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# A review of Rescue Methods After Intelligent Rescue Equipment Approaches a Drowning Person

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ABSTRACT

Drowning is still the main cause of accidental death worldwide, and intelligent rescue technology is needed for rapid and effective intervention. This study investigated the rescue methods used by intelligent devices - autonomous rescue devices, auxiliary self-rescue devices, and wearable intelligent rescue devices - when reaching a person who has fallen into the water. Using IEEE Xplore, Scopus, Web of Science and other digital databases, this paper systematically reviews the research on hardware design, sensor integration, control algorithm and human-computer interaction from 2009 to 2025. The results show that multi-sensor fusion, adaptive stability and safe human-computer interaction are crucial for reliable performance in complex aquatic environments. Future advancements are proposed, include enhancing robust perception, adaptive stabilization, and human-computer interaction security to critically address system-level challenges of cross-domain coordination, standardized interoperability, and reliable algorithmic decision-making in complex aquatic environments. These insights provide a basis for advancing intelligent drowning rescue systems, linking technological innovation with practical safety applications.

## 1 Introduction

Water activities play an important role in global leisure and commercial operations. However, frequent drowning accidents pose serious threats to human safety, as shown in Fig. 1. Statistical data indicate that the mortality rate of drowning accidents is extremely high [1-3]. During the rescue process, rescue time, tools, and methods critically influence the survival outcomes of drowning persons [4].

### 1.1 Traditional rescue tools and their limitations

Many devices such as lifebuoys, life jackets, rescue nets, rescue baskets, rescue stretchers, rope throwers, lifeguards, and other rescue tools have been developed [5]. In general, these rescue tools should be operated by professional rescuers only after reaching the drowning person to ensure safety [6]. However, in harsh environments, rescue team members may not be able to work properly and their safety is threatened [7].

Most drowning incidents (63%) were witnessed and the majority of witnesses (74%) were present at the time of drowning. One-fifth of rescue attempts are conducted by non-professionals, and these non-professional rescue operations inevitably have potential risks [8]. Therefore, reducing the difficulty of rescue tools and eliminating direct contact between rescuers and drowning persons can play a significant role in improving rescue efficiency and eliminating danger to rescuers. Consequently, improving or innovatively redesigning rescue devices to enable safe and efficient rescue proto-

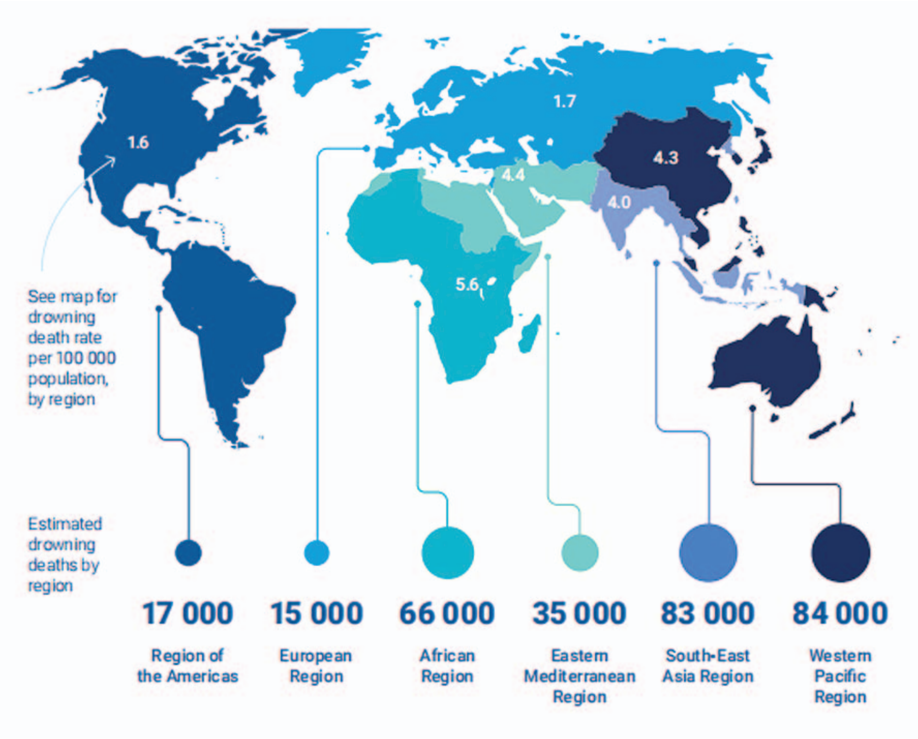


**Fig. 1** Number and rate of drowning deaths by WHO region [1]

cols after reaching drowning persons has emerged as an urgent challenge that requires prioritized resolution.

## 1.2 The role of intelligent technologies in drowning rescue

Advancements in intelligent technologies can significantly reduce the challenges in drowning rescue operations. From autonomously navigated Unmanned Surface Vehicles to UAVs equipped with advanced sensing systems, and intelligent life-saving devices featuring automatic triggering mechanisms, these smart technologies demonstrate substantial application potential in water rescue scenarios, such as rapid response, accurate positioning of drowning persons, and timely intervention thereby potentially enhancing operational rescue efficiency by enabling faster drowning person access and reducing the physical burden on rescue personnel [9-12].

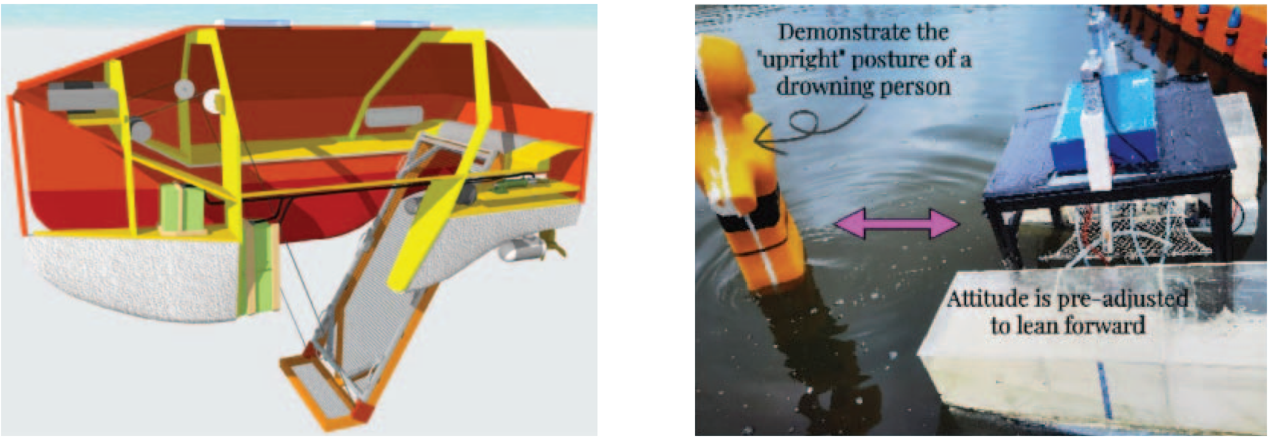
With the rapid advancement of artificial intelligence (AI) technologies, the research on intelligent devices for drowning rescue has increased. To facilitate systematic analysis, this study categorizes all intelligent rescue devices into three categories based on their operational methodologies after reaching drowning persons (See Appendix A: Table 1 Cross-technology comparison table): (1) autonomous rescue of drowning persons by remotely activated intelligent devices, (2) assisted self-rescue enabled by remotely deployed intelligent systems, and (3) self-rescue through wearable intelligent rescue devices.

