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Review

BeiDou-Enabled Personal Rescue Equipment for Urban Disaster Response: Functions, Scenarios and Technical Constraints

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Abstract: Disasters in urban areas are increasingly becoming complicated and this has required resilient positioning, communication and situational-awareness technologies of emergency responders. In this review, the potential of BeiDou Navigation Satellite System (BDS)-based individual rescue equipment in responding to disasters in urban and constructed settings will be discussed. A structured literature review was conducted to study representative rescue devices, including smart helmets, intelligent life jackets and personal positioning terminals, based on their technical functions and uses in disasters. The review combines the current capabilities of BDS-based positioning, satellite short-message communication, sensing integration and emergency information support. The findings indicate that BDS-based rescue systems can be used to enhance responder localisation, emergency communication and operational coordination particularly in situations where the terrestrial communication infrastructure is damaged or unavailable. However, they are constrained by urban signal blockage, multipath and non-line-of-sight effects, indoor positioning, power consumption and system integration problems. It is possible to note that the primary benefit of BDS, when compared to other GNSS constellations, is not necessarily a more accurate positioning in all circumstances, but a set of competitive PNT services and satellite short-message communication service. It also needs to be enhanced regarding hybrid positioning, multi-sensor fusion, low-power device design and integration with smart-city and digital-twin emergency-management platforms. These advances are essential to transform BDS-enabled rescue devices from standalone tools into components of resilient urban emergency-response networks.

Keywords: BeiDou Navigation Satellite System (BDS); emergency rescue; personal rescue equipment; urban disaster response; Positioning, Navigation and Timing (PNT); short-message communication

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1. Introduction

1.1. Urban Disaster Response Challenges

Natural disasters such as earthquakes, floods, landslides and forest fires can cause massive destruction to buildings, transportation systems, power systems and communication systems which makes it hard to respond to the emergency. In particular, terrestrial communication network failures can limit the flow of information between field responders and command centres when reliable connectivity is most needed [1,2]. Rescue workers may therefore be operating in collapsed structures, flooded areas, blocked roads and other hazardous environments with limited access to communications and incomplete situational awareness [1].

These challenges are further compounded in urban environments, where high-rise buildings, alleys, underground spaces and rubble make communication and positioning more difficult. Global Navigation Satellite System (GNSS) positioning can be impacted by signal blockage, multipath and non-line-of-sight (NLOS) effects, which impact the accuracy and integrity of satellite-based positioning in urban areas [3,4]. Furthermore, indoor and underground environments may also block GNSS signals, requiring other localisation methods to support emergency response [5,6]. Traditional communication systems can also be destroyed and lose power supply during large-scale disasters [1,2].

Consequently, urban disaster response requires resilient and integrated positioning, communication and sensing capabilities rather than reliance on a single technology [7]. Although terrestrial networks can provide high data rates under normal conditions, their availability may be compromised by infrastructure damage or power failure. Similarly, GNSS provides global positioning but is restricted in dense urban environments, whereas local positioning systems may require supporting infrastructure that could be unavailable during disasters [3–6]. Therefore, an effective emergency-response system should combine satellite, terrestrial and local sensing technologies to address operational requirements and improve urban resilience [7].

To this end, satellite systems can be a useful supplement in cases when infrastructure is affected. The BeiDou Navigation Satellite System (BDS) offers positioning, navigation and timing (PNT) services, and other services including high-accuracy positioning and short-message communication through satellites [8–10]. These capabilities have the potential to create personal rescue equipment that can improve responder localisation, emergency communication and situational awareness during urban emergencies. Past studies have indicated that BDS short-message services can be used in emergency applications particularly in areas where there are no terrestrial communication networks [1]. Therefore, personal rescue devices based on BDS are a good opportunity to enhance the efficiency of urban emergency-response systems.

1.2. Limitations of Existing Rescue Equipment

Wearable personal safety and rescue equipment is increasingly being integrated with positioning, communication, environmental sensing and physiological monitoring capabilities to improve personnel safety and situational awareness [11–14]. Smart personal protective equipment (PPE), including smart helmets and other sensor-equipped wearable devices, illustrates this transition from passive protection towards connected platforms capable of collecting and transmitting information about users and their surrounding environments [11–14]. However, the operational effectiveness of such equipment depends not only on the functions integrated into the device but also on the availability of communication networks, supporting infrastructure and reliable power. During large-scale disasters, damage to terrestrial communication and power infrastructure can therefore reduce the reliability of connected rescue equipment when these capabilities are most needed [1,2].

Localisation remains a major challenge. Global Navigation Satellite System (GNSS) devices can provide effective positioning in open environments but may become unavailable or less accurate in indoor, underground and complex urban environments because of signal blockage and adverse propagation effects [5,6]. Indoor positioning technologies can improve localisation under these conditions, but they often rely on additional sensing or communication technologies, such as Wi-Fi, Bluetooth, ultra-wideband (UWB), radio-frequency identification (RFID) and inertial sensors [5,6,15]. Moreover, indoor and outdoor positioning systems have traditionally operated as separate systems, making continuous localisation across changing environments difficult [15]. Such dependencies and transitions are particularly problematic in disaster-response environments, where infrastructure may be damaged and environmental conditions can change rapidly. Maintaining seamless localisation across outdoor, indoor and infrastructure-poor environments therefore remains a significant challenge for personal rescue equipment [15].

A further limitation is the integration of multiple equipment functions. Positioning, communication, physiological monitoring, environmental sensing and visual information may be provided by different devices or standalone subsystems, complicating data integration and the development of a unified real-time view of responder

status and surrounding hazards [13,16]. Smart helmets demonstrate how multiple sensing and communication capabilities can instead be integrated into a wearable platform [11–14]. However, increasing functional complexity also introduces practical challenges related to device integration, usability and implementation [14]. For rescue applications, these challenges are particularly important because additional functionality must be achieved without compromising mobility, reliability or ease of operation under hazardous conditions.

Therefore, the next generation of personal rescue equipment should be equipped with not only more capabilities but also better system resilience and integration capability. An effective system should support critical positioning and communication services in a compromised infrastructure environment, coordinate multiple information sources and interface with emergency command systems. Satellite positioning and communication services, such as BDS [8–10], can complement such architectures, particularly during terrestrial communication outages [17]. However, satellite services should be regarded as one component of a resilient multi-technology architecture rather than a replacement for terrestrial communication, local positioning or wearable sensing technologies. The key requirement is therefore the coordinated integration of complementary technologies so that the limitations of one subsystem can be mitigated by the capabilities of others.

1.3. BDS and Its Potential for Urban Rescue

The shortcomings of current rescue equipment underscore the importance of resilient positioning and communication systems that can sustain critical services in the face of damaged terrestrial infrastructure. Satellite-based solutions can offer a valuable complementary solution in these situations, but their performance in urban areas is still subject to signal blockage, multipath effects and indoor availability issues.

The BeiDou Navigation Satellite System (BDS) and, more specifically, the BDS-3 constellation offer global positioning, navigation and timing (PNT) services as well as other features such as high-precision positioning and satellite-based short-message communication [8–10]. The integration of positioning and satellite messaging allows BDS to facilitate both location awareness and simple information exchange in a single satellite-based system compared to traditional positioning-only applications.

These capabilities can be applied to urban emergency-response operations like responder localisation, status reporting and coordination in regions where terrestrial communication networks are not available. Past research has shown that BeiDou short-message communication can be successfully used in an emergency situation when there is no reliable coverage of the public network [17,18]. The practical usefulness of BDS-enabled rescue systems, however, relies on the availability of satellite services as well as their combination with wearable devices, sensing technologies, terrestrial communication and emergency management platforms.

Thus, BDS can be viewed as an adjunctive element of a heterogeneous urban rescue architecture instead of a replacement to the existing technologies. This review concentrates on the integration of positioning, communication and information-support capabilities of BDS-enabled personal rescue equipment, as well as on technical limitations associated with urban settings, system integration and operational deployment.

1.4. Research Gap and Objectives

The current literature on the topic of disaster-response positioning, communication and wearable rescue technologies has evolved along a number of independent research paths. The studies on GNSS have been primarily concerned with positioning performance and signal degradation in difficult conditions, whereas resilient connectivity under infrastructure disruption has been studied in emergency communications. In the meantime, multi-sensor integration to monitor responders and provide situational awareness has been investigated through wearable rescue systems and smart personal protective equipment. Though studies on BDS have proven its positioning and short-message communication capabilities, these areas of study have seldom been systematically studied in tandem in terms of individual rescue gear in complicated urban settings.

