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Limbed Robotics for Military Operations

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14. ABSTRACT In recent decades, technological advancements in robotics and automation have revolutionized military operations, offering novel capabilities and strategic advantages. The current rise of limbed robotic capabilities, including wheeled, tracked, and aerial robots with manipulators, quadrupedal robots, and humanoid systems, among other form factors, promises to further evolve the nature of military operations. This report begins by describing the capabilities of current commercially available and fielded limbed robots. It then describes a set of missions where future limbed robots could potentially add value through increased capability. Finally, it indicates many technical, operational, and logistical challenges preventing currently available robots from delivering the full set of desired capabilities today. The aim is to provide a foundation for future research and development in limbed robotic systems for the Army.					
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Executive Summary

Technological advancements have recently led to the commercial introduction of robotic systems with limbs, such as arms and legs. These systems have the potential to provide militarily relevant capabilities that can increase standoff and enhance Soldier safety. This report begins by describing the capabilities of commercially available limbed robotic systems as of 2024. It then describes how future limbed systems could bring new capabilities and advantages to a range of example military mission sets. Finally, it describes advancements still needed before limbed robots can effectively deliver those capabilities.

Currently, fielded limbed robotic systems for dismount operations are mostly tracked bases with manipulator payloads featuring two-jaw type end effectors. Some quadrupeds, such as Boston Dynamics' Spot and Ghost Robotics' Vision60, have just begun to enter field use for purposes such as intelligence, surveillance, and reconnaissance (ISR), and explosive ordnance disposal (EOD). The addition of legs offers the potential to expand usefulness to much more rugged terrain due to both the higher step height and the potential for dynamic maneuvers such as leaping. While single arm robots such as the Packbot and Talon have been in field use for quite some time, bimanual manipulation offers significantly more capability by facilitating the application of multiple forces and/or torques on the environment simultaneously. Consider the difficulty of opening a jar with only one hand/arm. A second limb is required to stabilize the jar so the lid can be removed. The combination of legs with arms can further increase the number of forces and torques that can be applied, while also increasing the system's overall effective workspace.

Several auxiliary factors have been critical to realizing practical limbed robotic systems. Actuator performance has continued to improve, bringing size, weight, and power (SWaP) into a regime where limbed systems make engineering sense. Battery life and efficiency also now permit sufficient endurance such that commercial entities are interested in purchasing limbed systems. Human-robot interaction (HRI) has improved such that teleoperation of limbed robots is fast and robust. Reliance on low-level autonomy for tasks such as end effector movement and automatic foot placement has become accepted, so that users can focus on providing higher-level commands describing paths to traverse and objects to grasp without considering the individual joint control needed to achieve those actions.

Limbed systems provide numerous advantages in terms of robustness to environmental ruggedness, workspace, and force application. Because of their increased step height, they can overcome large obstacles to reach challenging locations. They can also move objects around in the world, including placing and retrieving objects, providing better viewpoints for sensors, and generally changing

the environment as opposed to simply observing it. This means limbed systems have the potential to enhance capabilities to at least the following mission sets: ISR; communications; sensor deployment and management; chemical, biological, radiological, and nuclear (CBRN) decontamination; counter-mine operations; improvised explosive device (IED) detection and defeat; building clearing and breach; wide area security and sentry operations; logistics; maintenance; robot augmented protection; and medic assistance. This list is not intended to be comprehensive, but simply to suggest the breadth of impact future limbed robotic systems are likely to have on military operations.

To achieve this vision, many advancements are still needed just to overcome the technological challenges ahead. SWaP of actuators and hardware used to create limbed robots must continue to be improved if we are to achieve the multiday run-times desired for future military purposes. Sensing hardware must continue to improve, providing high-resolution access to many forms of data such as touch contact and slip. At the same time, perception algorithms processing that data must improve at filtering and making sense of multimodal data onboard the robot. Understanding our nonrigid, dynamic world is particularly difficult.

Control schemes and rapid behavior development must also improve. Reinforcement learning (RL) has proven to be a particularly effective tool for developing behaviors for highly complex limbed systems with many degrees of freedom. RL has the potential to use the robot's internal dynamics much more effectively than other methods, enabling larger peak force outputs without increasing motor sizes or power demands. However, while using simulation is relatively fast, safe, and cheap for learning these behaviors, successfully deploying RL policies on real robots remains challenging. Overcoming this "sim-to-real" gap is the subject of significant research at present. Finally, we need batteries with higher power densities, faster onboard computer processing and heat management to handle all the data, and materials that balance strength-to-weight requirements with flexibility and robustness to operate with accuracy and safety in near-human scenarios.

In addition to technological challenges, several operational challenges must also be overcome to realize this vision. Current robots rely heavily on continuous communication with their operators, which cannot always be guaranteed in environments with antagonistic actors. Even if a communications link exists, future robots will likely generate so much data that it may be impractical to send it to the operator due to bandwidth restrictions. Cognitive overload is also a concern. Sensible solutions to autonomous operations and data communication management are needed. Human-machine interfaces also must advance to support the complexity of limbed systems, simplifying their operation into intuitive controls.

Augmented reality or virtual reality is one promising modality that seems capable of supporting the required sophistication, intuitiveness, and speed. Beyond learning individual behaviors, teaming behaviors will also need to be learned for robots to effectively work with one another and with human teammates. Extensive training as teams will be needed to build the requisite trust to operate as an effective military unit.

