Chapter 2
Military Robotic Combat Casualty Extraction and Care

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Abstract Buddy treatment, first responder combat casualty care, and patient evacuation under hostile fire have compounded combat losses throughout history. Force protection of military first responders is complicated by current international and coalition troop deployments for peacekeeping operations, counter terrorism, and humanitarian assistance missions that involve highly visible, politically sensitive, low intensity combat in urban terrain. The United States Department of Defense (DoD) has significantly invested in autonomous vehicles, and other robots to support its Future Force. The US Army Telemedicine and Advanced Technology Research Center (TATRC) has leveraged this DoD investment with augmented funding to broadly focus on implementing technology in each phase of combat casualty care. This ranges from casualty extraction, physiologic real-time monitoring, and life saving interventions during the "golden hour" while greatly reducing the risk to first responders.

The TATRC portfolio of projects aims to develop, integrate, and adapt robotic technology for unmanned ground and air battlefield casualty extraction systems that operate in hostile environments that include enemy fire. Work continues on multiple ground extraction systems including a prototype dynamically balanced bipedal Battlefield Extraction Assist Robot (BEAR) capable of extracting a 300–500 pound casualty from a variety of rugged terrains that include urban areas and traversing stairs. The TATRC and the Defense Advanced Research Projects Agency (DARPA) are collaborating to investigate the use of Unmanned Aircraft Systems (UAS) to conduct casualty evacuation (CASEVAC) missions. TATRC has also sponsored research in robotic implementation of Raman and Laser-Induced Breakdown Spectroscopy (LIBS) to detect and identify potential chemical and biological warfare agents and explosive hazards to casualties and first responders during the extraction

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process, and patient monitoring equipment with sophisticated telemedicine and patient monitoring equipment such as “smart stretchers” that allow for real-time physiologic monitoring throughout the combat casualty care process, from extraction to definitive care. Other projects are intended to build upon these monitoring systems and incorporate telerobotic and near autonomous casualty assessment and life saving treatment to the battlefield. These have included the DARPA Trauma Pod and several TATRC efforts to integrate robotic arms with the Life Support for Trauma and Transport (LSTAT) litter for robotic implementation of non-invasive technologies such as acoustic cauterization of hemorrhage via High Intensity Focused Ultrasound (HIFU). Several projects have explored the essential telecommunication link needed to implement telesurgery and telemedicine in extreme environments. UAS were leveraged to establish a telecommunication network link for telemedicine and telesurgery applications in extreme situations. Another collaborative telesurgery research project at the NASA Extreme Environment Mission Operations (NEEMO) included performing telesurgery in an undersea location.

Research into identification and solutions of the limitations of telecommunication and robotics that prevent robust casualty interventions will allow future medical robots to provide robust casualty extraction and care that will save the lives and limbs of our deployed warfighters.

Keywords Surgical robotics · Military robotics · da Vinci · Zeus · BEAR · Battlefield Extraction Assist Robot · LSTAT · Life Support for Trauma and Transport · TAGS-CX · UAS · Unmanned Aircraft Systems · Trauma Pod · M7 · RAVEN · HIFU · High Intensity Focused Ultrasound · Tissue Welding · RAMAN Spectroscopy · Golden Hour · Hemorrhage · Telesurgery · Telemedicine · Teleoperator · Combat Casualty Care · Casualty Extraction · Trauma · DoD · Department of Defense · DARPA · Defense Advanced Research Projects Agency · TATRC · Telemedicine and Advanced Technology Research Center · NASA · NEEMO · MRMC · Medical Resarch and Material Command · Army · Military · Computer Motion · Intuitive Surgical

2.1 Introduction

Advancement in telecommunication and robotics continue to shift the paradigm of health care delivery. During the 1980s, the nascent field of telemedicine developed and allowed for increasing distribution of medical knowledge to large populations with limited local medical infrastructure and capabilities. Despite technologic strides, telemedicine has been primarily used in diagnostic applications such as radiology and pathology. However, telemedicine continues to evolve and will soon incorporate the full spectrum of medicine from diagnosis to treatment.

The United States military has provided significant impetus, focus and funding for telemedicine and medical robotics. The U.S. Army Medical Research and Materiel Command (MRMC), Telemedicine and Advanced Technology Research Center

(TATRC), and the Defense Advanced Research Projects Agency (DARPA) have spurred innovation in areas such as surgical robotics and the emerging field of "telesurgery." Telecommunication and robotic limitations that prevent robust intervention at a distance are areas of continued military research and development. Medical robots are force multipliers that can distribute expert trauma and subspecialty surgical care across echelons of care. This chapter provides a historical context of and future opportunities in military robotic casualty extraction and care that will save the lives and limbs of our deployed warfighters.

Military robotic combat casualty care has three primary goals: safely extracting patients from harm's way; rapidly diagnosing life threatening injuries such as non-compressible hemorrhage, tension pneumothorax and loss of airway; and delivering life-saving interventions. For optimum effect, medical robots must robustly operate in extreme environments and provide effective combat casualty care as close as possible to the point and time of injury. Robotic tactical combat casualty care begins with the extraction of casualties from the battlefield. In the short term, extraction robots will decrease the risk to the soldier and combat medic by safely moving wounded warfighters out of the line of fire. In the longer term, teleoperated and autonomous surgical robots will deliver expert surgical care within the "golden hour" on the battlefield as well as during transport to military treatment facilities.