A knowledge gap thus exists in the way BDS-enabled capabilities can be incorporated into individual rescue systems and how their practical worth varies in various urban disaster scenarios. The interplay of equipment functionality, disaster-response needs and built-environment constraints, such as urban canyons, indoor and underground spaces, satellite visibility restrictions and damaged communication infrastructure have not been adequately covered in existing literature. Moreover, quantitative analysis of positioning and communication performance, comparison of BDS with other major GNSS constellations, and combination with new smart-city and digital-twin frameworks need to be further synthesized.

To fill these gaps, this review explores the use of BDS-enabled personal rescue equipment for urban disaster response. The goals are to: (1) categorise typical equipment and examine their positioning, communication, sensing and safety-critical functions; (2) assess their suitability for various types of disasters and built

environments; (3) synthesise quantitative evidence on technical performance and compare BDS with GPS, Galileo and GLONASS where appropriate; and (4) discuss future trends such as multi-sensor integration, robust communication architectures and integration with smart-city and digital-twin platforms.

2. Literature Review Methodology

2.1. Literature Search Strategy

This review used a structured literature review method to find studies on the BeiDou Navigation Satellite System (BDS), personal rescue equipment, emergency communication and disaster-response technologies based on review methodologies [19–21].

Web of Science, Scopus, IEEE Xplore and Google Scholar were used to conduct literature searches. The main search was in the period between 2019 and 2026. The starting year was selected because BDS-3 reached its operational deployment phase at this time, which resulted in growing research interest in high-precision positioning, short-message communication and application-oriented services [8–10]. Past research was kept where it offered necessary technical underpinnings or commonly referred methodological inputs.

The search strategy was a combination of three sets of keywords:

(1) Satellite navigation: “BeiDou”, “BDS”, “BDS-3”, “GNSS”, “satellite navigation”, and “positioning”;

(2) Emergency and disaster applications: emergency rescue, disaster response, search and rescue, emergency communication, earthquake, flood, fire and landslide;

(3) Personal rescue equipment: smart helmet, wearable rescue device, personal positioning terminal, wearable sensor and rescue equipment.

These sets of keywords were combined using Boolean operators. Backward citation tracking of the selected publications and methodological references also helped to identify additional relevant studies [19–21].

2.2. Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were predetermined to enhance transparency and consistency in the screening of literature [19–21].

The studies were selected based on the following criteria: (1) they were published in peer-reviewed journals, conferences or other reliable technical sources; (2) they discussed BDS, GNSS, satellite communication, wearable sensing or emergency-response technologies; (3) they contained information about positioning, communication, monitoring, rescue equipment or command coordination; (4) they were available in English; and (5) they were directly relevant to disaster response or other high-risk operational scenarios.

The studies were rejected when they were commercial materials, non-technical webpages, not relevant to emergency applications, purely theoretical and without operational relevance, duplicated records or did not contain enough technical information to be analyzed.

Initial screening was conducted based on titles and abstracts, followed by a full-text assessment of potentially relevant studies. The retained publications were subsequently classified thematically and compared.

2.3. Literature Classification Framework

The chosen studies were categorized based on three dimensions, equipment type, technical function and disaster type.

The equipment dimension entailed smart rescue helmets, intelligent life jackets, personal positioning terminals and other wearable or portable rescue equipment. The technical-function dimension included positioning and navigation, satellite or emergency communication, physiological and environmental monitoring, situational reporting and command-platform connectivity.

To compare the requirements of different scenarios, studies were further grouped into five types of disasters: earthquake, flood, fire, geological hazards and multi-hazard/general disaster response. This allowed comparing functions and environments of equipment. For instance, earthquake-related studies were analysed with a focus on building collapse and communication constraints, while flood-related studies were analysed with a focus on water mobility, tracking and emergency messaging.

The three-dimensional structure enabled this review to assess not only the technologies themselves, but also the interactions among rescue equipment capabilities, disaster scenarios and urban operational constraints. The literature classification framework used in this review is presented in Figure 1.

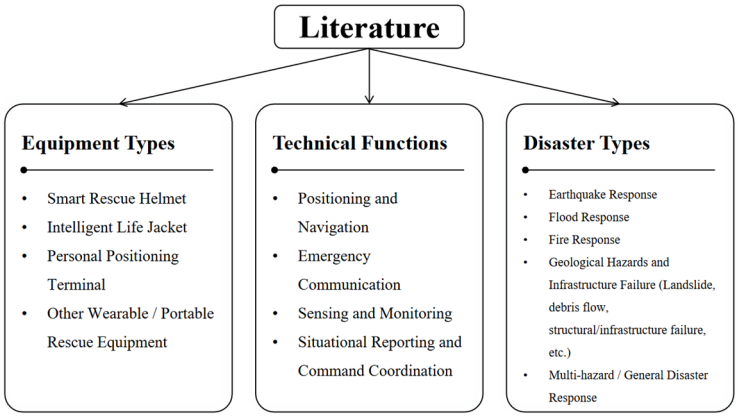


Figure 1. Literature classification framework used in this review, comprising equipment type, technical function and disaster-response scenario.

As illustrated in Figure 1, the framework organizes the reviewed literature into three parallel classification dimensions. The equipment-type dimension identifies the principal forms of personal rescue equipment, ranging from smart helmets and intelligent life jackets to positioning terminals and other wearable or portable devices. The technical-function dimension describes the operational capabilities provided by these devices, including positioning and navigation, emergency communication, sensing and monitoring, and situational reporting and command coordination. The disaster-type dimension links these equipment and functions to earthquake, flood, fire, geological-hazard and multi-hazard response scenarios. Together, these three dimensions provide a structured basis for examining how specific equipment and technical functions correspond to the operational requirements and constraints of different urban disaster environments.

2.4. Review Process (PRISMA-Informed Screening)

Figure 2 shows the literature screening process, which involves identification, screening, eligibility and final inclusion. It was designed based on PRISMA 2020 guideline [19] and structured-review approaches [20,21].

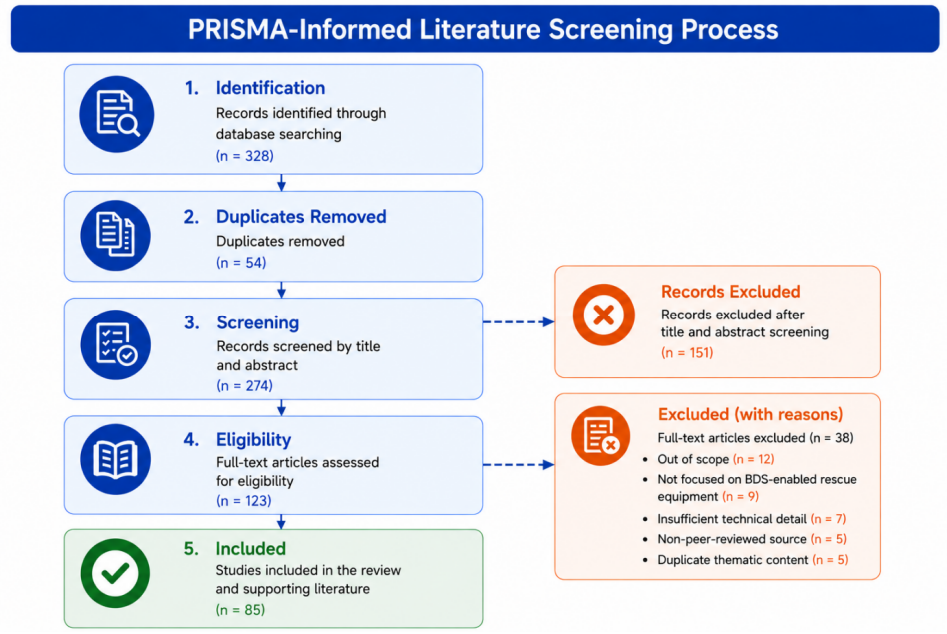


Figure 2. PRISMA-informed literature screening process for study selection in this review.

The identified records in the chosen databases were initially combined and duplicates eliminated. Screening of titles and abstracts was done based on the scope of the review and then full-text evaluation was done based on the predefined eligibility criteria. The studies that satisfied the criteria were kept to be classified thematically and analyzed thoroughly.

The process of enhancing transparency and reproducibility of study selection was conducted with the PRISMA-informed process. The last dataset contained literature on BDS and GNSS positioning, satellite communication, personal rescue equipment and disaster-response applications, as well as methodological and background references required.

3. Technical Capabilities of BDS-Enabled Rescue Systems

3.1. Positioning and Navigation

Positioning and navigation are key capabilities of BDS-enabled personal rescue equipment, supporting responder localisation, navigation, resource management and spatial awareness. BDS-3 provides global positioning, navigation and timing (PNT) services and can operate independently or as part of multi-GNSS positioning solutions [8,9,22]. In addition to standard positioning services, BDS supports high-precision positioning through augmentation and precise correction services, providing additional options for applications requiring greater positioning accuracy [9]. These capabilities are relevant to emergency applications because satellite visibility and positioning performance can vary substantially between open areas, urban streets and partially obstructed environments.

