Journal of Intelligent & Robotic Systems (2019) 96:401–418
https://doi.org/10.1007/s10846-019-00991-6

Review and Analysis of Search, Extraction, Evacuation, and Medical Field Treatment Robots

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Received: 20 October 2017 / Accepted: 27 January 2019 / Published online: 1 February 2019
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Abstract

One of the most impactful and exciting applications of robotic technology, especially autonomous and semi-autonomous systems, is in the field of search and rescue. Robots present an opportunity to go where rescuers cannot, keep responders out of danger, work indefatigably, and augment the capabilities of the humans who put their lives at risk while helping others. This paper examines the use of robotic systems in human rescue applications, with an emphasis on performing search, extraction, evacuation, and medical field treatment procedures. The work begins with a review of the various robotic systems designed to perform one or more of the above operations. The relative merits of each system are discussed along with their shortcomings. The paper also addresses the use of robotic competitions as a means of benchmarking field robotic systems. Based on the review of state of the art systems, a novel concept (Semi- Autonomous Victim Extraction Robot) designed to address the shortcomings of existing systems is described in the conclusion, along with detailed discussion on how it improves upon state of the art systems. The future research thrusts to be explored before realizing a fully integrated robotic rescue system are also detailed.

Keywords Search and rescue robots · Casualty extraction · Human-robot interaction · Autonomous systems

1 Introduction

Many fatalities in the aftermath of disasters and combat are due to treatable traumatic injuries that can be avoided by timely medical treatment [1, 2]. This notion of time-sensitive treatment is represented by "The Golden Hour of Trauma" [3–6], the theory that if medical assistance is provided within a short time following traumatic injuries, the survival rate of the injured person rises appreciably. While the debate on the exact definition and duration of this critical period is unresolved in the medical literature, a mandate from the Secretary of Defense in 2009 to prioritize transporting military causalities in an hour or less resulted in a significant decline in mortality due to traumatic injuries, especially those requiring blood transfusions [7]. As hemorrhage due to major trauma has been found to be the cause of death in up to 80% of potentially survivable wounds in the U.S. military, timely evacuation and transportation must be emphasized when improving medical care [8]. This emphasis led to the U.S. Army Medical Research and Material Command reopening investigation in this field [9]. While rapid medical assistance dominates the focus in the reduction of traumatic field injuries, the risks associated with first responders involved in victim handling procedures must not be ignored [10]. In disaster or combat scenarios, deployment of a medic or other rescue personnel into a dangerous area risks the lives of both the rescuer and the injured. Furthermore, during terror attacks or military operations there may be "leave behind" explosives or enemy troops targeting first responders [11]. Moreover, manmade catastrophic events often occur in remote locations, making it difficult to send qualified personnel. In the above cases, robots can make significant contributions to saving the lives of both the injured personnel and responders. A lack of a comprehensive review for robotic systems to perform or aid in victim extraction and evacuation was the impetus behind this work. Even though a majority of the systems reviewed were developed for military applications the inferences drawn from the review are applicable to civilian casualty handling from manmade and natural disasters.

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Despite the general categorization of existing state of the art systems as "search and rescue", not all of them are equipped to conduct human rescue operations independently. For better analysis of the robotics used in this area, these systems can be organized by where they fit into the medical response process: search, extraction, evacuation, and treatment [12]. In the search stage, robotic systems attempt to find and report the location of any injured personnel. Search robotics is a mature field, and robots have been actively incorporated into search procedures in numerous disasters as far back as the September 11 attacks in 2001 [13]. Next is the extraction phase, in which a robot physically maneuvers or carries the injured person out of the disaster zone. These 'rescue' robots are by necessity larger and at times, more complex, than their search-focused brethren. Compared to search, this is a less mature field. Systems such as the Battlefield Extraction-Assist Robot (BEAR) and the Robotic Extraction Vehicle (REX) are indicative of these types of robots [14, 15].

Following the safe extraction of an injured person from a dangerous area, there must be safe and efficient evacuation of the patient to a medical assistance location. The robots that are designed to perform this task include the Life Support for Trauma and Transport (LSTAT), a stretcher with a full set of sensory equipment and a robotic snake-like manipulator [16], and the Robotic Evacuation Vehicle (REV), a mobile patient transport robot [15]. At a better-equipped medical station, robotic surgical systems facilitate the treatment of the wounded person by allowing a remotely located surgeon to perform advanced surgical procedures on the wounded person *in situ*. While early robotic surgical systems such as the da Vinci [17] and the Zeus [18] were designed for this purpose, they are too large for field operation. Based on the review of state of the art robotic search, extraction, evacuation, and medical treatment robots, a future research direction would be the development of a unified system that can perform as much of the rescue procedures as possible.

This paper will review the existing ground robotic systems designed to play a role in one or more of the aforementioned stages, and will investigate the future of field rescue robotics. Historically, a large amount of attention has been devoted to the robotic systems that belong to the

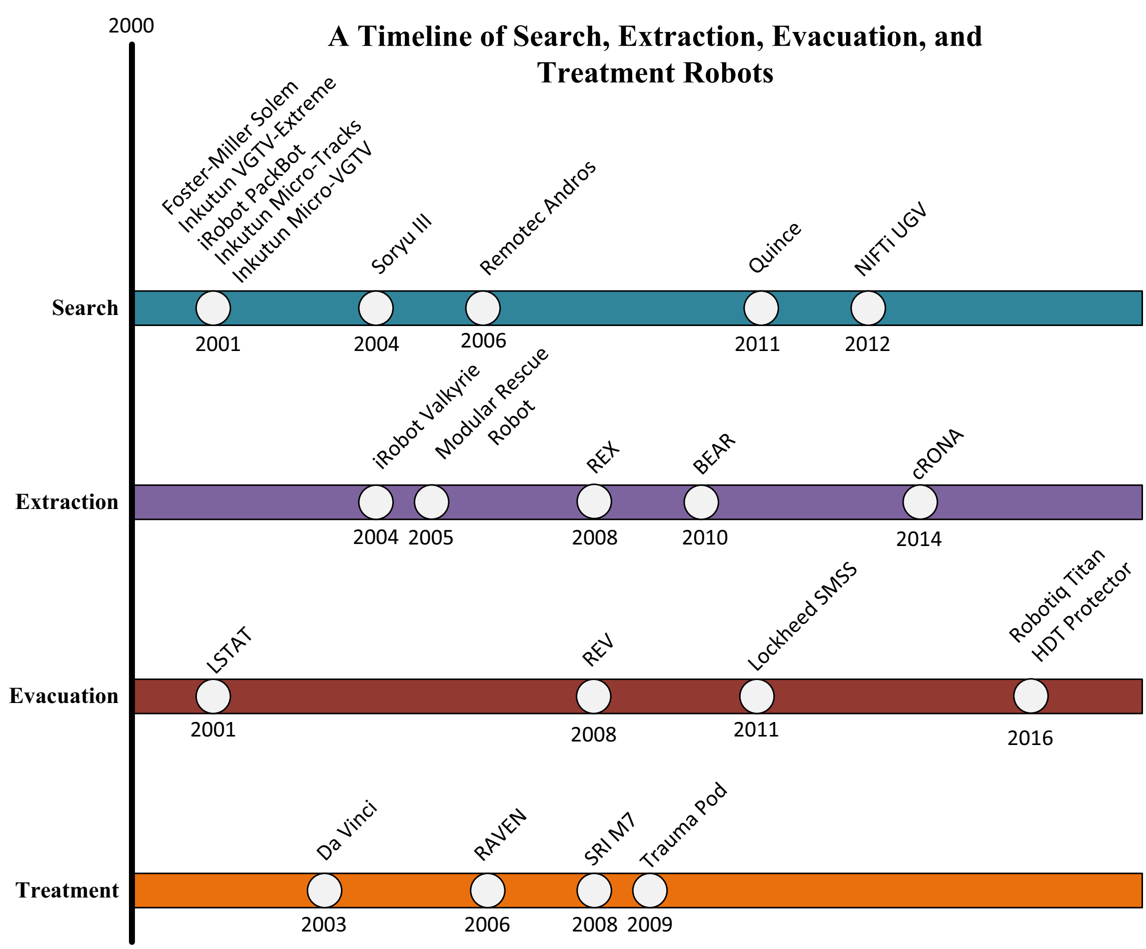

Fig. 1 Timeline of implementation of robots reviewed

search class. This work aims to highlight previously under-reported systems designed for the extraction and evacuation of injured personnel, culminating in the presentation of a novel solution for such scenarios. A timeline of the implementation and/or testing of these robots as described in the literature are shown in Fig. 1. The systems are reviewed in the following section in chronological order as given by Fig. 1. Section 2 of this paper contains a review of the search robots, Section 3 explores extraction systems, Section 4 describes evacuation platforms, Section 5 examines surgical robotic systems, and Section 6 details the need for robotic competitions to evaluate existing state of the art system. Section 7 of the paper provides a conceptual design for Semi-Autonomous Victim Extraction Robot (SAVER) that can satisfy the requirements for a combined search, extraction and evacuation platform with possible treatment capabilities. Section 8 concludes the paper with directions for future research in robotic casualty handling.

