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Robotic search and rescue in earthquake-collapsed buildings: capabilities, evidence gaps, and a roadmap for human-multi-robot rescue

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Highlights:

- A seven-stage rescue task chain brings together seven classes of robots for coordinated search and rescue after earthquake-induced building collapse.
- A two-axis evidence-grading method evaluates validation maturity and scenario relevance while separating victim cues from actionable 3D localization.
- A human-supervised multi-robot roadmap specifies uncertainty-aware information sharing, cross-platform handoffs, and safety-related authorization gates.

Abstract: Following an earthquake, rescue robots must search for and assist trapped individuals in complex environments characterized by unstable rubble, narrow cavities, darkness, dust, and unreliable communications. This paper reviews the technical evidence for seven categories of robots within the seven-stage mission chain of search and rescue (SAR) in building collapse scenarios, covering unmanned aerial vehicles (UAVs); tracked, wheeled, and reconfigurable robots; quadrupedal robots; snake-like and continuum robots; humanoid and hybrid robots; heavy-duty engineering robots; and casualty evacuation and medical transport robots. This paper evaluates representative "platform-sensor-mission" capabilities across two independent dimensions: validation maturity (E0–E4) and relevance to collapse rescue scenarios (S0–S4). The study clearly distinguishes between signals indicating the possible presence of trapped individuals, 3D positioning information usable to guide excavation operations, and the actual execution of subsequent rescue operations. Currently, evidence of field applications is primarily concentrated on tasks such as site entry, reconnaissance, mapping, visual search, and the detection of vital signs through rubble. In contrast, evidence regarding sustained communication, supply delivery, close-range manipulation of casualties, casualty management, evacuation, and mission handoffs is significantly lacking. This leads to the identification of three major gaps: the transition from search and detection to rescue operations; the coordinated transition between different platforms; and the assurance

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of safe deployment. The roadmap proposed in this paper emphasizes that human-supervised robot teams should share rescue information while preserving its uncertainty; maintain communication links where feasible; hand off tasks to appropriately equipped robots; and obtain authorization before performing critical operations involving safety. End-to-end evaluations should quantify information loss during task handoffs, positioning uncertainty, resilience following team failures, and the level of protection provided to trapped individuals.

Keywords: earthquake-collapsed buildings; search-and-rescue robotics; human-multi-robot systems; rescue task chain; evidence grading; task handoff; human-robot interaction; deployment assurance

1. Introduction

Search and Rescue (SAR) refers to the process of locating and rescuing people in danger across a variety of environments, ranging from open terrain to damaged buildings. Urban Search and Rescue (USAR), on the other hand, focuses more on emergencies in the built environment, where rescue teams may need to enter damaged or collapsed buildings. This paper reviews search and rescue operations following building collapses caused by earthquakes, including scenarios where structural failure results from seismic forces and individuals are trapped in confined spaces within the rubble. Defining this scope of research is crucial because, when citing evidence from fields such as general disaster robotics, building collapses caused by non-seismic factors, nuclear facility inspections, underground space exploration, and robotics competitions, one must consider that the applicability of these research findings to earthquake collapse rescue scenarios varies [1–5].

Earthquake-related fatalities are often associated with structural building collapses, and the likelihood of survival typically decreases as the duration of entrapment increases [2]. As shown in Figure 1, this qualitative downward trend coincides with a series of sequential and partially overlapping USAR operations, including Assessment, Search, and Rescue (ASR) Phases 1–2; Rapid Search (Phase 3); Comprehensive Search and Rescue (Phase 4); and Recovery Operations (Phase 5). The 72-hour reference value used in this paper is intended to support operational planning and does not imply that survival is no longer possible beyond this timeframe. Therefore, when evaluating the value of robots, it is essential to consider not only when they can be deployed but also whether the information they gather can be reliably communicated to rescue personnel and remain useful for subsequent decision-making. Based on this consideration, this paper examines deployment timing in conjunction with robot platforms, sensors, and missions in subsequent comparisons. Figure 1 is a qualitative schematic without a survival-probability scale or fitted curve; the 72-h line indicates only an operational reference.

The practical application of robots in urban search and rescue can be traced back to the deployment of ground robots during the 2001 World Trade Center collapse [3]. Since then, reports of robot applications in other disaster response scenarios have continued to emerge [6–10]. The relevant literature can generally be divided into two categories of research: platform-centered and sensor-centered [11–15]. The former involves aerial robots, tracked robots, wheeled robots, reconfigurable robots, quadrupedal robots, snake-like robots, continuum robots, humanoid robots, hybrid robots, remotely operated construction equipment, and casualty evacuation systems [16]; the latter focuses on methods for identifying trapped individuals, including optical and thermal imaging, acoustic and seismic sensing, vital signs radar, gas sensors, electronic noses, and biohybrid olfactory sensing [17–20]. Therefore, a meaningful evaluation

must clarify what tasks the robot-sensor combinations actually performed, under what conditions the demonstrations were conducted, and what evidence supports the relevant conclusions.

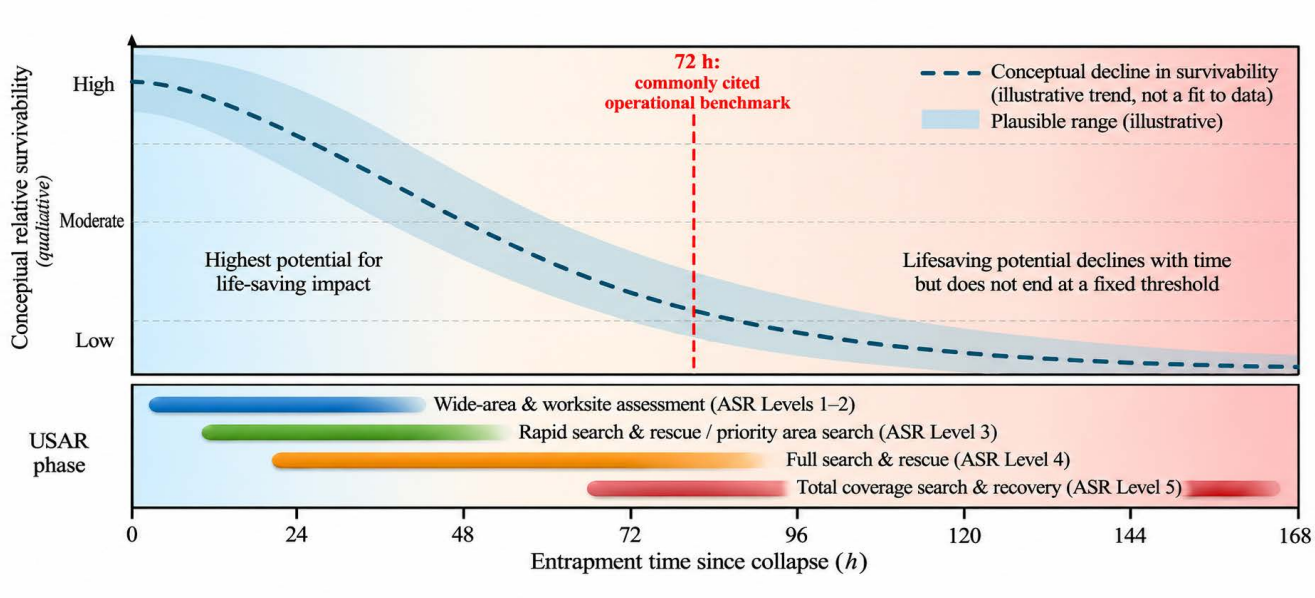


Figure 1. Schematic relationship between time trapped, the qualitative trend of declining survival probability, and the indicative timeline for USAR operations following a building collapse. The vertical axis does not represent a probability scale; the trend line is not a fitted survival function; and the horizontal axis is not drawn to scale. The 72-hour mark is provided for operational reference only and does not represent a survival threshold. The scope of activities for each phase of ASR is illustrative and not mandatory. Source: Conceptual synthesis by the authors based on data from Macintyre *et al.* [2] and the International Search and Rescue Advisory Group (INSARAG) [1].

Robots with different configurations are suited for different stages of response to building collapse incidents. Drones can quickly conduct reconnaissance and mapping and serve as communication relays, but they cannot access cavities deep within the rubble. Tracked, wheeled, and reconfigurable systems can inspect the surface of the rubble and accessible interior spaces using a variety of sensors and robotic arms, but they require sufficiently large openings to enter and face risks such as overturning and communication interruptions. Quadruped robots can navigate uneven terrain, but loose debris, balance control, and endurance remain challenges. Snake-like robots and continuum robots can carry small sensors into narrow spaces, but their payload capacity, pose estimation, and operational capabilities are limited. Humanoid and hybrid robots can use tools designed for humans. Heavy-duty engineering robots can perform tasks such as clearing passageways, removing rubble, providing structural support, and handling heavy loads, while casualty extraction and medical transport robots are responsible for making contact with casualties, loading them, stabilizing and supporting them, moving them, monitoring them, and handing them over to rescue personnel. Figure 2 provides an overview of the seven platform categories mentioned above.

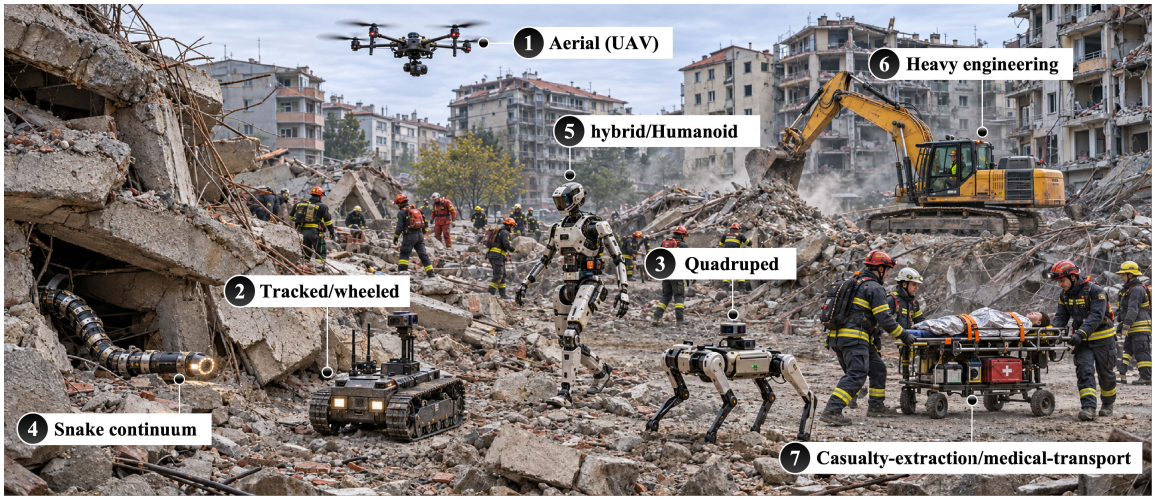


Figure 2. Schematic diagram of seven types of robotic platforms and their typical operational areas in earthquake rubble search and rescue: (1) Unmanned aerial vehicles (UAVs); (2) Tracked/wheeled/reconfigurable robots; (3) Quadruped robots; (4) Snake-like/continuum robots; (5) Humanoid/hybrid robots; (6) Heavy-duty engineering robots; (7) Casualty extraction/medical transport robots.

The differences described above are only meaningful when robotic capabilities are evaluated in the context of specific rescue missions. While the use of robots in disaster situations may demonstrate their mapping and inspection capabilities, this does not necessarily mean they can locate trapped individuals, communicate with survivors, deliver supplies, clear debris, or assist in rescue operations. Similarly, the detection of a signal in a laboratory setting that may indicate the presence of trapped individuals does not necessarily provide a sufficiently accurate three-dimensional location to guide excavation operations. Actual on-site performance also depends on the quality of communication links, operational endurance, operator workload, uncertainties in the robot's position and orientation, the complexity of the environment, and the degree of similarity between test conditions and real-world operating conditions [3,7–9].

Access to confined spaces requires a trade-off between payload capacity, stability, and force output capability. Therefore, search and rescue operations in earthquake rubble may benefit from teams composed of heterogeneous robots, each performing specialized tasks with clearly defined handover mechanisms [21–25]. Multiscale systems can combine early aerial assessment, ground exploration of rubble surfaces, legged locomotion over complex terrain, inspection of narrow cavities, human-scale operations, heavy-duty engineering interventions, and the extraction or medical transport of casualties [26]. However, simply organizing multiple robots into a single team does not bridge the evidence gap. Each capability claim must specify the actual test conditions, such as responses to real-world collapse incidents, laboratory or simulation environments, benchmarking sites or competitions, unrelated field test sites, remotely controlled construction tasks, or simulated casualty trials.

As the number of available robotic platforms continues to grow, merely listing the capabilities of individual robots does not explain how the completion of one task paves the way for the next. The key question is: Can subsequent robots and human rescue teams utilize the results of previous tasks without losing their reference coordinate systems, uncertainties, source information, communication status, or decision-making authority? Search and rescue operations in earthquake rubble present particularly demanding requirements for on-site robotics, as incomplete observations, shape-dependent spatial maneuverability, degraded communications, physical interactions between heterogeneous platforms,

and safety-critical human-robot collaboration occur simultaneously. Therefore, this paper not only examines the capabilities of individual robots but also focuses on the interfaces through which observational data is transformed into decisions, actions, or human approval.

This paper aims to clarify: which capabilities are supported by evidence relevant to rubble rescue; at which points information is lost between search and rescue operations; and which capabilities still require further testing before humans and multiple robots can jointly execute a complete task chain. Table 1 compares this paper with representative reviews in the fields of disaster robotics, urban search and rescue, trapped person sensing, single-robot platforms, and multi-robot collaboration. This paper does not rank robots but rather centers on four interrelated analyses.

First, we construct a seven-stage task chain for earthquake rubble search and rescue, linking rubble entry and navigation, mapping, trapped person detection, localization and identification, communication and logistical support, and finally, physical intervention and casualty management, thereby clarifying the dependencies between observation, verification, and action. Second, representative platform-sensor-mission capabilities are classified according to validation maturity (E0–E4) and scenario relevance (S0–S4), avoiding the misconception that the successful application of a single sub-capability implies that its untested downstream operations have also been validated. Third, the detection of signs of trapped individuals is distinguished from three-dimensional localization used to guide excavation, enabling the evaluation of sensor results based on the information required by rescue personnel to conduct confirmation and intervention. Fourth, task handoffs between robots and from robots to human rescuers are treated as analytical units, with clear requirements established regarding spatial references, uncertainties, source information, communication status, mission status, and authorization.