Positioning performance that can be achieved is dependent on positioning technique, availability of correction, receiver capability and observation environment. Traditional single-point positioning (SPP) offers metre-level precision and can be used in general responder tracking and navigation where there are no correction services. Centimetre-level accuracy can be obtained with real-time kinematic (RTK) positioning when reference-station corrections and stable communication links are present, but the reliance on external sources of correction constrains the flexibility of deployment [9,23,24]. Precise point positioning (PPP) reduces reliance on local reference stations, although convergence time remains an important operational consideration.

BDS-3 also offers PPP-B2b services via satellite broadcast for real-time precise positioning. According to reported results, PPP-B2b can provide decimetre-level positioning after convergence under appropriate observation conditions. BDS-only positioning has reached approximately 15 cm horizontal and 25 cm vertical positioning accuracy at the 95% confidence level, which can be further improved to approximately 10 cm horizontal and 20 cm vertical with combined BDS/GPS observations [9]. Other studies have reported centimetre-level static PPP-B2b and decimetre-level kinematic positioning after convergence [25–27]. These findings demonstrate the potential of BDS high-precision services while also indicating that positioning performance depends strongly on convergence, satellite geometry, receiver configuration and environmental conditions.

Table 1 summarises representative positioning methods and quantitative performance reported for rescue applications. The values should be understood as service or experimental results under certain conditions, not necessarily in a disaster environment.

Table 1. Quantitative performance of BDS positioning techniques relevant to rescue applications.

BDS Capability	Quantitative Metric	Typical Reported Performance	Operational Condition	Rescue Relevance	Ref.
SPP	Horizontal/vertical positioning accuracy	1.30 m horizontal median RMS; 2.71 m vertical median RMS	BDS-3 single-system, single-frequency SPP across 145 global MGEX stations; 7° elevation cut-offs	Basic responder and asset tracking without correction services	[28]
RTK	Positioning accuracy	2.1 mm east, 2.1 mm north, and 6.6 mm up RMS for dual-frequency B1I + B3I	BDS-3-only RTK; 10 m short baseline; 15° elevation cutoff; reference-pair observations available	Precise field positioning and rescue-team coordination under favourable short-baseline conditions	[29]
PPP-B2b	Positioning accuracy + convergence	Static: 2.1 cm horizontal/2.6 cm vertical RMS; kinematic: 21.5 cm horizontal/33.4 cm vertical (95%), with 17.4 min average convergence	BDS-3 PPP-B2b corrections and adequate satellite visibility	Satellite-broadcast corrections reduce dependence on terrestrial correction networks	[30]
Real-time PPP via BDS-3 GSMC	Positioning accuracy + convergence	Vehicle test: 4.1/2.2/7.1 cm E/N/U RMS after ≈21 min convergence	Vehicle real-time kinematic PPP using BDS-3 GSMC corrections; relatively open and unobstructed road conditions	Enables precise positioning where Internet-based correction delivery is unavailable	[31]

In real rescue operations, various positioning modes have varying operational needs. Responder tracking, evacuation guidance and resource coordination typically require metre-level SPP, but centimetre- to decimetre-level positioning can be used to support applications that demand greater spatial resolution, such as infrastructure

inspection, hazard-boundary mapping and precision field operations. BDS positioning data can also be combined with GIS, three-dimensional urban models and emergency-management platforms to aid in spatial visualisation and decision-making [8,9].

Nevertheless, high positioning accuracy achieved under favourable GNSS conditions cannot be directly extrapolated to dense urban disaster scenarios. Tall buildings, narrow streets, indoor spaces, collapsed structures and debris can reduce satellite visibility and introduce multipath and non-line-of-sight (NLOS) errors, thereby degrading the continuity and reliability of positioning [3,26,32,33]. Moreover, RTK depends on the availability of correction data and communication links, whereas PPP and PPP-B2b may be constrained by convergence time and service coverage. High-precision BDS positioning should therefore be regarded as one component of a resilient localisation architecture rather than as a standalone solution. Maintaining positioning continuity across outdoor, indoor and GNSS-challenged environments may require the integration of GNSS with complementary localisation technologies and sensors [16,34]. Depending on the operational environment, these may include multi-GNSS positioning, inertial navigation, vision, LiDAR and UWB.

3.2. Short Message Communication

One of the unique features of BDS-enabled rescue systems is the combination of short-message communication and positioning services provided by satellites. In contrast to terrestrial communication systems, which rely on cellular infrastructure, wired networks and local power supplies, BDS short-message communication offers an alternative information channel in situations when traditional communication networks are inaccessible or severely impaired [10,17]. This feature is especially applicable to urban disaster response, as communication infrastructure can be damaged at the same time as there is a surge in demand to coordinate responders.

BDS-3 offers two short-message communication services, regional short-message communication (RSMC) and global short-message communication (GSMC). These services vary in coverage, message capacity and frequency of transmission [10,22]. RSMC is mainly used in China and the neighboring areas and has a maximum message size of 14,000 bits (about 1000 Chinese characters), with a typical communication period of about 30 s [22,31]. GSMC offers worldwide short-message service but provides a smaller message capacity of 560 bits (around 40 Chinese characters) and a communication interval of about 1 min [10,22,31]. Such differences are trade-offs between geographical coverage and communication capacity.

Despite the fact that both services offer significantly lower data rates than terrestrial broadband networks, they can be used to transmit small emergency information, such as coordinates of responders, identification, safety status, distress signals and brief operational instructions. RSMC provides greater messaging capacity for regional emergency coordination, whereas GSMC is more appropriate for the exchange of short, high-priority messages over larger geographical distances. Neither service is intended to support multimedia transmission or continuous high-frequency sensor data streaming due to limitations in satellite payload capacity and terminal power [10,31].

Table 2 summarises the quantitative characteristics of BDS short-message communication services and their relevance to emergency rescue applications.

Table 2. Comparison of BDS-3 global and regional short-message communication services and their rescue implications.

Characteristic	GSMC	RSMC	Rescue Implication
Service scope	Global service supported by MEO satellites [27]	Regional service covering China and surrounding areas [27]	Determines deployment range of rescue operations
Maximum message length	560 bits (≈40 Chinese characters) [27]	14,000 bits (≈1000 Chinese characters) [27]	Supports transmission of coordinates, alerts and responder status
Communication frequency	Limited to once per minute [31]	Normally once every 30 s; maximum once per second [27]	Determines feasible reporting frequency
Service success rate	>95% designed; 95.6% measured average [27]	>95% designed; >99.9% person-to-person and >97.7% multicast in tests [27]	Indicates nominal and experimentally observed communication reliability
Response time	<1 min [27]	<1 s [27]	Important for distress information transmission
Terminal transmission power	<10 W [27]	<3 W [27]	Influences portable-equipment power and battery requirements
Data capability	Low-rate short-message communication; maximum 560 bits/message [27]	Higher-capacity short-message communication; maximum 14,000 bits/message [27]	High-bandwidth multimedia requires complementary communication networks
Primary operational role	Global low-rate satellite messaging	Higher-capacity regional satellite messaging	Provides a resilient supplementary communication pathway

The quantitative properties show that the main worth of BDS short-message communication is the resilience in communication instead of high-throughput data transfer. In cases where terrestrial communications systems are also present, cellular, Wi-Fi or dedicated emergency networks are more appropriate to exchange information in large volumes. Nevertheless, in case of infrastructure disruption, BDS offers a backup communication system to facilitate crucial low-rate information exchange between field responders and command centres. Their operational roles are also defined by the various service characteristics: RSMC focuses on larger capacity regional communication, whereas GSMC offers wider coverage with more limited message capacity and frequency restrictions [22,31].

This complementary role has been proven in practical studies in infrastructure-limited situations. Xu et al. created a vehicle-mounted emergency communication system based on BeiDou RSMC to conduct firefighting activities in the absence of coverage by the public-network, which proved the possibility of preserving basic communication and command capabilities using satellite messaging when terrestrial connectivity was not available [17]. Nevertheless, the research also revealed that the performance of communication might differ depending on terminal orientation and elevation angle of the satellite, which means that operational performance in complicated disaster scenarios cannot be directly expressed by nominal service specifications [17]. Moreover, Geng et al. have shown that BDS-3 GSMC is capable of transmitting compressed precise orbit and clock corrections even though it has a limited message capacity of 560 bits and a minimum communication interval of 1 min, which demonstrates the significance of efficient information encoding to low-bandwidth satellite communication [31].