DARPA and MRMC/TATRC partnered to develop the Digital Human Robotic Casualty Treatment and Evacuation Vision with robotic systems targeted on these priorities:

1. Mobility
2. Plan/execute search in unmapped interior environments, find and identify wounded soldiers
3. Track, record, transmit and act upon real-time physiological information
4. Conduct both remote and real-time diagnosis using heuristic algorithms integrated with pattern recognition imaging systems and physiological sensors
5. Perform semi-autonomous and autonomous medical procedures and interventions
6. Evacuate casualties from the battlefield using semi-autonomous and autonomous evacuation platforms and patient support systems like LSTAT

2.2 Assessment of Current State and Future Potential for Robotic Combat Casualty Care Within the Army

The Training and Doctrine Command (TRADOC) is the Army's organization for developing new doctrine on how the Army will fight in the future and what capabilities will be needed to support that operational doctrine. In 2009, TATRC contributed to TRADOC's assessment of the state of medical robotics and their potential application to combat casualty care. Currently only a few Warfighter Outcomes are involved with robotics use in medical and surgical tasks. The U.S. Department of Defense Uniformed Joint Task List suggests several topics for improvements in the areas of field medical care and force health protection through robotics. Areas of focus in combat casualty care and surgery are faster casualty recovery and evacuation by fewer personnel, faster and more certain recognition of injuries, and communications supporting remote telemedicine. TRADOC's desired future "Force Operating Capabilities" publication states that: "Future Soldiers will utilize unmanned vehicles, robotics, and advanced standoff equipment to recover wounded and injured soldiers from high-risk areas, with minimal exposure. These systems will facilitate immediate evacuation and transport under even the harshest combat or environmental hazard conditions; medical evacuation platforms must provide en route care," and TRADOC's "Capability Plan for Army Aviation Operations 2015–2024," states that "unmanned cargo aircraft will conduct autonomous..... extraction of wounded." Following was are assessment of the current state and future potential for the combat casualty care robotic applications cited by TRADOC:

1. *Perform battlefield first aid (tourniquets, splints, shots, IV drips, etc.)*: Self-assistance by the soldier or the availability of buddy care cannot be assumed in all combat situations; likewise, there are never enough combat medics or combat life savers (combat arms soldier with additional medical training) to treat and extract all casualties, especially during intense close combat or in contaminated or otherwise hostile environments. The Army Institute for Soldier Nanotechnology at MIT has ongoing basic research in uniform-based diagnostics and emergency injections. Further, sewn-in tourniquet loops on uniforms are under consideration for fielding, with Soldier-actuation required. Autonomous and robotic first aid treatment may dovetail well with robotic recovery and evacuation tasks. Slow progress is being made in the development of sophisticated sensors, autonomous analysis of sensory input, and autonomous application of intervention and treatment procedures, but deployment of such robots is years away. Likewise, local cultural concerns or confusion among the wounded may complicate acceptance of close contact by a first aid robot.
2. *Recover battlefield casualties*: As with battlefield first aid, universal availability of combat medics, combat life savers, or other soldiers assigned to perform extraction and recovery of casualties under fire or in otherwise hostile environments cannot be assumed. Therefore, a means to autonomously find, assess, stabilize, then extract casualties from danger for further evacuation is needed. This may be complicated by the unknown nature of injuries, which may complicate or confound a rote mechanical means of body movement. For example, a compound fracture or severed limb might not be gripped or gripping may increase injury. As part of several ongoing research and development efforts in both unmanned ground and air systems for casualty evacuation (CASEVAC), the MRMC is actively addressing the potential complications of robotic casualty extraction. Discussed further below, the tele-operated semi-autonomous Battlefield Extraction Assist Robot (BEAR) represents a developing casualty extraction capability which can carry a 300–500 pound load while traversing rough and urban terrain with dismounted soldiers. A fully autonomous version of the BEAR would need significant additional artificial intelligence programming and a transparent hands-free soldier-robot interface to integrate and perform this

mission in combat while keeping the soldier-operator focused on their primary mission. Research in autonomous flight control and navigation technologies needed for CASEVAC via Unmanned Air Systems (UAS) is ongoing (described below) but actual employment of operational systems is probably years away because of the current immaturity of autonomous en route casualty care systems.

3. *Robotic detection and identification of force health protection threats*: Detection and identification of chemical and biological threats to which combat casualty patients may have been exposed, along with segregation and containment of contaminated casualties prior to receiving casualties in forward medical and surgical treatment facilities are critical capability needs. The MRMC has several completed and ongoing research projects in robotic detection and identification of chemical and biological agents and chemical contaminants. The goal is to produce modular threat detection and identification systems that can be implemented on robots performing other missions, such as casualty extraction. These efforts utilize robotic enabled Raman spectroscopy, florescence, and Laser Induced Breakdown Spectroscopy (LIBS) as well as antigen-based technologies. One of these projects is discussed below.
4. *Perform telemedicine/surgery*: Remote tele-operated medicine is feasible, but with limitations. Visual examination information is planar and may lack depth and full five-sense information (e.g. tactile feedback). As a human assistant will likely be required, a question arises as to the feasibility of doing better than having a trained human assistant, local to the patient, relaying information back to the remotely located surgeon. However, vital signs (e.g. skin temperature, pulse, blood pressure) may be available via biomonitors contained on a simple robotic platform arm. Proof of concept projects have demonstrated the feasibility of remote robotic diagnosis and treatment of patients. The DARPA 'Trauma Pod' project discussed below was an attempt to leverage emerging advanced imaging technologies and robotics to enable autonomous casualty scan, diagnosis and intervention, MRMC also has several physiological sensor and image-based robotic casualty assessment and triage research projects underway. However, these capabilities are currently only experimental and are non-ruggedized, teleoperated component capabilities at best. The idea of far forward combat telesurgery in combat is compelling; a surgeon controlling a robot's movements in a distant location to treat an injured soldier could serve as a force multiplier and reduce combat exposure to highly trained medical personnel. At first glance, remote tele-operated surgery capability appears to already exist since minimally invasive operations have been remotely performed using dedicated fiber optic networks, the Zeus and da Vinci surgical robots have been and are currently used in civilian hospitals and many other telesurgery demonstrations and experiments have been conducted around the world. Military funded research as discussed below has demonstrated that surgical robotic systems can be successfully deployed to extreme environments and wirelessly operated via microwave and satellite platforms. However, significant additional research is required to develop supervisory controlled autonomous robots that can overcome the operational communication challenges of limited bandwidth, latency, and loss of signal in the deployed combat environment. Addressing acute and life threatening injuries such as major non-compressible

vascular injury requires development of new surgical robots that move beyond stereoscopic, bimanual telemanipulators and leverage advances such as autonomous imaging analysis and application of directed energy technologies already used in non-medical military robotic systems.