2 Search Robots

Spurred by the close succession of the catastrophic 1995 Oklahoma City bombing and Kobe earthquake [19], unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and autonomous underwater vehicles (AUVs) with search capabilities have all been deployed with some capacity in response to well-known disasters. Robot-human teams were deployed to probe the rubble of the World Trade Center following the attacks on September 11th in 2001, UAVs were used to assist in the search for those trapped by the flooding resulting from Hurricane Katrina in 2005, and an AUV surveyed the damage to the Rollover Pass Bridge caused by Hurricane Ike in 2008. While in Japan, mobile robots such as Quince were utilized to measure the radiation in the aftermath of the Fukushima nuclear disaster in 2011 [20–23]. Robots have the ability to play an integral part in surveying affected regions and locating people in distress during the aftermath of disasters or combat. Search robots are generally designed to act as mobile sensory platforms that perform small crucial tasks which enable the use of sophisticated detection equipment in spaces that may be unsafe or unreachable for humans [24]. Furthermore, with proper design, robots can run continuously, with just a momentary stop for refueling, facilitating nonstop search efforts and allowing human team members to divide shifts more effectively. This would mitigate the risks of sleep deprivation related errors in the operation of complex technology, a major issue in search and rescue efforts [25]. In this section, we provide a brief review of some of the most notable, existing search robots to provide a frame of reference for the reader. For the sake of brevity, only few successfully implemented and field-tested ground robotic systems shown in Fig. 2 are reviewed here. For a detailed review of search robots, the reader can refer to [22, 26]. Even though most of the systems discussed below

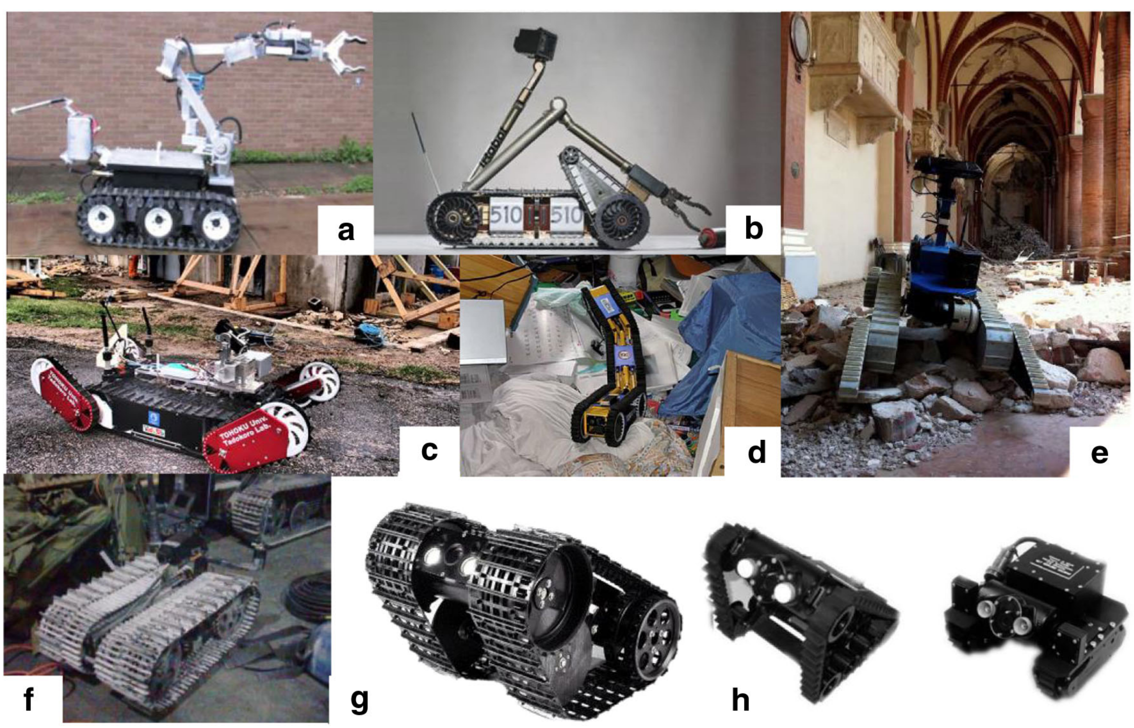

Fig. 2 **a** Remotec Wolverine, **b** iRobot PackBot, **c** Quince, **d** Soryu III, **e** NIFTi UGV, **f** Foster-Miller Solem, **g** Inkutun VGTV-Xtreme, **h** Inkutun micro-VGTV and micro-tracks

are classified as “search and rescue” systems in literature, here they only occupy the search category, as they alone cannot facilitate the extraction and evacuation of an injured personal from a disaster scenario.

The Inuktun VGTV-Delta series by American Standard Robotics and Inuktun Services Ltd. [27] shown in Fig. 2g, was developed for industrial inspection and was adapted later for search and rescue applications. This system was used in different disaster scenarios such as the La Conchita Mudslides (2005), Hurricane Katrina (2005), and the Prospect Towers parking garage collapse in Hackensack, New Jersey, USA (2010). Inuktun Micro-Tracks and Inuktun Micro-VGTV shown in Fig. 2h, were developed as part of the Tactical Mobile Robots program sponsored by the U.S. Department of Defense (DoD) Defense Advanced Research Projects Agency (DARPA). These robots were the most heavily used for the rescue activities at the World Trade Center (WTC) from September 11-21, 2001 [19, 28–30]. Both robots can each be carried in a backpack by one person and are small enough to enter openings the size of a shoebox. iRobot Packbot shown in Fig. 2b, is a widely used industrial robot for search and rescue operations [16, 19, 28, 30–33]. Packbot was developed under the DARPA tactical mobile robotics program. With its two main treads and flippers, it is capable of traversing rough terrain and climbing over obstacles. Foster-Miller SOLEM shown in Fig. 2f is among the tracked rescue robots that was used in the WTC [19, 22, 30]. The system was initially designed for military and civilian Explosive Ordnance Disposal (EOD) applications. With a weight of 15 kg, the SOLEM is too large to enter small spaces and as such was used only once during the September 11-21, 2001 recovery efforts [34]. The Soryu III shown in Fig. 2d is a serpentine robot, a class of robots often used for search and rescue operations because of their ability to reach deep into the rubble due to their unique structure, penetrating as far as 30 meters in some cases [35–38]. The Soryu III is an improvement on older versions built by the Tokyo Institute of Technology and International Rescue System Institute (IRS), possessing stable crawler design, greater anti-roll margin, water/dust proofing, and CO2 sensors for human detection. Remotec Andros Wolverine, shown in Fig. 2a, is manufactured by Remotec Inc. [39, 40]. The Wolverine class of robot is traditionally used for bomb disposal, which includes similar systems like the TALON [41]. The Wolverine variant is primarily used for rescue operations in mines by the Mine Safety and Health Administration (MSHA). This system has so far been deployed in seven mines, with a successful outcome in four cases [22, 29]. Quince, shown in Fig. 2c, was developed by Tadokoro et al. [23, 26, 42] with support from the New Energy and Industrial Technology Development Organization (NEDO) for search and rescue operations. The Tokyo Electric Power Company (TEPCO) used this system for relief operations in the Fukushima Daiichi Nuclear Power Plant after the 2011 earthquake. NIFTi UGV, shown in Fig. 2e, was part of the first deployment of a large human-robot team in Europe, fielding multiple types of robots for surveying damage to historical buildings and cultural artifacts in the Mirandola region of Northern Italy after the two major earthquakes that hit the region in 2012 [43, 44]. Recently the evolution of the NIFTi project, TRADR : Long-Term Human-Robot Teaming for Disaster Response, had field experimentation in a post-earthquake area in 2016 [45]. Another wide-ranging effort to build effective search and rescue robots is the ICARUS project. The ICARUS project is an EU-backed proposal made up of a collaboration of universities and private companies, which has a wide array of autonomous and semi-autonomous systems intended for search and rescue, including solar powered search UAVs, heavy UGVs with a crane arm, and smaller UGVs for searching in buildings [46, 47]. The ICARUS project has seen field deployment in the Bosnia floods in 2015; for a detailed description interested readers can refer to [48]. In addition to these mature and field tested systems, there are many innovative robotic systems built for search and rescue applications that have yet to see field use.

