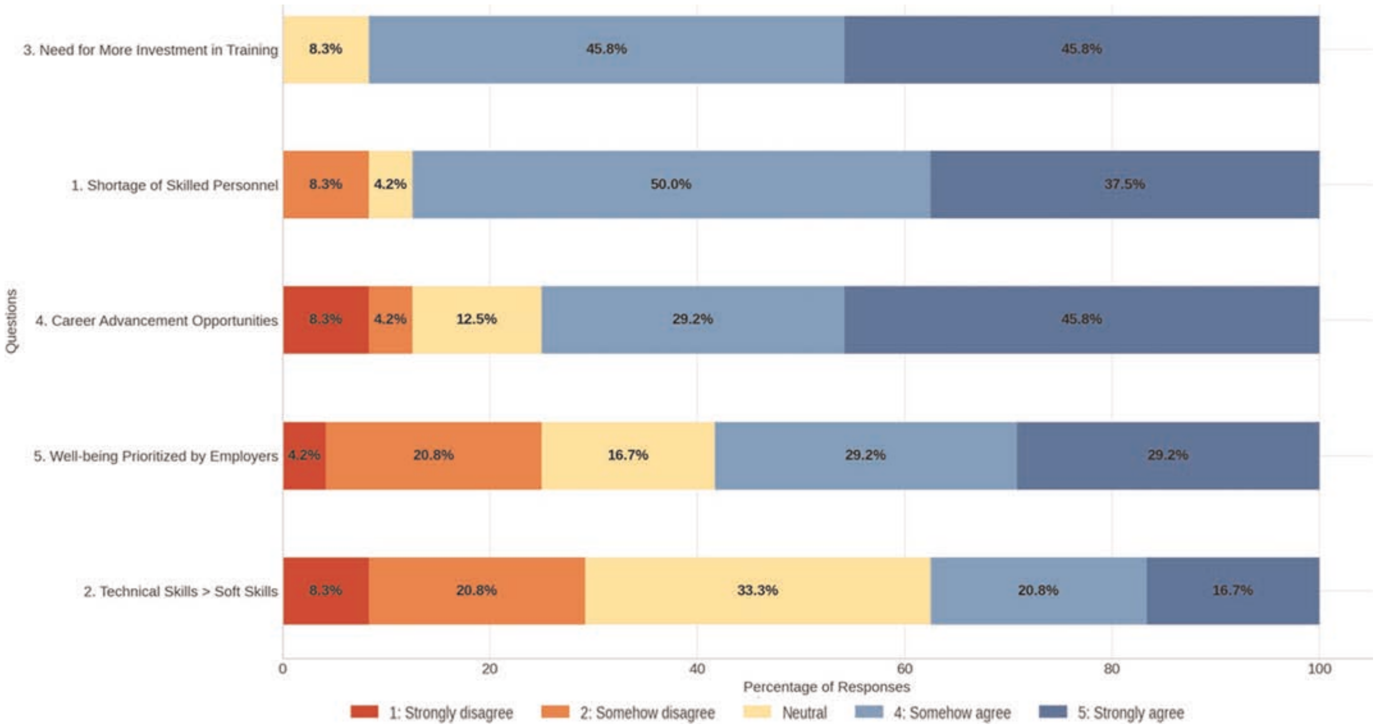
Figure 5 shows the result of the responses regarding ROV HR challenges. The HR challenges in the ROV industry provide valuable insights into the current state of the workforce, covering the importance of different skill sets, the quality of career development opportunities, and the prioritization of pilot well-being. A notable majority of respondents (91.6%) agreed that the industry should increase investment in training and development, with 45.8% selecting "strongly agree" and 45.8% selecting "somehow agree" on this matter. This underscores the complexity of ROV operations and the necessity for continuous skill enhancement to keep pace with evolving technologies and safety requirements. Addressing this gap could involve implementing comprehensive training programs that cover both technical proficiency and operational awareness. Echoing this aspect, the shortage of skilled personnel in the ROV industry was also highlighted. When asked if there is a shortage of skilled personnel in the field of ROV operations, 87.5% of respondents selected "strongly agree" or "somehow agree." These findings indicate that the industry is facing difficulties in attracting and retaining skilled workers, which could be addressed through targeted recruitment initiatives, partnerships with educational institutions, and development programs aimed at nurturing the next generation of ROV pilots.

Interestingly, career advancement opportunities within the ROV industry were positively appreciated. When asked if there are ample opportunities for career advancement in the field of ROV operations, approximately 45.8% of respondents strongly agreed and 29.2% somehow agreed. This indicates that although the ROV industry acknowledges the need for more training investments and to attract more talent, the internal opportunities for ROV pilots and professionals to grow their careers were perceived as positive. It may show the satisfactory effort of ROV companies to retain their existing talent pool by increasing the visibility of career pathways and offering more structured advancement opportunities to make career growth a more precise and more attainable goal for employees.