Finally, logistical, social, and legal challenges will need to be overcome before limbed robots can achieve their full potential for our military. Due to their high energy use, energy sustainment is a logistical issue to be conquered before we can achieve multiday operations without resupply. Soldiers will also need to be trained to provide regular maintenance, as these highly complex systems will take time to achieve the ruggedness of more established hardened equipment. Prevalent use of military robotics may present social difficulties depending on the type of military operation. They are not likely to “win hearts and minds” immediately. In addition, companies, universities, individuals, and nation states have publicly expressed concerns over the development of lethal autonomous weapons, which limbed robots may be classified as in some cases. Ethical implications of development and operation must be considered.

Limbed robots such as quadrupeds, mobile manipulators, and bipeds are becoming practical solutions to commercial problems, and they will soon become practical solutions to military problems. Through continued investment, research, and integration, our military can realize these capabilities, providing transformational overmatch over our adversaries and enhancing the protection of our military’s most valuable assets: our Soldiers.

1. Introduction

To secure victory in warfare, defeating the enemy is paramount, requiring the suppression of unacceptable actions. Escalated conflicts often feature a critical juncture where physical engagement with the enemy becomes imperative. Effective engagement necessitates the meticulous gathering and analysis of vast amounts of information to devise strategic plans with the highest likelihood of success. The evolution of warfare has seen robotics, notably unmanned aerial vehicles (UAVs), assume a pivotal role. UAVs are instrumental in information gathering and precise delivery of lethal payloads, minimizing collateral damage while effectively neutralizing intended targets and taking on protection roles. According to Gen. James E. Rainey, “First contact with the enemy should not be made in blood . . . current technology provides the capabilities now to ensure first contact with the enemy is made with sensors, (and) unmanned aerial systems.”¹ This technological advancement has consistently provided a significant strategic advantage in recent conflicts.

The deployment of UAVs has prompted the enemy to adapt, enhancing their ability to conceal their whereabouts and activities. Tactics include migration to urban areas to blend in with civilian populations and utilizing subterranean tunnels to evade detection by UAVs and other surveillance equipment. As dismounted forces are deployed to locate, engage, and neutralize threats, the risk to friendly forces intensifies due to the reduced proximity between friendly and enemy forces.

In dismounted operations, the use of limbed robotics can reduce risk to human friendly forces by performing physical actions on the world in dangerous and/or difficult to access environments, allowing humans to maintain a safer standoff distance. To fully achieve this vision, robotic systems should be capable of performing many tasks with human-like ability and speed. While such a vision has long remained in the realm of science fiction, the accelerating pace of advancement in robotics and artificial intelligence suggests that future may soon be realizable.

The sections that follow provide an overview of the capability advantages that limbed robotics could provide to the future force. We begin by assessing current capabilities of state-of-the-art limbed robotics. Next, we consider mission sets for which limbed systems could reduce risk to the dismount operations through integration into supporting roles. These mission sets were informed by a February 2024 Technical Exchange Meeting held at the U.S. Army Combat Capabilities Development Command Army Research Laboratory, which included cross-organization and cross-service participation of over 15 organizations. Each operation is broken down to better understand the environment and the level of

autonomy that must be achieved to accomplish various levels of task complexities. Finally, we assess the limitations and capability gaps currently blocking widespread adoption for those missions.

2. Limbed Robotics: Current Capabilities and Common Forms

Since life began, natural selection has worked to develop biological systems that can effectively move about the world. Many of those systems can also manipulate the environment to construct shelters, hunt and gather food, and even make tools and weapons. Appearing in many forms across many scales, highly capable limbs such as legs, arms, tails, and tentacles remain a consistent natural solution to the problems of mobility and manipulation. Further, humans have significantly reshaped much of the world to fit our own needs, capabilities, and form factor, exacerbating the advantages of limbed systems.

Despite these advantages, the development of limbed robotic systems remains a considerable challenge and has only recently become practical. This section aims to describe the advantages of using limbs to achieve certain capabilities. It also aims to describe the current state-of-the-art capabilities of commercially available limbed systems in both military and commercial contexts, providing background for how limbed robotic systems may fit into future military operations. Note that we aim to focus on describing what is commercially available or Army fielded. Academic research labs have often demonstrated more advanced capabilities than we describe, though the robustness of those capabilities in Army-relevant environments limits current application.

2.1 Mobility and Terrain Adaptability

Legged robots, with their adaptable and versatile capabilities, offer a host of advantages for traversing diverse terrains. Unlike their wheeled and tracked counterparts, legged robots excel in navigating challenging areas ranging from rugged terrains strewn with obstacles to uneven surfaces such as steep slopes or stairs.² The advantages of these platforms make them ideal candidates for operation in a military setting where the environment is constantly changing, possibly unstable, and actively hostile.

One key aspect of legged robot morphologies is their inherent adaptability. Legs provide the ability to dynamically change gait, stride length, and posture, allowing these robots to respond to challenging terrain conditions. This locomotive flexibility is particularly valuable in environments where the terrain is unpredictable and varied. Legs also allow the robot to change body position and

orientation while remaining in stable contact with the ground, permitting the robot to balance in areas where a wheeled or tracked platform might tip over.³

Another significant advantage of limbed platforms is their ability to navigate obstacles not just via locomotion, but through manipulation. Performing whole-body manipulation tasks allows the robot to (sometimes literally) open doors⁴ to new environments. It also enables movement of obstructions that may not be otherwise overcome,⁵ or even the construction of bridges across insurmountable gaps.⁶ Thus, limbed robots have the potential to go places that would otherwise be inaccessible by removing barriers to entry.