Based on the deployment history and operation modes, the search robotic systems can be divided into three major categories: surveying the scenario to estimate the extent of damage and the stability of structures, collecting data for post processing (such as 3D maps of the interiors of buildings), and looking for potentially injured persons. In order to perform the above functions effectively, the robots are designed to be small (man-packable), agile, and require only a small degree of supervision from the human operator. Most of the commonly used UGV systems were initially developed for military purposes such as EOD. However, these robots have been modified for search and rescue to become much smaller than their corresponding military systems, so that they can fit into openings that people and dogs cannot enter.

Robots can now provide a remote presence for rescuers in areas that are physically inaccessible or unsafe, while also allowing the rescuers to “sense and act at a distance” [26]. In comparison to existing active or semi-active articulated cameras used for similar tasks, robots travel further into the rubble while also interacting with the environment such as by taking samples or closing valves via a manipulator. Additional capabilities, such as the ability to work indefinitely without tiring and the use of a wide array of sensors to detect toxic or explosive gasses in the environment, make robots better equipped for search activities than humans or animals. Above all, robots should be used in scenarios where there is a risk to the life of the rescuers. Thus, the key factors in the advantage of robots over other search systems are their terrain adaptability and ability to interact with the environment. With the advancement of research, we can have robot-human teams that allow for faster coverage of the disaster environment, allowing for better allocation of resources and a collaborative system that performs better than the sum of its parts.

3 Extraction Robots

Extraction of a wounded person using a robot is a complex task due to the necessary interaction between a robot and an injured or possibly incapacitated person. Recent advancements in sophisticated actuation and control systems over the last 10-15 years have led to expanded efforts into robotic extraction. This area is less mature than search robotics and is not widely discussed in literature. Yet due to the substantial potential impact, this is a rapidly growing area of investigation and is a major focus of this paper. The extraction robots reviewed here can be found in Fig. 3.

iRobot Valkyrie: One of the earliest solutions to the robotic Casualty Evacuation (CASEVAC) question was created by iRobot in 2004, called the Valkyrie [33], is shown in Fig. 3a. Funded by the Army Telemedicine and Advanced Technology Research Center (TATRC), it had evolved from iRobot's earlier medic robot, Bloodhound [16]. Essentially a modification of the company's man-packable UGV Packbot, it consists of a flexible stretcher, called a Sked, which is tethered to the robot. The intent is that when rescuing a casualty in a combat zone, a medic can remotely operate the Packbot to drive out to the casualty, where the injured soldier can roll onto the stretcher and be pulled to safety.

One of Packbot's most appealing traits is the simplicity of operation. With no active manipulators or extra degrees of freedom, the Operator Control Unit requires only a simple joystick with video feedback. As a tracked vehicle, this makes the control intuitive and straightforward. With the Valkyrie, the operator can drive up to the target, and then deploy the stretcher. Once the injured person is on board, the robot will be driven back to safety. The feasibility of this design hinges on the stretcher having a low enough friction coefficient, so that it could slide when fully loaded. This allowed the small Packbot to pull and maneuver a load several times its own weight. However, the presence of non-uniform terrain with obstacles and rough patches does not guarantee this.

Another concern with this design is that it lacks an active patient transport component and requires the injured individual to roll or climb into the stretcher, precluding the unconscious or incapacitated. Therefore, in most cases the feasibility of this design hinges on either the injured person or someone at hand being capable of securing the injured party within the Sked. Unfortunately, relying on third party intervention decreases the efficacy of the system, while expecting the injured person to secure himself within the stretcher may not always be feasible. Moreover, in cases where a single PackBot is incapable of dragging the stretcher, as seen in Fig. 3a, multi-robot control becomes a concern. In addition, the risk of the Sked tipping over is another shortfall in patient transport. Even if the Sked does remain stable, the Packbot could itself tip over in situations

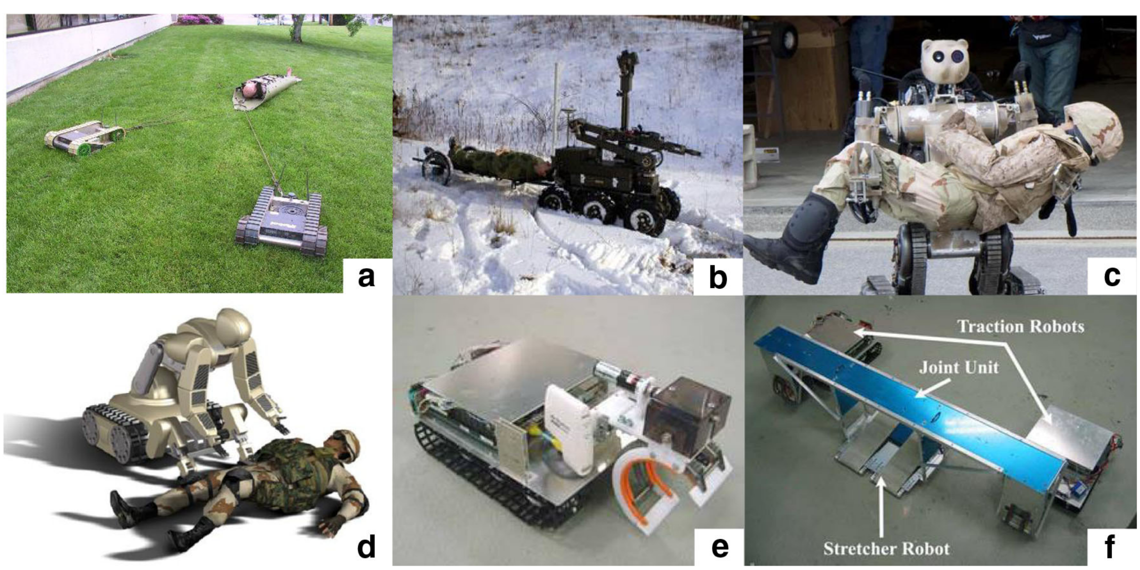

Fig. 3 **a** iRobot Valkyrie, **b** REX, **c** BEAR, **d** cRONA, **e** Modular rescue robot (Traction Robot), **f** Modular rescue robot

where the stretcher tethers apply large moments on the robot while traversing uneven ground. A positive aspect of this system is that by incorporating an existing platform into the design, repairs and maintenance are standardized with a robot that has already been field-tested. In short, the Valkyrie is an excellent modification of an existing platform but has several serious shortcomings, with its simplicity being the major drawback as the robot may have trouble operating in the unstructured terrain common in many rescue situations.

Robotic Extraction and Evacuation (REX): The Robotic Extraction and Evacuation platform is a "marsupial" robotic system. The larger and faster Robotic Evacuation Vehicle (REV) shown in Fig. 4a transported a smaller Robotic Extraction (REX) rover shown in Fig. 3b. The REX is designed to be deployed near the extraction site [16, 49] using the REV. Applied Perceptions Inc. designed the system in collaboration with TATRC. Like the Valkyrie, the extraction robot REX is intended to reach a wounded soldier and place them onto a stretcher that is pulled behind the robot. In this case, rather than dragging the stretcher, the REX tows a wheeled stretcher. Upon reaching the REV, the wounded personnel would be loaded into stretcher bays and then the faster REV would provide transport to the nearest medical station. Figure 3b depicts an image of the REX pulling a patient.