Opinions on the physical and mental well-being of ROV pilots

FIGURE 5

Responses regarding ROV HR challenges.



were split. About 58.4% of respondents agreed (29.2% selected "strongly agree" and "somehow agree," respectively) that employers sufficiently prioritize the well-being of ROV pilots. In comparison, a considerable percentage (41.6%) held a neutral or negative view on this matter. This suggests that although employers may make some efforts, a noticeable portion of the workforce still perceives a gap in the level of support for their physical and mental health. Enhancing well-being initiatives, such as mental health resources and ergonomic workplace adjustments, could improve job satisfaction and retention in this high-demand field.

Another interesting finding is about the perceived importance of soft skills compared to technical skills. Although it is well recognized that technical skills, such as electrical, ocean, and mechanical engineering, are indispensable in the ROV industry, only 37.5% of the respondents agreed that they were more important than soft skills. This highlights the high technical demands of the job, emphasizing that the industry places a premium on specific technical competencies. However, it is also crucial for industry leaders to recognize the complementary value of soft skills, which contribute to teamwork, safety, and efficient operations.

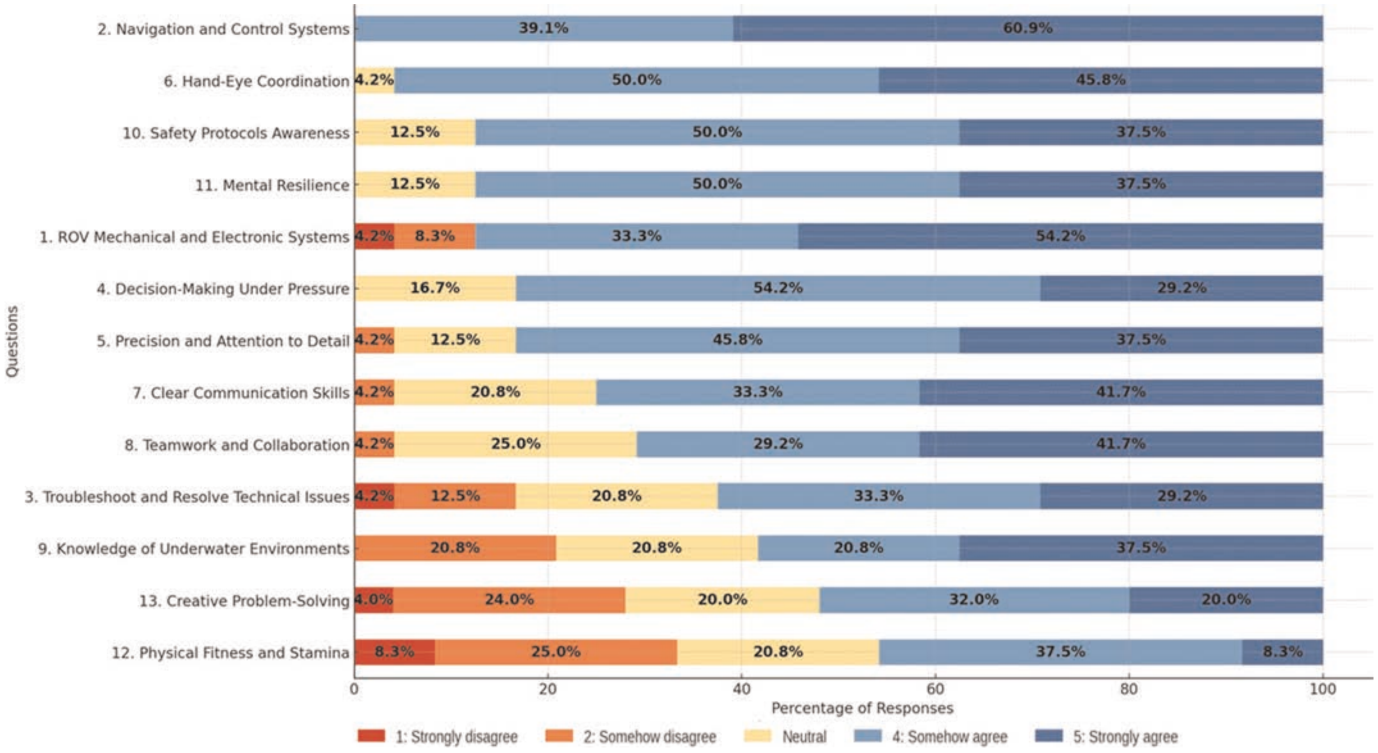
In summary, the findings reveal several critical HR challenges in the ROV industry, including a shortage of skilled personnel insufficient investment in training, the need to prioritize soft skills, and a greater focus on well-being. To address these challenges, the industry must take comprehensive actions, such as enhancing well-being programs, providing incentives for attracting talents, and investing in continuous training initiatives, to create a supportive and resilient environment for ROV pilots.