## 1.3 Overview of the three rescue device categories

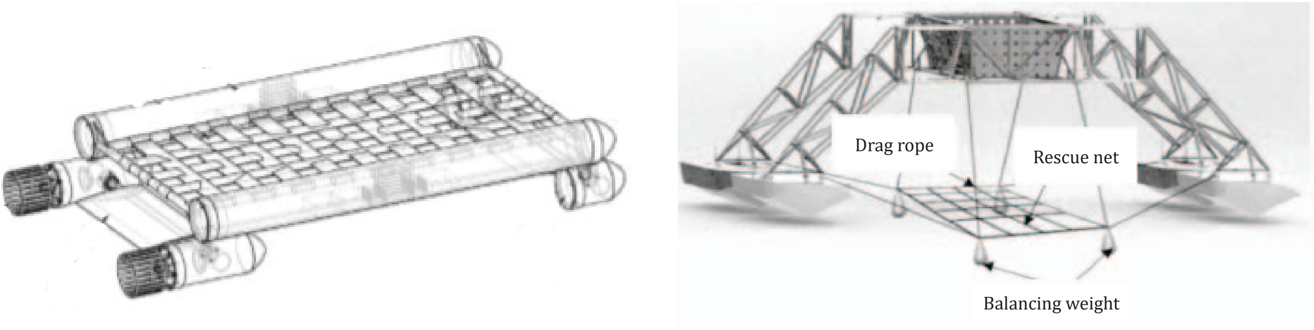
### 1.3.1 Autonomous rescue device

Autonomous rescue operations via remotely activated intelligent rescue systems have demonstrated significant potential for fully autonomous drowning person retrieval [13]. Through remote operation interfaces or embedded machine-learning algorithms, intelligent devices can actively rescue a drowning person to ensure that the head of the drowning person is exposed to the surface of the water, and even the body is completely exposed to the surface of the water, as shown in Fig. 2. All systems achieve fully autonomous rescue without drowning person cooperation. Detailed mechanisms are described in Section 3.

During the rescue process, the requirement for the self-rescue ability of the drowning person is not high, and even the drowning person does not need to have self-rescue ability. The next-generation intelligent rescue devices will be able to identify the drowning person more accurately and complete the rescue task independently, according to the attitude of the drowning person.

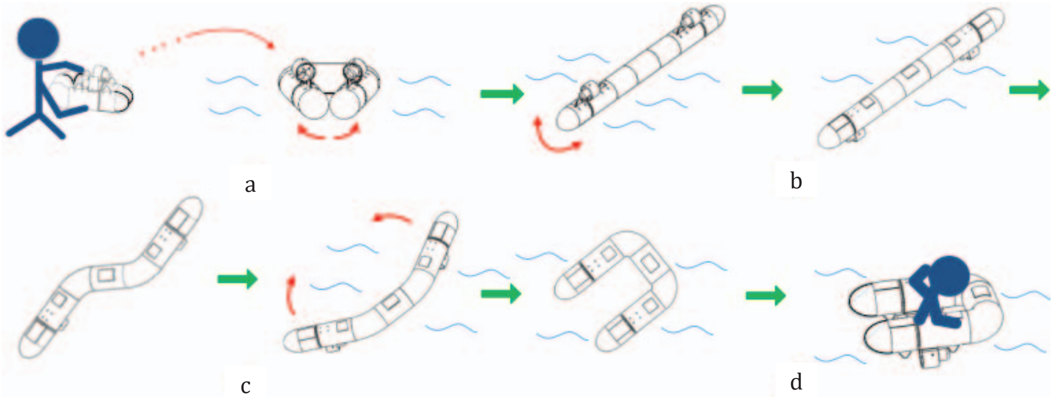


(a) Unmanned AGaPaS rescue vessel [14]   (b) Attitude adaptive rescue robot [15]



(c) Rescue underwater device [13]   (d) Wave-adapted rescue device [16]

(e) Mechanical arm [17]   (f) Human Lifting and Navigation System [18]



(g) Deformable Water-Mobile Robot [19]

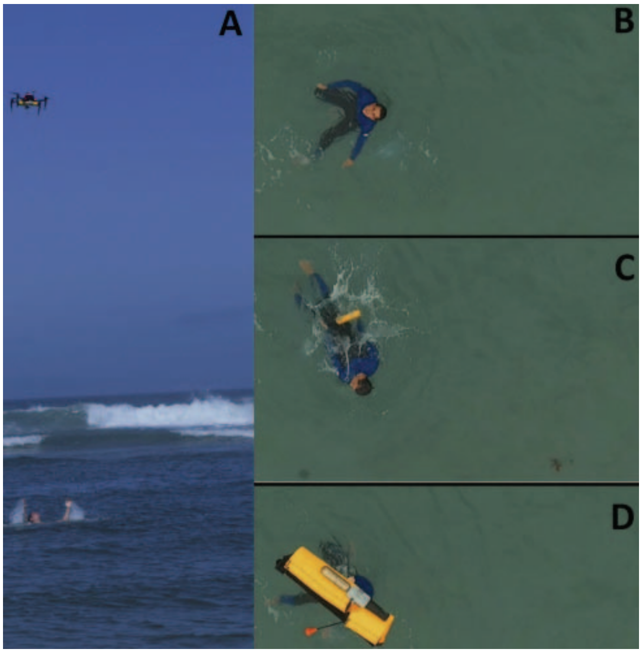
**Fig. 2** Autonomous rescue devices

### 1.3.2 Auxiliary self-rescue device

After the remote start of an intelligent device, it is necessary to use intelligent devices such as intelligent lifeboats and UAVs to assist drowning person in self-rescue, as shown in Fig. 3. Through remote control or autonomous navigation, it can quickly reach the position of a drowning person, release a rescue tool[20]. Both platforms rapidly provide flotation devices without rescuer entry. Operational details are given in Section 4. These devices are designed to reduce the risk to rescuers by allowing operations in complex or dangerous water environments that would be too hazardous for human responders.

### 1.3.3 Wearable intelligent rescue devices

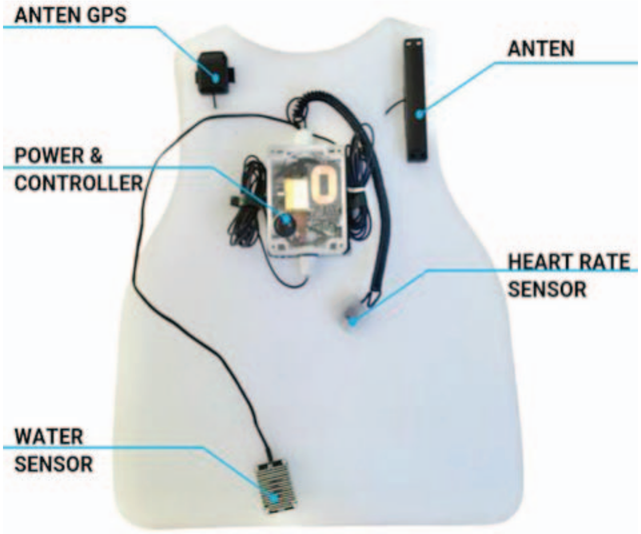
The intelligent device worn by a drowning person relies on the intelligence of self-rescue tools, such as intelligent life jackets and intelligent rescue bracelets, to provide a more reliable means of self-rescue for the drowning person [22]. These devices can be activated immediately after a person falls into the water, providing the necessary buoyancy support, physiological parameter measurement and information transmission functions, avoiding excessive energy consumption by the drowning persons and is inferred to significantly increased the survival opportunity, as shown in Fig. 4. Upon water entry, the integrated sensors trigger inflation and simultaneously transmit location and vital-sign data to the rescue centre, markedly improving survival probability.



(a) Unmanned aerial vehicles (UAV) [20]

(b) Remotely operated marine rescue vehicle [21]

**Fig. 3** Assisted self-rescue enabled by remotely deployed intelligent systems



(a) Diagram of the internal block distribution within the life jacket [23]

(b) Kingii Wristband [24]

**Fig. 4** Wearable intelligent rescue devices

### 1.4 Current challenges of intelligent rescue device

However, intelligent rescue device still faces many challenges in practical applications, including environmental adaptability, device performance in special rescue scenarios, operation threshold of rescue device, autonomous decision-making ability, interaction safety with drowning person, and rescue efficiency.

This paper provides a systematic review of the technical approaches and practical challenges associated with intelligent drowning rescue systems, establishing a comprehensive research framework for this field. Through comparative analysis of three primary technological categories—autonomous rescue devices, auxiliary self-rescue device, and intelligent wearable devices—the research identifies critical limitations in current intelligent rescue device, particularly regarding precise target localization, operational stability, and safe human-device interaction in complex aquatic environments, while specifically highlighting that advancements in multi-sensor data fusion and intelligent decision-making algorithms represent pivotal technological breakthroughs for enhancing rescue success rates.