In smart construction scenarios, these outputs can also be used to correlate observational data from within damaged buildings: aerial and ground survey data can be used to update three-dimensional representations of a building's damage status; information on structural hazards, access restrictions, and uncertainties can support assessment and intervention planning; and traceable task handoffs can link robotic inspections to engineering operations and rescue efforts conducted under human supervision.

Table 1. Positioning of this review relative to representative disaster-robotics and USAR review strands.

Review strand (representative sources)	Primary emphasis	Limitation addressed here	Added value of this review
Disaster robotics and USAR reviews [3,5,27,28]	Platform capabilities, control, human-robot interaction, and deployment lessons	No task-scoped E/S map spanning the complete search-to-rescue chain	Links seven platform classes to seven operational stages and grades only the task actually exercised
Victim-sensing, platform-taxonomy, and rescue-subtask reviews [13,18–20,29]	Cue-detection modalities, one morphology, or a rescue subtask such as extraction or transport	Cue detection, actionable localization, cross-platform transferability, and collapse relevance are not compared in one workflow	Separates detection from actionable localization and uses one evidence map across sensor, platform, and task constraints
Multi-robot coordination reviews [22–24]	Exploration, networking, and generic heterogeneous-team coordination	The physical rescue handoff and its structural and medical decision authority are not operationalized	Makes handoff a measurable rescue capability and defines the shared rescue-state information needed by downstream robots and responders

2. Review scope and evidence-grading protocol

This study employed a structured narrative review methodology and graded the evidence for each specific task. The literature search was primarily conducted using databases such as Web of Science, Scopus, IEEE Xplore, ScienceDirect, and PubMed. Additionally, forward and backward citations of relevant literature were traced, and official standards and operational reports were reviewed. Search terms covered disaster scenario terminology such as earthquakes, building collapses, rubble, and USAR, as well as various robotic platforms, including ground robots, tracked robots, wheeled robots, reconfigurable robots, quadruped robots, legged robots, UAVs, snake-like robots, continuum robots, humanoid robots, remote-controlled excavators, unmanned construction equipment, heavy engineering equipment, casualty extraction systems, evacuation systems, robotic stretchers, and patient transport systems. Search terms related to sensing technology included trapped person detection, radar, thermal imaging, acoustics, gas sensors, electronic noses, and olfactory sensing. The search covered relevant literature published up to July 31, 2026. Any research involving at least one stage of the search and rescue chain following an earthquake collapse was included in the scope of this review. Specific stages include site access, mobility, mapping, detection and localization of trapped individuals, communications, logistical support, operations, creation of rescue access routes, debris clearance and controlled movement, casualty loading, stabilization and shoring, transportation, and handover of casualties to rescue personnel. Studies that discuss only pre-disaster monitoring or motion control and have no direct relevance to rescue constraints following building collapse were excluded. Assessments of actual robot deployments were primarily based on on-site records and official operational data. The resulting evidence map aims to reflect representative research progress in this field; however, there may still be omissions in the literature coverage. This paper does not claim to meet the completeness requirements of the Priority Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, nor did it conduct statistical weighting, effect size pooling, or meta-analysis [1,30–33].

2.1. Search documentation and source-corpus construction

Supplementary data S1 lists the search queries for each database to facilitate readers' tracing of literature sources. The search was updated as of July 31, 2026, and covered Web of Science Core Collection, Scopus, IEEE Xplore, ScienceDirect, and PubMed. Each search query combines terms related to earthquakes or building collapses, robotics platforms, and the concept of trapped-person sensing, with appropriate fields and proximity operators configured according to the databases' search rules. Additionally, the research team supplemented the retrieved literature through forward and backward citation tracking, as well as by reviewing official standards and incident reports.

The included materials comprised English-language journal articles, conference papers, books and book chapters, standards and guidelines, as well as official technical reports and operational reports. Preprints were primarily used to identify emerging research directions; however, any determination that a technology was ready for practical application required supporting evidence from other sources. Duplicate removal began with screening based on Digital Object Identifiers (DOIs), followed by identification of potentially duplicate records using titles, authors, and publication years. When multiple versions of the same study existed, the peer-reviewed version or officially published version was prioritized. Literature screening consisted of two stages: title and abstract review, and full-text review.

During the screening process, the following were excluded: duplicate papers or those with updated versions; studies lacking a direct connection to earthquake or building collapse scenarios; studies not involving rubble environments, USAR, or damaged structures; studies unrelated to the rescue mission chain; materials for which full text was unavailable or not in English; and general pre-disaster monitoring and motion control studies unrelated to collapse rescue.

The initial literature set comprised 144 sources, each of which was coded at the task level. During the paper revision process, an additional six relevant studies were incorporated into the discussion as background comparative material; their topics included environmental changes, robotic construction machinery, trustworthy and interoperable digital twins, robot-assisted structural inspection, robot-mounted vision systems, and agile mobility [34–38]. The reference list and source registration table separately annotate these six publications, indicating their use for background analysis or comparability of transferability; they were not added to the E/S-classified set originally comprising 144 publications. During the initial narrative review phase, database export logs and records of the number of studies in each screening round were not retained; therefore, it is not possible to accurately reconstruct the PRISMA literature screening flowchart based on these records. If the flowchart were to be created retrospectively, the relevant numbers would lack support from original records. Given this situation, this paper does not provide a PRISMA flowchart and positions the review as a representative evidence map. Supplementary data S1 includes a list of sources, search terms for each database, and the fields used for evidence extraction at the task level.

Materials related to deployment support include official guidelines and peer-reviewed studies, focusing on emergency response robot testing methods, service robot safety, artificial intelligence (AI) risk management, human supervision, ethics, privacy, cybersecurity, accountability mechanisms, and emergency response governance. Key sources include emergency response robot testing methods published by the National Institute of Standards and Technology (NIST), guidelines from the INSARAG, standards from the International Organization for Standardization (ISO) and the Institute of Electrical and Electronics Engineers (IEEE), as well as representative regulatory documents. Peer-reviewed papers were used to analyze ethical issues and design requirements specific to rescue missions. The legal applicability of governance documents is influenced by factors such as jurisdiction, intended use, safety responsibilities, and the actual operational functions of the system; therefore, this paper classifies relevant materials as “directly applicable”, “partially transferable”, or “background reference”, and does not include them in the E/S classification [39–43].

2.2. Evidence tier and scenario relevance

Nuclear reactor inspections, underground robot challenges, benchmark testing sites, and various competitions can all provide valuable technical references for the research and development of rescue robots. However, the operating conditions of these activities differ from the rescue environment inside earthquake-collapsed buildings. To accurately evaluate various representative capabilities, this paper employs two independent dimensions. The evidence levels (E) listed in Table 2 reflect the maturity of technical validation, ranging from simulation or analytical studies (E0) to task execution in real-world disaster scenarios (E4). The scenario relevance (S) listed in Table 3 is used to measure the degree of similarity between the test environment and tasks and those found in earthquake-collapsed search-and-rescue scenarios, ranging from laboratory or simulation environments (S0) to cavity searches or the detection of signs of

life through rubble at actual earthquake-collapsed sites (S4). Extensive field experience does not necessarily mean that the relevant technology has been validated in collapse rescue scenarios; similarly, realistic rubble simulation experiments may not have been deployed in actual disasters. Classification is based on tasks actually completed. When evidence is questionable, the lower level supported by available data is adopted. Preprints can be used to understand promising technological advances, but preprints alone are insufficient to prove that a technology has met the requirements for field application. E4 indicates that the assessed task has been deployed and executed in a real-world disaster; this rating does not in itself imply that the task was successful. Whether the robot made contact with injured persons, whether detection or localization was successful, whether the rescue was completed, and other mission outcomes are recorded separately.

Table 2. Evidence tiers with representative boundary examples.

Tier	Definition	Representative evidence
E4	Real-disaster operational task execution: the scored task was deployed and actually executed in a real disaster. E4 denotes deployment maturity only; task outcome is reported separately and does not raise or lower E.	Mexico City snake-robot void search (no victim found) [44]; Fukushima reactor-building inspection [45]; Nepal Finding Individuals for Disaster and Emergency Response (FINDER) life detection [46]
E3	Field exercise or competition with operationally realistic constraints.	Defense Advanced Research Projects Agency (DARPA) Robotics Challenge [47,48]; DARPA Subterranean Challenge [25]; RoboCup Rescue [33]
E2	Engineered rubble test bed or standardized response-robot arena.	NIST response-robot test methods [32]; RoboCup Rescue arenas [33]
E1	Controlled laboratory or mock-casualty demonstration.	Entrapped-human sensor arrays [49]; casualty-extraction dummy studies [50]
E0	Simulation or analytical study without physical validation.	Simulation-only perception, coordination, delivery, or manipulation studies

Table 3. Scenario-relevance levels with representative boundary examples.

Level	Definition	Examples
S4	Real earthquake-collapse SAR operation involving in-void search or through-rubble life detection.	Mexico City snake-robot void search [44]; Nepal FINDER deployment [46].
S3	Real building collapse or earthquake-response deployment without in-void earthquake victim interaction.	World Trade Center (WTC) void search [6]; Amatrice mapping [51]; Lushan UAV response [52].
S2	Engineered rubble test bed or USAR training site.	NIST test methods and RoboCup Rescue arenas [32,33].
S1	Transferable non-earthquake setting, such as subterranean, nuclear, mine, or competition.	DARPA Subterranean Challenge (SubT) [25]; Fukushima reactor-building inspection [45]; DARPA Robotics Challenge (DRC) [48].
S0	Laboratory, mock indoor environment, or simulation.	Laboratory locomotion, sensing, coordination, and casualty-handling studies.

The ratings are based on specific tasks performed during actual demonstrations and do not directly extend to the full capabilities of the relevant robots. The E rating records the highest level of validation achieved for that task; the S rating is determined independently based on the similarity between the test task and earthquake collapse search-and-rescue scenarios. Source citations and publication types are recorded separately and do not affect the E/S ratings. See Supplementary data S1 for a complete coding description. In the category summary, “Highest validation level within the task scope” refers to the highest E-level demonstrated for a given task; if different tasks share the same E-level, the example most relevant to the collapse scenario is listed first. Therefore, the category summary rows only summarize

specific tasks supported by existing evidence within that category; they do not imply that all robots in that category have achieved the same level.

Each level should be understood in the context of typical evaluation environments: controlled laboratory tests and simulated casualty demonstrations are classified as E1; artificially constructed rubble test sites and standardized emergency response robot testing grounds are classified as E2; field exercises and competitions with real-world operational constraints are classified as E3; and E4 requires that the evaluated task be deployed and actually executed in a real disaster. The E-axis focuses on verifying maturity, while mission success is evaluated separately. Regarding the S-axis, S3 corresponds to deployments in response to real building collapses or earthquakes but does not yet meet the mission conditions required for S4, namely, conducting searches inside cavities at real earthquake collapse sites or detecting signs of life through rubble. S4 is specifically used to designate such real earthquake collapse search or life detection operations. Consequently, the inspection of the reactor buildings at the Fukushima Nuclear Power Plant is classified as E4/S1; the cavity search in Mexico City and the FINDER life-sign detection deployment in Nepal are classified as E4/S4; and the DARPA Robotics Challenge and Underground Challenge trials are classified as E3/S1. Supplementary data S1 lists complete examples of the boundaries for both classification systems.

The original coded records do not contain formal duplicate independent ratings, nor do they preserve records of disagreements among coders or statistics on inter-rater reliability. Therefore, the retrospective calculation of Cohen's kappa coefficient lacks methodological justification. The E/S ratings in this paper should be understood as task-specific assessments supported by documented evidence; the available data do not yet demonstrate consistency among different raters. In cases of ambiguous evidence, the lower rating that can be reasonably supported was adopted. Specific classification boundaries are shown in Tables 2 and 3 and Supplementary data S1.

Neither the E axis nor the S axis is used to evaluate the quality of publications. Supplementary data S1 records source types and origins based on the abbreviations in the reference list: journal articles or reviews (JA), conference papers or proceedings (CP), books or book chapters (BK), official or technical reports (OR), standards or guidelines (SG), preprints or emerging research materials (PP), official news or press releases (NP), and legal or regulatory documents (LR). These labels are used solely to identify the source of the information and do not affect the E/S rating. Official news is primarily used to confirm that relevant events have indeed occurred and cannot be used on its own as evidence of technical performance; legal and regulatory materials are used to illustrate the governance context and are not factored into the technical capability rating.

2.3. Transferability rules for non-earthquake evidence

A significant portion of robotics research is conducted outside the context of searching for trapped victims following earthquake-induced building collapses. Table 4 summarizes specific capabilities from various research environments that can be applied to earthquake collapse rescue operations. Technology transfer should be based on functions that have been practically tested in their original research environments. For example, GPS-free navigation in underground environments, teleoperation under limited communication conditions, operational capabilities in competition settings, and standardized benchmark tests for emergency response robots can all provide references for relevant rescue missions. While these results indicate that the corresponding sub-capabilities have been tested, they are not yet

sufficient to demonstrate that robots possess the comprehensive capability to independently rescue casualties amid earthquake rubble [25,32,33,47,48]. Based on differences in mission requirements, risk boundaries, performance evaluation metrics, and technological maturity, this paper discusses remote-controlled construction and heavy engineering operations, casualty extraction, and medical transport separately.

Table 4. Transferability rules for evidence from non-earthquake settings.

Setting	Supported transferable sub-capabilities	Claims not established
DARPA Subterranean Challenge	GPS-denied navigation, mobility in dark or dusty environments, multi-robot coordination, and communication relay under radio-frequency loss.	Victim detection in unstable reinforced-concrete rubble; casualty handling.
DARPA Robotics Challenge	Humanoid/hybrid manipulation of tools, valves, and doors; teleoperation under degraded communication.	Safe approach to or extraction of a live casualty in real rubble.
Fukushima reactor-building inspection	High-risk remote inspection, tracked-platform reliability, and communication/tether management in shielded interiors.	In-void life search; victim localization; supply delivery to survivors.
Robot competitions/ RoboCup Rescue	Benchmarked mobility and mapping on standardized arenas.	Field readiness under collapse instability and aftershocks.
UAV disaster mapping	Wide-area damage assessment, access-route evaluation, surface triage, and communication restoration.	Deep-void interior search; in-void victim localization.
Heavy-engineering/ remote-construction trials	Teleoperation, earthmoving, route opening, heavy manipulation, reaction-load stability, operator-interface evaluation, and retrofit deployment.	Precision work adjacent to an entrapped live casualty; structural safety in unstable earthquake rubble; casualty extraction.
Casualty-extraction and medical-transport studies	Mock-casualty loading, head and neck stabilization, body support, transport-aid mobility, contact-force and vibration metrics, and responder handoff concepts.	Autonomous contact, extraction, or transport of a live casualty in unstable earthquake rubble.