Finally, limbed robots can use their appendages to gather data about the terrain they are navigating. By using sensory feedback, the robot can assess and adjust to terrain properties in ways wheeled and tracked platforms might not. Subtle differences such as wet versus dry grass, or asphalt versus black ice, may be difficult for a robot's visual perception to distinguish despite having very different properties, leading to suboptimal planning.^{7,8} The use of sensory feedback allows the robot to make more informed navigation decisions beyond visual capability, and with finer detail than wheel slip measurement can provide.

Currently, commercially available quadrupedal robots such as Boston Dynamics' Spot, Ghost Robotics' Vision 60, Anybotics' Anymal, and Unitree's Go have demonstrated that they can effectively navigate a range of moderate terrains. These include mowed grass, easy hiking trails, icy pavement, shallow snow, and others.⁸ Some have demonstrated more advanced capabilities, including challenging National Institute of Standards and Technology-designed step fields. Efficient, robust gaits for these terrains are typically still hand-tuned, and the ability to autonomously adjust to changing terrain is nascent. More challenging capabilities such as reasoning about "obstacles" that might be pushed through (e.g., tall grass and other vegetation)⁹ and navigating marginally stable or unstable terrain is still in development, as well as seamless transitions between terrains.

Whereas quadrupedal robots have demonstrated themselves to be quite capable of navigating unstructured terrains, bipedal robots continue to be in development. Many of the commercially available robots come with support gantries to ensure they do not accidentally fall, potentially breaking an expensive asset. Agility's Digit is a notable exception for simple unstructured terrains, but robust bipedal mobility remains a work in progress.

2.2 Dexterity and Manipulation

To fully realize robotic capabilities for future military operating scenarios, robots must go beyond intelligence, surveillance, and reconnaissance (ISR); they must be able to physically interact with the environment and reshape the battlespace in significant ways. This includes simple pick-and-place tasks such as deploying and retrieving sensors; manipulating tools to perform maintenance¹⁰; increasing mobility and environmental access by opening doors¹¹ or removing obstructions,⁵ grasping rocky surfaces for climbing,¹² and recovering from tip-over or falling by self-righting¹³; among other possibilities. Figure 1 shows an example ARL demonstration from 2019 of a robot physically interacting with the environment to clear a path by moving a fallen tree.⁵



Figure 1. RoMan bimanual robot autonomously removing a tree from a notional roadway.⁵

Currently fielded and soon-to-be fielded military robots have some capacity to perform these tasks. The Packbot,¹⁴ Talon,¹⁵ Common Robotic System–Individual (CRS-I),¹⁶ Common Robotic System–Heavy (CRS-H),¹⁷ Man Transportable Robotic System (MTRS),¹⁸ and other similar platforms have 4–7 degrees of freedom (DoFs) in the manipulator, depending on the configuration, and a reach of up to 2 m. Grippers on these platforms are typically low-DoF end effectors, providing the ability to clamp down on items with features that fit between the two fingers. This is often sufficient for delivering a charge or grasping objects with a narrow range of geometries. Manipulation capabilities are used when the platform is static; any whole-body coordination is extremely difficult.

Door opening remains on the edge of current capability for Army-fielded systems, with opening some doors being slow but possible, and other doors not. Next-generation models are anticipated to extend this fundamental capability, which Boston Dynamics’ Spot¹⁹ has shown is well within reach of current commercially

available technology. The ability to open doors will be essential for any future system expected to operate in indoor environments.

Current commercially available manipulators have also been shown to aid in mobility to a limited extent. Systems often include presets that position the manipulator such that its mass increases the platform's stability during tasks like stair climbing. Further, open-loop scripts have been integrated to cycle the manipulator through a sequence of poses that cause the platform to recover after flipping over in simple cases.

2.3 Actuation Performance and Endurance

Limbed robotic systems face unique design challenges in the context of performance and endurance. While these systems are often compared with biological systems, they differ significantly in terms of actuation, energy storage, materials, and heat transfer. In the context of a legged robot, endurance refers to the stamina or traversable distance for a given terrain. Likewise, limbs and grippers used for manipulation have unique metrics of their own. Actuators span many physical domains, such as electromechanical, chemomechanical, and photomechanical, including subclasses beneath each of those categories. Today, most actuation technologies are inferior to the power density, specific power, and efficiency that electromechanical actuators deliver. As such, contemporary robots are predominantly electromechanical systems using brushless or hydraulic motors. There are numerous emerging actuator technologies that emulate soft muscles in the chemomechanical,²⁰ photomechanical,²¹ and electromechanical²² domains that may one day replace brushless motors.

Regardless of actuator type, a useful metric for endurance is the cost of transport.²³ The cost of transport is largely dictated by the robot's onboard energy storage, structural materials, kinematics, specific power (W/kg), power density (W/m³), and efficiency. Modern brushless motors tend to be superior actuators because they also offer a reversible process, the conversion of mechanical energy back into electrical energy. Limbed robots with high endurance require maximizing onboard energy storage, lightweight composite structures, efficient motors, and efficient spring-like locomotion. However, maximizing endurance tends to come at the cost of reduced performance.

The performance of limbed robots is commonly measured in terms of speed, strength, and agility.^{24,25} To achieve high performance, the robot must utilize actuators with maximum specific power and power density, and a reduction in energy storage mass. Furthermore, actuators are typically operated at their maximum power rather than maximum efficiency. This presents a significant

thermodynamics challenge. Biological organisms typically have some form of evapotranspiration for cooling, while robots presently do not. A combination of active and passive cooling technologies must exist in the design; otherwise, the robot will overheat and be forced to rest for extended periods of time. These cooling technologies can either be part of the robot's structure or exist as separate components (e.g., fans, heatsinks, radiators, heat pipes). It should be no surprise that the trade space between endurance and performance tends to be inversely related.