Empirical evidence from numerous case studies (including UAV-delivered life buoy systems and underwater robotic rescue operations) suggest that that smart rescue devices have the potential to reduce response times during the critical golden rescue window while potentially minimizing risks to emergency personnel, with findings that have significant implications for improving global drowning rescue outcomes. By eliminating the need for direct human entry into dangerous waters, the use of robotic rescue devices logically infers a substantial reduction in the risk of secondary drowning incidents where rescuers become drowning persons themselves. The research contributions extend beyond technological applications as they not only accelerate the implementation of rescue robotics but also provide an evidence-based foundation for developing more effective drowning prevention and emergency response strategies, offering valuable guidance for both technological development and public safety policy formulation in aquatic rescue operations.

## 2 Methods

Based on the analysis of multiple digital databases, this paper summarizes the search terms, study period, inclusion / exclusion criteria are shown in Table 2. A flow diagram is provided (Fig. 5).

**Table 2** Search strategy

| | |
|---|---|
| Search terms (AND, OR, NOT) and truncation<br>(wildcard characters like *) | (Drown* or drowning person) AND (smart rescue device OR unmanned rescue system OR autonomous rescue device OR intelligent drowning rescue device OR unmanned rescue vehicle OR unmanned surface vehicle OR UAV OR smart life jackets OR wearable intelligent rescue device OR wearable intelligent rescue device) NOT (animal)<br>(Drowning rescue OR water rescue OR aquatic rescue OR water emergencies) AND (autonomous rescue OR intelligent rescue devices (robots, UAVs, wearables) OR intelligent drowning rescue device OR autonomous rescue device OR auxiliary self-rescue device OR wearable intelligent rescue device) NOT (industrial robot) |
| Databases searched | WHO IRIS, Taylor & Francis, CORE, DOAJ, Biblioteka Nauki, ACM Digital Library, MDPI, Scopus, ACS Publications, Science Direct, Springer, IEEE Xplore, Web of Science (WoS), CyberLeninka, Civilica, Cnki, Wanfang |
| Years of search | 2009 ~ 2025 |
| Inclusion criteria (why did you include it?) | Intelligent rescue device approaches a drowning person<br>Rescue method of intelligent device<br>Hardware structure of intelligent devices<br>New technical methods or algorithm design or device improvement<br>Includes empirical data or case analysis or practical application effect evaluation |
| Exclusion criteria (why did you rule it out?) | Traditional drowning rescue tools<br>Robot without rescue function<br>Robots for land and air rescue<br>No new technical methods or device improvements were demonstrated<br>Studies on non-drowning water emergencies (e.g., shipwrecks, flood evacuation).<br>No empirical data or case analysis or practical application effect evaluation |

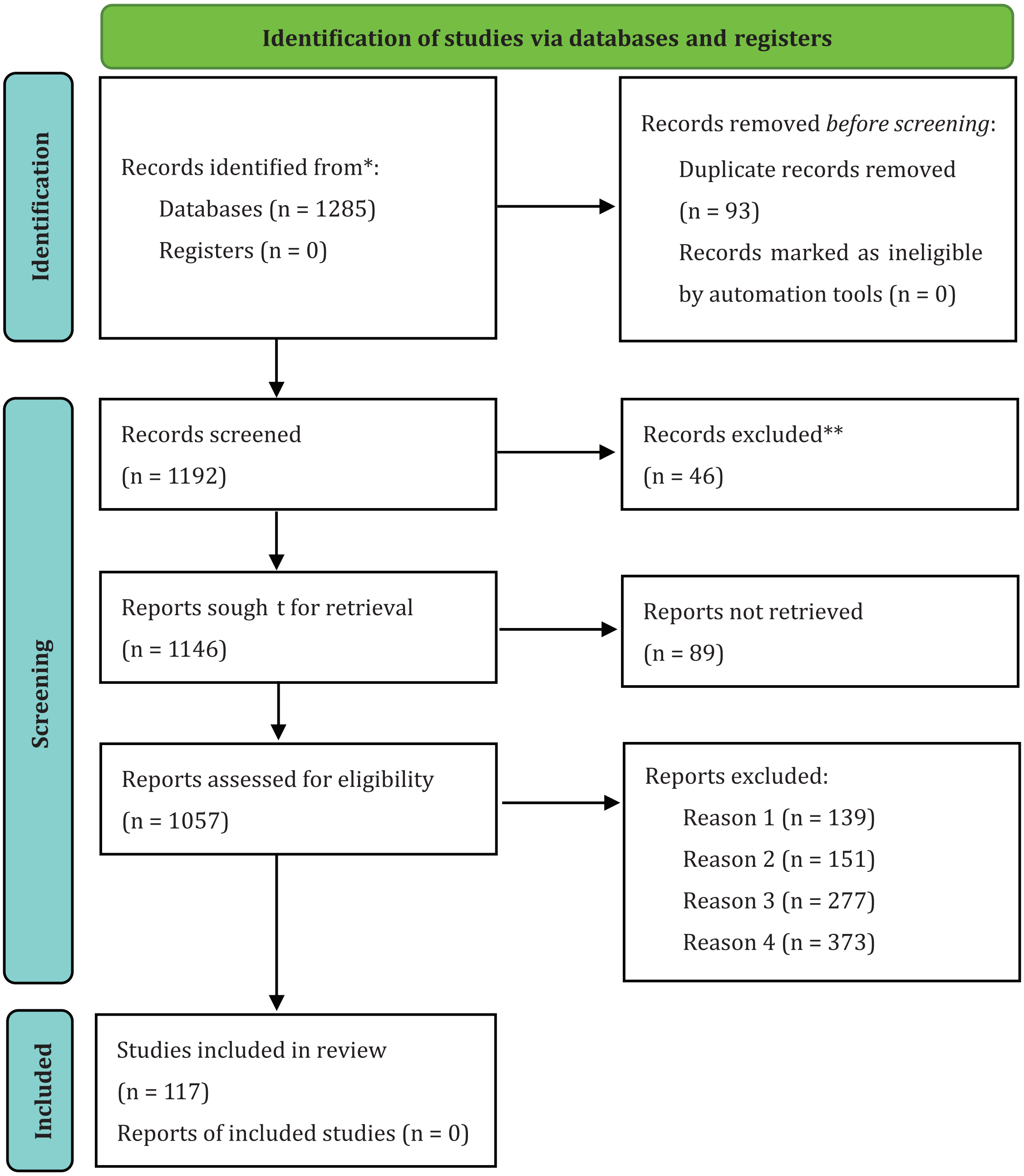


**Fig. 5** Flow diagram

## 3 Autonomous rescue of drowning persons by remotely activated intelligent devices

In water rescue work, it is very important and relatively rare for intelligent devices to quickly, autonomously, and effectively rescue drowning persons. Achieving this goal remains challenging because of various factors such as complex aquatic environments, unpredictable weather conditions, and limitations in rescue device and technologies. Researchers have explored diverse approaches to realize autonomous drowning person rescue under these constraints.

### 3.1 Intelligent devices employing rescue nets or lifting baskets for autonomous rescue of drowning persons

Rescue nets or lifting baskets are commonly used to recover drowning person in traditional maritime rescue work. However, large hulls are often constrained by factors such as the water depth, underwater obstacles, channel width, and maneuverability during operation. To address these challenges, researchers have designed small, agile, and slightly intelligent rescue device to improve the rescue effects.

Günther F. Clauss et al. realized the rapid deployment of the rescue basket by optimizing the hull dimensions of the unmanned AGaPaS rescue ship, enabling quickly approach and safely rescue of the drowning person [14]. Shuchao Ma designed a compact ice-surface rescue robot, which can carry a rescue stretcher instead of firefighters to complete the rescue missions [25]. The stretcher's linear and rotational movements eliminated posture constraints during drowning person rescue. The AUV invented by Taylor Davis et al. rescued the drowning person by releasing a mesh-based floating device from underwater according to the position of the drowning person, and dragged the device and the drowning person back to shore [26]. Zhang Yichi studied the method of combining two intelligent lifebuoys and rescue nets to rescue unconscious drowning person, which provides valuable insights for collaborative rescue robots to enhance operational efficiency [27].