Operating the REV can be simple and straightforward, while the REX can create greater challenges. Originally designed for full autonomy, an Army directive prohibiting the transport of wounded troops in autonomous vehicle required the REX-REV system to have a human operator. The difficulty in operating the REX first arises when trying to use a single manipulator to pull someone onto the towed stretcher. The initial concern is where to grasp an unconscious person using a single pincer end effector without causing new injuries or aggravating existing ones. Furthermore, using a single arm to lift a soldier and their gear, which can weigh up to 300 pounds, requires significant actuation that is difficult to integrate into the small robot. The use of a rolling stretcher allows for ease of transport, but can present difficulties when trying to load a wounded solider onboard. If the soldier is unconscious, they have to be maneuvered onboard with the single pincer, overcoming the above difficulties. In addition, the length of stretcher as well as the REX itself increases the navigational difficulty. The REX is a variant of an existing bomb disposal platform, which means that like the Valkyrie, the maintenance and operation is standardized and familiar to military personnel. However, the risk of tipping over and the availability of a single manipulator arm, while simplifying operation, pose difficulties in successful use of these systems.

BEAR: One of the most promising CASEVAC robots to date is the Battlefield Extraction Assist Robot (BEAR), built by Vecna Robotics [14, 50], is shown in Fig. 3c. It is a semi-anthropomorphic tracked robot designed with an emphasis on agility and maneuverability. The extraction procedure is simple: the BEAR approaches the wounded soldier, slides its arms under the wounded soldier, and then carries them to safety, as shown in Fig. 3c. The BEAR has 22 degrees of freedom, which along with its multiple modes of travel can possibly result in non-intuitive controls. As described in its patent, possible control methods include a multi-joystick operator control unit as well as a motion capture suit intended to couple the movements of the robot with the real time movements of the wearer [50]. While a motion capture suit would help make the operation more straightforward, there is no indication that work on such a suit has yet begun and the challenges in teleoperation of rescue robots are

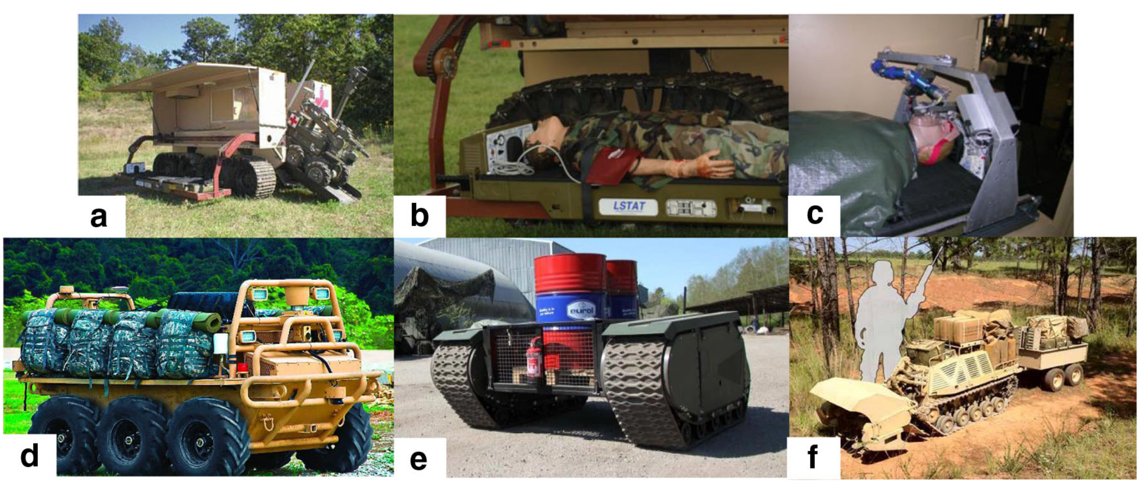

Fig. 4 **a** REV, **b** LSTAT on REV, **c** LSTAT with Snakebot manipulator, **d** Lockheed SMSS, **e** Qinetiq Titan, **f** HDT global protector

non-trivial, due to the limited communication capabilities present in disaster scenarios.

The method of carrying the wounded individual in robotic arms is well suited for picking up the person, but leaves much to be desired when safety is considered. In terms of extracting a prone person from the disaster scenario, this is the most suitable configuration for a two-armed robot as there is decreased risk of further injuring the person by using end effectors that go under the body. However, this method makes several assumptions that are somewhat overly broad when dealing with potentially life threatening injuries. The first assumption is that the injured has both legs present and can bear their own weight. The prevalence of improvised explosive devices (IEDs) makes this assumption uncertain. The other assumption is that the injured suffers from no head or neck trauma that require the head/neck to be supported or immobilized during transport, instead letting it fall limp with no restraint. Both these factors are critical [51] and needs to be addressed in the extraction and transportation of an injured person.

The driving idea behind the design of BEAR is agility. By having a torso that can be maneuvered into multiple positions to dynamically balance and achieve multiple track configurations, this robot was designed to handle multiple terrains. The hydraulic system onboard provides ample actuation force for lifting a person. However, the mobility platform introduces both control and mechanical complexities that affect robustness when operating in an unstructured environment.

cRONA: In a similar vein as BEAR, cRONA is a humanoid robot that uses two arms to lift up an injured person and carry them to safety while utilizing tracks for locomotion [52]. Based on a previously designed Robotic Nurse Assistant (RONA), the cRONA is the combat variant, shown in Fig. 3d. cRONA operates in a similar way, approaching an injured soldier, then bending down to gently lift them onto a stretcher pod which is then towed by the robot. The pods have the ability to be linked together to form a train, allowing cRONA to rescue multiple wounded at a time.

The challenges of lifting an injured person with two robotic arms are mitigated in cRONA as it only has to transfer them onto the stretcher, rather than out of harm's way. cRona is a robot specifically built to transfer patients from one horizontal plane to another, in which, it excels. In addition, the train of stretchers provides better support and protection for the wounded during transport, even though it may pose difficulties when attempting to traverse an unstructured environment and still requires the robot to lift the injured personnel in an unsupported fashion onto the stretcher. The lack of head/neck support for the injured and the assumption that the legs of the injured person are intact enough for lifting remain major problems with this robot.

Other Notable Works: In addition to the designs considered above, there have been several other notable attempts at creating a casualty extraction robot. One such design is a modification of Foster-Miller's widely used military robotic platform TALON [41]. The concept is to use an attachment to the robot consisting of an arm terminating in a conveyor belt meant to slide under a wounded person, then lift and transport them [16]. However, no further work was performed beyond the initial report. Another notable design is a modular patient transport system designed to help those effected in case of nuclear emergency [53]. This involves a set of small robots, designed to approach a prone person and readjust them into an acceptable posture for transport. A rolling platform is slid under the body to act as a stretcher base. The remaining robots then provide the actuation and guidance for the person on the rolling stretcher. The system is well designed, but meant only for the smooth concrete surfaces and large open areas available in a nuclear power plant. Attempting to utilize this system outdoors in rough environment would likely lead to failure. The traction robot in the modular patient transport system is shown in Fig. 3e, and the complete system, along with the joint unit and stretcher robot is shown in Fig. 3f.

The designs for extraction robots reviewed here attempt to balance complexity of operation with specificity of function. Systems such as Valkyrie and the REX are much simpler to control than the others, but lack the ability to effectively transfer the injured person onboard. On the other end of the spectrum, cRONA and BEAR are fully articulated humanoids capable of gently picking up a person in their arms. However, this complexity comes at a high control cost, with a multitude of actuators and sensors requiring high bandwidth communication, complex controller design, and high level computing. Both categories of systems have merits, yet further work can be done to find a more effective combination of the two. However, it can be seen that the major differentiating factors in terms of functionality between these systems are the stability of the injured person during the transfer from the robot to the ground and the stability during transit to the medical site.