2.3 Robotic Casualty Extraction, Evaluation and Evacuation

The US military has funded multiple robotic projects focused on casualty extraction, evaluation and evacuation. Robotic casualty extraction research is focused on the development of semi-autonomous systems that will safely extract the casualty from the line of fire, deliver the casualty to medical care, and limit risk to care providers.

Representative systems are briefly described below.

TAGS CX (Tactical Amphibious Ground Support system – Common Experimental).

The Army Medical Robotics Research through the Army's SBIR (Small Business Innovation Research) Program through TATRC contracted Applied Perceptions Inc. (Cranberry Township, PA) as the primary research entity for an extraction and evacuation vehicle. A tele-operated semi-autonomous control system capable of maneuvering a marsupial robotic vehicle was developed with a three module concept. The initial novel dual design prototype vehicle consisted of a small, mobile manipulator Robotic Extraction (REX) robot for short-range extraction from the site of injury to the first responder and a larger faster Robotic Extraction Vehicle (REV), which would deliver the wounded soldier to a forward medical facility. The smaller vehicle resided within the larger REV, which was equipped with two L-STAT stretchers and other life support systems. The TAGS platform provides a modular and interoperable ground robot system that could be modified for multiple purposes. The Joint Architecture for Unmanned Systems (JAUS) control platform was used to enable a standardized C2 interface for the OCU (Operational Control Unit) along with standardized mechanical, electrical, and messaging interfaces capable of supporting multiple unique "plug and play" payloads. This prototype robotic extraction vehicle also integrated other control technologies. These include GPS-based autonomous navigation, search and rescue sensing, multi-robot collaboration, obstacle detection, vehicle safe guard systems, autonomic vehicle docking and telemedicine systems (Fig. 2.1).

Subsequent to completion of the initial REV and REX prototypes, the US Army's TARDEC (Tank-Automotive Research, Development, and Engineering Center) developed a ground mobility, robotics systems integration and evaluation laboratory, TARDEC's Robotic SkunkWorks facility. This laboratory's goal is to assess and integrate novel unmanned systems technologies to support efficient conversion of these technologies to PM/PEO (program managers/program executive officer) and ATO (Advanced Technology Office) programs. The first unmanned system evaluated was the TAGS-CX, an enhanced version of the original TAGS designed to support multiple modular mission payloads. The most

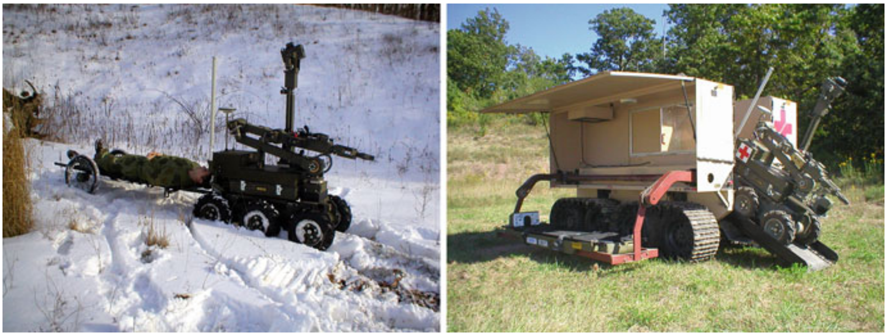

Fig. 2.1 Robotic extraction (REX) and Robotic evacuation vehicle (REV) prototypes (*left*); REX towing casualty on litter in snow (*right*)

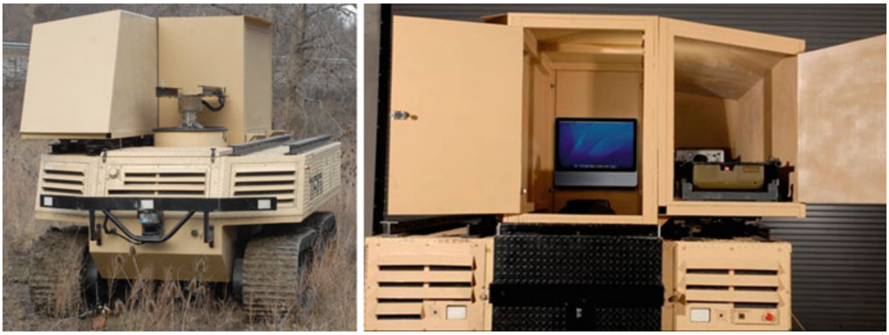

Fig. 2.2 Tactical amphibious ground system – common experimental (*left*); CX with patient transport & attendant modules (*Right*)

significant identified issue during the trials of the original REV vehicle was that the REV was designed to be completely unmanned and as a dedicated MEDEVAC vehicle. Currently and for the foreseeable future the US Army would not allow wounded soldiers to travel without a human medic or attendant. Based on this feedback the TAGS-CX concept was redesigned to incorporate a removable center module for an on-board medic and would allow for manual operation of the vehicle. Additionally the patient transport bays were designed and constructed as modular "patient pods" which would enable the TAGS-CX to be used for multiple combat support missions, CASEVAC being just one (Fig. 2.2).

2.4 BEAR: Battlefield Extraction Assist Robot

The BEAR (Vecna Technologies Cambridge Research Laboratory, Cambridge, MA) prototype was initially started with a TATRC grant in 2007 with the objective of creating a powerful mobile robot, which was also highly agile. It would have the capability to find and then lift and carry a combat casualty from a hazardous area in varying terrain. Vecna Technologies Inc. initially produced a proof of concept prototype (BEAR Version 6), which was featured in Time Magazine's Best Inventions of 2006. This machine was intended to be capable of negotiating any general hazardous terrain and not be limited only to the battlefield. The BEAR robot is extremely strong and agile approximately the size of an adult male. The original prototype was composed of an upper torso with two arm actuators and a lower body built around the Segway RMP base with additional tank tracks on its analogous thighs and calves. It is designed to lift 300–500 lbs (the approximate weight of a fully equipped soldier) and move at $\sim$10 miles/h. It utilizes gyroscopic balance that enables it to traverse rough and uneven terrain (Fig. 2.3).