In spite of these benefits, there are significant limitations to BDS short-message communication. Limited message size and transmission rate do not allow it to be used in transmitting images or communicating video or exchanging continuous sensor data [10,31,35]. In addition, the availability of communication can also be influenced by the urban environmental conditions such as high-rise buildings, underground structures, fallen materials and antenna blockage. The reported ≥95% service-success indicators of BDS-3 RSMC and GSMC are nominal system-level performance and not a guarantee of reliability under disaster conditions [22]. Real performance is based on satellite visibility, terminal configuration, antenna orientation, power and local conditions [17].

Thus, BDS short-message communication can be regarded as a robust additional layer of communication but not the substitute of terrestrial emergency networks. When available, a sensible urban rescue architecture must integrate BDS-based low-rate satellite communication with higher-bandwidth terrestrial systems, e.g. cellular, 5G, Wi-Fi, LoRa or dedicated public-safety networks [1,35]. This hybrid solution enables BDS to retain critical connectivity when infrastructure is disrupted and other networks are used to support bandwidth-intensive applications.

3.3. Data Integration and Command Support

Figure 3 shows the information flow architecture of BDS-enabled personal rescue systems. The architecture depicts how BDS does not operate as a standalone positioning technology but rather is an integrated part of an emergency-information system in which positioning, communication and sensing data are integrated to aid in operational decision-making.

As shown in Figure 3, information moves through five connected stages, from field equipment and communication networks to the emergency-management platform, command layer and field responders. Position, trajectory, health, environmental and operational data are transmitted upward for processing, while task instructions, warnings and route guidance are returned to rescue personnel. This two-way flow connects field data collection with digital-twin processing and operational decision-making.

At the equipment layer, wearable terminals, smart rescue helmets and other personal rescue devices collect heterogeneous field data, including responder location and movement, physiological status, environmental conditions and operational information [11–13,31]. BDS positioning provides one source of spatial information for locating responders and supporting the coordination of distributed rescue teams, while complementary wearable and environmental sensors provide additional information about responder status and surrounding hazards [11–13,36]. Together, these heterogeneous data streams form the field-level information basis for subsequent communication, data integration and emergency decision support [36].

The data collected are relayed via the available communication channels, such as BDS short-message communication, terrestrial wireless networks and hybrid communication systems based on infrastructure availability [1,10,17]. At the emergency-management platform layer, positioning information obtained with BDS can be combined with geographic information systems (GIS), building information models (BIM), infrastructure databases and environmental sensing networks to facilitate situational awareness, risk assessment and resource coordination [2,16,37–39].

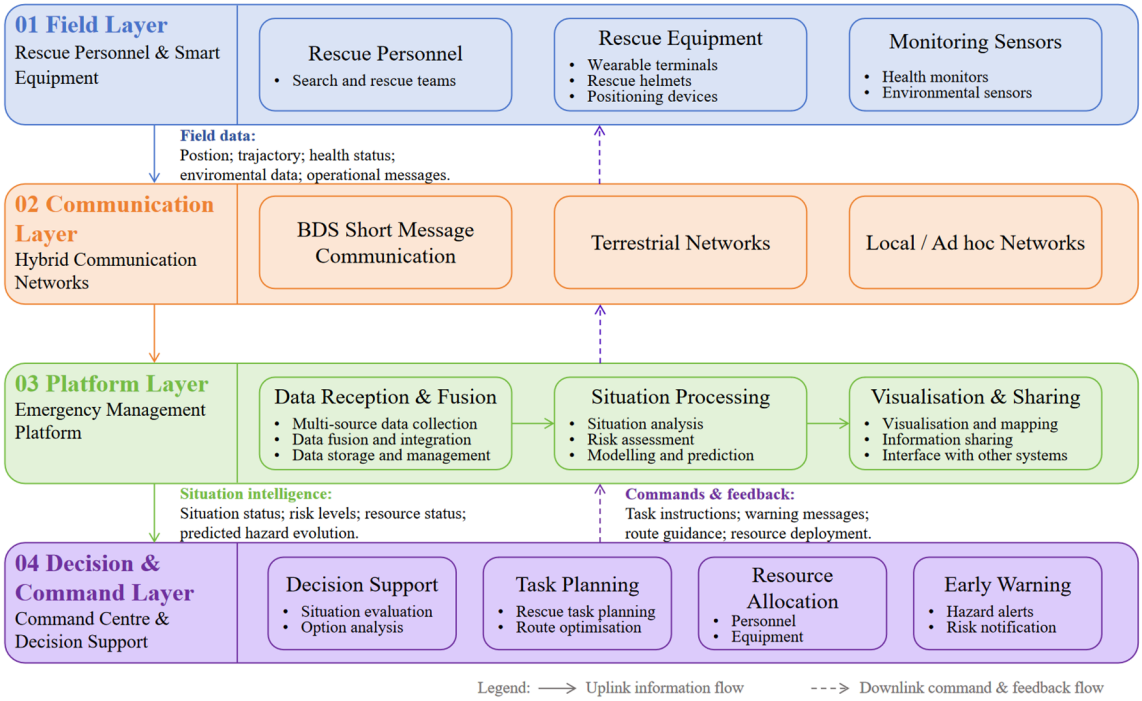


Figure 3. Closed-loop information flow architecture of BDS-enabled personal rescue systems, showing data acquisition, hybrid communication, emergency-management and digital-twin integration, decision support and operational feedback.

An emergency architecture based on digital-twin can be modeled as a closed data loop: BDS terminals deliver responder location, trajectory and status information; these are relayed via satellite or terrestrial communications to IoT gateways and emergency platforms; the combined information is used to update a digital twin of the urban environment for hazard assessment, route planning and task assignment. Navigation guidance, warnings and operational instructions can then be sent back to responders via available communication means, creating a closed-loop data flow from data collection to operational feedback.

Nevertheless, the implementation of such integrated systems remains constrained by heterogeneous data standards, communication latency, indoor positioning limitations, and limited access to accurate, real-time information about urban areas.

3.4. System Architecture

Figure 4 presents the overall architecture of BDS-enabled personal rescue equipment, illustrating the relationships among disaster environments, communication infrastructure, satellite-based services, rescue devices and emergency-management platforms. Unlike the information-flow architecture presented in Section 3.3, which describes how data are collected, transmitted and transformed into operational decisions, this architecture focuses on the functional components of the rescue system and the constraints affecting their interactions.

The architecture consists of four major functional layers. The disaster environment layer represents operational conditions, including collapsed structures, flooded areas, urban canyons and other built-environment factors that influence positioning, communication reliability and rescue operations. The infrastructure and communication layer includes BDS satellite services, terrestrial communication networks and complementary connectivity technologies. In this layer, BDS provides positioning, navigation, timing (PNT) and short-message communication capabilities, while terrestrial networks can support higher-bandwidth data transmission when infrastructure remains available [1,8–10,17].

The equipment layer consists of smart rescue helmets, intelligent life jackets, personal positioning terminals and other wearable or portable devices integrating positioning, communication and sensing functions. These devices act as the interface between rescue personnel and the information system by collecting location, environmental and operational data. The command-management layer represents emergency platforms responsible for information integration, situation assessment, resource coordination and decision support [16].

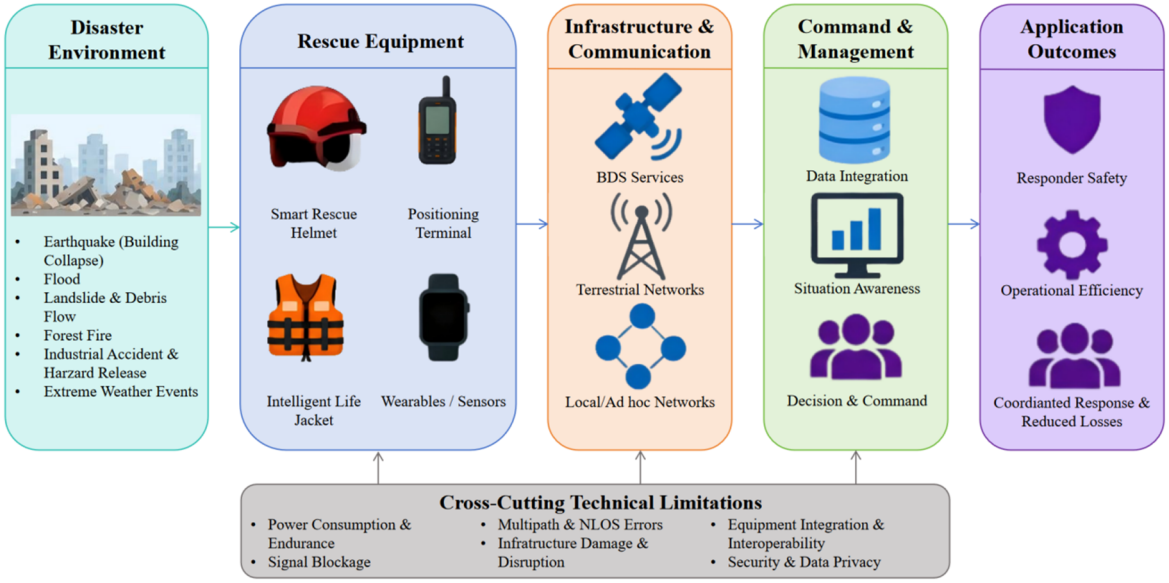


Figure 4. Overall architecture of BDS-enabled personal rescue equipment, showing the relationships among disaster environments, communication infrastructure, BDS services, rescue devices, emergency-management platforms, operational outcomes and cross-cutting technical constraints.