### 3.2 Optimization for environmental adaptability and stability

Reducing the impact of environmental forces and accurately controlling the rescue process are conducive to improving rescue efficiency. Fully dynamic diving strategies and precise positioning perception systems can ensure the flexibility and accuracy of rescue baskets when approaching the position of a drowning person [13].

The adoption of suspension systems can mitigate the effects of wind and waves on the stability of rescue baskets or lifting baskets salvaging the drowning person and providing a more stable operational environment for rescue operations [16, 28-29]. Shipeng Wang et al. proposed an optimization scheme for attitude adjustment of rescue robots based on dynamic programming algorithm, which eliminates the change of robot stability during the rescue process by adjusting the amount and position of ballast water in real time [15].

### 3.3 Intelligent devices employing robotic manipulators or mechanical arms for autonomous rescue of drowning person

When a drowning person is unconscious or physically unable to save themselves, it is feasible to return to a safe area by clamping the drowning person with a manipulator [30]. Canjun Yang et al. designed a manipulator that can rescue a drowning person. By precisely controlling and adjusting the stiffness, the manipulator can accurately perform rescue tasks and protect the rescue from secondary injuries [31].

The manipulator exhibits advantages of accurate position control, high mobility, rapid response, and operational stability. The vision-based drowning event automatic detection system calculates the position of the drowning person using image processing algorithms and starts the robotic arm to pull the drowning person out of the water [32]. The gantry robot arm moves in a three-dimensional space based on the drowning person's centroid coordinates, provides buoyancy to the drowning person via the lifebuoy, and pulls the drowning person back to the safe zones [33-36].

The robotic arm designed by Weihao Yuan et al. can constantly adjust its posture to adapt to dynamic body changes of a drowning person, ensuring that it can always grasp the person and remain stable [17]. Furthermore, Hao Deng et al. designed a soft robotic arm to approach a drowning person from multiple angles, applying a mild and secure contact force on the drowning person to prevent secondary injuries to the drowning person [37].

### 3.4 Intelligent device with airbag system for autonomous rescue of drowning person

The integration of airbag systems with power device enables precise control of lifter speed and ensures operational safety. Junjie Huang et al. developed a new type of underwater search and rescue vehicle(USRV) with a low hydrodynamic resistance profile, capable of submerging beneath the drowning person and releasing the airbag. This advanced prototype regulates inflation rates to achieve controlled buoyant ascent, with real-time buoyancy adjustment mechanisms maintaining USRV stability during surfacing operations [38,39]. Subsea prepositioned rescue systems demonstrate comparable efficacy, as seabed-mounted lifting devices can be rapidly inflated to vertically lift drowning person. The weight-balancing technologies incorporated in these systems maintain an optimal body orientation throughout the ascent trajectory [18].

### 3.5 Structural advantage-based intelligent device for autonomous rescue of drowning person

During the rescue process, an intelligent rescue tool assists the drowning person in maintaining an appropriate posture, which can reduce secondary injuries and help the rescue tool maintain sufficient stability. Changlong Ye et al. invented an adaptive aquatic rescue apparatus with reconfigurable structural morphologies, capable of transitioning between linear, triangular, U-shaped and curved configurations in response to environmental constraints and mission requirements. This polymorphic design can clamp the drowning person and bring the drowning person back to the shore [19].

Concurrently, Jiahou Zhao et al. designed a catamaran-style rescue platform based on ergonomic principles that has elbow support and chest support to stabilize the normal posture of the drowning person and prevent the drowning person from slipping off the rescue device. When the drowning person reaches the position specified by the robot, the airbag at the back of the rescue device is inflated and drained, which can enhance buoyancy, adjust the center of gravity, and ensure the safety of the drowning person and rescue device [40].

Currently, many intelligent devices are used to rescue drowning person. Most rely on drowning person to seize rescue tools themselves, and few intelligent devices can independently rescue drowning person. The above device can independently lift the drowning person out of the water. It also considers the influence of the position and posture of the drowning person on the performance of the intelligent device and drags the drowning person back to the safe zone, which is of great significance for rescuing those who are psychologically and physically affected.

## 4 Assistive intelligent devices for drowning person self-rescue

### 4.1 Unmanned aerial vehicle(UAV)

#### 4.1.1 Payload and deployment mechanisms

UAVs can be used to quickly deliver lifebuoys or life rafts to drowning person. After determining the location of the drowning person, the UAV applies life-saving device to the drowning person through a simple delivery mechanism [41-45]. In 2017, Celia Seguin et al. proved through 28 simulation experiments, that UAVs have been shown to be faster than traditional life-saving operations in delivering life-saving device. The efficiency of UAVs is more significant, particularly under medium and severe sea conditions. UAVs can also protect lifeguards from high sea-state risks [20].

#### 4.1.2 Positioning and navigation accuracy

Whether a drowning person can catch life-saving device depends on the deployment accuracy of life-saving device [46-49]. The DJI Phantom 4 UAV is equipped with a 60 Newton automatic inflatable lifebuoy, which is operated by a remote control and flies within the visual line of sight. It achieves precise delivery by hovering above drowning persons to deploy a life buoy [50]. Nikolay A.Mostakov et al. studied that UAVs can hover above the drowning person in a storm environment to ensure that the drowning person accurately grasps the life-saving tools, and successfully assisted in a rescue operation on the Anapa city beach in Russia [51].

A.Michael Shekari investigated the use of a communication device to guide a drowning person to seize life-saving tools [52]. Liu Jie designed a UAV system that deploys compressed inflatable life buoys to drowning person from approximately 2 meters above the water surface, then performs fixed-point circling around the drowning person while providing real-time Global Positioning System (GPS) positioning updates to support subsequent rescue operations [53]. Ropes can also assist UAVs to rescue multiple drowning person, such as UAVs that can deploy buoys with tow ropes [54].

Accurate position control technology is beneficial for the accurate delivery of life-saving device. The buoy carried by the UAV designed by Hoang Mai Tran is controlled by a servo motor, which can rotate between three different positions through a remote control signal to ensure that the drowning person can easily touch the buoy [55]. ROLFER uses the differential Global Positioning System (DGPS) algorithm to improve positioning accuracy and ensure that the UAV can accurately release the life buoy or other life-saving device automatically above the drowning person [56-58].

Unmanned Aerial Vehicles (UAVs) equipped with multiple rescue tools can simultaneously rescue several drowning persons in a single mission [59]. Li Min et al. designed a UAV ejection mechanism that deploys multiple compressed life rings, which rapidly inflate into standard ring-shaped lifebuoys within 15 seconds [60]. The Geofencing technology proposed by Anthony C Ijeh and Ahmed Naufal AL Masri effectively prevents potential collisions that may occur when UAVs continuously deliver rescue device to drowning person across multiple zones [61].

### 4.2 Autonomous Underwater Vehicle (AUV)

From 2014 to 2020, China recorded an annual average of 1923 water accidents, endangering approximately 14,000 people at risk. In general, few researchers have specifically designed AUVs for underwater search and rescue [62]. Eike Krieg et al. designed and experimentally validated a submersible robot for rescuing drowning person. The rescue device on top of the robot can fix the person and tow the drowning person from the water to the surface [63]. HaoDong Qi and Ying Tang designed a rescue robot capable of sinking below the drowning person by adjusting the amount of water in the tank, activating buoyancy-enhancement devices to encapsulate targets with an extended airbag and lifting it to the water surface [64]. To investigate the rescue performance in complex underwater environments, the multi-functional robotic arm designed by Bing Sun et al. carried out rescue dummy tests in the sea area near the Jigujiao reef in the Yangtze River estuary, and the results were good [65].

### 4.3 Unmanned Surface Vehicle (USV)

During a drowning rescue operation, an USV can quickly approach a drowning person and release life-saving tools automatically or remotely to provide buoyancy support [66-68]. In recent years, there are not many related intelligent products on the market, mainly including intelligent lifebuoys such as U-safe, EMILY, Hover Ark H3 and Dolphin 1, where U-safe and EMILY have attracted predominant research attention.