While current limbed robots can offer higher performance at the cost of endurance, several approaches are being explored to reduce the endurance cost. Hybrid limb designs with wheels as feet aim to use the efficiencies of wheeled locomotion when available while retaining the performance flexibility of limbed mobility when needed.²⁶ Also, the integration of high-performance brakes or clutches²⁷ within limbed actuators can significantly reduce power drawn during static operations (e.g., standing), extending operating times.

2.4 Human–Robot Interface

The human–robot interface, usually facilitated by an operator control unit (OCU), is a critical component of any robotic system. Much has been learned about the impact of multimodal communication and control on human–robot interaction, trust, and teaming.^{28,29} While there is a desire for a universal controller that can be used to control a suite of disparate systems, most present-day robots have custom interfaces tailored to the specific features and capabilities of the robot. Often this means one or more screens or windows dedicated to the camera views that are available; a variety of knobs or switches for controlling the navigation, manipulation (if present), and possibly sensor poses; and a custom communications protocol interfacing the OCU with the robot.

While affording the user “complete control” at the individual joint level, forward kinematic controls tend to make manipulation time consuming and counterintuitive. When it comes to limbed systems, the number of actuators in need of control becomes large enough that individual joint control ceases to be sensible. Inverse kinematic control, where the user provides a desired position and orientation (pose) of the body or end effector and the robot autonomously plans and moves the joints to achieve the intended effect, is a more sensible option. This is quite common for existing legged mobility systems, making them navigate similarly to wheeled or tracked platforms. It is becoming more common for manipulators as well, as operators see their speed advantages and learn to trust them.

The proliferation of touch screens has also impacted human–robot interfaces. It is common for more recently released robots, especially limbed robots, to be controlled via touch screen. These are often controlled via menu options where a variety of views and functions can be navigated. The touch screens provide a level of versatility beyond the limited number of buttons from older controllers and could help facilitate the desired universal controller, where a single hardware OCU can run a variety of software, encompassing all the capability needs of a heterogeneous set of robots in any given unit’s stock.

The recent explosion of the field of natural language processing (e.g., ChatGPT) has opened the door even wider to future interfaces with high levels of autonomy.^{30,31} While not in fielded use yet, it is likely that robots of the future will take commands more like an actual dog or Soldier teammate, executing on its own for minutes at a time and allowing a single Soldier to control multiple robots instead of multiple Soldiers controlling a single robot.

Finally, augmented reality (AR)³² and virtual reality (VR)^{32,33} headsets have begun to enter the market, providing an additional tool that could be flexible enough to control multiple robot types. This may reduce the need for screens to display camera viewpoints, affording the robot to communicate in a compact, lightweight package. Such headsets could also accept gesture commands for controlling the robot.

2.5 Teaming

In current Army applications of 2024, most robot-facilitated ground-based missions require multiple Soldiers per robot, with robots exhibiting few autonomous behaviors (i.e., mostly teleoperated). However, Army Futures Command’s long-term plans anticipate teams of robots working alongside dismounted infantry as part of an infantry squad or as an armored crewman team member. Robot teaming will lead to enhanced security, force multiplication, improved situation awareness, and most importantly, adversarial overmatch with an opportunity for reduced Soldier casualties.

Teaming is an umbrella term that encapsulates any group of agents (human, embodied agents such as robots, or non-embodied agents including computers and AI) coordinating their actions to achieve an aligned set of goals.³⁴ Human–animal teaming, for example, has been studied in order to gain insights into human–robot teaming.^{35–37} While limbed robots could team on a wide variety of tasks and missions, often in the same ways as non-limbed robots, for the purposes of this report, we focus the term “teaming” for limbed robotics on coordinated actions in the same space (i.e., co-located) at the same time (i.e., synchronization). In so

doing, we aim to distinguish teaming tasks that limbed robots are uniquely capable of. Therefore, the tasks and Army capabilities that teaming with limbed robotics facilitate are primarily either force sharing in nature (e.g., teaming to carry a large/heavy item) or literally leveraging an extra set of hands.

As of 2024, fielded robots are rarely used to team in this fashion. Operating a robot near humans is often considered unsafe, limiting opportunities and willingness to attempt human–robot teaming. Autonomous teaming behaviors for robotic vehicles are often used for leader–follower applications on larger vehicles to maintain convoys while reducing human risk. In addition, some robot–robot teaming behaviors via coordinated activities are under development within the Army’s 10X “Pack of Wolves” program.

2.6 Common Forms

While the space of limbed robots can encompass many different forms, certain configurations are more prominent than others, especially at scales appropriate for dismounted operations. These include wheeled or tracked robots with an arm, aerial robots with an arm or gripper, quadrupeds, and bipeds or humanoids. The sections below briefly describe each of these morphologies.

2.6.1 Tracked or Wheeled Base with an Arm

One of the most common robotic form factors in fielded use today are tracked robots with an arm. Much of this development and use has been due to the prominence of explosive ordnance disposal mission needs in Iraq and Afghanistan throughout the 2000s and 2010s. Early models included Endeavor Robotics’ (formerly iRobot) PackBot,³⁸ and Qinetiq’s (formerly Foster Miller) Talon.³⁹ Newer models include Teledyne FLIR’s MTRS Inc II,⁴⁰ and L3Harris’ T4 and T7.⁴¹

Wheeled systems are highly efficient on smooth ground, as long as they have traction. They are also simple to control and tend to be robust due to their few moving parts. Tracked platforms combine much of the efficiency of wheels with more robust mobility. The design of track treads can increase contact angles somewhat for more traction on less smooth surfaces, such as those covered by small rocks. In addition, tracks also distribute the robot’s weight over a wider area to reduce sinkage. Thus, tracks are better than wheels at traversing rocky surfaces, wet mud, and loose sand, for example. However, there are still significant limits to the degree of terrain ruggedness a tracked vehicle can surmount. Highly cluttered regions, such as those with larger rocks or rooms with furniture, present barriers that quickly become insurmountable for tracked vehicles.