ROV Skillsets and Competence Requirements

This study also examines the perceived importance of skills needed for ROV operations. Figure 6 shows the result of the responses regarding ROV skillsets and competence requirements. ROV pilots' skillsets and competence requirements are crucial for ensuring effective and safe operations, encompassing a wide range of technical and interpersonal abilities. Based on the survey responses, some skills stood out with a significant level of agreement among respondents, while others showed mixed perceptions. Below is an analysis of these competencies, grouped by similarity and ranked according to the level of agreement.

FIGURE 6

Responses regarding ROV skillsets and competence requirements.



Foundational Technical Knowledge and Skills

Proficiency in navigation and control systems of ROVs was seen as the most agreed-upon skill, with 60.9% selecting "strongly agree" and 39.1% selecting "somehow agree." This demonstrates that effective navigation and control are critical for helping to ensure mission success and avoiding obstacles during operations. An understanding of ROV mechanical and electronic systems followed closely, with 54.2% selecting "strongly agree" and 33.3% of respondents selecting "somehow agree." This emphasizes the necessity of technical expertise for ROV operations, as these systems are foundational to the equipment's functionality. Pilots would struggle to maintain and effectively operate ROVs without a deep understanding of these systems. Similarly, awareness of safety protocols and environmental regulations was noted by 50% of respondents as "somehow agree" and 37.5% as "somehow agree." This highlights the importance of understanding and adhering to regulatory requirements to ensure safety and protect underwater environments. Maintaining high safety standards is critical in mitigating risks associated with ROV operations. Good hand-eye coordination was recognized as highly necessary, with 50.0% selecting "somehow agree" and 45.8% selecting "strongly agree." This skill is fundamental for precise control of ROVs, particularly in navigating obstacles or manipulating robotic tools or objects underwater. Similarly, precision and attention to detail were highly valued, with 83.3% of respondents strongly or somehow agreeing on their importance. These skills are crucial for ensuring that delicate tasks, such as inspections or manipulations, are carried out accurately and safely. In addition to the above knowledge about technical systems of ROVs, these two sensorimotor skills are crucial for ROV controls, which are related to the foundational technical requirements.

Stress Management

Mental resilience and the ability to manage stress were appreciated and critical for ROV operations, with 50% of respondents selecting "somehow agree" and 37.5% selecting "strongly agree." Similarly, making effective decisions under pressure was another critical skill, supported by 54.2% of respondents who selected "somehow agree" and 29.2% who selected "strongly agree." These results reflect the need to adapt quickly to unpredictable underwater environments, making this a key competence for ROV pilots. Enhancing training programs to simulate high-pressure scenarios could further strengthen this skill among pilots.

Interpersonal and Professional Skills

Clear communication skills were seen as crucial soft skills, with 41.7% of respondents selecting "strongly agree" and 33.3% selecting "somehow agree." Effective communication is necessary for coordination during operations and ensuring safety and accurate reporting of underwater conditions. Teamwork and the ability to work collaboratively were also essential, with 41.7% selecting "strongly agree" and 29.2% selecting "somehow agree." Given that ROV operations often involve coordination with other teams and specialists, these interpersonal skills are essential to effective communication and operational success. Encouraging a team-oriented culture through collaborative exercises can further enhance these skills among ROV pilots.

Troubleshooting Skills

The ability to troubleshoot and resolve technical issues was recognized by 33.3% of respondents as "somehow agree" and 29.2% as "strongly agree." These findings reflect the complexity of ROV operations, where malfunctions are inevitable, and prompt troubleshooting is essential to maintain operational efficiency. Similarly, creative problem-solving skills, closely related to troubleshooting, were also highlighted, with 32.0% selecting "somehow agree" and 20.0% selecting "strongly agree." These skills are vital for navigating unexpected challenges and adapting to evolving underwater conditions. Knowledge of underwater environments and conditions was another key technical competence, with 20.8% selecting "somehow agree" and 37.5% selecting "strongly agree." A strong understanding of the underwater landscape is crucial for safe navigation and successfully executing tasks, underscoring the need for comprehensive environmental awareness training. Physical fitness and stamina were identified as the least essential requirements, with only 45.8% of the respondents voting favorably. Despite the physically demanding nature of ROV operations, new automation technologies may have helped relieve the concerns about the long hours in challenging conditions.

In summary, the survey results indicate that both technical and soft skills are crucial for ROV pilots. The most emphasized competencies include proficiency in navigation and control, foundational technical knowledge, decision-making under pressure, and troubleshooting and resolving issues. Additionally, soft skills such as teamwork and clear communication are vital for successful ROV missions. Addressing these skill requirements will involve continuous investment in training, scenario-based learning, and fostering a collaborative work environment to ensure that ROV pilots are well-prepared for the demands of underwater operations.