The interaction among these layers determines the effectiveness of BDS-enabled rescue systems under different disaster scenarios and infrastructure conditions. However, the architecture also highlights several practical constraints. Satellite signal blockage, multipath effects and non-line-of-sight (NLOS) errors can reduce positioning reliability in dense urban areas or collapsed structures. Communication disruption may limit data transmission when terrestrial infrastructure is damaged, while power limitations and interoperability issues can restrict long-duration deployment and information exchange among heterogeneous devices.

Therefore, the performance of BDS-enabled personal rescue equipment depends not only on the technical capability of individual components but also on the resilience and integration of the entire system. Future rescue systems should combine multi-GNSS positioning, hybrid communication, distributed sensing and intelligent decision-support platforms to improve reliability under complex urban disaster conditions.

4. Applications of BDS-Enabled Personal Rescue Equipment

4.1. Earthquake and Building Collapse

Earthquakes are one of the most complex urban disasters as they can lead to multiple effects including building collapse, communication breakdown, transportation disruption and dangerous working environments for emergency responders. Urban search and rescue in collapsed buildings often presents dynamic and unstable environments, restricted spaces and poor visibility, requiring effective localisation, communication and monitoring of responders for safe operations [1,5,40].

The personal rescue equipment that can be enabled by BDS can aid earthquake-response activities in terms of responder localisation, tracking their movements, emergency communication and coordination between field teams and command centres. Positioning terminals and wearable devices are sources of spatial information, whereas the BDS short-message communication is an alternative source of transmitting location information, status reports and emergency requests in case terrestrial communication infrastructure is destroyed or inaccessible [8,10,17]. Integrated wearable systems (e.g., smart rescue helmets) may also integrate positioning, sensing, imaging and physiological monitoring capabilities to enhance the awareness and safety of responders during complicated missions [11–13].

Nevertheless, the effectiveness of BDS-enabled systems in their operations is highly reliant on the rescue environment. Satellite positioning and short-message communication can be useful in open spaces surrounding collapsed buildings to support personnel tracking and exchange of information. Conversely, indoor areas, undergrounds and reinforced concrete structures may have a very destructive effect on satellite availability because of signal blockage, multipath effects and non-line-of-sight (NLOS) propagation. In these circumstances, BDS positioning might not offer enough continuity of localisation, which would necessitate its combination with other complementary technologies like UWB, inertial navigation, LiDAR and vision-based localisation [41–43].

This limitation is emphasised by quantitative evaluations. Hwang and Maeng [44] found that the mean positioning errors of GPS-GLONASS and GPS-NavIC were 22.92 m and 27.35 m, respectively, in simulated urban-canyon conditions, with maximum errors reaching over 70 m in certain tested configurations. These values are dependent on constellation choice and observation geometry but illustrate the extreme degradation that can be experienced under obstructed urban environments. By comparison, the multi-modal localisation system designed for first responders by Dahlke et al. [42], which integrated visual, Galileo-based and inertial localisation, had an overall mean positioning error of 1.73 m in challenging indoor and outdoor scenarios. Such findings suggest complementary localisation technologies are needed when satellite positioning fails.

Thus, the BDS-enabled rescue equipment cannot be regarded as a localisation solution to collapsed-building situations by itself. Rather, it must be used as a robust element of a hybrid search-and-rescue architecture in which satellite positioning and communication are integrated with local sensing, indoor positioning and environmental perception technologies. This kind of integration can enhance continuity of localisation and operational resilience in complex urban disaster environments [16,41,42,45].

4.2. Urban Flood

Urban flooding differs from rural flooding because it can affect densely populated areas, transportation networks, underground spaces and critical infrastructure. Flooded streets, damaged power infrastructure and disrupted communication systems can restrict responders' access to affected areas and reduce the effectiveness of coordination between field personnel and command centres [1,35].

Continuous localisation and communication are crucial in rescue operations in these environments. Intelligent life jackets and personal positioning terminals enabled by BDS can aid water-rescue efforts by offering location reporting, emergency alerts and tracking responders. Indicatively, intelligent life jackets based on satellite-positioning have been created by combining positioning, communication and safety-monitoring capabilities to enhance coordination and awareness of personnel during water-related emergencies [46].

In addition to individual rescue devices, BDS positioning and communication can be combined with remote sensing, unmanned aerial vehicles (UAVs), geographic information systems (GIS) and digital-twin platforms for flood-response planning and situational awareness [47,48]. This allows command platforms to integrate field responders' data with other urban environmental data for flood assessment, infrastructure assessment and emergency decision-making.

The quantitative prototype research shows that it is possible to combine localisation, sensing and communication into wearable water-rescue gear. Apriliansyah and Iqbal [49] developed a GPS/LoRa-based traceable life jacket that achieved a maximum communication range of 12.983 km in coastal testing and had an estimated operating time of approximately 5.99 h based on battery capacity and power consumption. A newer smart safety jacket with GPS, physiological sensing and IoT communication recorded an approximate operating time of about 2.9 h with a 2000-mAh LiPo battery [50]. These findings indicate the technical viability of multifunctional wearable rescue gear, as well as the significance of battery endurance as a constraint to long-term flood-response missions where constant positioning and sensing are required.

Nevertheless, these prototype findings must be viewed with caution. The coastal communication tests are not representative of dense urban flood conditions where buildings and damaged infrastructure and bad weather can influence wireless propagation. Likewise, the battery endurance estimates might not be indicative of continuous field performance in challenging rescue scenarios. Underground areas and highly blocked cities can also decrease the availability of satellites and reliability of communications. Hence, to ensure operational resilience in complex situations, efficient urban flood-response systems must integrate BDS-based positioning and communication with terrestrial networks, remote sensing and complementary sensing technologies [1,18,35,49,50].

4.3. Landslide and Infrastructure Failure

Mountainous areas, peri-urban regions and infrastructure corridors are common victims of landslides, debris flows and other geological hazards that threaten roads, bridges, utility networks and communities. Besides directly threatening the populations concerned, these events can damage transportation routes, communication facilities and critical infrastructure systems, complicating the emergency response and recovery efforts [51–53].

BDS-enabled technologies can play two complementary roles in emergency operations in geological-disaster situations: coordination of responders after an event and assessment of infrastructure conditions before or during recovery operations. Portable BeiDou terminals may be used to provide personnel location information, field observations and operational communication via satellite links when terrestrial communication infrastructure is

destroyed or unavailable during rescue missions [10,17]. In the case of remote locations and broken transportation routes, these capabilities offer an alternative channel of communication between the field teams and command centres.

In addition to the direct rescue operations, BDS positioning has been used in geological-hazard monitoring and early-warning systems as well. The GNSS-based deformation monitoring allows continuous monitoring of ground displacement, which can be used to detect landslides, evaluate slope stability and infrastructure-risk [51,53]. Together with IoT sensor networks, BDS-based monitoring systems have the potential to enhance observation capability in remote and high-risk locations where traditional monitoring methods are hard to implement [52]. This kind of infrastructure-level information can give more situational awareness to emergency managers and aid in safer deployment of rescue resources.

Quantitative research demonstrates the potential of BDS for infrastructure-deformation monitoring. In controlled bridge-monitoring experiments, Xi et al. [54] reported static BDS positioning precision of approximately 2–3 mm horizontally and 5–7 mm vertically, and demonstrated that millimetre-level displacements could be detected using BDS measurements. The study further evaluated BDS using monitoring data collected from the Baishazhou Yangtze River Bridge, demonstrating its applicability to structural deformation and dynamic-response monitoring under real bridge conditions [54]. Applications of BDS/GPS-based methods have also been explored in bridge, dam and slope monitoring [55–57]. These findings demonstrate the potential of high-precision GNSS techniques for detecting and tracking structural and terrain deformation associated with infrastructure degradation and geological instability.