### 4.3.1 U-shaped intelligent lifebuoy

#### 4.3.1.1 Structural design

Compared with traditional lifebuoy, intelligent lifebuoy demonstrate the advantages of remote control and accurate deployment, which are expected to improve the success rate of rescuing drowning person while reducing the technical requirements and operational risks of rescuers, as they eliminate the need for rescuers to enter hazardous waters directly [69]. The U-Safe lifebuoy developed by Portugal's Noras Performance Company incorporates navigational capabilities by redesigning the conventional circular structure of a traditional lifebuoy into a U-shaped configuration (Fig. 6), equipped with dual electric propeller thrusters at its stern [70, 71]. When the U-shaped intelligent lifebuoy reaches a drowning person, it slows down according to the actual situation and attempts to stop next to the drowning person. Once the drowning person grips the lifebuoy, he can stay in the U-shaped area of the lifebuoy. The intelligent lifebuoy activates its navigation system and power device to quickly bring the drowning person back to the shore or rescue ship [11, 72].

**Fig. 6** U-shaped intelligent lifebuoy [11]

#### 4.3.1.2 Interaction safety

To ensure that the drowning person can securely grasp and maintain the protection range of the lifebuoy, Shuaijun Wang et al. and YM Kalyan et al. integrated inflatable airbags in the inner ring of the U-shaped rescue device to expand and closely fit the waist of the human body.

The human body relies on the buoyancy generated by the main body of the rescue device to float on the water surface and provide sufficient stability and buoyancy [73, 74]. Chu Jing et al. conducted quantitative research on the aspects of manufacturing difficulty, structural strength, portability, motion efficiency, innovation, and comfort. The designed triangular rescue device demonstrated the characteristics of light weight, strong mobility, and high safety [75]. Auxiliary rescue devices are arranged inside a lifeguard designed by Gao Guangzhen, which can partially achieve the goal of rescuing unconscious people to a certain extent [76].

#### 4.3.1.3 Speed

To enhance the speed of U-shaped lifebuoys, Cao Jiaxiu integrated the multihull vessel concept with a conventional lifebuoy to design a trimaran fork-type rescue device that significantly improved the operational speed [77].

#### 4.3.1.4 Limited innovation and product homogeneity of the intelligent lifebuoy

The intelligent lifebuoy industry has experienced rapid development, particularly in China, where the combination of a large population and extensive water areas has driven accelerated growth in this sector. Nevertheless, current products show negligible competitive differentiation and exhibit relatively homogeneous configurations and functionalities. These products lack groundbreaking designs that are capable of effective breakthrough design in complex rescue scenarios to further enhance the rapidity design and ergonomics design [76, 116, 117].

### 4.3.2 Emergency Integrated Lifesaving Lanyard(EMILY)

EMILY (Emergency Integrated Lifesaving Lanyard) is a remote rescue robot invented by Tony Mulligan, as shown in Fig. 7.

**Fig. 7** EMILY [89]

EMILY can quickly rescue drowning person when rescuers find it difficult to reach quickly and can support multiple persons [87]. EMILY also supports the use of sonar technology for search and rescue missions. With its initial 10-day deployment in Greek territorial waters, EMILY assisted the Greek Red Cross in the safe transfer of more than 240 refugees to shore [88].

To improve the intelligence level of EMILY, Dr. Robin R. Murphy applied the artificial potential field theory to generate the vector field pointing to the target point, to realize the gradual decrease of the speed as EMILY approached the target position, to move quickly away from the target and decelerate when approaching the target, to avoid further damage to the drowning person [90].

### 4.3.3 Other USVs

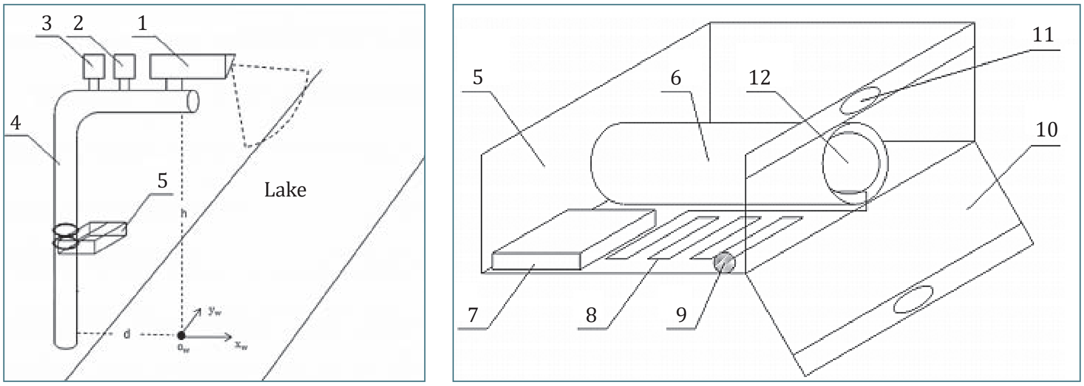
There are many challenges in the popularization and application of commercial water rescue products. Low-cost and easy-to-deploy remotely operated USVs provide an effective solution to these problems. Particularly in low- and middle-income countries, such robots are expected to play an important role in these areas because of their unique advantages and are expected to solve the problem of frequent drowning accidents [21, 89].

Researchers have pursued technological innovations to develop intelligent rescue systems with advanced functionalities to enhance the efficiency of USVs in delivering rescue tools. Jianhua Wang et al. designed a catamaran unmanned vessel with a payload capacity exceeding 100 kilograms, capable of transporting individuals back to secure locations [66]. Shashank M Gowda et al. developed rescue device that can quickly and accurately rescue drowning person under low-visibility and harsh sea conditions. This device is designed to automatically track the positioning device worn by a drowning person, known as the lifesaving band [91]. T. Gopu et al. proposed a gesture-controlled rescue robot where personnel on shore can control the robot's high-torque motors via intuitive hand signals [92]. Haiming Fu et al. engineered an amphibious rescue vessel equipped with infrared sensing, voice communication capabilities, remote control, and adaptive obstacle avoidance functions [93]. The design by Shuai Zhao et al. features a vertically separable structure that offers high stability and adaptability, ensuring the precise deployment of life-saving device via a pneumatic ejection mechanism [94].

Many drowning incidents involve multiple drowning persons. Aníbal Matos et al. studied the structure and control systems of small Unmanned Capsules (UCAPs), which are capable of autonomously navigating to designated "drowning person" locations. A single vessel can release multiple capsules, making it suitable for large-scale maritime search and rescue operations [95]. UCAPs designed by Bruno M. Ferreira et al. can accommodate an inflatable life raft designed for four people, making them suitable for simultaneously rescuing multiple drowning persons [67]. In the process of designing a trimaran unmanned surface vessel equipped with throwable lifebuoys, Zhang Di considered factors such as speed, maneuverability, seakeeping ability, and self-righting characteristics, with the capability to adjust the number of lifebuoys released each time [96]. J Zhang and Junfeng Xiong have researched unmanned surface vessel equipped with rope to rescue drowning persons and bring them back to safety [97,98].

## 5 Intelligent shore-based intelligent devices for life-saving device deployment

Intelligent shore-based throwing rescue devices demonstrate advantages in improving rescue accuracy and speed. Feng Dewei integrated motion detection with the PSPNet deep learning model to identify drowning persons' positions, triggering an alarm promptly and projecting a rescue rope toward the target location within 2 seconds, as shown in Fig. 8 [99].



(a) External view

(b) Internal view

1. surveillance camera, 2. red alarm light, 3. green indicator light, 4. support pillar, 5. device frame, 6. launch tube, 7. control module, 8. rescue rope, 9. fixed nail, 10. frame door, 11. magnet, 12. launch head

**Fig. 8** Shore based throwing rescue device [99]

The frame houses a camera, launch tube, control module and magnet-fixed rescue rope, enabling automatic projectile deployment once the drowning person's position is confirmed. Xiong Linlin et al. have invented a new type of throwing bomb for water rescue, which employs manual/motorized throwing methods to rescue drowning person in close proximity to the shore or at a distance [100]. After the rescue bomb enters the water, it can be remotely controlled in the vicinity of the drowning person, allowing for the decision to activate an airbag based on the actual situation. The rescue rope carried by the rescue device ensured that the drowning person could be pulled back to the shore.