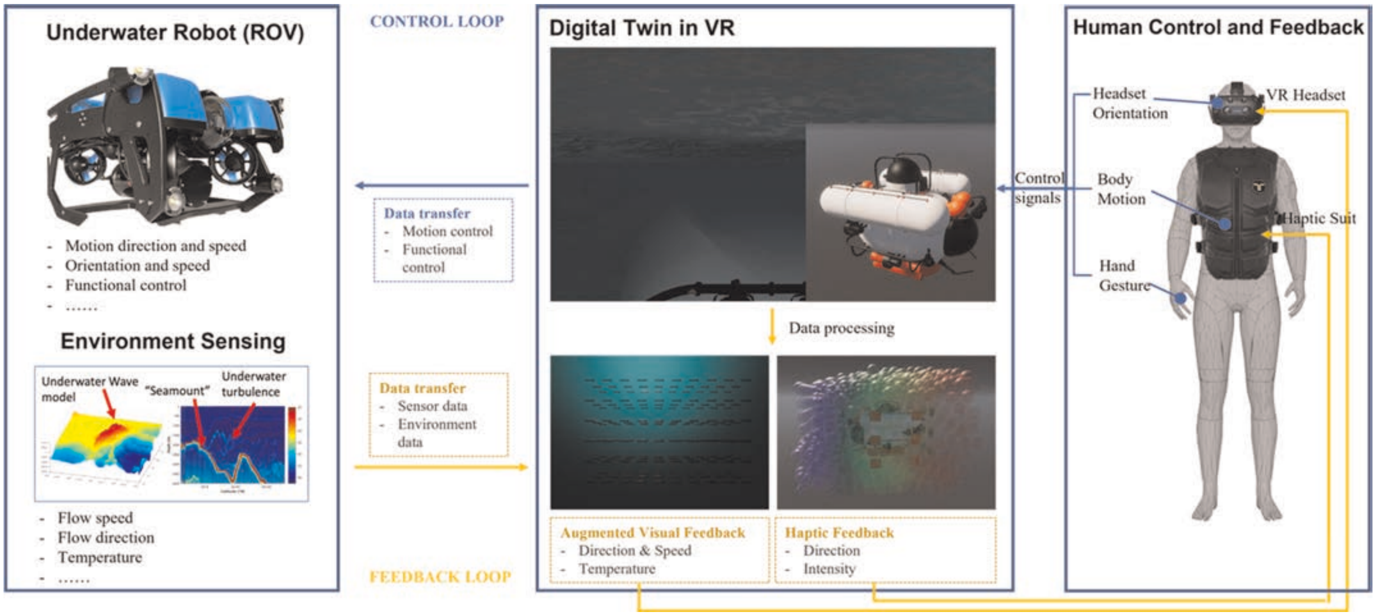
Novel ROV Teleoperation Technologies

This study also aims to test the acceptance of current novel teleoperation technologies. The survey provides a demo video of an embodied ROV teleoperation system designed by ourselves; please refer to https://youtu.be/8MismssRMpY?si=fZc9xOEazEWiXpd2. The demo video shows a VR-body motion ROV teleoperation system. Real-time camera feeds are displayed via the VR headset, offering an immersive, first-person perspective of the remote environment to enhance pilots' situational awareness. Additionally, a haptic suit provides tactile feedback, simulating the sensation of underwater currents to supplement visual information. This feedback allows pilots to interact directly with the system using natural body movements captured by the VR system and translated into ROV control signals. The ROV's orientation is synchronized with the operator's head movements, while body motions control navigation. For instance, a slight forward lean propels the ROV forward. This integration of control and feedback through VR creates an intuitive, immersive experience, allowing pilots to control the ROV most naturally.

The system design structure is shown in Figure 7. Conventional ROV teleoperation is constrained by its reliance on a limited control loop of joystick inputs and camera displays. Although prior research has sought to optimize this model through improved UI designs (Labonte et al., 2010), workload analyses (Riddle, 2002), and the integration of autonomous algorithms (Amundsen et al., 2021; Qomaruzzaman & Mardiyanto, 2018), these methods fall short of providing the rich sensory data required for effective spatial perception. The complex subsea workspace—characterized by dynamic currents, poor visibility, and unpredictable marine life—can threaten vehicle stability and create a significant proficiency barrier for pilots. Our system is engineered to overcome this sensory deficit by cultivating a more holistic and immersive awareness of the remote environment. It achieves this by integrating data from diverse sensors, including LiDAR and an acoustic Doppler current profiler, to render a realistic virtual reconstruction of the subsea setting. This virtual model encompasses not only static visual elements but also dynamic hydrodynamic forces. Developed algorithms then process these

FIGURE 7

The proposed ROV teleoperation technology with haptic feedback and motion capture.