4 Evacuation Robots

Once an injured person has been safely extracted from the point-of-injury the next step is often to transport them to a more secure medical station for first aid and/or triage or more in-depth medical attention. To provide an improvement on the existing manual approaches, a robotic system can be used with some degree of autonomy while providing feedback on the injured person's current state. Research and development in this area has largely been focused on the creation of a larger, multi-purpose, mobile ground vehicle that has configurable modules to facilitate the evacuation of injured personnel and the peripheral systems intended to provide onboard patient monitoring in such operations [54]. The reviewed systems can be found in Fig. 4. While this section tries to provide a detailed review of the existing robotic evacuation systems, it should be noted that similar to the previous section, limited information is available on the evacuation systems, mainly because most of them are developed by private organizations.

Life Support for Trauma and Transport (LSTAT): Once an injured person has been extracted from a dangerous area, there must be some manner in which to monitor his or her vital signs while being transported to receive further medical treatment. Even though not a mobile robot, Integrated Medical Systems Inc.'s Life Support for Trauma and Transport (LSTAT) patient care platform [16] is major effort in this direction. While appearing to be simply a stretcher, it possesses enough capabilities to be a mobile Intensive Care Unit (ICU). In addition to the stretcher itself the LSTAT consists of a ventilator, a defibrillator, a suction pump, a fluid and drug infusion pump, and a blood chemistry analyzer [55]. It also carries sensors that monitor blood pressure, pulse oximetry, end-tidal CO_2, temperature, oxygen flow, and electrocardiography. The patient data is shown on a display mounted on the stretcher, and broadcast to a hand-held monitor or available wireless networks.

The LSTAT, shown in Fig. 4b, was well received in multiple field trials, both in hospitals and in military use. The hospital trials confirmed that the combined functionality was analogous to that provided by the multiple devices normally used to conduct this level of monitoring in hospitals [56]. In addition, the LSTAT was utilized successfully in aeromedical evacuation, by forward surgical teams, in amphibious assault vehicles, and in military support for civilian landmine victims [57]. The system was also envisioned as a key component for integration into the evacuation and treatment stages of the medical response process. For instance, REV was designed to accommodate two LSTAT stretchers. Once an injured person is placed onto the stretcher and monitoring is started, the stretcher could provide any medical personnel interacting with the patient detailed feedback on their vitals. In addition, its standard size allows it to be transferred from evacuation vehicle to operating room to recovery, providing continuous monitoring and thereby reducing the labor required [58]. Integration with the flexible Snakebot [59] was also explored to provide the LSTAT with a dexterous attachment [60]. This appendage can be used for multiple applications, ranging from actively inspecting the injured person for possible wounds to cauterizing hemorrhages utilizing short-range high intensity ultrasonic waves. Over time, the LSTAT has been updated as the military moved away from an integrated stretcher. Integrated Medical has since designed an updated device called the LS-1, billed as a "suitcase intensive care unit" [61]. Instead of the entire stretcher unit, the LS-1 contains the data acquisition capabilities from LSTAT in a package that can easily be attached to a standard military stretcher.

Robotic Evacuation Vehicle (REV): As previously described, the Robotic Extraction Vehicle (REV) is the larger transport half of the marsupial pair REX and REV. Upon reaching a combat zone, REV will deploy a ramp and send REX into the field to extract a wounded solider. Once retrieved, REV will act as an autonomous, reconfigurable transport vehicle equipped with two Life Support for Trauma and Transport (LSTAT) stretchers and ballistic armor, in order to safely evacuate the wounded soldiers [15]. An illustration of REV offloading REX in a field trial can be seen in Fig. 4a above.

Squad Multipurpose Equipment Transport: The Squad Multipurpose Equipment Transport (S-MET) program is a U.S. Army initiative intended to drive development of an autonomous or semi-autonomous mobile robot that transports the supplies required by an infantry squad to operate for 72 hours and provides a mobile power source to recharge the electronics carried by the soldiers [62]. These mobile robots have manual operation, follow-the-leader, and autonomous navigation capabilities. In addition to the increased load carrying capabilities afforded by the S-MET, they are also reconfigurable into casualty evacuation platforms, either through attachment points for a standard stretcher or through inherent medical transport capabilities [63]. Therefore, prior to entering a possible combat scenario, the squad could offload the supplies carried by the S-MET and convert it to casualty evacuation mode in order to create a standby evacuation vehicle.

The Lockheed S-MET model, the Squad Mission Support System (SMSS) shown in Fig. 4d, is a field-tested mobile robotic platform that saw service by the U.S. Army in Afghanistan in 2012 [64]. The 4,300 lb vehicle has the ability to pack stretchers on either side or in its bed when it is set up to perform casualty evacuation. In addition, it is capable of remote teleoperation as well as operating in a supervised autonomous mode. A smaller S-MET design is the Titan Dismounted Troop Support System, built by Qinetiq [65] shown in Fig. 4e. A simpler design than the SMSS, the Titan consists of a platform supported by two diesel-electric hybrid tracks, with mission specific controls and automation being contained in modular payload frames. One of the possible configurations includes stretcher racks that can be mounted on the robot, allowing it to easily transition from equipment transport to casualty evacuation vehicle. A third S-MET is produced by HDT Global, called the Protector [66] shown in Fig. 4f. As with the previous versions, it is designed to transform into a casualty evacuation vehicle rapidly, with hard points built into the side to accommodate a folding stretcher. In addition, using ramps carried by the robot, a Protector can be driven directly onto a medical evacuation helicopter [67].

The evacuation systems described in this review possess many similarities, largely due to their military application. In disaster situations, the medical personnel generally respond after the primary danger has subsided, and thus require shorter operating ranges for their equipment as medical treatment centers can be located near the disaster zone. A purpose built evacuation platform would not be used often enough to justify the inclusion of such a large piece of equipment in a squad loadout. Therefore, the overly specific REV has been supplanted by the more versatile pack mule-like S-METs. This provides operational flexibility while still providing evacuation capabilities if necessary. However, this removes some of the patient-care specific benefits that REV incurred through the incorporation of the LSTAT into its design. The desire for a more compact and modular solution led to the creation of the LS-1. There are still no details into the incorporation of LS-1 type monitoring devices into the S-MET type vehicles in order to provide medical monitoring. As such, the largest variations between these systems are in their capabilities to provide targeted patient support and their modular, multi-use capabilities.

5 Field Treatment Robots

A challenge faced by many rescue operations is quickly allocating skilled medical personnel to the location of the incident, especially in remote areas. One way to alleviate this problem is to use systems intended to facilitate remote access to medical care. As mentioned previously, the initial research in this area led to the development of the Zeus and da Vinci telesurgery robots [68]. While groundbreaking, these systems are too large to be easily incorporated into mobile operating settings. Research building upon these two systems has led to significant advances in field-applicable robotic surgical systems. The reviewed treatment systems are shown in Fig. 5.

da Vinci: In addition to providing remote medical support, the da Vinci system was created as a solution to overcome the limitations of manual laparoscopic