## 6 Wearable intelligent life-saving robot

Common wearable intelligent rescue robots include smart life jackets and wristbands.

### 6.1 Intelligent Life Jacket

The intelligent life jacket can achieve automatic activation, real-time monitoring [105], and signal transmission [106] through the use of sensing activation devices [101], information technology and grid management [102], real-time monitoring device (such as heart rate and blood oxygen saturation monitors [103]), and sensing and intelligent devices (such as GPS tracking [104] and sound alarms). This enhance is anticipated to rescue efficiency and response speed, while also improving the intelligence level and management efficiency of life jackets through system integration and management [107].

#### 6.1.1 Intelligent life jacket with water level monitoring

The intelligent rescue functionality of the life jacket is reliably activated based on precise water-level measurements around the device. The intelligent life jacket system based on the OneNET cloud service platform can analyze signals from a water level sensor to ascertain whether someone has fallen into the water, automatically locate the position of the drowning person, and activate the sound and light alarm to issue an "SOS" signal [22].

#### 6.1.2 Intelligent life jackets with physiological parameter monitoring

An intelligent life jacket can accurately determine whether an individual faces drowning risk by real-time monitoring of physiological parameters and comparing them with a preset safety threshold. Nuhu Bello Kontagora et al. developed an intelligent drowning alarm system that utilizes a pulse sensor to monitor the heart rate of swimmers. When the heart rate exceeds 45–150 bpm, the inflatable life jacket swiftly elevates the drowning person to the surface of the water [108]. Simon Winkler designed a mobile device to prevent accidental child drowning, integrating a respiratory sensor with a hybrid framework: rule-based algorithms analyzing signal slopes and a convolutional neural network (CNN) classify signals to distinguish normal breathing from respiratory distress [109]. Duong Bao Nguyen embedded heart rate sensors, water immersion detectors, and GPS locators into life jackets. The system automatically activates alarms when detecting sudden heart rate spikes or immersion in water [23].

#### 6.1.3 Intelligent life jacket activated by human posture or motion patterns

The life jacket can monitor the wearer's posture or movement in real time through built-in sensors, and it automatically activates if any abnormal parameters are detected. Smart personal flotation device (SmartPFD) is a novel design of an intelligent inflatable life jacket that incorporates an Inertial Measurement Unit (IMU) to monitor the wearer's posture and acceleration [110]. The Smart Powered Life Jacket System (SPLJ) utilizes high-sensitivity triboelectric fiber sensors to monitor the movement status of a person who has fallen into the water. It integrates wireless sensor network and deep learning algorithm to analyze collected data, enabling comprehensive condition assessment and intelligent guidance for rescue operation [111].

### 6.2 Other wearable intelligent rescue robots

The innovative integration of multisensor technologies into critical body areas (e.g., wrists, chest, and joints) has emerged as a pivotal strategy for enhancing drowning rescue response efficiency.

#### 6.2.1 Smart rescue wristbands

An intelligent life-saving wristband typically combines functionalities, including physiological monitoring, emergency alerts, and GPS positioning [112]. When an accelerometer sensor detects abnormal motion patterns indicative of a drowning incident, it activates an inflation system to deploy an airbag on the wrist, providing buoyancy to keep the drowning person afloat while awaiting rescue [113]. Quan Qiu uses UCD theory to design a wristband integrated with a humidity sensor, heart rate sensor, temperature sensor and acceleration sensor, which can effectively reduce misjudgment and improve the accuracy and reliability of drowning detection [114]. Mostafa A. Ibrahim et al. designed a chest-worn belt for drowning detection, which triggers rescue mechanisms upon detecting anomalies in respiratory rate and cumulative displacement [115].

#### 6.2.2 Chest-worn devices

Furthermore, a bracelet designed by Lluís Peris Miralles continuously monitors the wearer's heart rate and blood oxygen saturation, ensuring automatic activation of buoyancy devices in genuine emergency [103].

## 7 Discussion

In this paper, the different methods of intelligent device to rescue drowning person are discussed, and the three types of rescue methods adopted by intelligent device after approaching a drowning person are summarized. This study introduces intelligent rescue device using rescue nets or lifting baskets, robotic arms or manipulators, airbags, structural integrations, UAV, AUVs, USVs, shore-based throwing rescue devices, wearable intelligent life-saving robots, and other methods to rescue drowning person. The subsequent discussion evaluates the current advancements and limitations of intelligent rescue technologies, providing a structured overview of potential research trajectories to address existing gaps.

### 7.1 Advancements and limitations in environmental force mitigation

The application of suspension systems, a fully dynamic diving strategy, a precise positioning perception system, and an attitude adjustment optimization scheme based on a dynamic programming algorithm can effectively reduce the impact of environmental forces. However, even with advanced localization and perception capabilities, current intelligent devices exhibit limitations in assessing drowning person status (e.g., injury severity and unconsciousness) and adaptively adjusting rescue strategies based on real-time physiological or situational changes. To address these challenges, future advancements should focus on multi-sensor fusion technologies to enhance robotic visual perception and contextual comprehension coupled with AI-driven decision-making frameworks optimized for complex aquatic environments. This is strengthened to achieve more efficient and intelligent rescue operations.

### 7.2 Challenges in robotic attitude stability and positioning accuracy

Under the conditions of significant surface wave disturbances, the attitude stability of devices can be significantly compromised. This instability directly propagates to the base of robotic manipulators or grippers, inducing pronounced oscillations and positional deviations that critically impair their performance in localization and grasping tasks. A variety of positioning methods, such as laser positioning, inertial navigation positioning and satellite positioning, are integrated to improve the accuracy and stability of positioning through data fusion algorithms. Concurrently, the development of platform stabilization systems specifically optimized for robotic arm operations is essential. Such systems should incorporate active balancing technologies and adaptive stabilization mechanisms to maintain the platform's attitude dynamically within tolerable thresholds, even in dynamic environments.

### 7.3 Limitations of airbag-based autonomous rescue in deep-water environments

In deep-water environments, the efficiency and reliability of intelligent devices that use airbags to autonomously rescue a drowning person may be reduced owing to the increased environmental complexity and resistance. Improve sensor technology and optimize mechanical design to increase mobility and operating range. Advanced algorithms are introduced to improve the autonomous decision-making ability of USRV, including three-dimensional path planning and three-dimensional obstacle avoidance, so that the device is more intelligent and efficient. To improve the safety and comfort of the drowning person during the lifting process, an intelligent control system is needed to adjust the lifting speed and posture, as well as the application of flexible materials to ensure the protection of the drowning person throughout the rescue process.

### 7.4 Adaptability challenges to diverse drowning person characteristics

There are significant differences in the physical characteristics, body shape, health status, and posture of different drowning person. Flexible materials and adaptive structures can make the actuator closely fit the body shape of a drowning person, prevent the drowning person from slipping, and provide a buffer to a certain extent. Furthermore, according to the dynamic adjustment mechanism of different individual special needs and psychological states, an adaptive ergonomic adjustment mechanism is introduced to make the rescue device better adapt to the body shape and posture of the drowning person and reduce the risk of discomfort and secondary injury.

### 7.5 Shortcomings of UAV-based rescue in complex environments

Complex environmental factors, such as wind, waves, light, obstacles, and ice, are changeable, which weakens the accuracy of the UAV to throw the rescue tool. The development of underwater or surface intelligent rescue device with power that can be thrown from UAVs can independently search for and approach drowning person, which can effectively reduce the shortcomings of throwing device and related algorithms. Such intelligent rescue device should integrate lightweight design and anti-environmental impact materials to ensure that it is easy to carry by UAVs and adapt to harsh natural conditions. At the same time, the UAV needs to be equipped with a self-stabilizing system to achieve post-throwing attitude adjustment, and relies on the propulsion system and navigation and positioning technology to ensure path planning and target positioning accuracy during autonomous operation.