To perform useful work on the environment, developers began adding manipulator arms to these robots. The wheeled or tracked base would then provide the mobility to move the manipulator around the environment and get to the location where the work needed to be performed. Often these manipulators would have 4–7 DoFs with a simple two-jaw gripper. These robots also sometimes include a second manipulator in the form of a mast, providing control of the sensor head to provide more targeted data about the environment. This could be especially helpful during the manipulation process.

While the ability to manipulate at the point of need is quite useful, current platforms remain challenging to use and perform tasks at human speed. Grippers tend to be simple, with few DoFs and little tactile feedback to the operator, instead relying mostly on visual information to understand the manipulator’s effect on the environment. Work to improve these conditions is ongoing in the academic setting, and we look forward to the integration of these developments on more commercially available systems.

2.6.2 Quadrupeds

Another common type of limbed robot is a quadruped. A quadrupedal robot has four legs and is often called a robot dog. Recently, many new commercial quadrupeds of various sizes and morphologies have become available on the market. These include Boston Dynamics’ Spot¹⁹ Ghost Robotics’ Vision60,⁴² Unitree’s Go2 and B2,⁴³ and ANYbotics ANYmal.⁴⁴ These robots are currently used commercially for inspection⁴⁵ and surveillance tasks, and search and rescue.⁴⁶ Quadrupeds have several advantages over current bipeds (e.g., humanoid robots). Due to their larger support base created by four legs, quadrupeds are more stable and robust to external disturbances, like a kick, and to unstable terrain. Quadrupeds also have larger payload capacities relative to their weight. Finally, quadrupeds tend to be faster than bipeds because four legs can spend more time in contact with the ground to propel the body forward over one gait cycle⁴⁷ and use their articulated torsos to deliver greater stride power.⁴⁸

Despite these advantages, the quadruped’s morphology creates a disadvantage when it comes to robots interacting with environments designed for humans. The robot may be too low to the ground to reach objects, or lack the dexterity provided by arms and hands on an upright humanoid robot. This can be somewhat remedied by attaching an arm to increase dexterity. However, it comes with the trade-off of added weight and reduced payload capacity. Despite the popularity and commercial success of some quadrupedal robots, there are still many advancements needed for quadrupeds to be used in military operations.

Current capabilities:

- Waypoint navigation over relatively simple terrain
- Proprioception of ground conditions
- Stair climbing
- If equipped with an arm, manipulation of doors and small objects
- Approximately 1 h of active run time

Areas in need of improvement:

- Movement in more complex terrains such as tall grass, mud, deep snow, or water
- Manipulation of larger obstacles using the whole body (e.g., jersey barrier)
- Dynamic movements like leaping
- Increased run time
- Increased robustness to environmental conditions

2.6.3 Bipedal and Humanoid Robots

Perhaps the hallmark of limbed systems is the humanoid robot, generally meaning a system with two arms, two legs, a sensor head, and the ability to walk with an upright torso. Because we have constructed our world around our own form, humanoid robots offer unique advantages to other forms in terms of their versatility, manipulation, communication, and adaptability to human environments. The integration of humanoid robots into military operations has the potential to enhance unit capabilities and contribute to safer and more effective mission outcomes. In particular, humanoid robots promise at least the following advantages over more traditional robot form factors:

- Navigation through cluttered human spaces due to small footprint
- Dexterous bimanual manipulation
- Large end-effector and sensor workspace
- Intuitive, human-like interaction
- Intuitive control
- Enhanced potential for human–robot collaboration and trust
- Adaptability to unpredictable scenarios

While humanoid robots have yet to be deployed in any military contexts to our knowledge, there has been a recent boom in commercial interest in humanoid robot development. An incomplete list of leading efforts in the development of humanoid robots includes Boston Dynamics' Atlas,⁴⁹ IHMC's Nadia,⁵⁰ Agility Robotics' Digit,⁵¹ Figure's Figure 01,⁵² Apptronik's Apollo,⁵³ Tesla's Optimus,⁵⁴ Unitree's H1,⁵⁵ and Sanctuary AI's Phoenix.⁵⁶ The availability of these platforms for commercial purchase and their actual out-of-the-box capability span a considerable

range. However, in general, much more research and development will be needed to fully realize humanoid robots for military operations.

Current general capabilities:

- Autonomous bipedal waypoint navigation over relatively simple terrain
- Independent bimanual pinch grasps of large objects (e.g., boxes)
- Some dynamic whole-body mobility (e.g., Atlas)
- Run time of roughly 1 h
- Limited hand/end effector capability (e.g., Phoenix)

Areas in need of improvement:

- Dynamic whole-body coordination and planning in real time
- Ability to return to standing (i.e., self-righting) on complex terrains
- Range of force delivery
- Stable walking and running on a variety of complex terrains
- Robustness to external disturbances
- Improved hand/end effector dexterity, speed, and effectiveness
- Haptic interfacing with human operator
- Increased run-time/endurance

2.6.4 Aerial Robots with Manipulators

A less commonly considered robot morphology is an aerial robot (sometimes referred to as a “drone” or “unmanned aerial system”) with an arm or gripper. Flight is an incredibly versatile form of mobility because it is relatively independent of the terrain properties. Therefore, flight can often be used to put the robot in almost any desired position and orientation. Challenges occur when physical barriers are present, such as doors or trees, or when operating near structures that might affect the aerodynamics of the vehicle. While fixed-wing vehicles are efficient, multirotor vehicles (e.g., quadrotors or octocopters) can be much more precise in their positioning and do not require runways, both important factors when seeking to manipulate the world. They can also maintain their position and orientation in the air under many circumstances, affording more flexibility than vehicles that require contact with the ground.