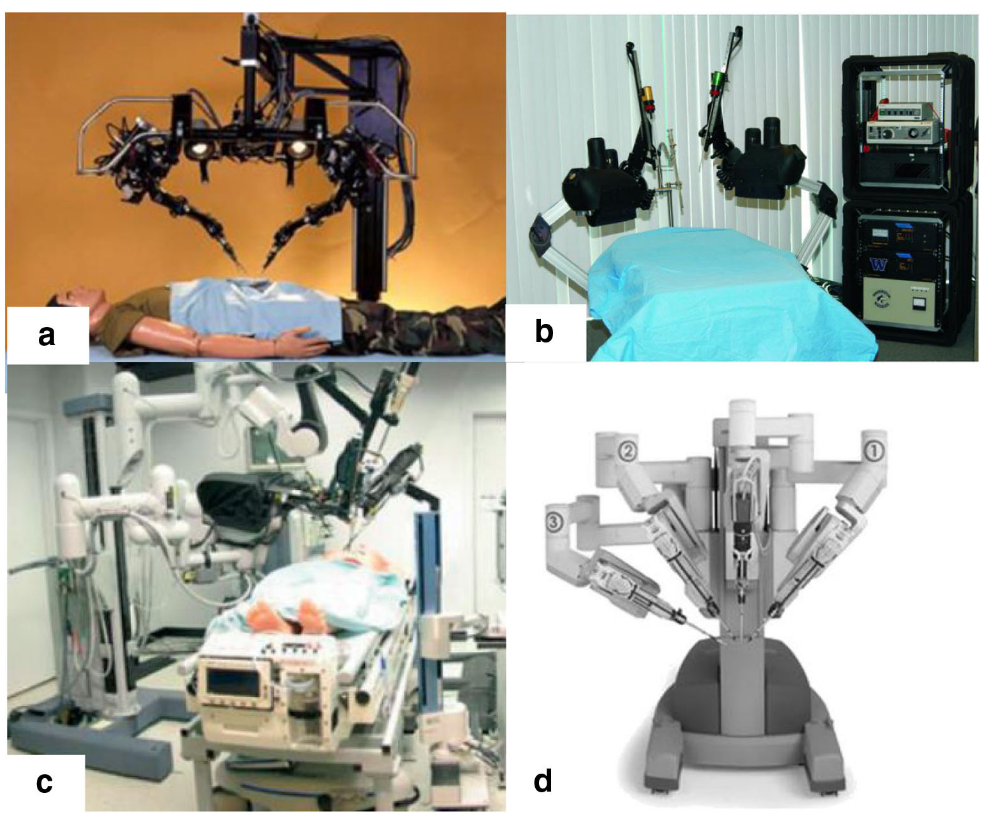

Fig. 5 **a** SRI M7, **b** RAVEN, **c** Trauma pod, **d** da Vinci

approaches which cause discomfort to the surgeon due to the awkward stance and fatigue during the long operations [69–71]. The SRI International with funds from the US Army initiated the development of the da Vinci surgical tele-manipulator, shown in Fig. 5d. The major goal was to create a system that improves the range of motion and dexterity of the surgeon while performing surgery, that could also be used to enable remote telesurgery, and allows integration into a mobile frontline trauma treatment unit. The da Vinci system is based on a master-slave concept with two major units. One is the surgeons console with the display, user interface and electronic controller. Second are the four slave manipulators, three of which are for telemanipulating the surgical instruments and one for endoscopic camera. During conventional laparoscopy, the surgeon has restricted degrees of freedom and range of motion, the da Vinci system restores these by providing seven-DOF (three orientation, three rotations, and grip) inside the patient, while actively filtering out surgeon tremor and providing variable motion scaling between the master and slave.

Over the years, the da Vinci system has been successfully used in several specialties with varied procedures and is now considered a mature piece of technology that facilitates complex surgical procedures with a low failure rate. Even though the da Vinci was initially proposed to be a field deployable system by which surgeons could operate on injured soldiers from a remote location, the actual prototype came out to be too large for field operation. Moreover, challenges of having reliable high-speed, high bandwidth communication also make it impossible for the da Vinci to be deployed for treating injured soldiers or disaster victims. Further research in the development of this system focuses mainly on integrating the system with augmented reality functionalities including haptic feedback and improved training of new surgeons on the da Vinci system

RAVEN: One of the state-of-the-art robotic surgery systems developed to work in challenging field conditions is University of Washington's RAVEN, shown in Fig. 5b. The motivation for RAVEN was to create a lightweight yet robust system that could be assembled on site and operated remotely via satellite link through an overhead unmanned aircraft [72]. Two specially designed serial spherical manipulators provide motion reproduction for the surgeons conducting the remote operations [73, 74]. Recent work with the goal of increasing the number of manipulators that can be incorporated into the surgical workspace, has allowed the system to accommodate two surgeons working at once, with the RAVEN IV designed to use two pairs of arms [75]. The surgeon site has two haptic feedback controllers and an adjustable video feed of the patient site, allowing for intuitive control of the manipulators. In order to aid research in robotic surgery, RAVEN is built using open-source standards such as Linux and ROS and has been provided to multiple universities for further experimentation [76].

RAVEN has also been subject to multiple field tests. On land, a remote surgical station was set up for experimentation in the California desert while the surgeon operated the system over a communication link routed through a drone. RAVEN was also a participant in the NASA Extreme Environment Missions Operation (NEEMO) 12 [77]. In this experiment, surgical robots were set up in the Aquarius Habitat, an underwater lab off the coast of the Florida Keys. In order to perform the prescribed surgical benchmark tests, RAVEN was successfully operated from Seattle, Cincinnati, and Nashville [73].

SRI M7: The Stanford Research Institute's (SRI) M7 robotic surgery system shown in Fig. 5a is another example of a portable surgical operating platform. Consisting of two 6-DOF robotic manipulators weighing only ten pounds each, the M7 can easily be transported where necessary and packed away into a small case. In addition to intuitive haptic controls such as those used by RAVEN, the M7 also has closed-loop autonomous capability to perform small procedures [78].

The M7 has also been tested extensively in the field. It was a participant in the same NEEMO 12 trials as RAVEN in the Aquarius habitat. In those trials, not only did the M7 successfully perform the benchmark surgical tests, it completed the world's first semi-autonomous remote medical task, an ultrasound-assisted intravenous line placement [79]. Additionally, the platform has been tested for use in low gravity applications. The M7 performed suturing tasks on a DC-9 hyperbolic aircraft, demonstrating the applicability of the robotic platform for space-related surgical tasks [80].

Trauma Pod: The ultimate goal in the design of remote surgical robots is to integrate them into a remote field operating room. A DARPA funded project led by the SRI resulted in the design of the Trauma Pod [49], shown in Fig. 5c. As originally designed, the Trauma Pod consists of the following subsystems: a surgical robot, a supply dispenser, a scrub nurse, a tool rack, a tool autoloader, a patient imager, and a stretcher [81]. Utilizing supervisory control planning and teleoperation, the overall system was designed to operate with no direct human involvement. A Trauma Pod prototype was successfully utilized with no on-site human assistance in a demonstration of a bowel closure and a shunt placement surgery on a surgical mock-up [82]. Speech commands are given by the surgeon and recognized by the scrub nurse system in order to present the correct instruments to the tele-operated surgical robot. The robot used in the experimentation and testing was a da Vinci surgical robot, the scrub nurse was a Mitsubishi PA10 manipulator with a dual-gripper end effector, and the LSTAT stretcher provided patient monitoring and diagnostics.

Current field medical robotic systems are focused on minimizing mechanical complexity while maintaining the necessary manipulability. The key to improving the feasibility of remote surgery is coupling the required minimal design with a control scheme designed to take into account the lag and intermittency that arise when using a remote video feed for direct operation. Both the SRI M7 and the RAVEN demonstrate that the systems are fully capable of this task, by operating in remote fields, underwater, and even in free fall. However, they are experimental systems that have not been fully tested yet. The da Vinci, while a mature system, is too large and involves too much setup for portable usage as a standalone device, while the Trauma Pod requires a fixed base, like a large transport vehicle or drone in order to be used in the field.

6 Robotic Rescue Competitions

Developing the proper metrics for an accurate comparison of robotic systems is a challenging task, especially in case of the search and rescue, and patient handling systems that have been reviewed in the above sections. Majority of the published work in this domain focuses only on how the proposed system will operate in a well-defined environment designed specifically for the intended problem. Since no clear criterion exists for the evaluation of these systems, the validation methods adopted by researchers vary greatly, making comparison of different systems solely based on published results nearly impossible. In this regard, robotics competitions are considered the major benchmarking method for field robotic systems, as they provide objective performance evaluation [83–85]. Many major robotics competitions have featured “medical assistance and extraction” as the central theme, a part of their overall challenge, or as an event for demonstration purposes. Some of these competitions include The European Land Robot Trial (ELROB), euRathlon, RoboCup Rescue, and the Darpa Robotic challenge, with the ELROB being the closest towards replicating the real life search, extraction, evacuation and treatment challenges.

The European Land Robot Trail (ELROB) is a robotics competition that has been conducted every alternate year since 2006 untill 2018, focusing on military and civilian applications of advanced robotic systems [86]. In the recent competitions (starting in 2014), search and rescue scenarios such as locating injured personnel inside collapsed structures and performing medical evacuations (MedEvac) have been included in ELROB. For the MedEvac challenge, two dummies representing wounded soldiers were hidden in non-urban terrain. Their approximate location was supplied to the team. The participant then had to locate the wounded ‘soldier’ and extract them to a base location, within a specified time limit. During the 2014, 2016 and 2018 ELROB, many major institutions proposed innovative solutions to the above challenges, some of which are reviewed here. For a complete review interested readers may look into [87, 88].