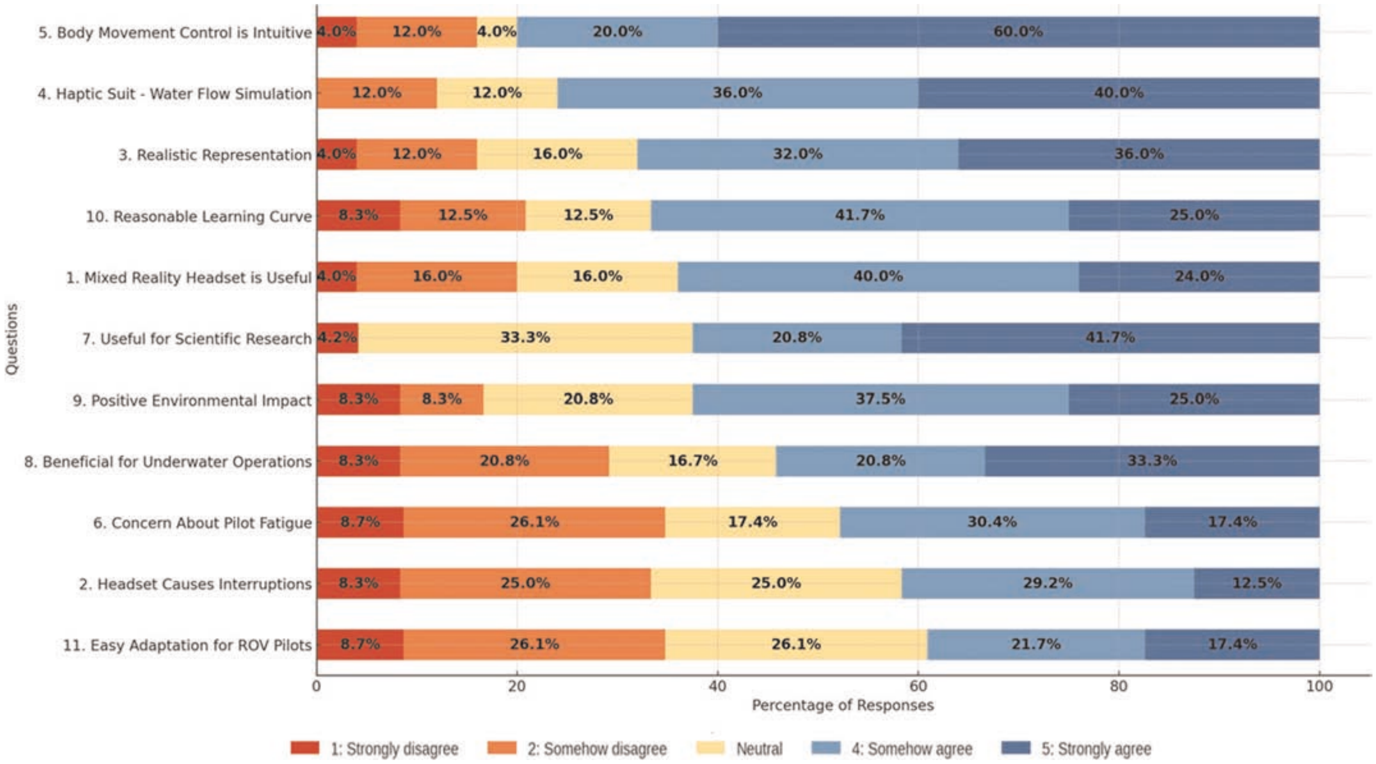
fused data to generate multi-level sensory information for the pilot, delivered as near-field haptic suit feedback and far-field visual augmentations.

Complementing this enriched sensory feedback is an embodied control scheme that translates the operator's natural body movements into corresponding ROV commands. This system maps the operator's physical actions to the vehicle's control parameters to create a more intuitive connection between pilot and machine. For instance, the orientation of the operator's head and torso directly dictates the ROV's pitch, roll, and yaw, synchronizing the vehicle's attitude with the user's posture. Translational movement through the environment is similarly controlled by body gestures, such as leaning forward to command the ROV to move forward and pitch downward. This synergy between intuitive motion control and multimodal feedback aims to create a more direct and seamless teleoperation experience. For vertical up-and-down operations, pilots could use their hand gestures for control, i.e., thumb up for vertical up. This body motion control system ensures a direct and intuitive control interaction with all the information gained from feedback system.

Figure 8 shows responses regarding these novel ROV teleoperation technologies. The survey gathered insights into the perceived usefulness and potential challenges of using novel teleoperation technologies for ROV systems. The majority of respondents showed a strong support for the proposed ROV teleoperation system. Expressly, regarding the intuitiveness of controlling ROVs using body movements, 80% of respondents strongly agreed or somehow agreed that it was an intuitive method, suggesting that motion-based control could lower the learning barrier for pilots. The haptic suit's simulation of water flow was also seen as valuable, with 40% "strongly agreeing" and 36% "somehow agreeing" that this feature could improve understanding of underwater dynamics. This reflects a positive reception for tactile feedback in aiding situational comprehension during complex operations. The respondents also highly valued the use of MR technology in ROV teleoperation. The MR headset was perceived as a valuable component for ROV teleoperation, with 40% selecting "somehow agree" and 24% selecting "strongly agree." In addition, 36% of respondents strongly agreed and 32% of respondents somehow agreed that the system could provide a more realistic

FIGURE 8

Responses regarding novel ROV teleoperation technologies.



rendering of the underwater environment. This indicates a general optimism about the value of this technology in enhancing situational awareness and immersiveness.