The use of drones has become quite common over the past 20 years, to the point that they have begun to impact military tactics in significant ways. This has become evident in both the war in Ukraine and the Second Nagorno–Karabakh War.⁵⁷ However, these drones are typically used for either ISR or to precisely deliver munitions in both space and time by leveraging their ability to loiter. The addition of grippers and/or arms to these vehicles, while not yet a common commercially

available product, holds promise for performing useful work across a broader range of locations and is an active area of academic research and exploration.⁵⁸

3. Potential Roles of Limbed Robotics in Future Military Operating Scenarios

The integration of limbed robots into military forces offers several strategic advantages that can contribute to victory in armed conflicts. By serving as force multipliers, these robots enable military units to accomplish missions with fewer personnel, reducing the risk to human lives and enhancing operational efficiency. Additionally, the presence of limbed robots on the battlefield may have a psychological impact on adversaries, instilling fear, confusion, and uncertainty. Moreover, these robots provide enhanced situational awareness to military commanders, enabling them to make informed decisions and adapt to evolving threats in real time. Perhaps most substantially, robots that can move with or even exceed human-like agility while also manipulating and reshaping the battlefield are likely to substantially alter the way war is conducted. This chapter aims to describe how *future* limbed robots might enhance the ability to succeed across a wide range of mission sets.

3.1 Intelligence, Surveillance, Reconnaissance (ISR)

Employing limbed robots to conduct ISR missions provides advantages over traditional wheeled and tracked unmanned ground vehicles. In general, robotic platforms provide an unwavering persistent observation of the environment and can analyze a large amount of data without fatigue and reduced accuracy that can be experienced by a human. A *limbed* system allows the robotic platform to maneuver through its environment with mobility comparable (or eventually superior) to humans. The limbs offer the ability to step over large obstacles rather than going around them, reaching locations on complex terrains that may not be obtainable to wheels and tracks (e.g., traversing rocky mountain sides to peer over an area of interest without being detected). Limbs also allow the robot to utilize its surroundings to conceal its location for long, persistent overwatch to avoid detection by the enemy. In urban environments, limbs allow common tasks such as door opening and manipulation of obstructions to create a passage and continue the mission. Information gathered can be reported to the human commander through the network to aid in decision making and planning.

3.2 Maintaining Communications

Virtually all operations require maintaining communications, whether a robot is involved or not. Operations involving robots tend to be even more dependent on high-quality communication, providing a means of control and to relay the information the robots obtain back to the humans and/or other robots for team situational awareness. The involvement of limbed robots can contribute to the communications maintenance mission by granting additional flexibility in placing communications links (e.g., signal repeaters) around the environment in locations that are more difficult to reach due to both the robots' enhanced mobility and manipulation capabilities. This may include accessing subterranean or urban environments where doors are present. They could even shift the comms nodes around the battlefield in real time if needed. They could also perform similar actions with deploying decoy nodes if deemed desirable for a given mission.

3.3 Sensor Deployment and Management

A mission similar to maintaining communications is sensor deployment and management. Due to their increased environmental access and manipulation capabilities, limbed robots can deploy and/or redistribute sensor nodes around the battlefield in more advantageous places than traditional morphologies. Figure 2 shows an example of sensor deployment. These sensors might be small, heterogeneous, single-purpose sensors (e.g., cameras) or nodes offering multiple sensing modalities combined with communications relays in a single package. Ultimately, the limbed robot could deliver a family of integrated sensors to enable early and continuous detection of enemy force maneuvers.

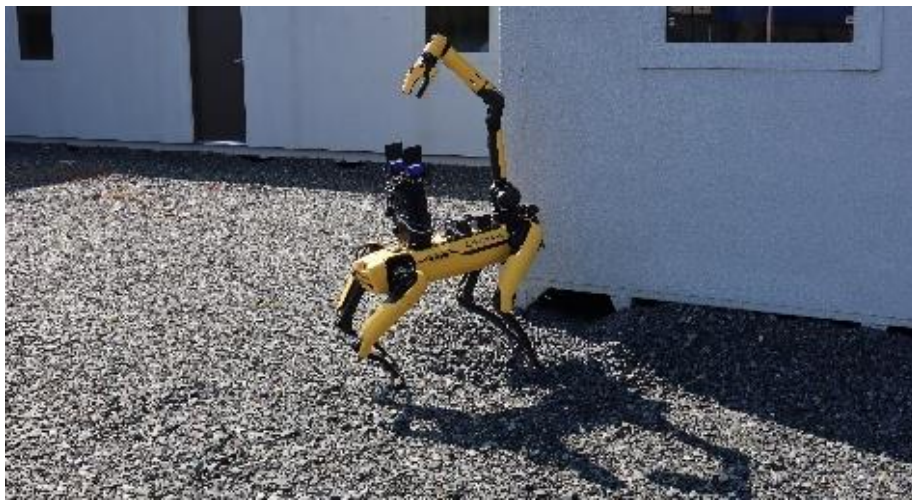


Figure 2. Boston Dynamics' Spot with a manipulator reaching to grasp and deploy a sensor payload.