The 2014 ELROB MedEvac, hosted by Warsaw Military University of Technology and co-organized by Fraunhofer FKIE, had no penalties for damaging the dummy. Most of the teams had manipulators (such as Team Cobham and ELP), but these were capable of handling only very small payloads. Therefore, most of the participants either used the manipulator to drag a dummy of reduced weight (Team Cobham and ELP) or used it to attach a hook to the dummy through teleoperation and then drag the dummy using the robot (Team FKIE). Other solutions included using lifting mechanisms (Team Oulu) or a forklift designed to lift heavy loads (Team Marek). Among the twelve teams that participated, only three were capable of locating and retrieving the dummies. In the 2016 ELROB all six participants were able to transport one of the full-size dummies for a short distance within the time limit. Three teams completed the full task of locating and extracting the two full-size dummies to the base location within the time limit. Four teams (Team Kobra, Cobham, ELP, and Bebot) used a single manipulator and gripper to partially lift and drag the person back to the base. Team FKIE used the previous method of attaching a hook using the manipulator and then dragging the person on the ground. Team Avrora needed manual help in lifting the dummy and securing it onto the vehicle. Despite major improvement compared to previous results, the evacuation and transportation methodologies adopted by the teams would not be acceptable in a real-life scenario. This in turn shows the amount of work needed in this area before robotic rescue and evacuation can be fully realized. The tenth and final ELROB was conducted at Lens, Belgium in September 2018 [89]. It involved multiple scored events including Transport / Convoying, Reconnoitring of Structures, Transport / Mule, and Search and Rescue (SAR) / MedEvac. Seven teams participated in the MedEvac event, all of them being tele-operated and two completed the mission in time, with Team Brokk Security and Rescue Solutions scoring the maximum. Additional details regarding the performance of the teams are expected to be published soon.

The RoboCup Rescue competitions were initiated as a part of the worldwide RoboCup competition in 2000 [90]. These include both the Rescue Robot League (RRL) and the Rescue Simulation League (RSL) [91, 92]. The Rescue Robot League involves exploring and searching for simulated casualties within an arena, including subtasks such as mapping, remote manipulation, and autonomous operations. The tasks, including the test environment, are based on the standard test methods for emergency response robots developed by the U.S. National Institute of Standards and Technology [93]. Since 2016, the CarryBot league, which involves using robots that can transport material or even injured personnel in an outdoor scenario, has also been added as part of the RoboCup Rescue competitions [94]. DARPA started robotics competitions in 2004 with the Grand Challenge [95]. Inspired by the Fukushima Daiichi nuclear disaster,the latest DARPA Robotics Challenge (DRC) had Urban Search and Rescue as the core theme fostering research on robots capable of assisting humans in response to natural and manmade disasters. A major focus of the DRC was to develop ways to combine the complementary strengths and weaknesses of the robot system and human operator(s). Even though the competitions required humanoid robots to perform complex tasks like driving a utility vehicle, opening a door, handling valves [96–99] etc, it did not involve any direct casualty extraction or evacuation challenges. The EU-FP7 euRathlon project was a three-year initiative funded by the European Commission, started in 2013. As an international competition, it welcomes universities, industries, and independent teams from any EU country. The Grand Challenge, conducted on September 2015, was inspired by the Fukushima accident of 2011, providing real world challenges focused on outdoor robotics. The Grand Challenge required a collaboration of flying, land, and marine robots to survey the disaster area, collect data, search for missing workers, identify critical hazards, and work together to perform high level tasks such as closing valves in synchrony [100, 101]. As a follow up to the euRathlon, the European Robotics League (ERL) Emergency Robots challenge are now being conducted, with a focus on realistic, multi-domain emergency response scenarios [102] including first aid kit dropping and victim search as part of medical related tasks for ERL 2017. The ERL builds on the success of the EU-FP7/H2020 projects: RoCKIn, euRathlon, EuRoC and ROCKEU2 and is now run by the H2020 project SciRoc. ERL is an established competition with several leagues (Consumer, Professional, Emergency) using a common benchmarking system.

Recently, there has been more work regarding standardizing the benchmarks and scoring techniques used by robotic competitions. A recent study by Ferreira et al. [103], presented critical analysis and comparison of existing scoring techniques used by robotic competitions with special focus on search and rescue. The study provides useful insight into improving existing scoring techniques as well as designing new approaches. The Robot Competitions Kick Innovation in Cognitive Systems and Robotics (RoCKIn) [104] project is a recent development with regards to benchmarking robotic systems. The RoCKIn project aims to develop competitions that come close to scientific experiments, providing an objective performance evaluation of robotic systems under controlled and replicable conditions. These techniques are now also used in the ERL competitions.

7 Novel Solution

Although no single system or group of systems exists to date that can do all the four tasks of robotic search, extraction, evacuation, and treatment; as depicted by the progression of systems above, the global research community is moving towards integrating co-robotic teams with the aim of achieving this ultimate goal. In order to continue the tremendous progress already achieved towards making this goal a reality, several key aspects need further research.

With regards to search, an effective mobile search robot is one that possesses the ability to adapt to the necessary terrain. From Soryu to Quince, this adaptability lends the robots the flexibility required for successful field deployment. Ongoing research in this area focuses on the use of these robots in autonomous and semi-autonomous multi-robot teams, in order to effectively search over a large area. Further work is required on methodologies and machine intelligence required for the robots to not only operate in tandem with other robots, but alongside search and rescue personnel with minimal training. Human-robot cooperation could vastly increase the usability and benefit imparted by search robots, and would help to further their implementation in the field.

In the area of casualty extraction robots, one of the critical challenges is keeping the injured person safe and secure during transport. One of the more difficult tasks in this operation is transferring the injured or incapacitated person from the ground to the transport platform. By necessity, patient transfer requires some combination of lifting, dragging, or sliding, and current designs fail to place sufficient emphasis on maintaining a stable transfer mode. Further attention to this problem could reduce the danger of exacerbating any existing injuries or causing new ones. In addition, the existing systems all rely on direct, continuous operator control, which may face challenges when operating in remote locations with poor network infrastructure. A robotic platform with semi-autonomous capabilities and lag-compensating control could help ensure the safety of the injured person when communication channels are unreliable.

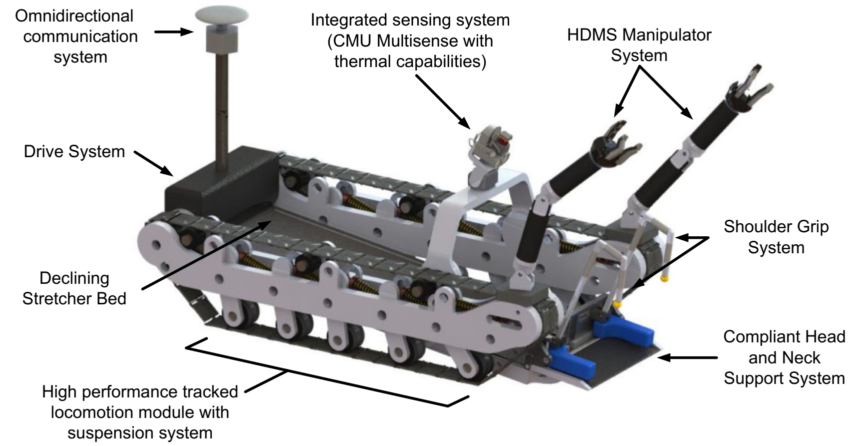

Fig. 6 Subsystems of SAVER

In military use, purpose-built evacuation robots appear to have been replaced by modified multi-purpose transport systems. While repurposing robots results in a more efficient allocation of materials and resources, care must be taken that key functionalities are not neglected including autonomous patient monitoring and in-transit first aid. Integration of a system like the LS-1 into the transport configuration of an S-MET may be a good compromise between multi-purpose equipment and medical functionality.