2.4. Extraction variables and limitations

Supplementary data S1 documents the source categories and origins on which each task's E/S rating is based, in order to distinguish between the source attributes of the literature itself and the validation maturity and collapse scenario relevance of the functions being tested. The fully coded evidence set comprises a total of 144 source documents. The six studies added during the revision process are listed separately in Supplementary data S1 and labeled as background comparison material to avoid confusion with the task-level E/S evidence set.

For each type of robot, the variables extracted in this paper include: accessible spatial range, mobility and self-recovery capabilities, payload or force output capabilities, operational endurance, autonomous functions, degree of reliance on communication, applicable sensors, and task-specific evidence levels. For heavy-duty engineering robots, the following were also recorded: rated payload, digging or lifting force, operating range, ground pressure, reaction load stability, remote control latency, camera coverage, equipment deployment time, and the minimum distance required between the equipment and unstable structures or trapped individuals.

For casualty extraction and medical transport systems, the extracted metrics also include loading time, forces applied to the patient's body, methods of body support, head and neck stability, vibration and shock during transport, passageway width, obstacle-crossing capability, medical monitoring, and the process of transferring casualties to rescue personnel. Since the measurement metrics for these

systems differ significantly from those for construction machinery, Chapter 4 categorizes and discusses construction machinery and casualty handling equipment separately.

Sensor-related variables include target cues, requirements for line-of-sight accessibility or signal penetration, installation constraints, sensitivity to environmental conditions, the ability to detect trapped individuals when obscured, and whether the localization results can support subsequent interventions. Based on these variables, this paper establishes two qualitative high/medium/low (H/M/L) matrices. The platform-task matrix is used to evaluate the suitability of various robotic platforms for the seven stages of rescue operations; the platform-sensor matrix is used to evaluate the feasibility of installing and operating different sensing modalities in rubble environments. H, M, and L represent high suitability, moderate or conditional suitability, and limited suitability, respectively; these are all qualitative judgments and do not represent quantified performance metrics. Given the differences in existing research regarding test environments, evaluation metrics, rubble geometry, casualty surrogate models, and even task definitions, this paper adopts a cautious, inductive approach for both matrices.

The specific criteria for determining H/M/L ratings are as follows. For the platform-task matrix, if a robot's morphological characteristics and demonstrated capabilities align closely with the target task, and there are no fundamental limitations at the category level, it is rated as H; if task completion depends on factors such as access conditions, payload, stability, communication, operator control, or environmental conditions, it is rated as M; if the robot's morphology, available forces or payload, safety requirements, or existing evidence impose significant limitations on the task, it is rated as L. For the platform-sensor matrix, "H" indicates that the sensor can be practically installed and operated under the constraints of the evaluated rubble environment; "M" indicates that its application is subject to certain conditions, such as the need for a stable platform, static measurement conditions, low payloads, favorable spatial geometry, or motion compensation; "L" indicates a clear mismatch between the sensor and the application scenario, or a lack of sufficient evidence for its practical application in a rubble environment.

3. Earthquake-collapse search-and-rescue task chain

Figure 3 illustrates the seven phases of SAR operations in earthquake-collapsed buildings. Phases 1 and 2 are "entry into the rubble environment" and "mobility and autonomous recovery capabilities," respectively. These two foundational capabilities determine whether a robot can reach a target cavity or rubble area and operate within it. Phases 3 through 5, which include scene mapping and understanding, detection of trapped individuals, and localization and identification, constitute the search phase. Phase 6 involves communication and logistical support, while Phase 7 covers rescue intervention and casualty care; both phases require collaboration between human personnel and robots.

The seven phases reflect the functional dependencies between tasks and do not constitute a fixed operational timeline. For example, while rescue personnel are planning a controlled debris clearance strategy, drone mapping and ground searches can proceed simultaneously; newly discovered signs of trapped individuals or changes in structural hazards may also prompt the rescue team to return to a previous phase for reassessment. Figure 3 maps robotic tasks to the INSARAG ASR activities; however, the two classifications are not a one-to-one correspondence. ASR Phase 1 (Wide-Area Assessment) and Phase 2 (On-Site Triage Assessment) primarily support site mapping, prioritization of operational areas, and planning of access strategies. Level 3 (Rapid Search and Rescue) and Level 4 (Comprehensive Search and Rescue) encompass controlled access, technical search, confirmation of trapped individuals,

communication and support, and the extraction of injured persons. If comprehensive coverage of the entire operational area is required, Level 5 (Full-Coverage Search and Recovery) may also overlap with subsequent intervention and recovery operations [1].

This paper conducts an evaluation based on the mission phases that various robotic platforms and sensors can support. The framework also takes into account on-site constraints such as narrow entrances, unstable debris, darkness, dust, reduced communication capabilities, and time pressure, while focusing on the differences in the maturity of evidence between the search and rescue phases [1,2,4].

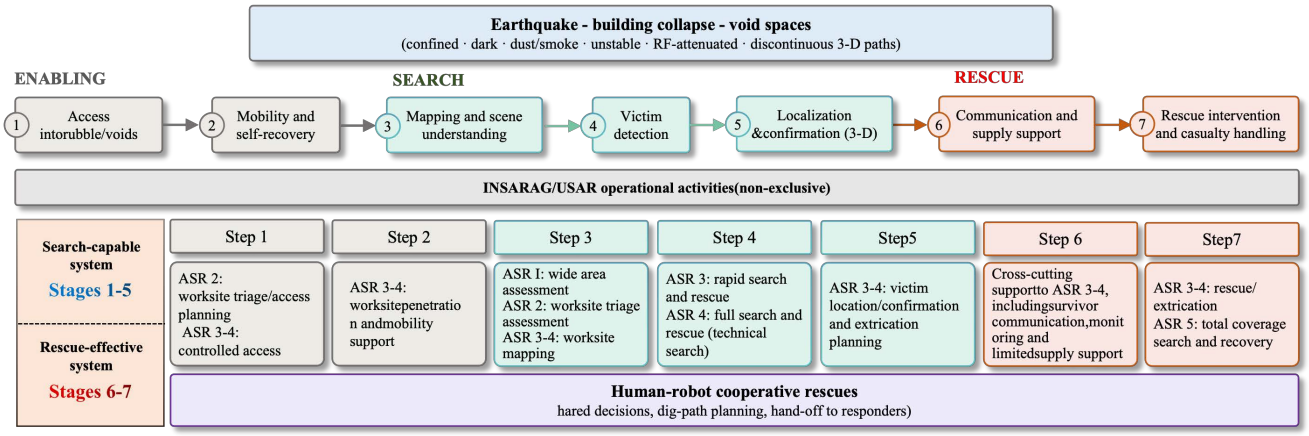


Figure 3. Seven-stage earthquake-collapse search-and-rescue task chain with explicit functional mapping to INSARAG ASR Levels 1–5. The mapping is non-exclusive because INSARAG work levels may overlap and do not form a strict one-to-one chronology with the robotic stages.

Robots equipped with search capabilities can enter specific areas and identify signs that survivors may be present. To provide a reliable basis for rescue operations, it is also necessary to obtain sufficiently precise localization results, a process that relies on reliable sensor data and accurate platform pose estimates. This paper links a robot system's rescue effectiveness to its ability to perform at least one quantifiable function that directly serves rescue operations. Such functions include: establishing communication with trapped survivors; delivering essential supplies to them; assisting with structural assessment or light-duty operations; clearing controlled access routes; supporting safe contact with casualties; assisting with the loading or transfer of casualties; and successfully handing off casualties to rescue personnel.

When evaluating the above functions, multiple performance metrics can be employed, including the time required to reach the target area, the probability of detecting trapped individuals, 3D localization error, false alarm rate, communication link duration, successfully delivered cargo payload, operational forces, time to clear a passage, reaction forces and vibrations generated by the intervention, forces exerted on the patient, loading time, shocks and vibrations during transport, and mission handover time. These metrics form the basis for the analysis of search-and-rescue coordination issues in Chapters 7 and 8. Although tasks in actual rescue operations may be carried out consecutively, existing published research still shows significant gaps in the validation of stages following localization and identification.

To evaluate the complete rescue process, it is also necessary to examine the information transferred between activities. At each task handoff, the robot or rescue personnel receiving the task should obtain a minimum set of rescue status records. This record should include: time-stamped 3D scene reference

information; assumptions regarding trapped individuals and their confidence levels; the robot platform's position and orientation and their uncertainties; access routes and structural hazard information; communication quality; data sources and their traceability; the current mission status; and the authorization requirements necessary to perform the next critical operation. Based on this record, the receiving party can verify whether information is missing or outdated, thereby making the quality of mission handoffs a measurable indicator of rescue capability.

4. Robotic platforms for rubble search and rescue

Sections 4.1–4.7 analyze various robot platforms in relation to the same set of questions: what environments the platforms can access, what tasks they have actually completed, what sensor payloads they can carry, what conclusions can be drawn from existing E/S evidence, and what limitations still exist. By synthesizing these questions, we can see how access capability, mobility, payload capacity, and perception capabilities influence the practical applications of various robots. Heavy-duty engineering robots and robots designed for casualty extraction and medical transport are evaluated separately, as they differ fundamentally in terms of force and contact conditions, safety requirements, and validation metrics. Figure 4 summarizes the various platform types. The "primary intervention node" for a given platform category refers to the earliest stage in the mission chain where the platform can play a unique role based on its typical dimensions, form, payload, and force application or contact capabilities. This sequencing is intended to facilitate comparisons among different platforms and does not prescribe the actual order of deployment; depending on on-site conditions and mission requirements, robots may continue to operate in subsequent stages or re-engage in earlier tasks.

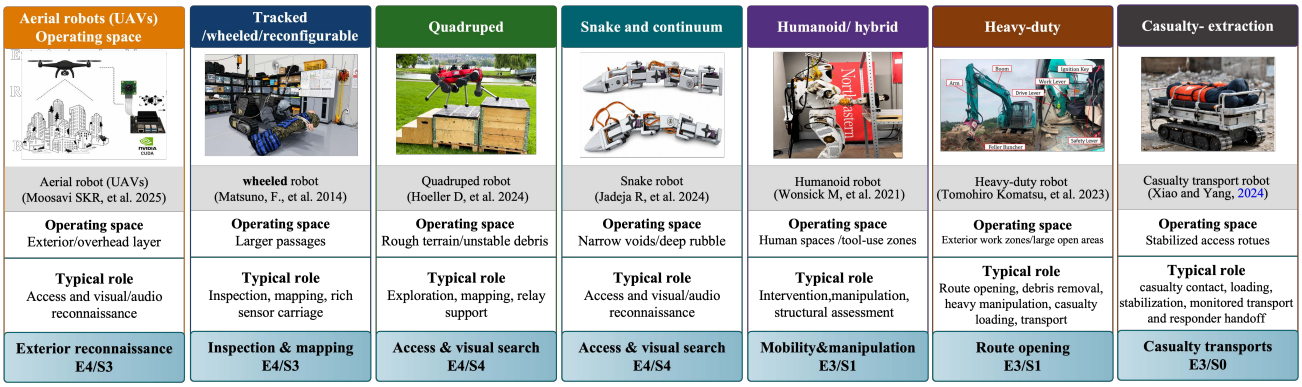


Figure 4. Seven platform classes ordered by their primary operational-entry point in the earthquake-collapse search-to-rescue chain. Here, "primary entry point" means the earliest task-chain stage at which a class typically provides a distinct operational contribution; the ordering is heuristic and non-exclusive, and platforms may contribute at multiple later stages. Heavy engineering robots and casualty-extraction/medical-transport robots are shown separately because their operating spaces, task roles, force/contact regimes, and task-scoped evidence grades differ.

4.1. UAVs

In early ground reconnaissance missions following an earthquake, rotorcraft drones have become a relatively well-established platform for rescue operations [53,54]. Their typical tasks include rapidly conducting external inspections of buildings, assessing potential access routes, inspecting building

damage from high-altitude or oblique perspectives, performing ground thermal imaging surveys, generating photogrammetric maps or orthophotos, and temporarily serving as communication relays. Operations following the 2013 Lushan earthquake and the 2016 Amatrice earthquake in Italy demonstrated the role of UAVs in situational awareness and building damage assessment [51,52,55]. This section first discusses UAVs, focusing primarily on their rapid deployment; UAVs can continue to provide aerial support during subsequent phases of rescue operations.

Imagery collected during actual earthquake disasters also provides data for research on automated on-site reconnaissance and damage assessment. Researchers utilized drone imagery from the 2023 Hatay-Malatya earthquake in Turkey to develop deep learning-based methods for detecting damaged buildings, classifying damage severity, and identifying wall damage [56]. Following the 2022 6.8-magnitude Luding earthquake, orthophotos acquired by unmanned aerial systems (UAS) were used for detailed instance segmentation of damaged buildings to estimate disaster losses, identify priority search areas, and protect rescue personnel [57]. Furthermore, researchers evaluated the ability of UAV vision systems to identify rescue teams, equipment, structural damage, and fully or partially exposed trapped individuals under varying lighting, flight altitude, and observation conditions [58,59].

UAVs can also provide communication support to ground rescue teams. Reviews of disaster response typically categorize UAV operations into three types: information collection, delivery of relief supplies, and restoration of communication networks [60]. Research on multi-UAV coordination and edge computing has shown that UAVs can provide temporary network coverage and accelerate information transmission, while also facing challenges such as deployment layout, routing, communication security, data processing, battery life, weather impacts, and airspace coordination [61,62]. In contrast, existing evidence regarding the use of UAVs to detect trapped individuals buried deep beneath rubble is very limited. Obstacles, concrete, steel, dust, concealed heat sources, airflow variations, the absence of GPS signals, and the risk of collision all limit the observational capabilities and safe access of aerial platforms.

Existing field evidence supports the use of UAVs for reconnaissance, mapping, monitoring, communication relaying, and preliminary screening of individuals visible at the surface. Tasks such as external building reconnaissance, rapid damage assessment, access route evaluation, and command support have reached the E4/S3 level [51,52]. However, UAVs have not yet been proven capable of reliably locating survivors deeply buried in rubble, nor have they demonstrated the ability to deliver supplies into cavities within collapsed buildings. Their most significant value lies in providing a common geographic reference for ground robots, legged robots, and confined-space robots, and in helping rescue teams determine priorities for subsequent searches.