3.4 Chemical, Biological, Radiological, and Nuclear (CBRN)

Many military mission roles come with risk; CBRN is no exception. When there is contamination of any sort, humans are risking their lives and health with every moment of potential exposure. In addition, the time spent detecting, decontaminating, moving contaminated items, etc., takes Soldiers and their equipment off the battlefield and out of the fight. Current Army decontamination practices include large quantities of water and decontamination fluid, heavy equipment, and numerous personnel donning protective equipment and following safety protocols. By using robotic systems such as the one shown in Figure 3 to aid in these practices, the hope is a roughly five-fold reduction in both personnel and resource requirements, while simultaneously offering significant risk reduction to human life and diminished downtime.

Further, contamination detection is currently performed using multiple systems, which can be either manipulated directly in Soldiers' hands or located on vehicles. These systems risk exposing Soldiers and, if on a vehicle, restrict the areas that can be searched. Using limbed robotic systems to venture inside buildings or over complex terrains inaccessible to wheeled vehicles can reduce the risk to the Soldier and time spent removing the threat.

By using autonomous systems in conjunction with an indicator solution to identify and spray contaminated areas, the application time decreases drastically when compared with the current practice of Soldiers manually decontaminating with hoses, hand sprayers, and other resources. In addition, the use of autonomous systems seeks to protect personnel from prolonged exposure and limit supervisors from having to coordinate personnel for work and rest periods, especially in conditions in which humans are sensitive, such as extreme heat.



Figure 3. Development robot using a mobile robot with a manipulator to perform chemical decontamination.

3.5 Countermine Operations

In South Korea, it is estimated that hundreds have been killed by mines placed during the Korean War.⁵⁹ There are still hundreds of thousands of largely unaccounted for mines in or near the Korean DMZ, which South Korea spends over \$300,000 USD per year to clear.⁶⁰ Due to the many situations like this around the world, there is huge opportunity for robotic countermine operations. Currently, mine placement and detection can be performed by hand, from air vehicles, or by ground vehicles. Detection using air or large ground vehicles can be used when precision detection is not required. Several wheeled and tracked vehicles and robots are currently used to clear mines, such as the M60 Panther, MiniFlail, and the M1 Grizzly with a rake. However, when precision is required, Soldiers detect and clear the mines.⁶¹

Clearing a minefield is a stressful, labor-intensive job. Time limits are placed on Soldiers performing this duty. Soldiers must get close to the ground in prone position to look and feel for signs of mines. Soldiers use a probe to penetrate the ground to search every inch of the target area. When they find a mine, they lightly dig out around the sides and mark the location. Once the mines are detected, they can be cleared several ways including line charges, disrupters, Bangalore torpedoes, and vehicles with mine-clearing blades and rollers.

Given the current state of mine/countermine operations, dexterous limbed robots with advanced manipulation capabilities could be extremely useful to detect and clear mines with precision. Some mine detection capability development is already underway using quadrupeds.⁶² These robots need to have limbs with proprioceptive capabilities and sophisticated control capabilities to carefully dig out and mark mines during a clearing operation. Limbed robots could be tele-operated during operations as well. This would not reduce the amount of labor required, but it would reduce the stress of and risk to Soldiers that would typically perform the operations by hand.

3.6 Improvised Explosive Device (IED) Detection and Defeat

Improvised explosive device (IED) detection and defeat is highly complex, and limbed platforms may help close the gap on this dangerous and difficult task. IEDs are a significant threat and were responsible for nearly 49% of all hostile-fire deaths of U.S. servicemen and servicewomen in Iraq and Afghanistan.⁶³ As IED detection is primarily a visual task, limbed platforms may provide the first set of “eyes” to aid in identifying threats through detection of disturbances in the environment. Like mine detection, limbed robots provide advantages for IED detection due to their increased terrain accessibility and ability to position cameras and other sensors with

more dexterity than most non-limbed robots currently in use. Further, they have the potential to contribute to defeat in substantial ways.

Explosive Ordnance Disposal (EOD) units and engineers are primarily responsible for IED detection and defeat. Current EOD robots (MTRS, Telemex, etc.) have been successfully deployed in various operating scenarios across the Army. These wheeled or tracked robots can traverse common terrain types and are typically outfitted with a single arm and parallel jaw end effector for object manipulation. They are commonly used for IED detection and can perform some neutralization activities such as use of water disruptors and neutralization charge placement. However, it is still quite common for operators to suit up and risk exposure due to many circumstances beyond the current capabilities of EOD robots.

Future limbed systems offer hope for reducing the rate of such incidence. Explosive-sensing dogs with a human handler are also employed with a high rate of success for IED detection, and as such an equivalent electronic “nose” on a Quadrupedal Unmanned Ground Vehicle for detection of explosive compounds may be employed in the future, expanding detection capabilities. Limbs can assist with access and sensor placement.

In addition, the parallel jaw grippers used in current EOD robots lack force sensors, limiting operator feedback to visual data. As such, delicate objects may be crushed during manipulation. Force feedback for object manipulation may be enabled through haptics or visual display. Pressure sensing in the form of electronic “skin” may also provide valuable feedback on the distribution of force/pressure on an object during manipulation tasks.⁶⁴ Future highly dexterous hands with such high-quality haptic feedback could perform many of the tasks currently requiring EOD technicians in bomb suits.

3.7 Building Clearing and Breach

The primary concern in tactical breach scenarios is speed, executing the breach operation as quickly and efficiently as possible to ensure the element of surprise. In such missions, the first one through the door is the most vulnerable to enemy fire and risks of booby traps. Allowing a robotic platform to enter the door first helps reduce the risk to the human Warfighter due to a reduction in direct threat exposure. Unfortunately, current robotic systems are too slow and unreliable to meaningfully participate in tactical breach scenarios.