### 7.6 Gaps in autonomous underwater rescue systems

The deployment of autonomous underwater intelligent devices for drowning person rescue can compensate for the shortcomings of surface search and rescue boats and expand the application scope of intelligent device to rescue drowning person. During the rescue process, it is crucial to ensure the safe fixation and stable improvement of a drowning person. The development of multi-functional rescue tools that can adapt to different body shapes and states of the drowning person, real-time monitoring of the fixed state of the drowning person, attitude change during the lifting process, and real-time adjustment of the robot's attitude and floating device through the dynamic balance system. This angle can compensate for the impact of water flow and the movement of the AUV. Multifunctional rescue devices that integrate initial medical support, monitor the vital signs of drowning person in real time, automatically implement necessary medical interventions, and maintain communication with the water surface support team have the potential to significantly improve the survival opportunities of drowning person.

### 7.7 Optimization directions for USV buoyancy support

This is a mature intelligent rescue method for USVs that provides buoyancy support for a drowning person. To further improve the rescue effect, a buoyancy support device can be designed with a modular structure. For example, the buoyancy module can be flexibly combined or split as required to meet the needs of different body types. Simultaneously, an adjustable mechanism is introduced. For example, an inflatable buoyancy device can adjust the buoyancy by accurately controlling the amount of inflation, and the buoyancy components of the mechanical structure can change the buoyancy distribution by stretching and rotating to adjust the position and size of the buoyancy support in real time.

### 7.8 Improvements for shore-based throwing rescue systems

The intelligent device throws life-saving tools from the shore to assist the drowning person not only reduces the dependence on manpower and reduces the technical threshold of the intelligent device to assist in the rescue of the drowning person, but also can respond quickly in the early stage of the key rescue operation, which greatly shortens the rescue time window. If an intelligent device can walk autonomously on the shore, automatically plan the path according to the position of the drowning person, fix it in an ideal position, and throw the rescue tool at a suitable angle, it will make the rescue tool closer to the drowning person and reduce the number of robots. Additionally, it is necessary to strengthen the interconnection between robot systems and build an intelligent collaborative rescue network to improve the overall emergency response capacity and resource utilization efficiency.

### 7.9 Misjudgment issues of wearable device algorithms

An intelligent life jacket integrates a variety of cutting-edge technologies, such as sensor technology, Internet of Things (IoT) technology, data processing, and analysis technology. The integration of these technologies provides powerful monitoring, early warning, and rescue capabilities for intelligent life jacket. However, whether it is an algorithm based on physiological parameters to determine the risk of drowning or an algorithm to identify dangerous situations based on human posture, there is a certain misjudgment rate. Using a variety of sensor fusion technologies, comprehensive water levels, physiological parameters, human posture, environmental factors (such as water temperature and water flow velocity), and other multi-source data through advanced signal processing and data analysis algorithms is inferred to improve the accuracy of drowning judgment. For instance, deep learning algorithms can be deployed for multi-modal data analysis, significantly improving drowning risk identification accuracy. Furthermore, the design algorithm should be able to automatically adjust the judgment threshold and model parameters according to the user's individual characteristics and real-time environmental conditions. To ensure that the life jacket can play an accurate role at a critical moment, it is necessary to conduct long-term follow-up research, analyze the stability and reliability of the algorithm in different seasons, different water types, and different groups of people, and constantly optimize the algorithm to improve its judgment accuracy in various complex situations.

## 8 Conclusion

Through an in-depth investigation of the rescue method after the intelligent device is close to the drowning person, the research shows that in different rescue environments, these three methods(autonomous rescue device, assisted self-rescue device and wearable intelligent rescue device) have their own adaptability. In order to translate these research insights into practical engineering progress and guide future development, we propose the following actionable engineering recommendations and the corresponding list of key research indicators.

## 8.1 Engineering recommendations

### 8.1.1 Enhance multi-sensor fusion for robust sensing

Integrate heterogeneous sensors (e.g., multispectral camera, lidar, millimeter-wave radar, IMU) and develop advanced data fusion algorithms (e.g., Kalman filter, fusion network based on deep learning) to ensure reliable target detection, recognition and condition monitoring in complex and adverse aquatic environments (e.g., strong light, waves, weak light).

### 8.1.2 Develop adaptive stabilization and control systems

Design active stabilization mechanisms for rescue platforms (e.g., dynamic ballast systems, gyroscope stabilizers or control moment gyroscopes) to counteract wave-induced oscillations. This is essential to provide a stable foundation for precise robot operations and the safe rescue of drowning persons in rough waters.

### 8.1.3 Achieve safe and compliant human-computer interaction

Soft robot principles, flexible materials and force/torque sensing are used in grippers and lifting mechanisms. A control algorithm is developed to ensure that the physical interaction force is kept within the biomechanical safety threshold to prevent secondary damage to the drowning person during grasping and transportation.

### 8.1.4 Optimize cross-domain mobility and deployment

Design lightweight, amphibious or hybrid (air-water) robot systems that can be quickly deployed from shore, air, or onboard. Emphasis is placed on overcoming the challenge of switching between different media and operating effectively in restricted or obstacle-rich waterways.

### 8.1.5 Establish standardized communication and interoperability protocols

Promote the use of general communication protocols (such as MQTT, DDS on LTE / 5G / satellite links) and data standards to achieve seamless coordination between heterogeneous rescue assets (UAVs, usv, auv, wearable devices) and command centers, and achieve efficient multi-robot collaborative rescue tasks.

### 8.1.6 Improve the drowning detection algorithm in wearable devices

Beyond single-parameter triggers. We use multi-modal sensor data (e.g., exercise, heart rate, water immersion, hydrostatic pressure, skin temperature) and train AI models on a wide range of real-world datasets to significantly reduce false positives and false negatives in automated activation systems.

## 8.2 Checklist of research indicators

In order to quantitatively evaluate and benchmark the performance of the intelligent drowning rescue system, the following key performance indicators need to be evaluated during development and field testing (Table 4).

**Table 4** Checklist of research indicators

| Category | Key performance indicator | Target/Consideration |
|---|---|---|
| Deployment & response | Response time (alarm to on-site) | ≤ 90 seconds for near-shore operations |
| | Operational range & endurance | Scenario-defined (e.g., > 10 km range, > 45 min endurance) |
| Target acquisition | Detection accuracy / false alarm rate | > 99% accuracy, < 1% false alarm rate in tested conditions |
| | Positioning error at point of action | < 0.5 meters |
| Rescue operation | Successful grasping/deployment rate | > 95% success rate |
| | Drowning person secure time | Minimize (e.g., < 30 seconds from arrival) |
| | Return speed (with drowning person) | Maximize safely (e.g., > 1.5 m/s) |
| Human-robot interaction | Maximum allowable interaction force | Defined safe threshold (e.g., < 200 N for grasping) |
| | Platform stability (pitch/roll) | < ±10° in specified wave heights (e.g., 0.5 m significant wave height) |
| Robustness & reliability | Operational environmental limits | Significant wave height > 2.0 m, wind speed > 15 knots |
| | Mean time between failures | > 500 hours |
| | Communication link reliability | > 99.9% within operational range |
| Wearable devices | Drowning detection accuracy | > 99.5% (minimizing both false positives and negatives) |
| | Inflation activation time | < 15 seconds from trigger event |
| | Battery life (standby/operation) | > 24 hours standby, > 2 hours active operation |

## 8.3 Limitations of the study

Although this study systematically searched major scientific databases and English publications such as Web of Science, IEEE Xplore, Scopus and cnki, there are still some limitations. First of all, since the search scope is limited to the above platforms and English literature, non-English published or unincluded studies (such as some conference reports and technical literature) may be omitted. Secondly, as a systematic review, the conclusions of this paper depend on the quality and scope of the included studies. However, due to the differences in methods, performance indicators and experimental conditions, it is difficult to conduct direct quantitative comparison and meta-analysis. Thirdly, the field of intelligent rescue robots is developing rapidly, and the latest research progress and commercial products after the search deadline may not be included. Finally, this paper mainly provides qualitative technical analysis. Due to the lack of standardized test data and protocols in existing research, quantitative performance comparison cannot be achieved.