4.2. Tracked, wheeled, and reconfigurable robots

Track-type, wheeled, and reconfigurable robots rely on a large ground contact area, swiveling arms, or shape-changing modules to navigate environments such as rubble, stairs, slopes, and crevices, while also being capable of carrying relatively heavy sensors and actuators [3,63–66]. After completing aerial site surveys, ground robots can further inspect the surfaces of rubble and openings of sufficient size; aerial and ground operations can also be conducted simultaneously [67]. In tests simulating urban disaster environments, flexible tracks and automatically driven articulated arms have enabled robots to navigate damaged ground, stairs, and stepped obstacles [68–70].

Among various types of ground robots, tracked, wheeled, and reconfigurable systems have a wealth of practical application experience. Such platforms can carry cameras, thermal imagers, LiDAR, radar, chemical sensors, communication relay equipment, and robotic manipulators. Prototype Unmanned Ground Vehicle (UGV) systems, designed for reconnaissance and disaster response and supervised by personnel, have integrated color-depth (RGB-D) imaging, thermal imaging, ground-penetrating radar (GPR) or LiDAR mapping, radiation or chemical detection, wireless communication, and sampling or valve operation via robotic arms [71]. Related test missions include navigation over rubble terrain, map construction, searching for signs of trapped individuals, deployment of relay equipment, payload delivery, and operational tasks within test environments [72,73].

Typical application cases include cavity inspection and mapping following the 2001 World Trade Center collapse, which supports an E4/S3 rating for such robots performing relevant tasks within real-world collapsed structures [3,6,7]; inspections inside the Fukushima Nuclear Power Plant buildings achieved an E4/S1 rating, serving as a transferable case for remote inspection in hazardous environments [45,74]. These deployments demonstrate that robots are capable of remotely inspecting and mapping hazardous spaces while maintaining normal equipment operation. However, existing cases do not yet demonstrate their ability to locate trapped individuals within cavities, deliver rescue supplies, clear pathways through heavy debris, or extricate injured persons. Practical applications remain limited by factors such as entrance dimensions, the risk of overturning, the management of tethered or wireless communications, and access to the narrowest cavities.

4.3. Quadruped robots

Quadruped robots achieve mobility on terrain where wheeled or tracked robots are prone to instability through independent foot support, active foot placement control, and whole-body balance [75–77]. Relevant reviews have summarized advancements in leg structure, drive mechanisms, gait control, autonomy, and applications, while also noting that issues such as device reliability, energy consumption, adaptability to deformable surfaces, and safe interaction with people or the surrounding environment remain to be resolved [11,78]. Learning-based body perception and environmental perception technologies have enhanced robots' ability to navigate obstacles and perform dynamic, parkour-like movements [79–82]. Such locomotion capabilities are expected to expand the search and rescue range to include stairs, inclined surfaces, separated support surfaces, and passages navigable by legged robots [83].

Research outside the field of rescue robotics has also provided insights into autonomous robot self-extrication and the generation of large forces for short durations on irregular terrain. Ma *et al.* [37] proposed a jumping and flying robot inspired by felines and driven by combustion-powered soft actuators. Reportedly, its actuators have response times on the order of milliseconds, can generate forces up to 70 times the robot's own weight, and are capable of escaping from confined and obstacle-filled environments. These behaviors may serve as a reference for robots to autonomously extricate themselves or traverse complex obstacles. Given that this system is not a quadruped robot developed for earthquake SAR applications, this paper treats it as background reference material and does not include it as direct E/S evidence [37].

The DARPA Underground Challenge conducted robot tests under various complex conditions relevant to rescue operations, including GPS-denied environments, darkness, limited perception capabilities, complex underground passages, intermittent wireless link interruptions, and time constraints on search operations. The Cooperative Exploration of Underground Environments with Walking and

Flying Robots (CERBERUS) team combined the ANYmal quadruped robot with a drone reconnaissance platform to achieve autonomous exploration, mapping, localization, and target detection [25]. The team from the Czech Technical University, Center for Robotics and Autonomous Systems, and Northern Robotics Laboratory (CTU-CRAS-NORLAB) also demonstrated multi-platform underground collaborative exploration, map generation, target search, and operational capabilities under limited wireless communication conditions [84]. These achievements support their exploration and search missions reaching the E3/S1 level; however, they do not yet prove their ability to rescue trapped individuals in earthquake rubble environments.

Currently, there are still few publicly reported cases of quadruped robots searching for trapped victims at actual earthquake collapse sites. Relevant scenario studies cover rescue personnel attitudes, semantic maps incorporating elements such as people, cracks, stairs, and doors, thermal imaging-based identification of trapped victims, mixed reality assistance, delivery of rescue supplies, and air-ground coordination [85–88]. A review of legged robot manipulation research categorizes these efforts into interactions that do not require grasping, operations performed using walking legs, the use of dedicated robotic arms, and multi-legged robot collaboration [89]. The ability to move over rubble does not necessarily mean a robot can safely manipulate it. Pushing or lifting objects on loose debris requires stable foot support, controllable reaction forces, terrain assessment, and maintaining a sufficient safety distance from trapped individuals. Current challenges include ensuring the sustained reliability of communication links, operator workload, battery life, the impact of dust on cameras, and a lack of field testing for rescue supply delivery and operational tasks.

4.4. Snake and continuum robots

Snake and continuum robots achieve motion through the bending of jointed chains or flexible bodies, and use body undulations and contact with surrounding obstacles to propel themselves forward [12,90–92]. Their slender, multi-jointed structures can carry cameras or other end-effectors to enter narrow openings that rescue personnel or conventional ground robots cannot access [93–94]. These robots are particularly well-suited for conducting further internal exploration after suspected entrances are identified during mapping or surface inspections. Their structural configurations include rigid modular designs, soft systems, continuous flexible bodies, and hybrid structures [13,95–98].

Existing experiments have primarily demonstrated the ability of snake-like and continuum robots to enter confined passages and acquire local images or audio. Common payloads include head-mounted cameras, microphones, small thermal detectors, or sampling tubes mounted at the robot's end effector. Factors such as a sensor reference frame that changes with robot motion, limited payload capacity, uncertain contact conditions, and the difficulty of fully observing the robot's pose all limit their reliable perception, mapping, and localization capabilities. Recent research has explored solutions to these problems in engineered collapse environments through methods such as using learning algorithms to identify partially obscured survivors, performing 3D reconstruction based on stereo vision, developing steerable vine-like robots, and utilizing portable reverse-expansion robots [99–103].

The most well-documented case of such robots being deployed at an earthquake site occurred during the 2017 Mexico City earthquake. A snake-like robot developed by Carnegie Mellon University (CMU) entered a collapsed building and transmitted video footage of two internal cavities [44]. The E4/S4 rating assigned to this case applies only to the actual entry and visual inspection tasks that were completed. No

personnel were found at the scene; therefore, this operation could not demonstrate the robot's ability to locate people, deliver supplies, clear debris, or extricate injured individuals. Tests conducted in laboratory and engineered environments further validated its mobility, perception, mapping, and small-gripper capabilities; however, these were insufficient to prove that it possessed the capacity for actual on-site rescue operations [104,105]. The fact that the search did not locate any personnel does not affect the determination that the robot successfully entered the site and completed the inspection; similarly, the E4/S4 rating should not be interpreted as evidence of successful detection or completion of a rescue.

Current snake-like and continuum robots lack the payload capacity and output force required for large-scale debris clearance or direct handling of injured persons. More feasible tasks at this time include entering confined spaces, conducting visual and acoustic inspections, collecting signs of survivors, relaying communication signals, performing end-of-arm sampling, and delivering small items [106]. End-of-arm sampling devices equipped with chemical or biological hybrid sensors may help identify directions warranting further search; however, to obtain the three-dimensional coordinates of trapped individuals for rescue decision-making, it remains necessary to accurately estimate the robot's pose and independently verify relevant indications.

Such systems can inspect openings that are inaccessible to larger robots, but they are not yet capable of performing physical rescues independently. They can extend the scope of investigation from areas of a building where people are suspected to be present into specific cavities, directly acquiring sensory information. Long-duration operations are primarily constrained by factors such as endurance, tether and communication link management, autonomous recovery capabilities after becoming trapped, pose uncertainty, and payload limitations.

4.5. Humanoid and hybrid robots

Humanoid robots and hybrid robots are designed for human-scale operational environments and tools [107–110]. Their structural configurations include bipedal robots, wheeled-legged or tracked-legged hybrid robots, and mobile manipulation robots with a humanoid upper body, typically employing whole-body control methods [111–115]. The primary value of these robots typically becomes apparent after rescue personnel have narrowed the search area and confirmed the location of injured individuals. At this stage, rescue operations may require human-scale operational ranges, the use of hand-held tools, sensor deployment, the transfer of supplies, or limited structural work. Currently, most earthquake-related demonstrations primarily involve post-disaster building inspections or teleoperation tasks [116].

Most humanoid and hybrid robots designed for disaster response tasks are tested in competitions, benchmark tests, or controlled demonstration environments. The 2015 DARPA Robotics Challenge required robots to complete mobility and manipulation tasks under deteriorating communication conditions; robots falling over, difficulty recovering after a fall, slow task completion speeds, and insufficient robustness remain major obstacles [47,48,117]. CENTAURO demonstrated the ability to navigate around obstacles using wheeled-legged locomotion combined with sensor data [108]. HURCULES, a robot with a humanoid upper body and a tracked-legged lower body, has performed casualty extraction and hazardous object handling tasks in laboratory and outdoor tests [118]. These examples illustrate the potential of such platforms to participate in rescue operations, but they have not yet demonstrated the ability to safely extract real casualties from earthquake rubble.

Recent reviews on earthquake SAR and studies on stakeholder perspectives consistently point out shortcomings in mobility, autonomy, connectivity, situational awareness, location of trapped individuals, sensor fusion, supervised autonomous operation, and safe physical interaction [27,78,119,120]. Therefore, this paper treats the evidence for humanoid or hybrid robots separately from that for excavators and patient transport equipment. The primary potential advantage of such robots lies in their dexterous use of tools designed for humans. Difficulties with falling and autonomous recovery, slow movement speeds, limited operational range, communication delays, operator burden, contact risks, and high costs remain significant barriers to their practical application.

4.6. Heavy engineering robots

Heavy-duty engineering equipment can perform excavation, lifting, and structural shoring operations with levels of force that small rescue robots cannot achieve. This category includes remote-controlled excavators, dual-arm engineering robots, and engineering equipment that has been modified for clearing pathways, removing debris, transporting or lifting materials, and installing support structures. Such equipment requires separate evaluation, as its key constraints primarily involve excavation and lifting forces, operational range, forces transmitted to the machine's base, ground support conditions, positioning accuracy, teleoperation latency, vibration, and safe distances from damaged structures. These metrics differ significantly from the requirements for patient contact and transport in clinical settings.

Remote-controlled excavators and other engineering equipment can clear materials and reposition heavy debris using forces far greater than those of small SAR platforms. Experiments related to the ImPACT Tough Robotics Challenge and research on excavator modifications have provided transferable research findings regarding high-force remote operations, operator control, multi-camera perception, and reaction load management [15,121,122].

Experiments in the field of robotic construction also provide insights for precise movement and load handling. Xiao and Yang [38] tested an automated mobile crane framework based on robotic kinematics and loop-shaping control for the supply of construction materials, and evaluated its final positioning accuracy and continuous tracking capability. Although these findings may provide insights for controlled load placement, the experiments did not involve moving debris near trapped individuals or operating on unstable seismic rubble [38].

Task-level evidence for heavy-duty engineering robots primarily reaches E3/S1, based on tests conducted in environments with relevant engineering characteristics rather than in seismic rubble environments for casualty rescue. Compared to on-board control, remote operation may be more time-consuming, especially when precise positioning of equipment is required [123]. Operating safely near casualties also requires approval from structural engineers, the establishment of isolation zones, assessment of ground conditions, limitation of forces and vibrations, assurance of reliable communications, configuration of emergency stop mechanisms, and clarification of command authority for rescue personnel. Therefore, successful handling of debris does not demonstrate that equipment can safely perform interventions near casualties, nor does it elevate the level of evidence for casualty transport platforms.

4.7. Casualty-extraction and medical-transport robots

Platforms for extrication and medical transport of injured patients include mobile rescue and extrication equipment, stair-climbing stretchers, patient support devices, and reconfigurable transport aids [14,29,124–126]. Their primary functions include carefully adjusting the casualty's position and completing loading [127], supporting the body and neck, reducing impacts during transport, monitoring the patient's condition, and handing the casualty over to rescue personnel. Therefore, performance evaluations should focus on patient contact forces, loading time and safety, body support and stability, clearance through passageways, vibration and impact during transport, medical monitoring, the workload of rescue personnel, and the final handover process.

Most publicly reported demonstrations to date remain at the E1/S0 stage, primarily utilizing simulations, anthropomorphic manikins, individual functional components, or preliminary prototypes. Relevant studies have demonstrated functions such as head stabilization, obstacle navigation, and the transformation between stretcher and wheelchair configurations; however, autonomous transport of real casualties from unstable rubble environments has not yet been achieved [125,128]. The higher E3/S1 level of evidence for heavy engineering equipment cannot be used to demonstrate capabilities related to patient contact, casualty extraction, or medical transport.

Table 5 and Figure 5 summarize the evidence for seven categories of robots in specific tasks, as well as the qualitative suitability of each platform. Engineering interventions and casualty transport are listed separately to avoid mistaking the technical maturity of heavy-duty operations for the maturity of safe patient handling capabilities.

Table 5. Platform fit, rescue-support potential, task-scoped evidence, and principal limitations.