Nevertheless, this high-precision performance cannot be directly translated to the anticipated performance of portable rescue terminals. Millimetre-level deformation monitoring typically depends on special observation setups, stable installation conditions and sophisticated GNSS processing, whereas individual rescue equipment must be mobile, low-power and continuously operating in uncertain conditions. The positioning reliability can also be diminished by mountainous terrain, vegetation, satellite obstruction and atmospheric effects. Thus, the contribution of BDS in geological-disaster cases can be viewed as complementary: high-accuracy services are used to evaluate infrastructure and raise awareness about the risk, and portable terminals are used to localise responders and communicate with them. The combination of BDS and IoT sensing, remote sensing and multi-source data fusion can therefore enhance long-term hazard monitoring as well as time-sensitive emergency response [51,52,54–57].

4.4. Wildland–Urban Interface Fire

Wildland-urban interface (WUI) fires pose complicated emergency-response issues since vegetation, residential communities and essential infrastructure are directly related. WUI fires also demand responders to work in highly dynamic environments where smoke, fire behaviour, damaged infrastructure and limited access routes may impair visibility and make communication between field teams and command centres more difficult compared to traditional wildfires [1,58,59].

In such cases, positioning and communication technologies that are enabled by BDS can be used to assist in firefighter localisation, team coordination and exchange of emergency information. Location reporting and simple communication capabilities are offered through personal positioning terminals and satellite-based communication devices when terrestrial networks are not available or are impaired [1,17]. These functions are especially useful in ensuring coordination between dispersed firefighting teams working in large and dynamic areas.

Wearable rescue technologies also add to these capabilities by incorporating positioning, sensing and communication capabilities into firefighter gear. Cameras, environmental sensors and physiological monitoring modules can be integrated into smart helmets and wearable monitoring systems to give information about the surrounding conditions, firefighter status and operational risks [12,13,60–62]. These systems aid in not only tracking personnel but also ongoing evaluation of firefighter safety during high-risk operations.

The potential of these wearable systems is shown through quantitative prototype evaluations. Ni et al. [63] created a multi-node firefighter monitoring system that combines physiological sensing, environmental monitoring, edge-based posture recognition and heterogeneous LoRa -BLE communication. In a 21-storey building communication experiment, the LoRa receiver was placed about 750 m away in the building and the packet-loss rate was less than 10% in complex NLOS conditions. The edge-based recognition model had a recall rate of 95 percent in recognizing lying-posture, which has the potential to detect firefighter falls or incapacitation during emergency operations [63].

Nevertheless, these prototype findings are to be viewed with caution. The experiments reported were carried out in building conditions as opposed to real high-temperature fireground conditions. Sensor reliability, communication performance and battery endurance may be influenced by heat exposure, smoke, protective

equipment, water ingress, rapidly varying propagation conditions and long operation. Thus, the performance at the prototype level cannot directly reflect operational reliability when responding to WUI fires.

In addition to specific equipment, remote sensing, UAV platforms and smart emergency-management systems can offer a wider situational awareness in monitoring wildfires, mapping fires and coordinating resources [16,58,59]. BDS-based positioning and satellite communication should be combined with wearable sensing, local wireless networks, aerial observation and command platforms in effective WUI fire-response systems. These multi-layer architectures are more resilient than using any one positioning or communication technology especially in situations where smoke, complicated terrain and infrastructure disruption all have a concurrent impact on emergency operations.

4.5. Overall Architecture of BeiDou-Enabled Personal Rescue Equipment

The BDS-enabled personal rescue equipment combines positioning, communication, sensing and emergency-response capabilities into various forms of equipment. Nonetheless, the design requirements of these systems differ based on operational conditions, user needs and disaster situations. Thus, the choice of equipment must be based not only on the functions provided but also on practical considerations such as portability, endurance, sensing capability and deployment conditions.

Table 3 compares three typical types of BDS-enabled rescue equipment: smart rescue helmets, intelligent life jackets and personal positioning terminals. Although BDS positioning and short-message communication offer ubiquitous underlying capabilities, further sensing and monitoring capabilities define the applicability of each category of equipment to various operational needs [1,10,17].

Table 3. Functional and operational comparison of representative BDS-enabled personal rescue equipment.

Function/Capability	Smart Rescue Helmet	Intelligent Life Jacket	Personal Positioning Terminal
Primary objective	Situational awareness and responder protection	Water rescue and emergency localisation	Location tracking and communication
BDS positioning	Integrated positioning for personnel tracking	Location reporting in water-rescue scenarios	Core function for navigation and tracking
Short-message communication	Emergency reporting and status transmission	Distress alert and location transmission	Primary emergency communication function
Sensor integration	High—imaging, physiological and environmental sensors	Medium—safety and environmental monitoring	Low to medium
Situational awareness	High	Medium	Limited
Portability	Medium	Medium	High
Endurance	Medium	High	High
Main advantages	Multi-modal information acquisition	Flotation protection and rapid emergency alert	Portable positioning and wide-area emergency communication
Main limitations	Weight, power consumption and system complexity	Scenario-specific application	Limited sensing and contextual-awareness capability

Intelligent rescue helmets are designed primarily to enhance responder situational awareness by integrating positioning, communication, imaging and sensing capabilities into a wearable platform. Such systems are particularly relevant to complex rescue environments, including building collapse and firefighting operations, where location information, environmental observations and physiological monitoring can support both individual safety and command-level situational awareness [11,13,60–62]. However, integrating multiple sensing, communication and processing modules into a single wearable platform increases system complexity and may introduce practical constraints related to device weight, power consumption and operational endurance [11,12,14]. These trade-offs are particularly important in physically demanding and prolonged rescue operations, where additional equipment burden can affect responder performance and where functionality must therefore be balanced against ergonomics, mobility and operational endurance [14,64].

Smart life jackets are primarily intended to be used in flood and water-rescue scenarios, where the ability to quickly locate a person and communicate an emergency is essential. BDS-equipped life jackets offer more features than traditional flotation devices, including location tracking, emergency alarms and communication assistance, which enhance coordination during water rescue incidents [46]. However, they are more specialised and have more limited sensing capabilities than multifunctional wearable systems.

A more communication-oriented type is personal positioning terminals. These gadgets focus on satellite navigation and positioning, trajectory recording and short-message communication, which can support search-and-rescue efforts in locations where terrestrial networks are unavailable [10,17]. Their primary strengths include portability, long-lasting and large-area communication capacity, but they tend to offer less contextual information than sensor-rich wearable systems.

The comparison indicates that no single equipment category can address all operational requirements of urban disaster response. Smart helmets provide enhanced situational awareness, life jackets are specifically adapted to water-based rescue, and personal positioning terminals offer flexible positioning and communication capabilities across a broader range of environments. These complementary roles suggest that BDS-enabled rescue systems should emphasise multi-device and multi-sensor cooperation rather than attempting to replace individual equipment categories with a single universal device. Wearable sensing and IoT-based emergency platforms can integrate heterogeneous field information to improve information availability, situational awareness and operational coordination [16,36,39]. Within such an architecture, satellite communication and multi-source positioning can provide additional communication and localisation capabilities when integrated with other sensing and command-support technologies.

5. Critical Discussion and Future Directions

5.1. Technical Constraints and Reliability in Urban Environments

Though BDS-enabled personal rescue equipment offers positioning, navigation and communication capabilities to urban disaster response, its operational reliability is highly dependent on the built environment around it. Tall buildings, fallen structures, underground spaces and partially enclosed areas may decrease the visibility of satellites and cause multipath and non-line-of-sight (NLOS) errors, which lead to the degradation of positioning performance achieved under open-sky conditions in realistic rescue scenarios [4,32,44,65].

A fundamental limitation of satellite positioning is its dependence on the local signal-propagation environment. In urban canyons, satellite visibility can be reduced and positioning geometry degraded, while multipath and non-line-of-sight signals may introduce substantial measurement errors even when a valid GNSS solution remains available [4,32,66]. Integrating multiple GNSS constellations, including BDS with GPS, Galileo and GLONASS, can increase the number of available observations and improve satellite availability, geometry and redundancy in partially obstructed environments [44,67]. However, the contribution of BDS in such configurations should be interpreted as an additional source of positioning observations and redundancy rather than a guarantee of reliable standalone positioning. Multi-GNSS integration can mitigate limited satellite visibility, but it cannot eliminate propagation-induced errors or maintain satellite-based positioning when the environment becomes fully GNSS-denied [4,32,44].