## 8.4 Research gaps and future trends

### 8.4.1 Research gaps

#### 8.4.1.1 Limited environmental adaptability

Most autonomous rescue devices (such as underwater rescue robots and wave adaptive rescue robots) lack stable operation capabilities in extreme scenarios such as high waves (effective wave height > 2.0 meters), low visibility (turbid waters), and ice coverage.

#### 8.4.1.2 Weak ability of independent decision-making and situational understanding

Most of the existing systems rely on remote control or preset path to perform tasks, and lack the ability of autonomous judgment and real-time response based on the dynamic changes of the environment and the state of the drowning person (such as struggling, coma), so it is difficult to achieve ‘autonomous rescue’ in the true sense.

#### 8.4.1.3 Inadequate human-computer interaction security

The mechanical arm used for autonomous rescue mostly uses rigid materials, and its force control algorithm is difficult to fully adapt to the dynamic body shape change of the drowning person (such as the body posture deviation in the unconscious state), and the safety threshold of the interaction force between the device and the person lacks a unified standard.

#### 8.4.1.4 Limited intelligence of wearable devices

Intelligent life jackets, wristbands and other devices are still in the preliminary research stage in the detection technology of multi-modal data such as water temperature, water flow velocity and human motion mode, and lack of long-term verification in different populations (children, middle-aged and elderly people) and water environment.

#### 8.4.1.5 Lack of verification in real complex environment

The vast majority of the research remains in laboratory simulation or calm water test, lack of robustness verification in real marine environment such as wind and wave disturbance, ocean current change, communication delay, and lack of long-term operation stability and reliability data of the system.

### 8.4.2 Future trends

#### 8.4.2.1 Environmental adaptability technology integration

Multi-sensor fusion systems such as fusion lidar, millimeter-wave radar, underwater sonar, and thermal imaging sensors are developed to improve the accuracy of target detection in extreme environments.

#### 8.4.2.2 Intelligent Algorithms and Context Awareness Systems

An intelligent algorithm integrating computer vision, behavior recognition and environment modeling is developed to realize real-time assessment of drowning severity, water flow state and obstacle distribution, and support autonomous decision-making and dynamic path planning.

#### 8.4.2.3 Security human-computer interaction innovation

The mechanical arm is made of bionic materials to reduce contact damage; a biomechanical safety model of drowning person of different ages and body types was established, and a force control algorithm with real-time adjustment ability was developed to control the interaction force within the range of human safety threshold.

#### 8.4.2.4 Intelligent upgrade of wearable devices

A multimodal drowning detection model based on deep learning was constructed, integrating physiological parameters (heart rate, blood oxygen), environmental data (water temperature, flow rate), and human movement characteristics (struggle frequency), reducing the false alarm rate to less than 0.5%. Develop ultra-low power consumption sensors to extend the standby time of wearable devices to over 72 hours.

#### 8.4.2.5 Digital Twin and Simulation Training Platform

A high-fidelity hydrodynamic simulation model and a digital twin system are established for algorithm training, system testing and emergency drills to reduce the cost and risk of field tests and accelerate technical iteration.

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# Appendix A

**Table 1** Cross-technology comparison table

| **Technology category** | **Autonomous rescue devices** | | | **Auxiliary self-rescue devices** | | | **Wearable intelligent rescue devices** | | |
|---|---|---|---|---|---|---|---|---|---|
| Subtype | Rescue net/lifting basket robot | Robot arm / manipulator rescue robot | Airbag-type rescue robot | UAV | USV | AUV | Intelligent Life Jacket | Smart rescue wristbands | Chest-worn devices |
| Core rescue mechanism | To approach the target autonomously, lift the drowning person through the net or basket, and maintain the head surface. | Accurate grasping under visual guidance and flexible contact through stiffness adjustment | After underwater positioning, the airbag is released, and the drowning person is vertically lifted to the water surface by controllable buoyancy | Quickly reach the target area, airdrop the lifebuoy / inflatable lifejacket, and lock the drowning person through visual recognition | Remote control approach, release of life-saving platform / traction rope, drag the drowning person to the safe area | Underwater autonomous positioning, through sonar and visual identification of drowning, carrying a life rope or buoyancy device to guide it to the surface, or drag it directly to the safe area. | Real-time monitoring of physiological parameters (heart rate / respiration), automatic inflation after falling into the water, GPS positioning and sending SOS signals | Acceleration / humidity sensors recognize abnormal movements (such as drowning struggles) and trigger wrist airbags to provide buoyancy | Monitor respiratory frequency / displacement changes, trigger sound and light alarms when abnormalities occur, and link rescue centers |
| Application scenarios | Unconscious / physically exhausted | Unconscious / physically exhausted | Deep water area, rescue of seriously injured | Open water area | Water surface | Turbid waters, deep waters (more than 10m), dense areas of underwater obstacles (such as reef areas, near shipwrecks) | Waterborne workers (fishermen/crew members) | Water sports (surfing / diving), child safety | Non-professional swimmers, child / elderly protection |
| Advantages | No drowning person cooperation is needed to reduce the risk of secondary injury | Adapt to different body types, adaptive adjustment of posture | The lift is controllable and suitable for vulnerable drowning persons | Fast response speed | It has strong wind and wave resistance and can drag multiple people | It can adapt to complex underwater environments such as low visibility, and can complete the search and guidance independently without relying on the water surface vision | Take the initiative to prevent and extend the golden rescue time | It is highly portable and wearable for daily wear | Close to the chest cavity, the physiological signal monitoring is precise |
| Limitations | Poor stability in complex waters (high waves/ obstacles) | Wave interference leads to positioning deviation and deep-sea operation is limited | Deep water pressure affects inflation efficiency and relies on precise positioning | The delivery accuracy of strong wind / low light environment is reduced, and the load is limited | Poor mobility in shallow water | The underwater communication delay is high, the endurance is limited, the device is heavy and the transportation is inconvenient | Intense exercise may cause false triggering, and the wearing comfort is limited | The buoyancy is limited and only supports short-term floating | It has a strong sense of restraint when worn and is prone to interference during exercise |
| Typical researches/ devices | Unmanned AGaPaS rescue ship [14], ice-surface rescue robot [25] | Stiffness adjustable manipulator [31], soft robotic arm [37] | USRV[38], seabed-mounted lifting device[18] | Multi-rotor UAV [20,46] | U-shaped intelligent lifebuoy [69]<br>EMILY [87] | multi-functional robotic arm [65] | Intelligent life jacket [22,23]<br>SmartPFD [110] | Kingii Wristband [24] wristband integrated with multisensor [114] | Chest-worn devices [103] |

## Appendix B

**Table 3** List of top wireless remote control lifebuoy [78]

| Brand | Weight | Endurance Time | Maximum speed | Operational mode | Load capacity | Country |
|---|---|---|---|---|---|---|
| **Fiturntech** [79] | 18 kg | 60 min | 6 m/s | wireless control (1000 m) | 1500 N (Effective buoyancy) | China |
| **Oceanring** [80] | 12.45 kg | 90 min | 6 m/s | wireless control (1000 m) | 2500 N (Effective buoyancy) | China |
| **OceanAlpha Dolphin 1** [81] | 13 kg | 60 min | 3.35 m/s | wireless control (800 m) | 2250 N (Drag force) | China |
| **Skysailing** [82] | 10 kg | 60 min | 5 m/s | wireless control (600 m) | 1500 N (Effective buoyancy) | China |
| **Marine Safety** | — | — | — | — | — | Canada |
| **Shenzhen Fuyuda** [83] | 12 kg | 60 min | 6 m/s | wireless control (1000 m) | 2000N (Effective buoyancy)<br>500N (Drag force) | China |
| **Norsta Asia** | — | — | — | — | — | China |
| **Noras Performance** [84] | 13.7 kg | 5.9km | 4.17 m/s | wireless control (800 m) | 2000 N (Effective buoyancy) | Norway |
| **KINGSON** [85] | 8.9 kg | 10 min | 3 m/s | wireless control (300 m) | 180 N (Effective buoyancy) | China |
| **Hoverstar** [86] | 13.8 kg | 45 min | 4.17 m/s | wireless control (800 m) | 300 N (Effective buoyancy)<br>2400 N (Drag force) | China |