Platform	Search tasks	Rescue tasks	Sensor fit	Highest task-scoped validation (E/S)	Key limitations
Aerial (UAV)	Limited void access; high suitability for rapid reconnaissance, mapping, and surface screening	Communication relay and small-payload carriage	Vision, thermal, photogrammetry, communication payloads	Earthquake reconnaissance -> E4/S3 [51,52]	Endurance, payload, confined flight, dust, weather, airspace
Tracked/wheeled/ reconfigurable	Moderate access; high suitability for mapping, detection, and payload carriage	Communication relay, supply support, and manipulation potential; mostly test-bed evidence	Broad payload suite, including radar, gas sensors, LiDAR, and manipulators	WTC void search and mapping -> E4/S3 [6]	Aperture size, rollover, tether and communication management
Quadruped	Moderate access; high suitability for rough-terrain mobility and mapping	Relay, light delivery, and manipulation potential	Mid-weight vision, thermal, radar, communication, arm payloads	SubT artifact search -> E3/S1 [25]	Loose rubble, foothold and contact stability, endurance, communication loss
Snake/continuum	High suitability for confined access; moderate suitability for close-range detection; limited localization	Limited relay, distal sampling, sensor placement, or light-object delivery	Micro-camera, microphone, compact thermal sensor, distal gas inlet	Mexico City void access and visual search -> E4/S4 [44]	Pose uncertainty, endurance, payload, self-recovery, communication
Humanoid/ hybrid	Limited deep-void access; moderate suitability for human-space inspection and assessment	Tool use, intervention, supply handoff, and controlled extraction research	RGB-D, LiDAR, force/torque, tactile, proprioception, human-scale payloads	DRC manipulation/ post-earthquake assessment -> E3/S1 [48,116]	Falls, self-recovery, speed, endurance, latency, workload, contact safety, cost

Table 5. *Cont.*

Platform	Search tasks	Rescue tasks	Sensor fit	Highest task-scoped validation (E/S)	Key limitations
Heavy engineering robots	Limited confined search; conditional suitability for route and work-zone assessment	Route opening, debris removal, shoring, lifting, and heavy manipulation under structural authority	Vision, LiDAR, hydraulic/force sensing, haptics, machine-state and vibration monitoring	Engineering intervention trials -> E3/S1 [121,122]	Large footprint and logistics; ground stability; secondary-collapse risk; reaction loads and vibration; precision near victims; latency
Casualty-extraction/ medical-transport robots	Not a primary search platform; requires a confirmed casualty and a prepared or responder-controlled access route	Casualty contact, repositioning, loading, whole-body/cervical stabilization, monitored transport, and responder handoff	Patient-contact force/pressure, inertial measurement unit (IMU), vibration/shock, vision, and medical-monitoring payloads	Mock-casualty extraction/transport prototypes -> E1/S0 [50,125,128]	Live-casualty safety; loading time; body support; route width and obstacles; shock/vibration; medical oversight; handoff safety

Note: E/S grades are task-scoped. Heavy engineering and casualty-extraction/medical-transport are separate platform classes: E3/S1 applies only to heavy engineering intervention demonstrated in field-relevant non-earthquake trials, whereas E1/S0 applies to casualty loading, stabilization, and transport prototypes. Engineering deployment evidence should not be extrapolated to patient contact, live-casualty extraction, or medical transport. In this table, "Highest task-scoped validation" is a class-summary selector (highest E; if E is tied, the more collapse-relevant S example), not a grade assigned to every task in the class. For tracked/reconfigurable robots, WTC void search/mapping is therefore summarized as E4/S3, while Fukushima reactor-building inspection remains a separate E4/S1 task-level entry in later task-level evidence tables.

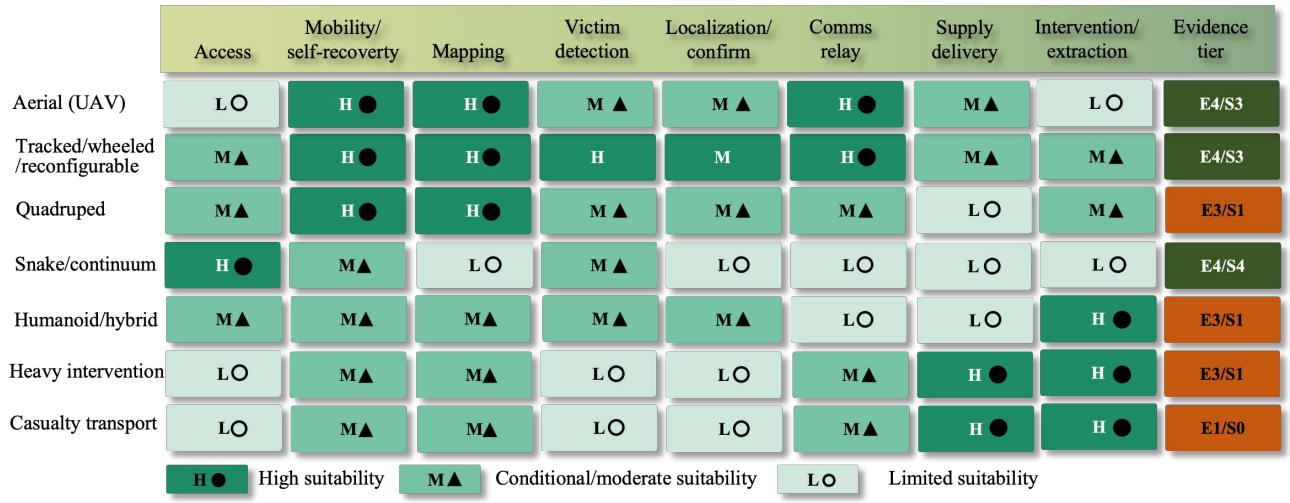


Figure 5. Qualitative platform-task suitability for seven platform classes in operational entry order; each cell uses redundant H/M/L text, symbol, and pattern encoding (H● = high suitability; M▲ = moderate/conditional suitability; L○ = limited suitability).

5. Victim detection and localization sensors on robots

After detecting signals that may originate from individuals trapped under rubble, their exact location must be further determined to provide a basis for rescue operations. Beyond-line-of-sight sensors can detect signs of activity propagating through rubble, but location estimation is susceptible to the on-site

environment and is subject to a certain degree of error [18,19,129–131]. This paper uses only quantitative results explicitly reported in the original studies; data not provided are marked as NR (Not Reported). Given the significant variations among studies in test protocols, rubble configurations, types of target signs, and the motion states of robotic platforms, the existing data do not yet meet the conditions for pooled analysis.

5.1. Optical, thermal, acoustic, and seismic sensing

Visible-light cameras and thermal imaging cameras are widely used on tracked platforms, snake-like robots, and unmanned aerial vehicles [44,45,52,74]. When a camera can directly capture images of a person or their body parts, the images provide rescue personnel with visual evidence to assess the situation on-site. Thermal imaging is commonly used for screening exposed areas and can also assist in checking for trapped individuals within shallow cavities. Such methods are highly constrained by line-of-sight conditions: debris can block the view, while dust, smoke, lens contamination, and insufficient temperature differences between the target and the background can also impair recognition performance. Machine learning-based methods for detecting trapped individuals have been tested on image datasets and in controlled, simulated environments [100,132], but their effectiveness in unstable earthquake rubble has yet to be validated in the field.

Images captured by mobile robots can also be used for infrastructure inspection and structural damage assessment. Jiao *et al.* [35] combined underwater robots, visual processing methods, time-varying damage assessment, and early warning technologies for marine and offshore concrete structures. Zhang *et al.* [133] integrated a biomimetic manta ray underwater robot with the YOLOX-DG detector and reported the results of its field evaluation on large-scale underwater concrete infrastructure. These studies link robotic mobile platforms with visual measurement, defect analysis, and asset documentation. Major interfering factors in underwater environments include turbidity, corrosion, and hydrodynamic motion; in post-earthquake debris environments, common challenges include dust obscuration, concealed heat sources, complex geometries, and weak wireless communication. Therefore, relevant visual inspection and assessment methods can provide guidance for post-disaster inspections; however, their applicability in SAR missions involving earthquake-collapsed buildings still requires specialized testing [35,133].

Even if trapped individuals cannot be directly observed by a camera, they may generate sound and vibration signals through shouting, knocking, footsteps, or physical movement. Acoustic devices can also be used to establish two-way voice communication with trapped individuals. Actual effectiveness depends on whether the individuals can respond; signal recognition can be disrupted by the operation of mechanical equipment, the movements of rescue personnel, aftershocks, reverberation, and the complex propagation paths of sound waves through mixed rubble [131]. Acoustic measurements can be used to detect and confirm signs of trapped individuals and to support on-site communication. However, to determine the location of individuals based on these measurements, challenges such as the difficulty in determining propagation paths and significant positioning errors must be addressed.

5.2. Radar sensing of vital signs

Ultra-wideband (UWB) radar and frequency-modulated continuous-wave (FMCW) radar can detect periodic chest movements caused by breathing; some systems are also capable of sensing subtle movements

associated with the heartbeat. Relevant algorithms extract vital sign information from relatively stable background signals by analyzing subtle periodic changes in phase or distance data [18,129,130,134]. Following the 2015 Nepal earthquake, rescue workers used handheld FINDER devices to conduct search-and-rescue operations and, with the aid of these devices, located four survivors beneath collapsed buildings [46]. This real-world case demonstrates that radar-based life detection can be applied to disaster relief; at that time, the devices were handheld or placed by personnel and had not yet been integrated into robotic platforms.

Currently, there is still limited evidence regarding field searches conducted by robot-mounted radar. Factors such as platform movement, multipath reflections caused by metallic debris, detection range, antenna orientation, and confusion between animal and human signals may all affect measurement results [18,130]. Existing research is best suited to support the following approach: first narrowing down the search area using other search methods, then using radar for close-range confirmation. There is still a lack of sufficient validation data regarding the ability of robot-mounted radar to conduct reliable, large-scale searches within complex rubble areas.

5.3. Chemical sensing and electronic noses

When the target substance and its potential source are relatively well-defined, chemical sensors can be used to determine whether trapped individuals are present in a blocked-off area; this is particularly useful for individuals who are unable to respond through sound or movement. Potential volatile organic compounds include acetone, isoprene, and 6-methyl-5-hepten-2-one (6-MHO); ammonia is a volatile inorganic compound, while carbon dioxide and water vapor are the primary byproducts of respiration [17,20,49,135]. Some gases occur at high concentrations and may still be detected at a distance, but they lack specificity as indicators of human presence. Substances more closely associated with human activity typically occur at very low concentrations; they are easily lost as they pass through rubble and are susceptible to interference from environmental odors.

Simulated entrapment experiments have shown that some chemicals released by the human body can diffuse outward through the pores of rubble. Airflow conditions, pore structure, adsorption, leakage pathways, temperature, humidity, and background environmental emissions can all alter the gas propagation process [17,20,49]. Electronic noses typically consist of multiple chemical sensors, classification algorithms, and sensor drift correction modules. Controlled experiments have demonstrated that such systems can distinguish between scenarios where a person is trapped and those where no one is trapped; presence-gated sensing methods also combine chemical alarms with radar verification to reduce false alarm rates [19,49,136]. Chemical signals can help rescue personnel pinpoint areas where a person is suspected to be trapped and provide directional cues for subsequent searches. Currently, however, such methods still struggle to provide reliable three-dimensional coordinates that can directly guide excavation efforts.

5.4. Biohybrid biological olfaction

Hybrid biological olfactory systems combine living tissue or organs capable of olfactory perception with robotic platforms. Common approaches use insect antennae as odor receptors and record their responses via electroantennography [137–140]. Existing prototypes include the Smellicopter, which utilizes moth antennae; a scent classifier based on locust antennae; and the Sniffbot, designed for active odor

classification and odor source tracking. Related studies have demonstrated the feasibility of odor detection and guided odor source search under laboratory conditions; however, there are currently no reports of such systems being applied in real-world earthquake rubble environments.

Existing research indicates that bio-hybrid olfactory systems can be used to locate concealed odor sources and provide regional clues for further searches. Their operation depends on airflow conditions and is influenced by factors such as individual variations among biosensors, service life, repeatability, disturbances to local airflow caused by mounting structures, calibration difficulties, and the degree of standardization; as a result, their field application still faces significant limitations. Future research could conduct direct comparisons between conventional chemical sensors and bio-hybrid sensors under standardized experimental conditions, and evaluate their practical effectiveness relative to existing search methods.

Table 6 provides a qualitative comparison of the detection and localization capabilities of different sensing methods and summarizes the quantitative results reported in the original studies. Comparison metrics include detection range, distance from obstacles or penetration capability, localization error, false alarm rate or detection performance, and the impact of platform movement on measurement results. Since the data are derived from different experimental conditions, the values in the table are intended solely to present the reported results of each study and should not be used to quantitatively rank different sensing methods. Figure 6 further summarizes the compatibility of various robot platforms with different sensors.

Table 6. Victim-sensing modalities: study-reported quantitative performance, localization actionability, and platform-motion constraints.

Sensor	Detection distance/penetration or standoff	Localization error/actionability	False-alarm/detection performance	Platform-motion sensitivity; representative evidence/context
Vision	Distance: NR. Opaque-rubble penetration: none; optical path required.	Victim-location error: NR. Actionable only when a body/body part is visible.	False-alarm rate: NR. YOLOv10: mAP@0.5 98.4%, accuracy 98.5% on a 200-image trapped-survivor test set.	Numeric motion tolerance: NR; susceptible to blur/viewpoint changes [100].
Thermal	Detection/standoff distance: NR. No opaque-rubble penetration; thermal path or exposed/shallow signature required.	Localization error: NR; supports visual confirmation when a thermal signature is observable.	False-alarm rate: NR. YOLOv3: mAP 85%, recall 95%; experimental victim-detection efficiency > 90%.	Numeric robot-motion degradation: NR. Controlled robot tests; vibration/viewpoint effects remain platform dependent [87].
Acoustic/seismic	Detection/penetration distance: NR; microphone was inserted at/into rubble openings in the pilot study.	Acoustic-only localization error: NR; primarily cue detection/confirmation.	Voice classification 89.36%; human-related suspect noise 93.95%; environmental noise 100% correct classification.	Numeric platform-motion sensitivity: NR; vibration/acoustic coupling can contaminate measurements [131].
Radar (UWB/FMCW)	FINDER: up to 9 m crushed rubble, 6 m solid concrete, and 30 m open-space standoff. Earlier microwave system: ~3 m rubble/barrier.	Controlled through-wall UWB multiple-input multiple-output (MIMO): absolute coordinate-component errors 0.03–0.22 m; excavation-ready rubble 3-D error: NR.	False-alarm rate: NR. Li *et al.* used constant false-alarm rate (CFAR); FINDER reports a reliability score but no published false-positive rate (FPR) in the cited operational report.	High motion sensitivity for vital-sign phase; stationary/compensated sensing is required and robot-motion tolerance is NR. FINDER values are portable, hand-emplaced, not robot-mounted [46,129,130].

Table 6. *Cont.*

Sensor	Detection distance/penetration or standoff	Localization error/actionability	False-alarm/detection performance	Platform-motion sensitivity; representative evidence/context
Electronic nose/gas sensing	Spatial detection/standoff distance: NR; performance depends on plume transport and sampling geometry.	Spatial localization error: NR; typically provides presence evidence or a search bearing rather than 3-D position.	Entrapped-human array concentration errors: 19/21/3 ppb (acetone/ammonia/isoprene), $r \geq 0.9$. CO2 pilot: sensitivity 75%, specificity 53.1% at a 27-ppm threshold.	Numeric robot-motion sensitivity: NR; motion can disturb plume/sampling geometry [49,131].
Biohybrid olfaction	Smellicopter lab trials started ~1.41–2.02 m downwind of the odor source; rubble penetration: NR/not tested.	Crosswind endpoint offset 0–5.5 cm; 14/15 trials ended within 4 cm and all within 6 cm. This is odor-source, not victim 3-D localization.	False-alarm rate: NR; the cited study reports 15 odor-localization trials rather than a false-positive metric.	Motion/plume coupled: flight at ~1 m/s wind and an upwind-facing requirement; generalized motion tolerance NR [137].