The dexterity and control of remote surgery and treatment systems has been steadily improving over the years. However, there are still facets of robotic surgery that require further attention, especially when considering field implementation. One such area of challenge is that the current systems have manipulators that can only work in the predefined workspace for which they are initially configured. In an emergency triage situation in a remote locale, surgical robots should be able to perform procedures on any location of the body without requiring human intervention to reposition the entire system. Furthermore, the challenges of transmitting high quality, low latency visual feedback from areas with poor communications bandwidth remains a difficult open research problem.

In addition to the above improvements in each of the individual facets, several additional optimization points present themselves when considering the design of a rescue robot as a whole. An important one is to emphasize the stabilization of the head and neck in transport to minimize further injury to the cervical spine. In the robots reviewed above, this is not addressed purposefully in any design. At best, the placement of a cervical collar by the robot is mentioned in passing in the patents. A second area in which focus can be directed towards is the issue of creating a well-balanced all terrain mobility platforms. BEAR is one of the most complete of the designs discussed, but the tracked system coupled with the height of the robot adds complexity. Finally, simplified operational complexity should be a key goal without leaving out functionality, such as the simplified function offered with Valkyrie. These robots would be deployed in some of the most dangerous areas on the planet, whether in a war zone or a disaster area, and as such should be easy and intuitive to operate. Scaling back on the degrees of freedom and making the operator control unit straightforward to control could save precious time when attempting a rescue.

Based on the review of the state of the art systems for robotic rescue and the analysis of their shortcomings, we propose a novel rescue robot design: the Semi-Autonomous Victim Extraction Robot (SAVER) [105]. The proposed conceptual design was developed at the Robotics and Mechatronics Lab at Virginia Tech, in collaboration with RE^2 Inc. funded by the U.S. Army Telemedicine and Advanced Technology Research Center. The proposed system as shown in Fig. 6, is designed for an average soldier in full battle gear weighing around 135 kg (300 lbs), with a height of approximately 6 feet. The system is designed for an overall size of 2.21m x 1.2m x 1.25m (L x W x H), with a total curb weight of less than 180 kg.

The procedure can be summarized as follows; the rescue robot will be brought in to the scene using external means like the SMSS or air dropped into the disaster scenarios using a helicopter, similar to the marsupial concept used by REX/REV systems. Launched within range of the disaster scenario, the SAVER system will locate the injured, drive up to the person, estimate the posture and then align the person so that he/she can be easily transferred on to the stretcher. The head support system slides down the stretcher and stabilizes the head and neck of the person and then engages the shoulder support hooks. The injured person is then slowly pulled on to the declined stretcher. The various steps of the extraction procedure are detailed in Fig. 7 and the evacuation scenario is depicted in Fig. 8.

In order to successfully execute the above-mentioned procedures, the robot is designed to be a semi-autonomous system. Navigating towards the already located injured personnel and then evacuating the extracted casualties to

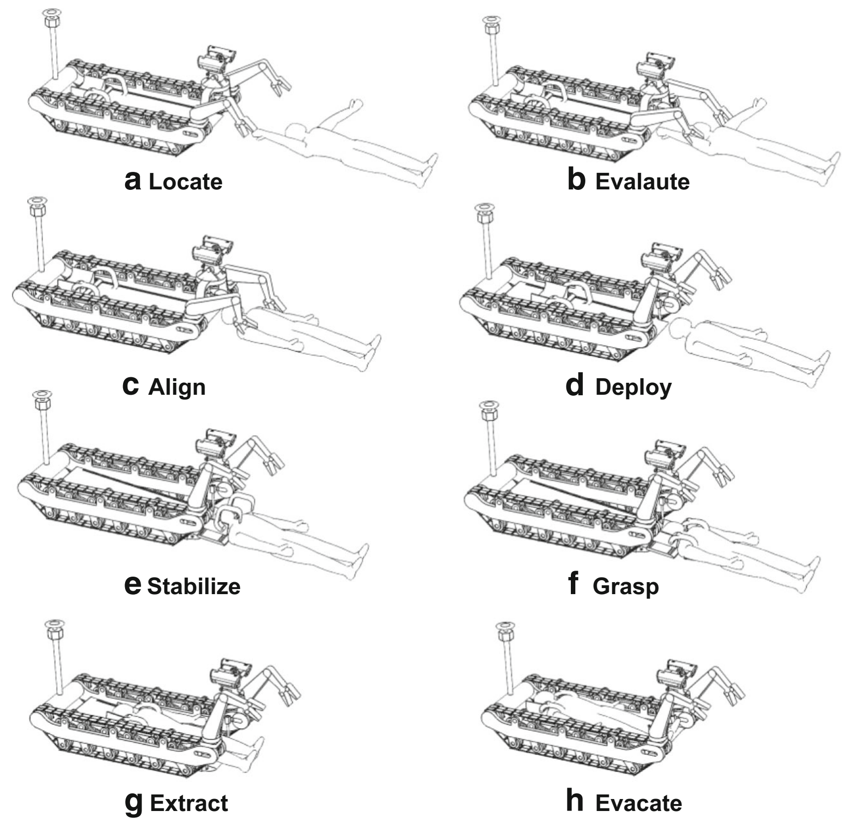

Fig. 7 Extraction procedure for SAVER

the triage zone will be done autonomously. This require the robot to be able to navigate autonomously in rugged terrain, taking into account the challenges introduced by dynamic robot-terrain interactions, initial efforts in this direction show promising results [106]. In addition the project will explore ways to enable the robot to follow a field medic so as to enable co-operative behaviors with the system. Handling injured personnel fully autonomously in unstructured terrain is still beyond the state of the art in robotics. As such, the SAVER system is designed to do this with the help of a remote operator using the HDMS developed by RE^2. With an extensive sensor suite providing real time visual and force feedback, the operator will be able to successfully manipulate the injured person

Fig. 8 Proposed casualty evacuation by SAVER

into the right posture using the dual arm manipulation system. In addition a robotic head stabilization system that autonomously stabilizes the head and neck of a patient has been fully designed, built and tested to guarantee desired degree of performance [107].

8 Conclusion

In rescue scenarios, reducing the time between injury, assessment, and treatment improves the odds of medical intervention saving someone's life. In this paper, we have reviewed existing state of the art robotic systems designed to handle the casualties of natural and manmade disasters. The systems were organized by the four major tasks they need to perform in order to facilitate the ultimate goal of rescuing a wounded person from a disaster scenario, namely search, extraction, evacuation, and treatment. For each of the categories, relative merits and demerits of the existing systems were discussed and the major shortcomings that need to be addressed by future systems were detailed. Efforts to replicate the real life challenges of casualty extraction and evacuation by rescue robotic competitions were also discussed.

Conducting the human rescue process in a fully autonomous manner will require further development in the fields of machine intelligence and human robot interactions. Instead, advancement human-robot cooperative teams that employ human in the loop control, where the human operator makes high-level decisions and the robotic system interprets the high-level commands to perform the dangerous rescue operation is a more effective and feasible solution. Based on the review of existing state of the art systems, a novel rescue robot design, SAVER that tries to address all of the desired requirements was proposed. The proposed casualty extraction and evacuation methodology used by SAVER was explained in detail along with a summary of existing and future work to realize the system. The work on rescue robots is by no means finished, as realizing a successful implementation of SAVER will involve further development of sensing strategies to estimate the posture of an injured person and development of an intuitive Robot-Operator interface to assist the tele-operator in locating the victim and manipulating the victim safely.

The use of robotic systems to augment the efforts of search, rescue, and medical response teams has the potential to improve the efficiency of these humanitarian efforts and save lives. Many innovative systems have demonstrated effective solutions to the problems presented by rescue and medical response. With further advancement, a single cooperative robotic team may someday carry out search, extraction, evacuation, and treatment of disaster victims and military casualties. The research presented here forms the base for these further advancements in the robotics field that can lead to robots that save lives and better prepare humanity to respond to catastrophic and disastrous situations.

Acknowledgements This work is supported by the US Army Medical Research & Materiel Command's Telemedicine & Advanced Technology Research Center (TATRC), under Contract No. W81XWH-16-C-0062. The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other documentation.

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