Most respondents were also positive about the learning feasibility of this system, with 66.7% strongly agreed or somehow agreed that the learning curve for initiating and using this teleoperation system seems reasonable. However, only 39.1% of respondents thought that the existing ROV pilots would adapt quickly to this system (strongly agree or somehow agree). This result conflicts with the perception of the easy learning curve. Still, it reflects the concerns about potential interruptions to existing workflows rather than the difficulty of learning how to use the system. In fact, 41.7% of respondents believed that the use of headset would cause significant interruptions to the existing operation flows with current ROV systems, versus 33.3% of respondents who did not think so, and 47.8% of respondents were concerned about the additional fatigue with using the system, versus 34.6% of respondents who did not have such a concern. This suggests that, while the concept is promising, practical integration may present challenges for pilots accustomed to traditional methods. This emphasizes the need for ergonomic considerations and a balance between technology integration and operator well-being.

As for the benefits of deploying this system, it was seen as particularly useful for scientific research, with 41.7% “strongly agreeing” and 20.8% “somehow agreeing” that it would benefit such applications. Similarly, 33.3% “strongly agreed” and 20.8% “somehow agreed” that the system would benefit underwater operations like oil and gas inspections and search and rescue missions. There was also strong agreement on the positive environmental impact of enabling more precise operations, with 20.5% “strongly agreeing” and 37.5% “somehow agreeing” that this would contribute positively. This suggests that these technologies are perceived to improve efficiency and reduce unintended environmental impact.

Discussion

This study aimed to explore the challenges faced by ROV pilots, human resource issues within the industry, essential skillsets required for effective ROV operation, and the acceptance of novel teleoperation technologies with MR, haptic feedback, and motion capture systems. The survey results provide valuable insights into these areas, highlighting critical gaps and opportunities for improvement in ROV operations.

Interpretation of ROV Pilot Challenges

The survey revealed significant challenges associated with the ergonomic design of ROV control systems and the adequacy of current training programs. A majority of respondents agreed that existing interfaces could be more user-friendly and that training is insufficient. These findings align with previous research indicating that complex and non-intuitive control interfaces impose a high cognitive load on pilots, potentially leading to errors and decreased operational efficiency. The lack of ergonomic considerations not only affects operator comfort but can also contribute to musculoskeletal issues and long-term health problems (Abdullah et al., 2024). Psychological challenges such as feelings of isolation and negative impacts on work-life balance were also prominent. The remote and solitary nature of ROV operations can lead to increased stress levels and impair decision-making capabilities (Cahill et al., 2020), a factor that is compounded by the inability for offshore personnel to leave the work environment behind at the end of a shift. The absence of physical feedback mechanisms further exacerbates these issues by limiting pilots’ situational awareness and making it more difficult to maintain spatial orientation in complex underwater environments. These challenges underscore the need for a reevaluation of current HRI methods in ROV operations. Enhancing ergonomic design, improving training programs, and incorporating multi-sensory feedback could mitigate these issues. By addressing the ergonomic and psychological challenges, the industry can improve operator well-being and operational effectiveness.

HR and Skill Development

The findings indicate a perceived shortage of skilled personnel in the ROV industry, with a strong consensus on the need for increased investment in training and development. This shortage is consistent with projections of a growing demand for ROV pilots and the challenges associated with attracting and retaining talent in a highly specialized field. It is important to note, however, that several major employers offer extensive in-house “zero-to-hero” training programs that provide a viable pathway into the industry for candidates with minimal experience. Better advertisement of these opportunities could help address the perceived talent shortage. While career advancement opportunities are viewed positively, the industry must address the gap in initial training and skill development to build a robust workforce. Furthermore, while our data show a high proportion of pilots hold formal degrees, industry experience suggests that on-the-job training and practical experience are highly valued pathways to developing elite piloting skills. The role of high-fidelity, shore-based simulators is critical in this context. Simulators provide a safe, repeatable, and cost-effective environment for initial training, continuous skill development, rehearsing complex missions, and testing novel control interfaces before offshore deployment.

The mixed opinions on whether employers sufficiently prioritize the well-being of pilots suggest that while some efforts are being made, there is room for improvement. Enhancing well-being initiatives, such as providing mental health resources and ergonomic workplace adjustments, could improve job satisfaction and retention rates. Additionally, recognizing the importance of soft skills alongside technical competencies highlights the need for comprehensive training programs that develop both aspects. This development ecosystem is supported not only by educational institutions and corporate training but also by the vital contributions of learned societies, such as the Society for Underwater Technology and the Marine Technology Society, which provide continuous professional development and networking opportunities.