Note: NR means that the cited primary study did not report the metric. Figures are reproduced for their original experimental conditions without normalization across sensor modalities. FINDE's reported range and penetration were obtained from manually positioned portable equipment and must not be regarded as performance of robot-borne radar. Coordinate errors reported by Li *et al.* [130] were measured for individual components under controlled through-wall conditions, not as excavation-ready 3-D errors in heterogeneous rubble.

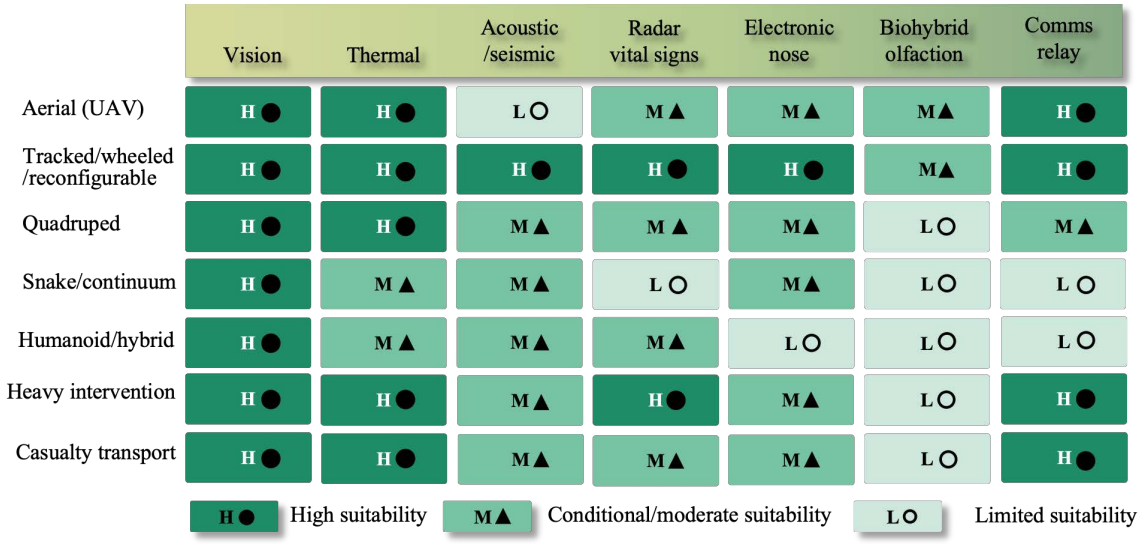


Figure 6. Qualitative platform-sensor mounting compatibility in operational entry order; each cell uses redundant H/M/L text, symbol, and pattern encoding. Note: H ● = high mounting/operating compatibility; M ▲ = moderate/conditional compatibility; L ○ = limited compatibility. The symbols, letters, and hatch patterns avoid color-only encoding. Assignments follow Section 2.4 and are traceable by platform row to Sections 4.1–4.7, by sensor column to Sections 5.1–5.4 and Section 6, and to the source register/task-scoped extraction fields in Supplementary data S1.

6. Platform-sensor-task compatibility

The selection of sensing equipment requires a comprehensive consideration of the robot's payload capacity, available power, platform motion state, measurement geometry, communication link quality, pose estimation capabilities, and the spatial accuracy required for the mission. Tracked robots, quadruped robots, humanoid robots, and construction machinery typically have large payload spaces and can carry sensing equipment that is large in size or requires contact force measurement. Snake-like robots and

continuum robots rely on their slender bodies to enter narrow spaces and have relatively limited payload capacities; UAVs are better suited for long-range imaging, surveying, and communication relaying. Casualty evacuation platforms, on the other hand, require both navigation sensors and measurement devices to monitor patient contact, body stability, vibration, and impact.

Platform movement can interfere with radar phase, odor distribution, acoustic measurements, and thermal imaging or chemical sampling results. Heavy machinery operations also generate vibration, dust, and moving objects; the casualty evacuation process requires a focus on monitoring contact forces and impacts. For different sensing methods, data collection timing should be appropriately scheduled: some measurements are best performed after the robot has come to a stop, while others require motion compensation and verification through independent means. Detection results from chemical sensors and biohybrid olfactory systems are typically used to indicate the possible presence of targets nearby or to suggest search directions; they rarely provide directly verifiable three-dimensional coordinates [21,23,141]. This paper lists corresponding numerical values only when original studies have explicitly quantified motion sensitivity; where quantitative results are lacking, they are marked as "NR" and supplemented with qualitative descriptions.

Figure 7 illustrates the process by which human-derived odors pass through rubble, are sampled by the robot, and undergo signal analysis. Airflow, leakage, adsorption, humidity, temperature, rubble porosity, and environmental emissions can all alter the composition and intensity of chemical signals before they reach the sensor. For rescue personnel to develop excavation plans based on such signals, they must also know the robot's precise pose and independently verify the detection results through other means. The allocation of tasks among various platforms will be discussed in Chapters 7 and 8 and will not be repeated in this chapter.

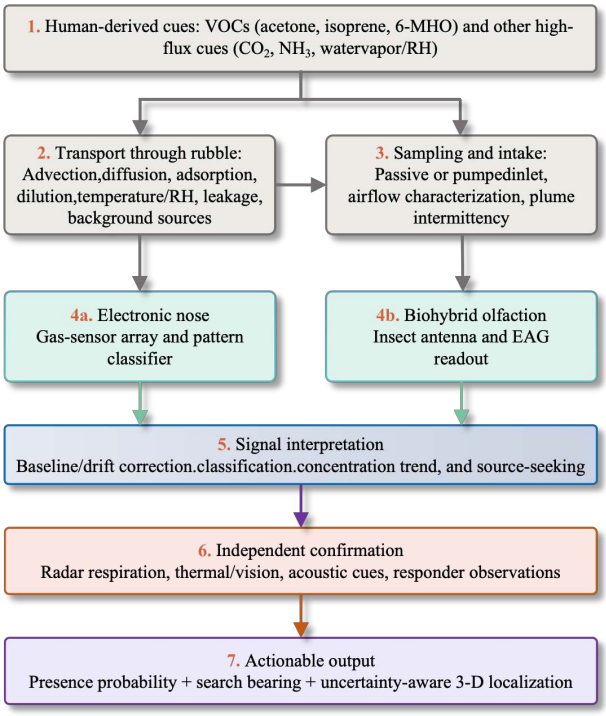


Figure 7. Olfactory victim-detection chain. Note: Authors' synthesis based on the literature cited in Sections 5.3–5.4. Rubble transport and sampling alter human-derived chemical cues. Actionable localization requires independent confirmation and platform pose estimation.

7. From search to rescue: capability, handoff, and human-robot gaps

A review of the existing literature reveals that the primary shortcoming at present lies in the lack of proven coordination mechanisms between various rescue operations. The fact that a robot can enter a cavity does not necessarily mean it is capable of rescuing people inside that cavity; detecting signs of life does not necessarily mean the robot can accurately pinpoint the location of trapped individuals to guide excavation efforts. Even when sufficiently precise location data is obtained, it remains to be verified whether the robot can subsequently maintain continuous communication, deliver essential supplies, clear a path, or treat injured individuals without causing harm. As observational findings are translated into actual rescue operations, the strength of existing evidence gradually diminishes; this issue constitutes a capability gap between search and rescue operations.

Information handoffs also present another set of challenges. While different platforms, operators, and data systems may each demonstrate capabilities in adjacent stages, the seamless integration of these capabilities is rarely systematically evaluated. Therefore, reliable localization and false alarm suppression require independent verification, transparent uncertainty estimates, interoperable status information exchange, and task assignment supervised by rescue personnel [18,136]. Figure 8 lists the highest level of evidence currently achieved at each stage of the rescue mission chain. Each level applies only to tasks that have been actually completed and validated; it does not directly prove that subsequent tasks or handoff points possess the same capabilities.

Figure 8 shows the highest confirmed levels of validation maturity (E) and scenario relevance (S) for each stage of the rescue task chain, along with representative examples. Portable, manually deployed sensors are represented by hollow diamonds; evidence from robots or platforms is indicated by solid circles; and independent sensors or bench tests are represented by hollow squares.

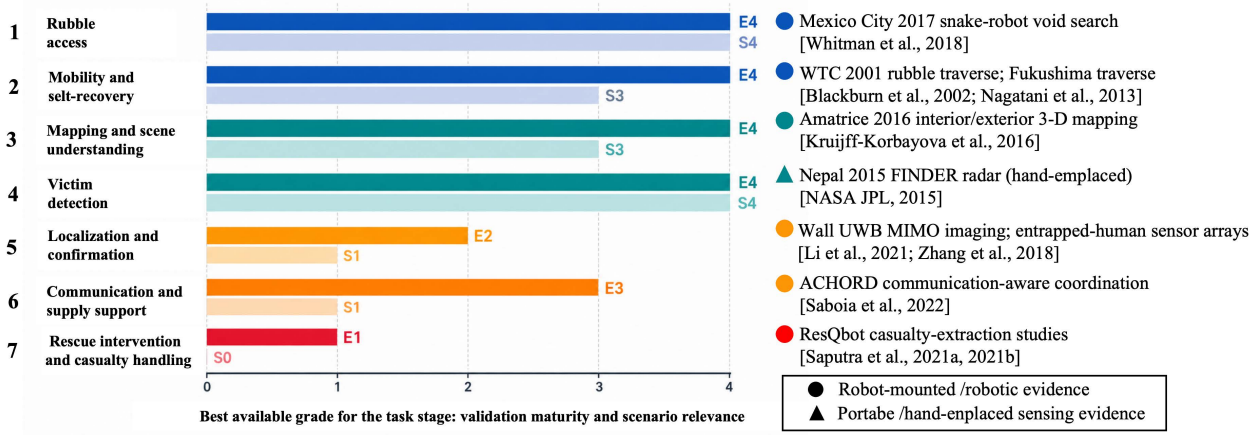


Figure 8. Highest validation-maturity (E) and scenario-relevance (S) grade identified at each stage of the rescue chain, with the supporting exemplar. Portable hand-emplaced sensing is shown with a hollow diamond; robot/platform evidence uses a filled-circle category marker, and stand-alone/bench sensing uses an open square.

7.1. Communication and supply support

Radio signals often have difficulty transmitting reliably through rubble containing reinforced concrete. Possible solutions include deploying temporary relay nodes, adjusting the robots' autonomous behavior

based on link conditions, and forming heterogeneous robot teams capable of operating under intermittent communication conditions [25,84,142,143]. The fact that robots can transport supplies on the exterior of buildings or on exposed ground does not imply that they can deliver supplies into internal cavities; direct evidence regarding the delivery of supplies within cavities remains limited at present.

Relevant validation should document the effective duration of communication links, data rates and latency, deployment time of relay devices, the actual payload delivered and its placement accuracy, as well as plans for equipment recovery or disposal; it should also confirm whether supplies can be delivered to confirmed trapped individuals without increasing structural or medical risks.

7.2. Heavy debris clearing and engineering intervention

Before moving debris or installing support structures, it is first necessary to ensure that mechanical equipment has a stable support base, measure the contact force between the equipment and the debris, and assess the potential response of the damaged structure. Remote-controlled excavators and dual-arm construction robots have provided valuable research findings regarding high-force operations, multi-camera control interfaces, and disaster engineering operations [15,121,122]. However, most demonstrations have been conducted in controlled environments or in field tests not directly related to earthquake rescue operations. Currently, there remains a lack of direct evidence regarding how to safely position operational tools on unstable rubble in close proximity to trapped individuals.

When construction machinery operates near injured persons, rescue personnel should supervise the entire process. Supervision should include approval by structural engineers, delineation of hazard zones, joint determination of excavation paths, setting force and vibration thresholds, continuous updating of on-site geometric information, clarification of emergency stop responsibilities, and task handoffs between machine operators and USAR personnel. Teleoperation studies have found that task duration increases when equipment positioning is difficult or the operator's field of view is limited [123]. Relevant tests should record the total mission duration and the time required for equipment positioning, as well as the visibility of tool contact status, communication latency, vibration, reaction forces, and structural changes.

7.3. Casualty extraction, transport, and assisted evacuation

Among tasks directly related to the physical handling of injured patients, extrication is currently one of the least thoroughly validated aspects in field settings. Published research has primarily relied on simulations, laboratory test benches, human models, component-level evaluations, and experimental transport aids [50,125,126,128,144]. The safe evacuation of casualties involves multiple requirements, including providing appropriate body support, controlling contact and traction forces, stabilizing the head and neck, minimizing impacts during loading and movement, continuously monitoring or maintaining communication, ensuring sufficient clearance in the evacuation route, and obtaining authorization from rescue or medical personnel.

Existing demonstrations have primarily validated the technical concepts of assisted evacuation schemes but have not yet proven that robots can autonomously evacuate real casualties from unstable rubble. Evaluation metrics should include loading time and success rate, maximum contact force and its spatial distribution, body posture, neck stabilization effectiveness, vibrations and impacts during transport, obstacle-crossing capability, ease of access to casualties during movement, rescue personnel workload,

and the final handoff of casualties to stretchers or medical teams. Even when construction machinery and casualty transport platforms are used in conjunction, validation evidence for the two types of equipment should be evaluated separately.

For the foreseeable future, robots performing actual rescue missions should function as tools, operating under the command of professionally trained rescue personnel. Shared autonomy or supervised autonomy modes may be adopted, with clear delineation of authority for rescue and medical decision-making, collaborative planning of excavation paths, outcome verification accounting for uncertainty, standardized human-robot interaction, and the establishment of structured task handover procedures [1,48,110,145]. Clarifying these responsibilities helps prevent search performance or human-model demonstrations from being mistaken as proof of comprehensive rescue capability. At the same time, it enables the identification of functions that have not yet been validated, including stable communication; position estimation directly applicable to interventions; logistical support; precise debris manipulation; safe contact; loading; stabilization; transport; and mission handover.

7.4. The missing interface: robot-robot handoff and human-multi-robot coordination

Current robotics research still focuses primarily on testing individual platforms, with relatively few efforts to validate robots as integral components of a full rescue team. Although some useful data can be displayed on the operator's interface, it is not necessarily organized in a way that allows other robots or rescue personnel to use it directly. For example, orthophotos from UAVs, maps from ground robots, images from snake-like robots, radar echoes, and chemical sensor alarms may all contain critical information; however, existing research rarely demonstrates that other platforms can directly read this data and continue executing tasks without the need for manual reinterpretation. This creates a gap in coordination and handoffs that is distinct from the lack of individual rescue capabilities: while the capabilities of adjacent links may have been demonstrated separately, the information interfaces connecting these links have not yet been validated [7,23,25].