The second weakness is related to the distinction between nominal positioning accuracy and operational performance in disaster situations. Under appropriate observation conditions, centimetre- to decimetre-level positioning can be achieved with high-precision BDS services such as PPP and PPP-B2b [9,22,26]. But this kind of performance necessitates constant high-quality satellite observations and proper correction services. In urban rescue applications, convergence can be interrupted by frequent signal blockage, cycle slips and poor quality of observation, which can decrease positioning reliability [9,26]. Hence, positioning systems should be considered in rescue applications based on both peak accuracy and availability, continuity and resilience to varying environments.

Moreover, precise correction services cannot completely eliminate local signal propagation errors. PPP-based positioning mitigates satellite orbit and clock errors through precise correction products, but its performance remains affected by local multipath and non-line-of-sight (NLOS) signal propagation. Therefore, environmental awareness and complementary technologies, such as 3D building models, NLOS detection, inertial sensing, LiDAR, vision-based localisation and other hybrid positioning methods, are needed to improve urban positioning reliability [32,65,66,68].

Another challenge is maintaining positioning continuity during transitions between outdoor, semi-covered and GNSS-denied environments. Emergency responders may move from open areas into damaged buildings, tunnels or underground structures, where satellite visibility progressively decreases and GNSS signals may eventually become unavailable [5,6,33]. Multi-GNSS integration can improve satellite availability in partially obstructed environments, but GNSS-only positioning cannot provide continuous localisation once satellite signals become insufficient or unavailable. BDS-enabled rescue equipment should therefore form part of a hybrid localisation architecture that integrates GNSS with complementary positioning technologies and sensors to support seamless indoor–outdoor localisation [15]. Depending on the operational environment, these may include inertial measurement units (IMUs), visual localisation, LiDAR and other local sensing technologies [5,6,33]. When satellite signals remain available, BDS measurements can contribute to the reliability of integrated GNSS/INS positioning; as satellite availability decreases, complementary sensors must assume a progressively greater role in maintaining localisation continuity [34,69,70].

Reliability of communication is subject to the same limitations. BDS short-message communication offers an autonomous satellite-based communication channel that does not rely directly on terrestrial cellular

infrastructure, which can be useful in the aftermath of earthquakes, floods and infrastructure failures [10,27]. The availability of satellite communication however may also be influenced by obstruction, antenna orientation and operating conditions. Thus, it is mainly a robust backup communication system as opposed to a reliable substitute to terrestrial emergency networks.

These weaknesses imply that rescue equipment with BDS capabilities must be analyzed based on a layered reliability model. On the satellite level, the multi-GNSS integration enhances redundancy and availability. At positioning level, correction services and error-mitigation methods minimize particular sources of uncertainty. GNSS, inertial and environmental sensing integration at the device level enhances continuity in case of signal degradation. At the communication level, BDS short-message services are an alternative route when there is no terrestrial infrastructure.

Thus, the role of BDS in urban disaster response is not to remove the inherent challenges of satellite navigation in dense urban areas. Rather, BDS offers more positioning options, high-accuracy services and satellite communications that can be combined with other technologies for robust rescue operations. The usefulness of BDS becomes evident when it is compared to other major GNSS constellations, as outlined in Section 5.2.

5.2. Comparison with Other GNSS Systems

BDS is one of the four major global navigation satellite systems (GNSS), together with GPS, Galileo and GLONASS, all of which provide global positioning, navigation and timing (PNT) services [71,72]. BDS can operate independently while also contributing additional observations to multi-GNSS positioning solutions that combine measurements from multiple constellations [67]. Therefore, the value of BDS for personal rescue equipment should not be evaluated solely in terms of standalone positioning accuracy. A rescue-oriented comparison should instead consider positioning capability, high-precision services, communication functions and operational robustness in obstructed urban environments.

Under favourable open-sky conditions, all major GNSS constellations can provide metre-level standalone positioning, while precise positioning techniques can improve accuracy to the decimetre or centimetre level when appropriate corrections and sufficient observation conditions are available [22,26,28,71,73]. Current evaluations indicate that modern GNSS systems provide broadly comparable baseline PNT capability. GPS has improved its signal-in-space performance in recent years, with reductions in signal-in-space range error reported compared with previous performance levels [74]. BDS-3 also demonstrates competitive signal-in-space and precise-positioning performance [26], while Galileo provides high-accuracy positioning services through its High Accuracy Service (HAS) programme [75,76]. These results indicate that no individual constellation can be considered universally superior for all rescue applications.

Differences among GNSS systems become more relevant when considering high-precision augmentation services. BDS-3 provides PPP-B2b corrections through satellite broadcast, enabling decimetre-level positioning after convergence under suitable conditions [9,24,30]. Galileo provides the High Accuracy Service (HAS), which delivers precise corrections through the E6 signal and Internet-based services. Reported Galileo HAS evaluations achieved approximately 13.1 cm horizontal and 18.6 cm vertical 95% RMS accuracy for a combined Galileo/GPS kinematic PPP solution, with approximately 7.5 min convergence time under the evaluated conditions [76]. These results demonstrate that BDS high-precision services have practical value, but they should be considered comparable to, rather than universally better than, competing augmentation solutions.

As shown in Table 4, high-precision positioning capability alone does not determine the suitability of a GNSS system for urban rescue equipment. PPP and other precise-positioning services require sufficient satellite visibility, observation continuity and convergence time, which can be difficult to maintain when responders operate near high-rise buildings, collapsed structures or partially enclosed environments. Therefore, the practical value of GNSS integration depends more on improving availability, robustness and continuity than on achieving the highest theoretical accuracy.

A more distinctive difference among the systems is satellite communication capability. BDS-3 integrates PNT services with regional and global short-message communication functions [10,27]. These services allow compact information, including coordinates, responder status and emergency messages, to be transmitted through satellite links without relying exclusively on terrestrial communication infrastructure [10]. Compared with GPS, Galileo and GLONASS, which primarily provide positioning and timing services together with separate augmentation solutions, BDS incorporates an integrated short-message communication capability within its service architecture. This feature provides an additional communication pathway for transmitting essential emergency information and is particularly relevant for personal disaster-response equipment operating in areas where terrestrial networks may be disrupted.

Table 4. Rescue-oriented comparison of major global GNSS systems.

Metric	BDS	GPS	Galileo	GLONASS	Rescue Implication
Global PNT availability	Yes	Yes	Yes	Yes	All four systems provide the primary outdoor positioning layer. Multi-GNSS reception is preferable to reliance on a single constellation.
Standalone positioning	Metre-level under favourable open-sky conditions	Metre-level under favourable open-sky conditions	Metre-level under favourable open-sky conditions	Metre-level under favourable open-sky conditions	Nominal standalone accuracy is less important than satellite visibility, geometry and continuity in obstructed urban environments.
High-precision capability	PPP-B2b and other precise positioning services	PPP through established correction and augmentation infrastructures	Galileo High Accuracy Service (HAS)	PPP through external correction infrastructures	Precise positioning services can support mapping and command applications but require sufficient observations, correction availability and convergence time.
Representative quantitative performance	PPP-B2b: BDS-only kinematic tests reported 21.5 cm horizontal and 33.4 cm vertical accuracy (95%), with 17.4 min average convergence [30]	SISRE reduced by approximately 30% in early 2024; dual-frequency P(Y)/LNAV SISRE decreased from about 45 cm to approximately 30 cm RMS [74]	Galileo HAS: combined Galileo/GPS kinematic PPP achieved 13.1 cm horizontal and 18.6 cm vertical 95% RMS, with 7.5 min 95% convergence time [76]	Static PPP: 9.4 mm horizontal 2D and 16.9 mm 3D mean error in the 2019 evaluation; approximately 33 min convergence to a 10 cm threshold [77]	Published values were obtained using different performance metrics, correction services and experimental conditions and should not be interpreted as a direct ranking of rescue performance.
Satellite short-message capability	Yes; regional and global short-message communication services [27]	No equivalent general-purpose GNSS-integrated user messaging service	No equivalent general-purpose GNSS-integrated user messaging service	No equivalent general-purpose GNSS-integrated user messaging service	A distinctive BDS capability: compact emergency information, such as coordinates and responder status, can be transmitted through an integrated satellite short-message service.
Urban-canyon limitation	Multipath, NLOS and signal blockage	Multipath, NLOS and signal blockage	Multipath, NLOS and signal blockage	Multipath, NLOS and signal blockage	No individual constellation can eliminate GNSS degradation in dense urban environments.
Indoor/deeply obstructed operation	Limited or unavailable	Limited or unavailable	Limited or unavailable	Limited or unavailable	GNSS integration with INS, vision, LiDAR or wireless positioning remains necessary for indoor and collapse-zone navigation.
Value in multi-GNSS architecture	Additional satellites plus differentiated communication and high-precision services	Mature and widely supported primary constellation	Additional observations and HAS corrections	Additional constellation diversity	Combining constellations improves satellite availability, geometry and redundancy rather than selecting a single "best" GNSS.
Principal rescue relevance	Competitive PNT + integrated satellite short-message communication	Mature and broadly interoperable PNT	High-performance PNT and open high-accuracy service	Additional positioning redundancy	BDS is particularly valuable as a component of a resilient multi-GNSS, multi-sensor and hybrid-communication architecture rather than as a replacement for other GNSS.