The latest iteration of the BEAR (version 7) has several redesigned components. These include a sleeker, stronger, and more humanoid appearing upper torso, integration of NASA's Actin software for coordinated control of limbs and upper torso, and a lower body with separately articulating tracking leg subsystems, a novel connection and integration of the lower body and upper torso components, completion of the "finger-like" end effectors, and a Laser Induced Breakdown Spectroscopy (LIBS) detector for chemical, biological, and explosive agents. The system will incorporate a variety of input devices including multiple cameras and audio input. The initial control of the BEAR is via a remote human operator but work is underway for more complicated semi-autonomous behaviors in which the robot understands and carries out increasingly higher-level commands. Other planned inputs include pressure sensors that will allow it to have sensitivity to a human cargo. Another milestone is the completion of the first phase of continuing BEAR characterization and operational simulation and assessment at the Army Infantry Center Maneuver Battle Lab (MBL). The humanoid form enables the robot to access most places that a human would, including stairs. The versatility of this robot includes applications within hospitals and nursing homes where infirmed patients with limit mobility could be easily moved.

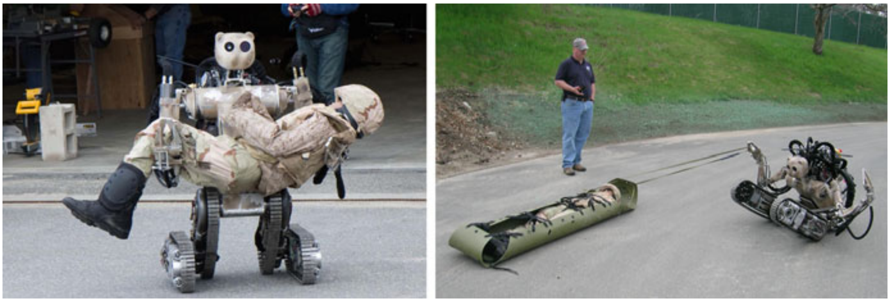

Fig. 2.3 Battlefield extraction assist robot (BEAR) prototype (*left*); BEAR extracting casualty with foldable litter (*right*)

2.5 Combat Medic UAS for Resupply and Evacuation

TATRC has also provided support for aerial robotic systems. This project focused on autonomous UAS (Unmanned Aircraft Systems) takeoff, landing, navigation in urban and wooded environments and the coordination and collaboration between UAS ground controllers and human combat medics so that proper care and evacuation can be performed during the golden hour. Five Phase I SBIR grants were given out to identify notional concepts of operation as well as develop technical models that recognize requirements in implementable UAS system designs. Phase II grants went to Dragon Fly Pictures Inc. and Piasecki Aircraft both of Essington, PA. Phase II focuses on navigation through urban/wooded terrain to combat site of injury, selection of a suitable autonomous landing and takeoff site with minimal human input, autonomous safe landing and takeoffs, communication with a human medical team, and carrying a payload of medical supplies including a Life Support for Trauma and Transport (L-STAT) system. Phase II concludes with live demonstrations of these capabilities using real aircraft.

2.6 Raman Chem/Bio/IED Identification Detectors

Research interest exists in providing these unmanned ground vehicles (UGV) extraction platforms with chemical, biological, and explosive (CBE) detection systems based on Raman spectroscopy so that they have the operational ability to identify environmental toxins and provide force protection. Currently UGVs are unable to provide any early information as to the possible toxic hazards in the environment. TATRC along with MRMC and other governmental agencies have funded development of several JAUS compliant robotic CBE identification systems that could be placed on unmanned extraction vehicles.

The Raman detection technological advantages are that it is reagentless, which simplifies deployability and can detect a broad range of CBE threats in a single measurement cycle. Reagent based detection methods must start with some assumption as to the possible threat. The Raman Effect has been used for years and depends on the phenomenon that when a photon encounters a molecule it imparts vibrational bond energy to this molecule. This exchange creates a slight disturbance in the frequency in a small amount of scattered light. Each chemical bond has its own unique frequency shift, which allows for creation of the Raman spectrum and the identification of chemicals. Further research sponsored by the Army Research Laboratory (ARL) has shown that concurrent deployment of both Raman and LIBS systems results in a significant improvement in sensitivity and accuracy of agent detection when the results are merged through a fusion algorithm developed by ChemImage Corporation, designer of the proximity RAMAN detector shown in Fig. 2.4a.