Skillsets and Competence Requirements

The survey identified essential technical skills as critical for ROV pilots, including proficiency in navigation and control systems, understanding of mechanical and electronic systems, and adherence to safety protocols. These foundational skills are essential for effective and safe ROV operations (Nitonye et al., 2021). Sensorimotor abilities such as good hand-eye coordination and precision were also emphasized, reflecting the importance of fine motor skills in manipulating ROVs in complex environments. Stress management and the ability to make effective decisions under pressure were highlighted as crucial competencies. The unpredictable nature of underwater environments requires pilots to adapt quickly and remain composed during high-pressure situations. Soft skills like clear communication and teamwork are vital for coordination during operations and ensuring safety. Interestingly, physical fitness and stamina were considered less critical, possibly due to advancements in automation technologies reducing the physical demands of the job. This shift suggests a greater emphasis on cognitive and interpersonal abilities in current ROV operations.

Acceptance of Novel Teleoperation Technologies

Respondents showed strong support for the proposed ROV teleoperation system utilizing MR and haptic feedback. The majority found body movement control intuitive and valued the haptic suit's ability to simulate water flow, enhancing their understanding of underwater dynamics. The MR headset was perceived as a valuable tool for providing a more realistic rendering of the environment, which could improve situational awareness. However, concerns were raised about potential workflow disruptions and additional fatigue associated with using MR headsets. A significant practical challenge, particularly for operations on smaller vessels, is the potential for motion sickness when using an immersive headset on a pitching and rolling platform. This is a critical ergonomic barrier that must be addressed for such a system to be viable offshore. Potential engineering solutions, such as mounting the operator's station on a gimbal-stabilized platform, warrant further investigation to mitigate this issue. Pilots accustomed to traditional methods may face challenges adapting to new technologies, highlighting the need for ergonomic considerations and comprehensive training. Addressing these concerns is crucial for the successful integration of advanced teleoperation systems. The perceived benefits of these technologies for applications such as scientific research, oil and gas inspections, and search and rescue missions indicate significant potential for adoption. The positive environmental impact associated with more precise operations further supports the integration of MR and haptic technologies in ROV operations.

Bridging the Technology Adoption Gap

There appears to be a gap between established ROV technologies and the futuristic systems proposed here. To understand how emerging technologies like MR and haptics might achieve successful adoption, it is instructive to consider the integration of "novel" technologies from the past decade, such as advanced 3-D sonar visualization and digital photogrammetry. The adoption of these tools has been mixed, often hindered by challenges in data integration, information overload for the pilot, and a steep learning curve. For the current generation of technologies to succeed, they must not only demonstrate a clear return on investment but also prioritize seamless integration into existing workflows and prove that they reduce, rather than increase, the cognitive load on the operator. Lessons learned suggest that successful adoption depends as much on human factors and implementation strategy as on technological capability.

Implications for Industry and Future Work

The findings have several implications for the ROV industry. There is a clear need to improve ergonomic design and enhance training programs to address the challenges faced by pilots. Employers should prioritize operator well-being by implementing support systems that mitigate feelings of isolation and stress. Addressing the shortage of skilled personnel requires targeted recruitment strategies and investment in training and development. Collaborations with educational institutions and the promotion of career opportunities within the industry could attract new talent and build a more robust workforce. The adoption of novel teleoperation technologies offers promising avenues to enhance operational efficiency and safety. However, successful integration will depend on addressing concerns related to workflow disruptions and operator fatigue. User-centered design principles and ergonomic considerations should guide the development of these systems. Future research should explore the practical implementation of MR and haptic technologies in ROV operations, including pilot studies and field trials. Understanding the long-term effects on operator performance and well-being will be critical for widespread adoption. This study has limitations; the survey was not followed by focus groups to explore the identified gaps in greater detail, and a higher proportion of responses from frontline, offshore pilots would have strengthened the findings. Future work should seek to address this. Furthermore, the industry is moving towards new operational paradigms, such as the teleoperation of ROVs from uncrewed or remotely operated surface vessels. This “nested teleoperation” will introduce an entirely new set of HRI challenges that future research must begin to investigate.

Conclusions

This study has shown the multifaceted challenges faced by ROV pilots and the broader industry, encompassing ergonomic deficiencies, psychological strains, skill gaps, and the complexities of integrating novel technologies. The findings underscore a critical need for improvements in control system design, emphasizing user-friendly interfaces that reduce cognitive load and physical strain. Current training programs have been deemed inadequate, revealing a gap in equipping pilots with the necessary technical expertise and soft skills essential for navigating complex underwater environments. Additionally, the psychological toll of ROV piloting—characterized by feelings of isolation and negative impacts on work-life balance—highlights the necessity for robust support systems to enhance operator well-being and job satisfaction.