Nevertheless, all GNSS constellations are subject to similar fundamental limitations in dense urban environments. Buildings, debris and indoor structures can block satellite signals and introduce multipath and non-line-of-sight (NLOS) errors, irrespective of the constellation used [4,44,65]. The practical benefit of combining BDS, GPS, Galileo and GLONASS therefore lies in increasing satellite diversity, improving positioning geometry and providing greater observational redundancy rather than in selecting a single optimal constellation [44,67,72]. Multi-GNSS integration can increase the likelihood of maintaining sufficient satellite observations for positioning when

signals from some directions are obstructed [44]. However, constellation diversity cannot eliminate multipath or NLOS errors and provides limited benefit when satellite signals are severely attenuated or completely unavailable.

From the perspective of rescue-equipment design, BDS should not replace other GNSS systems but should complement them. The main rationale for incorporating BDS into personal rescue equipment is not a universal positioning advantage, but the combination of competitive PNT capability and satellite short-message communication. Accordingly, BDS-enabled rescue systems should be considered components of a resilient multi-GNSS, multi-sensor and hybrid-communication architecture rather than standalone BDS solutions.

5.3. Device Constraints

Even though BDS-enabled rescue equipment combines positioning, communication and sensing functions in personal devices, the deployment of such equipment is still limited by hardware constraints, power consumption, system complexity and ease of use. The suitability of different types of equipment depends not only on their technical capabilities but also on whether they can provide these functions with acceptable weight, sufficient endurance and manageable maintenance requirements [11–13,46,60].

Smart rescue helmets can enhance situational awareness by integrating positioning, imaging, physiological monitoring and environmental sensing capabilities [11–13,64]. However, integrating multiple sensing, communication and processing modules into a wearable platform increases system complexity and may introduce constraints related to device weight, power consumption and battery endurance [11,12,14]. These constraints are particularly important in physically demanding rescue environments, where personal protective equipment and additional wearable devices can affect the physiological and physical performance of responders [64]. Future designs must therefore balance sensing and communication capabilities with ergonomic requirements, mobility and operational endurance [14,64].

Smart life jackets show the same trade-offs. These systems enhance flood and water-rescue efforts by combining positioning, communication and emergency-alert capabilities with personal protective equipment [46]. Nonetheless, they are very scenario-specific, and other sensing or communication functions can be costly, require more maintenance, and consume more energy, which restricts their use on a large scale.

Personal positioning terminals offer benefits in terms of portability, endurance and communication resilience especially in remote locations where terrestrial networks are not reliable [10,17]. However, their simpler construction tends to offer less contextual information as compared to sensor-rich wearable systems. Additional sensing capabilities or sophisticated positioning capabilities can enhance functionality but also add complexity to hardware and power needs.

In addition to the specific equipment types, the combination of positioning, communication, sensing and data-processing capabilities introduces more general issues of reliability, cost and maintenance. The use of low-cost GNSS and sensor components can reduce deployment barriers but may result in inconsistent performance in challenging environments [78]. On the other hand, more sophisticated solutions with GNSS/INS integration, accurate corrections and multi-sensor fusion can enhance performance but demand extra hardware resources, computing power and system management [24,69,70,79].

Thus, there is a need to balance between functionality and deployment limitations in the development of BDS-enabled rescue equipment. The lightweight hardware, low-power architectures, modular designs and reliable multi-sensor integration should be considered in future systems. The aim is not to maximise the number of integrated functions, but rather to achieve an optimal balance among positioning capability, communication resilience, endurance and operational usability.

5.4. Smart City and Digital Twin Integration

BeiDou-based rescue equipment has more than just an individual positioning and communication value in its operations. Personal rescue devices can be used as distributed sensing nodes that deliver field information to larger urban information infrastructures, along with UAV platforms, environmental sensors, infrastructure-monitoring systems and emergency-management platforms [16,39].

In these integrated architectures, BDS-equipped devices offer crucial field-level information, such as responder position, movement path, emergency alarms and personnel status. These data can be relayed via satellite or terrestrial communication networks and integrated with geographic information systems (GIS), infrastructure databases and urban monitoring platforms to aid situational awareness, resource coordination and operational decision-making [2,16,39]. Thus, the contribution of BDS is not just in providing coordinates but also in providing reliable spatial information as part of a broader ecosystem of emergency information.

Digital twin technology offers a potential platform for integrating and analysing heterogeneous data sources in disaster response. Digital twins can combine real-time observations with three-dimensional urban models, infrastructure information and simulation results to support dynamic disaster assessment and emergency decision-making [48,80–83]. UAVs can provide complementary aerial observations for disaster monitoring, damage assessment and search-and-rescue operations, particularly in areas that are difficult or hazardous to access directly [80,84]. In building-collapse or flood scenarios, such observations can be integrated with responder positions obtained from BDS-enabled devices, building and infrastructure information, and environmental sensor data within an emergency-management or digital-twin platform [47,48,80–83]. The resulting integrated information can support the assessment of accessibility and operational risks and inform route planning and resource allocation.

The integration of artificial intelligence (AI), IoT and digital twins can also enhance the analytical capacity of BDS-enabled emergency systems. The multi-source information analysis, damage assessment and decision support can be supported by AI-based methods, whereas the continuous data acquisition of distributed devices and sensors is possible with the help of IoT networks [16,37,38]. Nevertheless, in practice, deployment is difficult because of heterogeneous data formats, communication latency, incomplete urban models and inability to keep real-time synchronisation across platforms [16,39,48].

Thus, the next generation of BDS-based rescue devices should not only aim to enhance device-level positioning and communication capabilities but also be compatible with smart-city emergency systems. Through integration of individual rescue devices with digital platforms, BDS-enabled systems can develop from stand-alone positioning and communication devices into elements of smart urban resilience systems. To achieve this, we need robust communication networks, data interfaces and realistic real-time urban models validated in disaster scenarios.

6. Conclusions

As this review shows, BeiDou-enabled personal rescue equipment can offer value in addition to standalone satellite positioning. Combining positioning, short-message communication, sensing and information-support functions, BDS-enabled systems have the potential to offer an extra degree of resilience to urban disaster-response activities, especially when terrestrial infrastructure is damaged or inaccessible.

The analysis shows that different types of equipment are designed to meet specific operational needs, rather than providing a one-size-fits-all solution. Wearable systems can improve situational awareness by integrating multi-sensors, water-rescue devices can assist with localisation and emergency communication in aquatic conditions, and personal positioning terminals can offer portable positioning and communication in infrastructure-disrupted situations. Thus, successful rescue systems will probably be based on complementary sets of equipment and technologies.

Nevertheless, the actual implementation of BDS-based rescue devices is limited by environmental and engineering factors. The signal blockage in urban areas, multipath and NLOS effects, indoor positioning problems, battery constraints, complexity of hardware and interoperability issues do not allow BDS to be used as an independent solution. Rather, BDS must be combined with multi-GNSS measurements, hybrid positioning technologies, multi-sensor fusion and complementary communication networks to provide reliable performance in complex disaster scenarios.

Future research should aim to enhance localisation continuity, minimise device-level limitations with lightweight and low-power designs, and integrate with smart-city emergency-management systems. Connectivity with IoT networks, artificial intelligence and digital-twin platforms offer the potential to turn individual rescue devices into elements of smart urban resilience frameworks. However, existing studies are constrained by the lack of field-validated rescue applications and the variability in reported performance metrics. Extensive experiments, standardised testing protocols and long-term operational validation are therefore needed before the use of BDS-enabled rescue equipment can be fully realised in disaster response.

Author Contributions

Conceptualization, X.L. and F.W.A.; methodology, X.L. and X.W.; formal analysis, X.W.; investigation, X.W. and X.T.; data curation, X.W.; writing—original draft preparation, X.W.; writing—review and editing, X.L. and F.W.A.; supervision, F.W.A.; project administration, X.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

Xun Liu and Xiaohui Tang are employed by Chengdu Leadus Digital Equipment Co., Ltd., and Xinqiao Wei is employed by Southwest Electric Power Design Institute Co., Ltd. Neither company had any involvement in the study design, data collection, analysis, interpretation, manuscript preparation or decision to publish the results. The authors declare no other conflicts of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, grammatical corrections, and improvements in clarity and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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