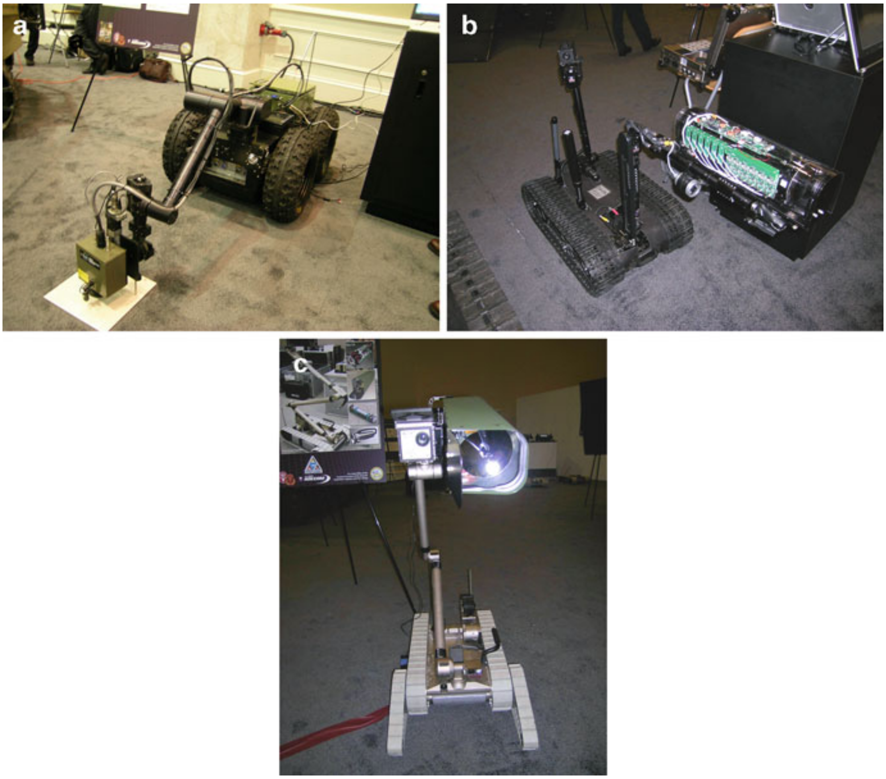

Fig. 2.4 (**a**) Chemimage proximity robotic Raman spectroscopy chem/bio/explosive detector on ARES robot; (**b**) Transparent model (enlarged) of photon systems stand-off robotic Raman florescence chem/bio/explosive detector on Talon robot; (**c**) Photon systems stand-off robotic Raman florescence chem/bio/explosive detector on packbot

The overall concept of this technology is to integrate a Raman sensor head onto a manipulator arm on the UGV, which is then coupled to an onboard or self contained spectrometer analyzer. When integrated with a robot, Raman spectroscopy detectors contain a video camera and fine positioning system that will allow for targeting of the head, laser illumination of the sample to induce the Raman Effect, optics to collect and focus the scattered light, and a fiber optic bundle to transport the scattered light to a spectral analyzer. In proximity applications, the Raman detector needs to be close but not necessarily touching the object; in stand-off applications the laser, spectroscope, and analysis computer can operate from a distance. Once the materials unique Raman effect has been detected it can then be compared to a spectra library of known materials to provide robust identification of whether the chemical is a threat. Several TATRC funded proximity and stand-off prototypes have been developed and integrated with robots.

2.7 L-STAT

The L-STAT system (Life Support for Trauma and Transport, Integrated Medical Systems Inc., Signal Hill, CA) was developed by a DARPA funded grant in 1999 in conjunction with the United States Marines. This system has seen deployed to the 28th and 31st Combat Support Hospitals (CSH) in Iraq and Afghanistan, Navy amphibious assault ships, national guard units in Alaska and Hawaii, special operations teams in the Philippines and Cambodia, and also domestically at select United States trauma centers (University of Southern California and the Navy Trauma Training Center both in Los Angeles, CA). L-STAT could be used to integrate components of intensive care monitoring and life support functions during unmanned CASEVAC (Fig. 2.5). This platform acts as a force multiplier and allows for patients to be cared for with less direct attention by medical personnel during transport to Combat Support Hospitals or Battalion Stations. As stated before focus on the golden hour of trauma is due to the fact that 86% of all battlefield mortality occurs within the first 30 mins. The majority of which are due to hemorrhage (~50%) followed by head trauma which leads to seizures and ischemic reperfusion injuries and these are the focus of L-STAT. The original version of L-STAT was

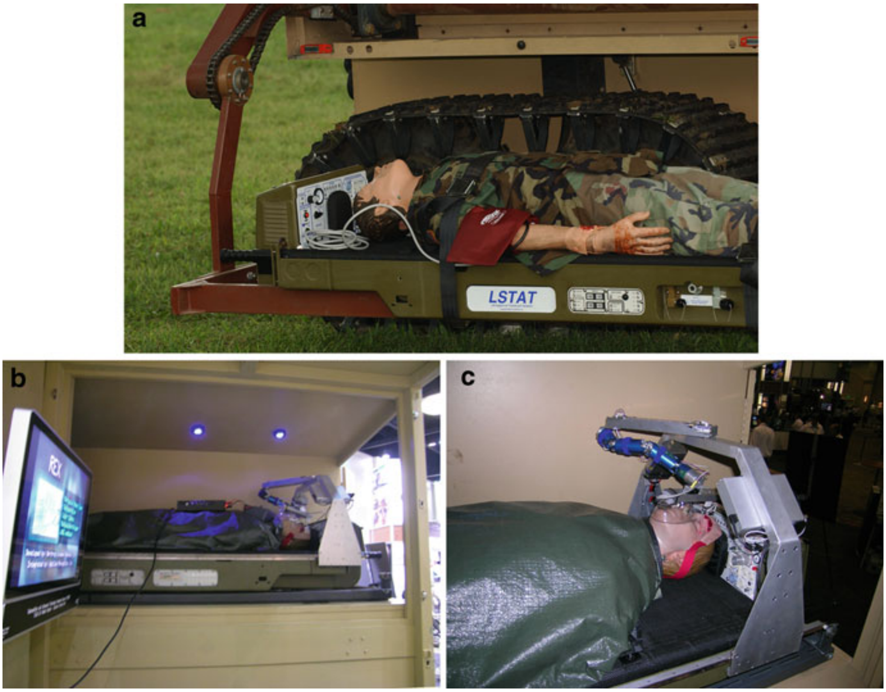

Fig. 2.5 Life support for trauma and transport (L-STAT): (**a**) integrated with REV; (**b**) L-STAT mounted in TAGS-CX patient transport pod;(**c**) L-STAT with Carnegie Mellon University serpentine robotic arm casualty assessment prototype

extremely cumbersome and weighed 200 lbs which severely limited its utility. Some more recent systems are much more mobile and include the L-STAT Lite, MOVES, and Lightweight Trauma Module.

A review of L-STAT identified possible future technologies for the next generation L-STAT (NG-LSTAT) and concluded there were multiple areas of potential improvement in diagnostic and therapeutic capabilities. The possible diagnostic additions included digital X-ray, portable ultrasound, medical image display and telediagnosis via remote controlled camera. Prospective therapeutic additions included the utilization of serpentine robotic manipulators for performing intubation, ultrasound catheterization for intravenous access and assisting in the application of HIFU (High Intensity Focused Ultrasound) for treating hemorrhage. The addition of bioinformatics, wireless data communication, additional imaging capabilities, robotic manipulators, and increased mobility would move the NG-LSTAT further toward the goal of an autonomous field deployable surgical platform. A lightweight version of the LSTAT called the MedEx-1000 which weighs less than 40 lbs and can be used independently of a litter was developed and released for sale in 2009.