Addressing these challenges is imperative for enhancing the safety, efficiency, and sustainability of ROV operations. Employers and industry stakeholders must invest in comprehensive training and development initiatives to mitigate the shortage of skilled personnel and foster a more resilient workforce. Embracing a human-centered approach, with a focus on ergonomic design and operator well-being, can lead to improved retention rates and operational effectiveness. The adoption of advanced teleoperation technologies like MR and haptic feedback presents a promising avenue for transforming ROV operations. While pilots recognize the potential benefits—such as enhanced situational awareness and more intuitive control mechanisms—concerns related to workflow integration and operator fatigue must be carefully addressed. The proposed solutions primarily target the enhancement of sensory feedback and spatial awareness; this is a critical first step, but other challenges will require different approaches. User-centered design principles and ergonomic considerations are essential to ensure these technologies augment rather than impede operator performance.

In conclusion, the success of future ROV operations depends on addressing these challenges and leveraging technological advances. Prioritizing human factors and skill development will enhance operational efficiency and sustainability. Collaborations among employers, educational bodies, learned societies, and tech developers are key to creating effective training for skilled pilots. Future research should expand on these findings by involving broader participant groups and testing new technologies in real-world scenarios, aiming to maximize the benefits of advanced teleoperation systems and foster growth and innovation in the ROV industry.

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Appendix

Survey Questions

Demographics:

1. Please specify your role: (ROV Manufacturer, ROV Service Provider, frontline ROV Pilot, ROV service user (such as Shell; Exxon), Other: ____)
2. Years of experience in your field: ____
3. Age: ___ (optional)
4. Gender: ___ (optional)
5. Education background (optional)

Current ROV pilot challenges and difficulties (Likert scale. 1: strongly disagree; 2: somehow disagree 3: neutral; 4: somehow agree 5: strongly agree)

1. The interface and controls of existing ROV systems are not user-friendly.
2. The training for current ROV systems is inadequate.
3. Operating an ROV for long periods leads to a sense of isolation.
4. The remote nature of ROV operations negatively impacts my work-life balance.
5. The lack of physical feedback in current systems can lead to accidents or mishandling.
6. There are specific areas in current ROV systems that need significant improvement (Please specify: ____).
7. I would prefer ROV systems that offer better ergonomic design to reduce physical strain.
8. The most challenging aspect of being an ROV pilot is (Please specify: ____).
9. Open comments____

ROV human resources (Likert scale. 1: completely disagree; 5: completely agree)

1. There is a shortage of skilled personnel in the field of ROV operations.
2. Technical skills (e.g., electrical engineering, ocean engineering, mechanical engineering) are more important than soft skills for an ROV pilot.
3. The industry should invest more in the training and development of ROV pilots.
4. Open comments - how would you feel the current ROV training could be improved, or other major issues not mentioned above: ____

Job Satisfaction and Career Development (Likert scale. 1: completely disagree; 5: completely agree):

1. There are ample opportunities for career advancement in the field of ROV operations.
2. The physical and mental well-being of ROV pilots is sufficiently prioritized by employers.
3. I have suggestions for improving the skill development of ROV pilots (Please specify: ____).

ROV skillsets and competence needs (Likert scale. 1: not important at all; 2: somehow important; 3: neutral; 4: somehow not important 5: very important)

1. Understanding of ROV mechanical and electronic systems.
2. Proficiency in navigation and control systems of ROV.
3. Ability to troubleshoot and resolve technical issues of for ROV.
4. Effective decision-making under pressure.
5. Precision and attention to detail.
6. Good hand-eye coordination.
7. Clear communication skills.
8. Teamwork and the ability to work collaboratively.
9. Knowledge of underwater environments and conditions.
10. Awareness of safety protocols and environmental regulations.
11. Mental resilience and the ability to manage stress.
12. Physical fitness and stamina.
13. Creative problem-solving skills.
14. Are there any other skills or competencies you believe are crucial for ROV pilots that have not been mentioned? (Please specify: ____)

Impression and opinions regarding our system (Likert scale. 1: completely disagree; 7: completely agree) The concept of using a mixed reality headset for ROV teleoperation is useful.

1. I don't think the headset would cause significant interruptions to my existing operation flows with current ROV systems.
2. The headset appears to provide a realistic representation of the underwater environment.
3. The haptic suit's simulation of water flow is a valuable feature for understanding underwater dynamics.
4. Controlling the ROV using body movements is intuitive.
5. I am concerned about the potential for pilot fatigue with this control method.
6. This system would be particularly useful for scientific research.
7. The system would be beneficial for underwater operations (e.g., oil and gas, pipeline inspections, and search and rescue missions).
8. The system would have a positive environmental impact by enabling more precise operations.
9. The learning curve for initiating and using this teleoperation system seems reasonable.
10. Existing ROV pilots would adapt easily to this system.
11. I have concerns about this system (Please specify: ____)
12. Are there specific modifications or improvements you would suggest for this system?
13. Would you be interested in further collaboration or trials with this technology? If so, please leave your email here: ___