Every handoff of a mission, whether between robots or between robots and rescue personnel, requires a clear information interface. The information received by the recipient must include not only map coordinates but also the spatial reference system, measurement uncertainties, data sources and acquisition processes, access restrictions, structural hazards, communication status, and recommended follow-up actions. The robot receiving the mission must also determine whether the data is sufficiently recent and whether its accuracy meets the requirements of its sensors or operational tools. Rescue personnel, in turn, need to understand the basis for taking action and the hazards still present at the scene. Therefore, interoperability requires not only functional communication links but also consensus among all parties regarding the meaning of the information, as well as a clear definition of decision-making authority.

Example of a mission handoff. Suppose a drone has completed an external survey of a damaged building and identified a potential entrance leading to a cavity. When handing off the mission to a snake robot, the following information should be provided: (i) Spatial reference: on-site/world coordinate systems, map version, candidate entrances or areas of interest, and any coordinate transformations required by the receiving platform; (ii) Uncertainties: error ranges for the map, the robot's pose, and the entrance location; (iii) Data sources: timestamped RGB images, thermal imaging, and photogrammetric data, as well as the UAV's pose history; (iv) Communication status: link quality, relay schemes, time of the last communication, and contingency measures; (v) Mission status: "Candidate cavity mapping completed;

awaiting entry for inspection and confirmation"; (vi) Authorization information: approval from the on-site command center and the robot operator is required before entering the operational area. Using this information, the snake robot can correlate its own route and measurement results with a unified on-site coordinate reference system, avoiding reliance solely on independent local maps.

The next mission handover should also include the transformation relationship between the snake robot's local coordinate system and the on-site coordinate system, the error range for signs of trapped personnel or cavity locations, timestamped visual/ acoustic/thermal imaging observations, the robot's pose, tether or radio status, access routes and hazards along the way, as well as updated mission labels, such as "Suspected signs of a person confirmed; location requires further verification" or "Localization accuracy meets intervention planning requirements." Rescue personnel must obtain appropriate authorization before carrying out direct interventions: operations involving changes to the state of the rubble must be approved by structural engineering professionals; contact with or movement of injured persons must be approved by USAR or medical personnel. The mission handover chain described in Section 8.3 is an example proposed in this paper and has not yet been validated in the field as a complete process.

Unclear decision-making responsibilities are also a common cause of mission handover failures. If all participants are collectively referred to as "supervisors," it becomes difficult to clarify who is responsible for various high-risk decisions. The on-site command center determines mission priorities; robot operators are responsible for equipment control and manual takeover; structural engineers approve operations that may alter the state of the rubble; and qualified medical or USAR personnel approve the contact and movement of casualties. Robots can gradually assume responsibilities for navigation, perception, mapping, and task execution within clearly defined scopes. Excavation, high-force operations, and the movement of casualties still require separate authorization procedures, along with safety contingency plans to be activated in the event of communication failure. Coordinating multiple semi-autonomous robots with personnel responsible for rescue decisions remains a research challenge in this field [1,43].

8. Current evidence, deployment challenges, and a roadmap to human-multi-robot rescue

8.1. Evidence map and the search-rescue gap

Two evidence-grading dimensions reveal significant differences in the strength of evidence across various rescue activities (Tables 7 and 8, and Figure 9). Currently, evidence that is highly relevant to earthquake collapse scenarios and has a high level of validation primarily focuses on entering the operational area, on-site reconnaissance, surveying and mapping, visual search, and detecting signs of life through rubble. For auxiliary tasks such as maintaining continuous contact with survivors trapped under rubble, delivering supplies into voids, performing precise rubble manipulation near injured individuals, installing support structures, loading and stabilizing injured individuals, transporting injured individuals, and final handover, the existing evidence primarily comes from competitions, manually constructed test sites, non-earthquake field exercises, simulations, and laboratory demonstrations.

Research on heavy engineering machinery has added evidence regarding remote-controlled path clearing and high-force operations; however, it has not yet demonstrated that such equipment can safely handle actual casualties. The case study of the serpentine robot in Mexico City provides E4/S4 evidence, indicating that the robot entered a void and conducted a visual search at a real earthquake collapse site [44]; however, the report does not document a successful rescue. Table 7 lists representative task evidence for

various platforms according to the approximate sequence of on-site operations. The evidence levels obtained from real disasters or field trials apply only to tasks that have actually been performed and cannot be extended to untested aspects of detection, localization, communication, supply delivery, operation, loading, stabilization, transport, or casualty handling.

Table 7. Representative task-scoped evidence by platform, task stage, maturity, scenario relevance, and source type.

Platform	Task stage	Representative evidence	E/S	Source type/note
Aerial (UAV)	Earthquake reconnaissance	Lushan and Amatrice [51,52]	E4/S3	Real earthquake reconnaissance/mapping
Tracked/reconfiguration	Void search/mapping	WTC 2001 [6,7]	E4/S3	Real non-earthquake collapse deployment
Tracked/reconfiguration	Inspection (transfer)	Fukushima reactor-building inspection [45,74]	E4/S1	Real-disaster reactor-building inspection; transferable non-earthquake setting; not victim search
Tracked/reconfiguration	Mobility/manipulation test	NIST/RoboCup and rescue rigs [32,72]	E2/S2	Engineered test bed
Quadruped + aerial	Subterranean search	DARPA SubT Finals [25,84]	E3/S1	Competition/field setting; transferable
Snake/continuum	Access + visual search	Mexico City 2017 void search [44]	E4/S4	Real earthquake-collapse field report; no victim found; E4/S4 applies only to access + visual search
Humanoid/hybrid	Mobility and manipulation	DRC Finals 2015 [47,48]	E3/S1	Competition; no casualty interaction
Heavy engineering	Route opening/heavy manipulation	ImPACT dual-arm construction robot [15,122]	E3/S1	Field-relevant disaster-engineering trials; not live-victim work
Casualty extraction/transport	Loading, stabilization, transport	ResQbot, head stabilization, and reconfigurable multi-terrain adaptive casualty transport aid (RMTACTA) [50,125,128]	E1/S0	Laboratory, dummy, component, or prototype evidence
Portable sensing	Through-rubble life detection	FINDER in Nepal 2015 [46]	E4/S4	Real earthquake; hand-emplaced, not robot-mounted
Electronic nose	Entrapped-human cue detection	Controlled sensor-array study [49]	E1/S0	Laboratory study
Biohybrid olfaction	Odor localization/ discrimination	Smellicopter and Sniffbot [137,140]	E1/S0	Laboratory feasibility

Table 7 lists traceable, representative comparative cases; it is not a statistically representative sample. The table includes fields such as task activities, verification maturity, scenario relevance, types of evidence sources, and whether the relevant functions were actually performed by the robot or are merely transferable. Trials involving the remote control of heavy equipment and prototype studies on casualty evacuation should be evaluated separately; experience with remote-operated construction cannot be used as evidence for safe contact with or the rescue of trapped casualties. Table 8 further lists documented deployment cases and field-related trials, assigning a corresponding E/S level to each task. Figure 9 similarly uses distinct markers to indicate portable sensing devices manually placed by personnel.

Table 8. Documented deployments and field-relevant trials with task-scoped evidence tier and scenario relevance.

Event/year	Platform	Task (scored)	Note/transferability	E/S
WTC 2001	Tracked/small UGV	Void search and mapping	Real building collapse; operational USAR [6,7]	E4/S3
Fukushima 2011	Tracked (Quince)	Reactor-building inspection	Real-disaster reactor-building inspection; transferable non-earthquake setting; not collapse-void victim search [45,74]	E4/S1
Mirandola 2012	Ground robots	Earthquake-response inspection	Real earthquake field deployment [146]	E4/S3
Lushan 2013	Rotary-wing UAV	Search support and aerial reconnaissance	Real earthquake deployment [52]	E4/S3
DRC Finals 2015	Humanoid/hybrid	Mobility and manipulation tasks	Competition under degraded communication [47,48]	E3/S1
Nepal 2015	Portable FINDER radar	Through-rubble vital-sign detection	Real earthquake-collapse search; hand-emplaced [46]	E4/S4
Amatrice 2016	Ground + aerial robots	Interior/exterior 3-D mapping	Real earthquake damage assessment [51]	E4/S3
Mexico City 2017	Snake robot	Void camera search	Real earthquake-collapse in-void search; no victim found; grade applies to access + visual search only [44]	E4/S4
ImPACT Tough Robotics Challenge (TRC) 2019 report	Dual-arm construction robot	Remote heavy manipulation	Field-relevant disaster-engineering trials; not live-casualty work [15,122]	E3/S1
SubT Finals 2021	Quadruped + aerial team	Subterranean artifact search	Transferable GPS-denied, communication-limited setting [25]	E3/S1
Prototype studies 2019-2024	Casualty extraction/transport	Loading, stabilization, and transport	Dummy, component, and prototype studies; no live-rubble validation [50,125,128]	E1/S0

To determine whether search capabilities can be translated into actual rescue capabilities, repeatable tests must be conducted in environments that closely mimic real-world collapse conditions. The NIST Emergency Robotics Test Program and the RoboCup Rescue test site provide a preliminary methodological foundation for this purpose [30–33]. Tests simulating earthquake scenarios should also replicate narrow entrances, dust, radio signal attenuation caused by reinforced concrete, loose debris, and human-like models capable of emitting realistic breathing, heat, or odor signals, while evaluating supervised debris clearance and operational time constraints within the same task sequence.

Evaluation metrics should include the time required to enter the operational area, target detection probability, 3D localization error, false alarm rate, communication connection duration, actual payload delivered, applied force, time to place supplies, time to clear a passage, induced vibrations, contact force with casualties, loading time, transport impact, and the handover of casualties to rescue personnel. Figure 9 presents a selection of representative mission results organized according to two evidence-ranking dimensions.

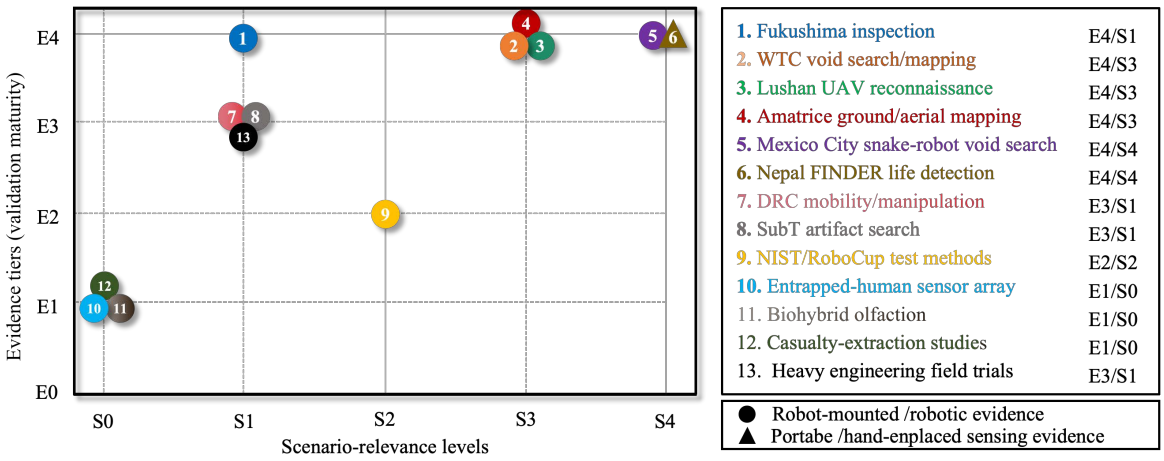


Figure 9. Representative task-scoped evidence by validation maturity (E0–E4) and scenario relevance (S0–S4), updated to include heavy engineering and casualty-transport evidence. Portable hand-emplaced FINDER evidence is shown with a hollow diamond and is not grouped with robot/platform evidence. Note: Numbers identify the examples listed at right. Small within-category offsets prevent overlap; all assigned grades are integers. Heavy-engineering evidence is plotted separately from casualty-extraction evidence. The map is interpretive and does not imply statistical weighting. Marker categories distinguish robot/platform evidence (filled circle), portable hand-emplaced sensing (hollow diamond), and stand-alone/bench sensor evidence (open square).

8.2. Deployment assurance, ethics, regulation, and standardization

The evidence distribution map documents the technical tasks the robot has completed; however, based on these results alone, it is not yet possible to determine whether the robot is ready for deployment in multi-agency, time-sensitive rescue operations. Actual deployment requires clear authorization mechanisms, safe failure behaviors, traceable decision logs, interoperable information exchange, and appropriate validation conducted in accordance with relevant standards. In addition to the capability gap between search and rescue operations, these insufficiently validated safeguards constitute another gap: even if a technology has been successfully demonstrated, evidence regarding liability, safety governance, and compliance may still be incomplete [42,43,119].

8.2.1. Task-oriented standardization and conformity assessment

The NIST Emergency Robot Testing Program and its efforts to advance standardization through the ASTM International E54.09 Committee provide repeatable evaluation methods for mobility, operational capability, perception, power, communications, human-machine interfaces, logistics, and safety. While these methods serve as important starting points, most tests still focus on individual functions. Rescue agencies also need to establish acceptable performance thresholds and validate complete, interconnected operational workflows [32]. Therefore, standardized assessments for USAR in earthquake-induced collapses should gradually expand from component capability testing to mission completion and rescue outcomes. Test procedures should document responses to communication disruptions, emergency stops, the exchange of maps and uncertainty information, sources of sensor data, and authorization and handover

points; they should also evaluate whether robotic intervention can shorten response times while avoiding increased structural or medical risks.

Service robot standards include safety principles that can serve as references, but they cannot be directly applied to the certification of earthquake rescue robots. ISO 13482 addresses hazards and physical contact between personal care robots and people, including manned devices; ISO Technical Report ISO/TR 23482-1 outlines corresponding safety testing methods. However, ISO 13482 does not apply to robots classified as medical devices, nor to robots used for public law enforcement purposes. Relevant aspects include collision avoidance, stability, safe contact, and personnel transport [41,147]. ISO 31101 specifies safety management system requirements for robotic service applications in unstructured spaces where people are active; it can serve as a reference for institutional responsibilities, incident reporting, and interagency coordination, but it is not a product safety certification standard [148].