2.8 Robotic Combat Casualty Care

The definition of telesurgery varies but in general practice it is the "use of telecommunication technology to aid in the practice of surgery." This commonly used broad based definition of telesurgery encompasses the entire gamut of surgical practice from ancillary guidance or evaluation to direct patient interventions. The initial roll of telesurgery focused on the supplementary or instructive components include: pre-, intra, and postoperative teleconsultation and teleevaluation, to intraoperative telementoring and teleproctoring. Recently a more limited view of telesurgery focuses on telecommunication and a distributed surgeon performing direct patient interventions through robotic telemanipulation and telepresent robotic surgery. This revolutionary idea was borne from the combination of advances in communication and robotic technology and the explosion in minimally invasive surgery in the 1990s. There are two components of telesurgery, first is the "teleoperator" which encompasses the insertion of technology between the surgeon and the patients so that the surgeon never directly touches the patient, and the second is the use of telecommunication technology to allow for the geographic distribution of surgical care. The idea of teleoperators is not a new phenomenon, but built upon ideas developed much earlier in the twentieth century. Ray Goertz of Argonne National Labs in the late 1940s and early 1950s coupled mechanical effectors with a mechanical system of cables and pulleys, which allowed for manipulation of objects at a distance. Though extremely effective and still in contemporary use this technology was fundamentally limited to short distances and similar size scales. The modern surgical teleoperator arose from the technologic advances that established the potential platform for technical feasibility while the laparoscopic context provided the surgeon the skill set needed to manipulate and master this new potential surgical schema. These fields developed synergistically with surgical demand driving a critical mass of technology in the form of optical cameras and manipulators which allowed the surgeon better visualization and dexterous manipulation of tissue in minimally invasive surgery. The physical disconnection of the surgeon from the patient created surgical telemanipulators, the first component of telesurgery.

In the early 1990s, Stanford Research Institute International (SRI, Menlo Park, CA) developed a two-handed teleoperated surgery unit through a DARPA (Defense Advanced Research Projects Agency) funded project. This provided the direct progenitor for the development of surgical robots currently in use. Two start-up companies were created to address the civilian surgical market: Computer Motion Inc. (Goletta, CA) and Intuitive Surgical Inc. (ISI), which was spun off of SRI in 1995. Both of these companies subsequently produced FDA approved surgical robot platforms, Computer Motion's Zeus and ISI's da Vinci system. These companies merged in 2003 effectively eliminating private surgical robotic competition. The da Vinci system is used around the world with more than 1,000 systems used currently.

2.9 Telesurgery

Strides toward the realization of the widespread application of telesurgery have been made with several historic procedures. The seminal event in telesurgery was Project Lindberg. On September 7, 2001, Jacques Marescaux in conjunction with his team at the European Institute of Telesurgery (EITS)/Universite Louis Pasteur in Strasbourg, France established the feasibility of telesurgery by performing the first transatlantic telerobotic laparoscopic cholecystectomy. Marescaux performed this successful operation with the Zeus robot (Computer Motion, Inc., Goleta, CA now operated by Intuitive Surgical, Inc., Sunnyvale, CA) in New York City on a patient located in Strasburg, France. Mehran Anvari has since extended viable telesurgery by bringing surgical therapy to underserved populations in rural Canada. He utilized a modified Zeus surgical system (Zeus TS) with a private network to perform advanced laparoscopic surgery from the Centre for Minimal Access Surgery (CMAS)/McMaster University, Hamilton, Ontario. He has performed 25 telesurgeries including laparoscopic fundoplications, colectomies, and inguinal hernias with outcomes comparable to traditional laparoscopic surgery.

In 2005, The US military funded the first transcontinental telesurgery utilizing the da Vinci robot. This collaborative project included Intuitive Surgery, Inc., Walter Reed Army Medical Center, Johns Hopkins University, and the University of Cincinnati. The experimental setup had the porcine subject in Sunnyvale, CA while the remote surgeon performed a nephrectomy and was located in Cincinnati, OH (March 21–23) or Denver, CO (April 17–19). A da Vinci console was located at both the remote and local sites and control of the three manipulator arms were shared by the two surgeons with the local surgeon controlling the electrocautery. This novel experiment performed several telesurgery firsts including: utilization of a non-dedicated public Internet connection, the first stereoscopic telesurgical procedure, and collaborative telesurgery with two separate consoles controlling different parts of the same robot.

The replication of patient side activity from a distance represents the fundamental goal of telesurgery. Recent telesurgery experiments have focused on the fidelity of replication without incidence, which would allow for confidence in the overall safety. A multidisciplinary, multi-institutional team approach has been undertaken because of the need to incorporate diverse, substantial expertise including robotics, surgery, and telecommunications. The general approach of these experiments in telesurgery has utilized a surgical robot in combination with high bandwidth, low latency, and high-Quality of Service (QoS) telecommunications. The Zeus (no longer commercially available) and the da Vinci robotic systems represent the past and current versions of commercially available robotic telesurgery platforms. During initial experimental and clinical trials, common problems and themes arose and generated a common vocabulary of technical terms specific to this burgeoning field. The most important definitions refer to the time delay inherent to telesurgery and include: control latency, visual discrepancy, round trip delay, and the CODEC. Control latency represents the time delay between the remote telesurgeon's controller manipulation and when the surgical manipulator moves within the patient. Simply it is the flow of information from the surgeon to the patient. Visual discrepancy is the time delay between an operative field action and when the surgeon appreciates this action at the remote controller site and represents the duration of time that visual information egresses from patient to surgeon. Round trip delay is the additive time increments of control latency and visual discrepancy and is the time it takes for a telesurgeon to manipulate a tool at the remote site and then be able to acknowledge the effect in the patient's surgical environment. An important software technology is the coder-decoder (CODEC) which through compression reduces the bandwidth required for video transmission. TATRC has funded multiple research projects to mitigate the effect of operationally relevant telecommunication limitations.

2.10 Extreme Environment Surgical Robotics

While the embryonic field of telesurgery has primarily utilized robots designed for minimally invasive surgery, the military goal is to develop battlefield telerobotic surgery for use in trauma. The current minimally invasive robotic surgery system cannot be used in an operationally and clinically relevant manner for battlefield or en route combat casualty care as trauma surgery currently requires open exposure to identify and manually treat injuries (e.g. abdominal packing, tissue mobilization, retraction, etc). The commercially available current surgical platform, da Vinci, is large, bulky and has a time consuming and complicated setup and is generally ill suited for trauma. Future battlefield robotic surgical system will have to provide life saving trauma care and will incorporate novel technologies that permit distributed and automated performance of simple "damage control" procedures. Battlefield interventions need to focus on the idea of the "golden hour" where the majority of trauma casualty deaths occur and where immediate and definitive care can prove life saving. The principle injuries that would be amenable to expeditious intervention include control of: airway, tension pneumothorax and non-compressible bleeding, Telesurgery is a potential force multiplier that could protects surgical assets and deliver immediate and definitive care to wounded soldiers. Due to the extreme nature of battlefield environments, the next generation mobile surgical robots will be smaller, robust trauma focused systems that leverage non-medical military telecommunication, computing, imaging, and mechanical resources.

A couple of robotic surgical platforms have been routinely used in the research and development of surgical robotics for use in extreme environments: the University of Washington RAVEN and the SRI International M7. The RAVEN is a small deployable surgical robot being developed at the University of Washington BioRobotics Laboratory with support from multiple government agencies including the US Army. The system consists of a slave component that resides with the patient and a master controller permitting remote control of the slave by the surgeon. The master site has a surgeon console that currently employs dual PHANToM Omni devices to control two surgical manipulators/instruments, a foot pedal, and a video screen displaying images from the surgical site. The video and robot control are transmitted using standard Internet communication protocols. The user interface uses open source commercial off the shelf technology and therefore it is remarkably low cost, portable, and interoperable (i.e. can readily control other systems with limited modifications). SRI's M7 surgical robot was initially developed in 1998 with funding from the US Army. The M7 leveraged military funded development of SRI's original telepresence surgical system. The features of this robot include a large workspace accessible via two anthropomorphic robotic arms with seven force-reflective degrees of freedom. These robotic arms manipulate conventional "open" surgical instruments allowing for complex surgical tasks to be performed. The system was recently upgraded with high definition stereoscopic vision, ergonomic hand controllers, and limited automation. Both of these surgical robotic systems have been utilized in extreme environments to evaluate feasibility as well as guide future research and development.

2.11 NASA Extreme Environment Mission Operations (Neemo)

Collaborative telesurgery research was conducted within the NASA Extreme Environment Mission Operations (NEEMO) program. US Army TATRC telesurgery research within NEEMO missions has been conducted in collaboration with the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), the Centre for Minimal Access

Surgery (CMAS), and the Canadian Space Agency. The NEEMO missions occur within the NOAA National Undersea Research Center Aquarius habitat located at 19 m depth within the Florida Keys.

In 2006, NEEMO 9 explored the use of telementoring, and telerobotic surgery to provide emergency diagnostic and surgical capabilities in an extreme environment. Mission accomplishments included: the first successful deployment and use of a surgical robot (SRI's M7) in an extreme environment and the use of microwave wireless telecommunications in support of telesurgery. Simulated surgical procedures were performed to evaluate the effect of increasing latency on surgeon performance. Latency of over 500 ms was found to greatly impact performance. While the remote surgeon was able to suture simulated tissue despite 2 s latency, placing and tying a single suture in 10 mins is not clinically relevant. These experiments demonstrated that latency compensation up to approximately 500 ms was possible by modifying surgical technique to include slow, one handed movements. Several technologic solutions were successfully used to overcome subsecond latency such as motion scaling. These M7 telesurgical experiments suggested further research in automation was necessary. Astronauts on NEEMO 9 also evaluated the University of Nebraska – Lincoln (UNL) in vivo robots. These novel miniature mobile robots were deployed inside a laparoscopic simulator and found to improve visualization of the surgical field.

In 2007, NEEMO 12 primarily focused on evaluation of image guided, supervisory controlled autonomous function to overcome latency. A modified M7 was used to perform an ultrasound guided, semi-autonomous needle insertion into a simulated blood vessel. The RAVEN surgical robot was also deployed and used to objectively assess telesurgical performance of SAGES' (Society of American Gastrointestinal and Endoscopic Surgeons) Fundamentals of Laparoscopic Surgery (FLS) tasks.

2.12 Mobile Robotic Telesurgery

Battlefield operations are dynamic and challenging, and do not permit routine operational use of traditional "wired" telecommunications. As geosynchronous orbit is 35,900 km above the earth's surface, satellite-based communications has a minimum round trip communication latency between surgeon and patient above 500 ms. Unmanned airborne vehicles (UAV) represent a readily available battlefield asset that could provide an extremely low latency "last mile" solution for telesurgery. TATRC funded the High Altitude Platform/Mobile Robotic Telesurgery (HAPs/MRT) project to evaluate the feasibility of deploying a mobile surgical robotic system to the high desert and operating this system using of a UAV based telecommunication link.

In 2006, a collaborative research team including the University of Cincinnati, University of Washington, AeroVironment Inc. (Monrovia, CA), and HaiVision Inc. (Montreal, Canada) conducted this research in the high desert of southern California.