8.2.2. Human authority, ethical constraints, and regulatory context

A specific person must be designated to make decisions for every high-risk activity during a rescue operation. Robot operators are responsible for equipment control; the USAR on-site command center is responsible for task assignment; structural engineers approve debris intervention operations near trapped individuals; and qualified medical personnel approve the access, transfer, and handover of injured persons. Until the prescribed risk escalation and authorization procedures are completed, robots must not make excavation decisions on their own based on uncertain detection results, must not apply significant force near trapped individuals, and must not initiate the movement of injured persons without authorization. Ethical design should consider harm caused by missed detections and false positives, respect for trapped individuals, transparent disclosure of system limitations, the appropriateness of data collection, and accountability in the event of manual takeover or system failure [1,40,119].

Relevant decisions must also be documented in auditable technical records. If AI is involved in perception or planning, these records should support risk reviews, continuous model monitoring, and post-incident investigations. The NIST Artificial Intelligence Risk Management Framework (AI RMF) and ISO/IEC 23894 propose general risk management processes that can be implemented through model version control, confidence estimates, test logs, records of human intervention, cybersecurity measures, and change control [42,43].

The broader legal landscape continues to evolve. Recent studies indicate that AI regulation in China is moving toward clearer requirements, greater coordination, and a more centralized system; the EU's Artificial Intelligence Act, meanwhile, adopts a risk-based legal framework [39,149]. Neither of these frameworks is specifically designed for rescue robots. The specific regulations applicable to a given system depend on the jurisdiction, intended use, safety functions, data processing methods, and actual deployment context.

8.2.3. Deployment-assurance requirements across the task chain

Table 9 relates assurance needs to all seven stages of the rescue task chain. Its categories are proposed for research and evaluation rather than as a formal checklist of legal compliance, identifying areas in which standards and operational evidence still fall short.

Table 9. Task-specific deployment-assurance requirements across the earthquake-collapse rescue chain.

Task stage	Principal deployment risk	Required assurance evidence	Main standardization gap
Rubble access	Secondary collapse, platform loss, or obstruction of responder routes	Entry authorization; work-zone limits; withdrawal or abandonment plan; communication-loss state	Repeatable unstable-aperture and aftershock-aware tests
Mobility and self-recovery	Rollover, entrapment, uncontrolled motion, or blocked egress	Stability evidence; self-recovery; safe stop; operator takeover; route trace	Common failure and recovery metrics on loose rubble
Mapping and scene understanding	Inaccurate or stale geometry misdirects rescue decisions	Timestamped maps; uncertainty and provenance; interoperable exchange; update rules	Map and uncertainty formats validated under dynamic collapse
Victim detection	False alarms or missed victims misallocate scarce resources	Calibrated detection performance; multimodal confirmation; audit trail; responder review	Multimodal victim surrogates and realistic background interference
Localization and confirmation	An incorrect excavation point causes delay or injury	3-D error bounds; confidence; independent confirmation; platform-pose traceability	Excavation-actionable localization thresholds
Communication and supply support	Privacy or security breach, failed delivery, or loss of contact	Authenticated links; minimum link duration; delivery confirmation; access control; fallback plan	Degraded-link, cybersecurity, and in-void handoff tests
Rescue intervention and casualty handling	Structural destabilization, excessive force, or secondary medical injury	Structural and medical authorization; force/vibration limits; emergency stop; body support; monitoring; handoff record	Live-safe proxies, medical outcome metrics, and integrated rescue-chain trials

This matrix reflects three operational-level requirements. First, deployment support must cover the entire rescue process; it should not be limited to evaluating the performance of a single robot. Evidence of compliance should separately address product safety, service and organizational risk management, operator competence, and acceptance criteria for specific tasks. In addition to standard technical metrics, on-site demonstrations should also document approval processes, manual takeovers, hazardous situations, communication failures, cybersecurity incidents, and patient safety metrics. This approach allows for a combined analysis of E/S evidence and deployment safeguards, while avoiding the reduction of ethical or legal judgments to a single numerical rating.

8.3. Future directions: from isolated capabilities to human-supervised multi-robot rescue

Chapters 7 through 8.2 evaluate the existing evidence; this section proposes systematic approaches that still require testing. Sharing rescue status, assigning tasks based on robotic capabilities, establishing authorization checkpoints, and defining safety boundaries for artificial intelligence are all research concepts awaiting evaluation; they have not yet been validated in the field or achieved E/S-level certification. Each approach addresses specific points of failure in the rescue process and should be tested individually through future experiments.

8.3.1. Shared, uncertainty-aware rescue state

This paper proposes the establishment of a shared rescue state representation to preserve critical information during task handoffs between robots and rescue personnel. This state should include timestamped 3D geometric information and structural changes, assumptions regarding the location of trapped individuals and their confidence levels, sensor data sources, the robot's position and health status, communication quality, route accessibility, as well as the current task and approval status. Multimodal sensor data can be used to continuously update the shared representation while preserving

the inherent uncertainty of each type of measurement. It is essential to verify whether this approach can reduce decision-making latency and improve the accuracy of subsequent task handoffs [18,136,150].

Building Information Modeling (BIM) or a digital twin model reflecting the structural damage status can link the shared records to structurally identifiable features on-site. In this way, robotic observations, obstacles, access routes, uncertainties, communication connectivity status, and decision-making information can be mapped to the same set of physical spatial locations. The approach presented here is an information exchange scheme and does not imply that a digital twin system for rescue operations has already been deployed and evaluated in a real-world post-earthquake scenario. Reference [36] is cited solely as a transferable example of modular, traceable data integration methods in the field of smart construction.

8.3.2. Cross-platform handoff and adaptive task allocation

Which robot should perform the next task remains an open system design problem. Task assignment can be dynamically determined based on the operational range of available robots, their force and payload limitations, positional accuracy, exposure to structural hazards, communication conditions, remaining energy, expected information gain, and any required human approval, without the need for a fixed sequence of platform operations [22–25,143]. Figure 10 illustrates the process by which a drone transfers a task to a snake-like robot and then to a rescue worker. The coordinate system, uncertainties, data sources, communication status, task status, and authorization records are all passed along during the task handoff. The end-to-end performance of this process has not yet been verified.

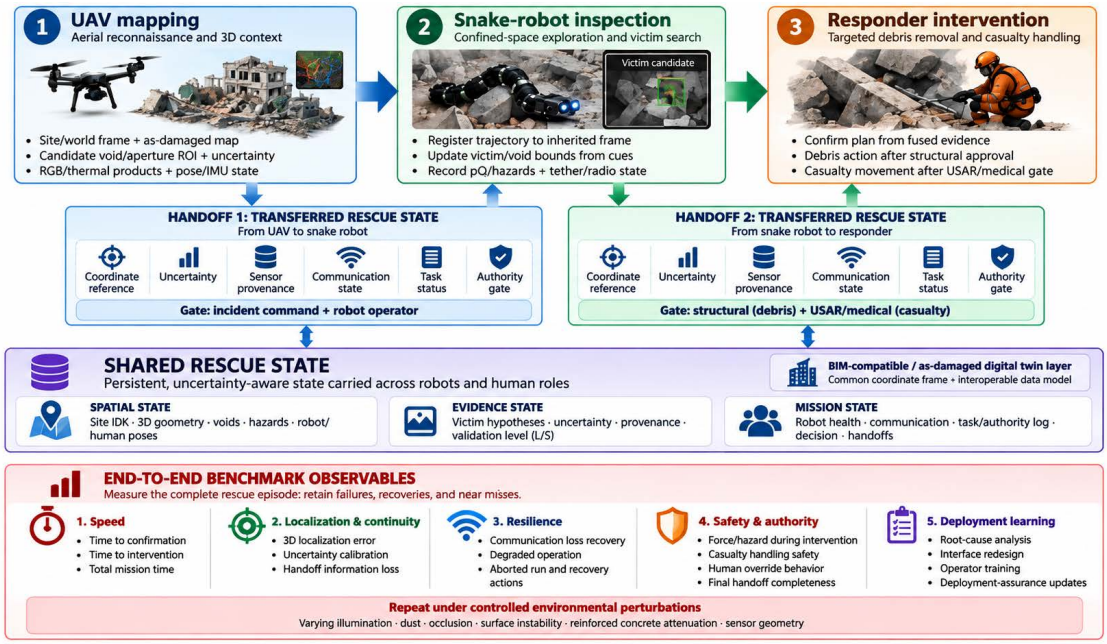


Figure 10. Worked handoff example within the human-supervised multi-robot rescue architecture: UAV mapping to snake-robot void inspection to responder intervention. Note: Prospective, illustrative workflow proposed in this review; it is not E/S-graded and has not been field-validated end-to-end. Each handoff preserves coordinate reference, uncertainty, sensor provenance, communication state, task status, and an explicit authority gate. A BIM-compatible or as-damaged digital-twin overlay is presented only as one possible implementation of the shared rescue state, not as a demonstrated rescue architecture.

8.3.3. Human-multi-robot interaction and authority

To ensure traceability of decision-making accountability, the user interface must clearly present relevant evidence and the decision-making process. The interface should display the shared rescue status, calibrated uncertainty, robot operational status, network connectivity, and recommended follow-up tasks, while clearly distinguishing the respective permissions of the on-site command center, robot operators, engineers, and medical or USAR rescue personnel. The evaluation should include decision-making delays, users' understanding of task handover information, reasonable reliance on automated recommendations and instances of manual takeover, as well as the system's ability to recover from communication interruptions [1,7,119].

8.3.4. AI-enabled autonomy under explicit safety envelopes

Any AI system providing assistance near injured personnel must be subject to explicit and testable constraints on machine behavior. Embodied intelligence or general AI systems may be used for on-site environmental understanding, sensor data fusion, task planning, or natural language interaction. Operations with severe consequences must be based on sensor measurements, confidence levels, a shared spatial reference frame, auditable activity logs, explicit authorization, and deterministic safety fallback states. The core question to be addressed through experimentation is whether, under constrained conditions, AI can improve mission efficiency without increasing unsafe behavior or unauthorized actions [43,78].

8.3.5. End-to-end benchmarks and deployment learning

Deployment readiness should be evaluated through repeatable, full-scale rescue missions conducted in an engineered rubble environment, rather than solely based on the test results of the robot's individual functions. Benchmark testing should integrate the following elements: entry into confined spaces, multimodal casualty identification and localization, cross-platform mission handoffs, degraded communications, supervised rubble manipulation, and the final handover of casualties to rescue personnel, while incorporating time constraints that reflect real-world rescue scenarios [1,30–33].

After each task handoff, evaluators should verify that coordinate information, uncertainty estimates, sensor data sources, communication status, task status, and authorization records have been fully preserved. Core evaluation metrics should include the time required from the start of operations to the identification of casualties and the implementation of interventions; calibrated 3D localization errors; information lost during handoffs; recovery capability following communication interruptions; forces and vibrations generated by intervention operations; safety of casualty handling; records of human decision-making and takeover; and the completeness of information during the final handoff.

The trials should also document aborted attempts, recovery measures, malfunctions, and near-misses, and the same rescue mission should be repeated under controlled environmental variations. The study by Chea *et al.* [34] provides a transferable experimental basis for varying lighting and obstacle arrangements; for building collapse scenarios, dust concentration, line-of-sight obstructions, ground stability, signal attenuation caused by reinforced concrete, and sensor placement should also be varied. Figure 10 illustrates possible forms of task handoffs, rescue status sharing, and approval checkpoints among UAVs, snake-like robots, and rescue personnel. Test records should clearly identify failure mechanisms to provide a basis

for interface improvements and rescue personnel training, and to update deployment inspection requirements accordingly. Evaluation results should not be simplified into a single composite score.

9. Conclusion

Robotic systems designed for building collapse scenarios should be evaluated in the context of the entire rescue process, with particular attention paid to collaboration between robots and rescue personnel during safety-critical phases. Existing representative evidence indicates that robots have relatively robust research support in terms of entering the operational area, moving, mapping, and detecting signs of potential survivors; however, the level of validation remains low regarding precise positioning to guide excavation, continuous communication, in-cavity material support, interventions near injured persons, safe loading and stabilization, transport, and mission handoffs. The seven-stage rescue mission chain reveals the stages where direct validation evidence begins to decrease significantly. It is essential to assess the E/S rating separately for each specific task, as success in one operation does not imply that the robot possesses other untested capabilities.

Currently, no single robot configuration can independently complete the entire rescue process. Aerial, tracked, legged, snake-like/continuum, humanoid/hybrid, heavy-duty engineering, and casualty transport robots should form a heterogeneous team, share rescue information, and establish a task handover mechanism with clearly defined responsibilities. When search results are relayed to rescue personnel, spatial coordinates, uncertainties, data sources, communication context, and planned next steps must be fully preserved. Signs of suspected trapped individuals and precise 3D positioning results capable of guiding excavation must be handled separately. Therefore, the quality of task handoffs is itself an operational capability that requires validation and cannot be viewed solely as a software integration issue.

Existing evidence points to three research directions. First, the search-and-rescue capability gap: while research on access and detection is relatively mature, validation of auxiliary rescue and casualty extraction remains insufficient. Second, the collaboration and task handover gap: the complementary capabilities possessed by different robots have not yet been integrated into a complete, end-to-end validated mission workflow. Third, the deployment and support gap: there remains a gap between demonstrations of technical feasibility and obtaining explicit human authorization for safe and accountable deployment. Future research must address all three of these issues simultaneously and ensure that corresponding decision-making authority rests with personnel with appropriate authority, responsibilities, and qualifications, including on-site command personnel, robot operators, structural experts, and qualified medical or USAR personnel. All autonomous functions should be restricted to safety boundaries established through testing.

Future evaluations should focus on the overall effectiveness and safety of the collaborative rescue team’s mission, rather than on performance improvements of individual robots. Key questions to be addressed include the following: Under human supervision, can the robot team reduce the time required to identify casualties and perform interventions? Can it maintain calibrated uncertainty information during mission handoffs? Can it safely recover from communication or platform failures? And can it complete interventions or casualty handoffs without increasing risks to structures, operators, or casualties? Testing the complete mission chain will further strengthen the evidence base in the field of earthquake rescue and help identify collaboration and safety challenges common to other heterogeneous field robot teams.

Data availability statement

The datasets generated and analyzed during this study are provided in Supplementary data S1 accompanying this article. Additional data are available from the correspondence author (Email: ffsun@tongji.edu.cn) upon reasonable request.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. Specifically, the authors used ChatGPT for language polishing only. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

D.X: conceptualization, methodology, investigation, visualization and writing—original draft; F.S.: conceptualization, supervision, funding acquisition and methodology; S.H.: investigation, data curation, visualization and writing—original draft; X.C.: investigation, data curation and writing—original draft; Y.G.: conceptualization, supervision, funding acquisition and methodology; H.W.: investigation, data curation and writing—original draft; Z.W.: investigation, data curation, writing—original draft. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this article.

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