A high bandwidth and low latency network was created using AeroVironment's PUMA (Point Upgraded Mission Ability) small UAV. The PUMA is hand-launched and currently in use in Iraq and Afghanistan primarily for local reconnaissance. The radio link onboard the PUMA provided a digital link between the RAVEN slave and master controller which were located in separate tents within Simi Valley. The UAV based network provided over 1 Mbps bandwidth with transmission times of less than 10 ms. The remote surgeon successfully used the UAV – RAVEN mobile robotic system to perform simulated surgical tasks. This experiment demonstrated that a readily deployed surgical robot and a routinely used small UAV could potentially deliver surgical capabilities to the battlefield. Challenges encountered during this research emphasized the need for continued development of telecommunications hardware and software to facilitate operationally and clinically relevant telesurgery.

U.S. Army TATRC also funded University of Cincinnati and SRI to explore distributed, automated surgical robotics as a means to augment en route care of injured warfighters. In 2007, the M7 was modified to overcome acceleration and movement routinely encountered during vehicle transport. Three-axis acceleration compensation was developed to dampen turbulence and apply a neutralizing force during periods of more constant acceleration. Multiple military personnel, including a U.S. Air Force Critical Care Air Transport (CCAT) surgeon, demonstrated robust performance of the acceleration compensating M7 during parabolic flight aboard NASA's C-9 aircraft.

2.13 Next Generation Technologies

The military continues to develop diagnostic and therapeutic modalities to improve care of injured warfighters. Two of the more promising technologies that could readily be incorporated into medical robotic systems are HIFU and laser tissue welding.

2.13.1 High Intensity Focused Ultrasound (HIFU)

HIFU continues to be evaluated as a non-invasive method of controlling bleeding. Military funded research has demonstrated that HIFU can seal vascular injuries of up to 3 mm in diameter. Recently, a DARPA funded project, "Deep Bleeder Acoustic Coagulation" (DBAC) has begun to develop a prototype HIFU device capable of limiting blood loss from non-compressible vessels. DBAC would be applied in a combat situation by minimally trained operators, automatically detect the location and severity of bleeding, and use HIFU to coagulate the bleeding vessel. The project includes Doppler based automated hemorrhage detection algorithms coupled with volumetric data to localize the bleeding source. HIFU delivery and dosing for safe acoustic hemostasis has been proven to raise the tissue temperature to a range of 70–95 C in an operationally relevant 30-s timeframe.

2.13.2 Robotic Laser Tissue Welding

TATRC funded SRI to investigate robotic assisted laser tissue welding as a means to circumvent the need for suturing. As previously mentioned, telerobotic suturing is especially challenging at longer latencies which would be encountered during robotic combat casualty care. These experiments used a robot to uniformly deliver laser energy as well as tissue pressure and apposition. Two methods were demonstrated for direct tissue welding: bovine serum albumin/hyaluronate acid solders and chitosan films. Robot controlled tissue welding of lacerations in explanted pig eyes decreased the total time of tissue apposition from a manual suturing from approximately 8 to 3 min. Laser welded tissue had similar burst pressure as manually sutured tissue. These experiments demonstrated that robotic laser tissue welding has great potential value and further research is indicated.

2.14 Trauma Pod: Distributed, Automated Robotic Combat Casualty Care

Trauma Pod (TP) is a DARPA program to develop automated robotic combat casualty care. Trauma Pod represents a semi-autonomous telerobotic surgical system that can be rapidly deployed and provide critical diagnostic and acute lifesaving interventions in the field.

The Phase I proof of concept platform was comprised of a da Vinci Classic surgical robot supported by an automated suite of commercially available and custom designed robots. The surgeon remotely controlled the robotic suite to perform representative tasks that included placing a shunt in a simulated blood vessel and performing a bowel anastamosis.

TP footprint was 8 × 18 ft to fit within an International Standards Organization (ISO) shipment container for ready deployability. The Phase I system is comprised of 13 subsystems that include: the Surgical Robot (SRS), the Scrub Nurse (SNS), Tool Rack (TRS), Supervisory Controller (SCS), Patient Imaging (PIS), and the User Interface (UIS). The Scrub Nurse Subsystem system was developed by Oak Ridge National Laboratory and automatically delivered instruments and supplies to the surgical robot within 10 s (typically faster than a human). The University of Washington developed the Tool Rack System which held, accepted, and dispensed each of 14 surgical tools. The University of Texas developed the Supervisory Controller System which provided high-level control of all automated subsystems involved in supply dispensing/tool changing and coordinated these functions with the SRS. The Patient Imaging (GE Research) utilized the L-STAT platform to embed CT like capabilities as well as 2-D fluoroscopic data. The User Interface System developed by SRI International provided a visual, verbal, aural, and gesture based interface between the surgeon and TP system. The visual display consisted of a stereoscopic view of the surgical site augmented by physiologic data, icons and other supporting information.

In 2007, the phase I demonstration included:

1. Automatic storing and dispensing of surgical tools by the TRS with 100% accuracy
2. Automatic storing, de-packaging dispensing and counting supplies by the SDS (Supply Dispenser)
3. Automatic change of surgical tools and delivery and removal of supplies by SNS
4. Speech-based interface between a tele-operating surgeon and the TP system through the UIS
5. Automatic coordination and interaction between SRS and SNS
6. Performing iliac shunt and bowel anastamosis procedures by a tele-operated SRS on a phantom patient

Phase 1 proved that a single operator can effectively tele-operate a surgical robot and integrated suite of automated support robots to perform relevant surgical procedures on a simulated patient. Phase II of this project will integrate TP subsystems into a single robot designed to rapidly diagnose and innovatively treat life threatening battlefield.

2.15 Summary

The technological revolution of the past three decades is catalyzing a paradigm shift in the care of battlefield casualties. Telecommunications and robotic technology can revolutionize battlefield care by safely extracting patients from harm's way, rapidly diagnosing life threatening injuries, and delivering life-saving interventions. Telecommunication and robotic limitations that prevent robust intervention at a distance are areas of continued military research and development. As these limitations are overcome, medical robots will provide robust casualty extraction and care that will save the lives and limbs of our deployed warfighters.

Disclaimer The views expressed in this chapter are those of the authors and do not reflect official policy or position of the Department of the Army, Department of Defense or the U.S. Government.

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