Limbed robotics provide advantages in tactical breach operations due to the inherent nature of their design. Employing limbs on a robot addresses the need for increased dexterous manipulation of tools to conduct breaching operations through

the use of arms and hands (end-effectors), as well as agile motion supplied by robotic legs to maneuver through breached passageways, which are often cluttered with debris. In addition, limbed mobility systems can move holonomically (e.g., laterally), whereas most wheeled or tracked systems must turn, drive forward, then turn again to execute a lateral move (similar to the challenge of parallel parking a car).

Several topics must be addressed to provide effective robot breaching. The manipulation of tools to conduct the breaching operation is a complex task that requires quick motion planning to get the tool to the desired location and the ability to dynamically use the tool to apply the forces and torques. The complexity of such tasks is quite challenging through teleoperation and beckons for at least semi-autonomous solutions. As far as mobility, the legged robot must be able to stabilize itself as it traverses difficult terrain, but also stabilize itself while using a tool to perform potentially highly dynamic motions with large reaction forces. This requires a whole-body motion planning capability that must be autonomously controlled due to the quick response needed.

3.8 Sentry/Wide Area Security

One common Army job is to serve as a sentry, guarding or keeping watch over an area to control access. Current robot technologies can perform many of the duties required for this role, including monitoring using sensors and targeting. Wheeled and tracked robots can extend this functionality beyond stationary activity to patrol a region more actively, depending on the terrain. Limbed robots could bring two potential advantages to the task. They can patrol much more rugged areas, such as those with fallen trees and small boulders, and they can also move holonomically (i.e., in any direction from any orientation), making them more agile in the heat of the fight.

The potential use of a legged robot as a military direct-fire weapon entails several strategic considerations and operational procedures. We will ignore the important ethical considerations to be addressed for the purpose of this report. First, the robot must be equipped with robust armor plating to withstand enemy fire and harsh battlefield conditions, but the amount and placement of armor must be strategically considered. Like UAV platforms, weight on legged systems should be minimized and allocated judiciously. Weight directly impacts performance of legged robotics because when a robot runs, it achieves a flight phase where all legs are not touching the ground. To enable this flight phase, the robot must have enough energy in the battery and strength in the motors that actuate the legs to achieve sufficient ground thrust to initiate the flight phase during running. Additional platform weight

requires bigger motors and batteries, which reduces agility and allowable payload. As the platform becomes larger and heavier, the efficiencies that enable it to locomote using legs diminish.

Legs should be designed for both agility and stability, allowing for rapid maneuverability across diverse terrain types. Integrated weapon systems, such as machine guns, cannons, or missile launchers, should be mounted securely onto the robot's chassis, enabling precise targeting and effective engagement of enemy forces. Additionally, advanced sensors and targeting systems are essential for acquiring and tracking hostile targets with accuracy. Prior to deployment, thorough training programs are imperative to ensure operators can safely and effectively control the robot and its weaponry on the battlefield. Tactical coordination with other military assets and adherence to rules of engagement are crucial for the safe and effective employment of legged robots as direct-fire weapons in military operations.

3.9 Logistics

Logistics is one of the missions on which the Army spends the most time and resources. The transport and delivery of materiel, including food, water, fuel, ammunition, gear, and other equipment, is essential to providing Soldiers what they need, when they need it, to win the fight. While robots can be helpful throughout the entire process, some of the most challenging tasks are those at the very start and very end of the process where individual pieces are packaged/unpackaged, and packages are palletized/unloaded. As one example, highly capable robotic arms can grasp, lift, and accurately place heavy objects, supporting missions such as loading Army artillery ammunition supply vehicles.⁶⁵

In addition, limbed robots could transport supplies, ammunition, and equipment across the battlefield at the front line where the threat is the highest to reduce human exposure. Specific examples might include 60-mm mortar rounds, extra machine gun ammunition, Javelin missiles, and command launch units. Legged robots enable the traversal of rough, obstacle-ridden terrain, making them well-suited for navigating challenging environments and delivering payloads to remote and hard-to-reach areas, such as dilapidated buildings and subterranean tunnels.

In the forward operating base, the limbed robots could conduct inventory management, autonomously scanning and tracking inventory located in storage facilities or on vehicles, freeing humans to do other tasks. Another advantage of the robotic element conducting inventory might be improved accuracy because the robot does not get tired while performing tasks.

The dexterity of limbed platforms could also be useful in refueling military vehicles. This allows the human element to stay focused on security while the limbed robot performs the exposed, heads-down refueling operation. That same dexterity, combined with increasingly good planning algorithms, could similarly allow limbed robots to create pallets of material at a shipping warehouse, stacking goods together in a stable configuration on top of a pallet and wrapping to secure it as a single unit for transport. Overall, limbed robots with arms and legs offer valuable capabilities for military logistics tasks, enhancing the efficiency, safety, and reliability of supply chain operations in various military environments.

3.10 Maintenance

Limbed robots with both arms and legs offer tremendous potential for maintenance tasks across a variety of environments. These robots could perform a wide range of maintenance activities, including inspections, repairs, and servicing, with dexterity and efficiency. Specific examples might include changing a road wheel or tread on an M1 Abrams tank or M2 Bradley, or changing a tire on a Stryker. Equipped with advanced sensors and cameras, robots can navigate complex environments, identify potential issues, and assess the condition of equipment with precision.

Limbed robots have many DoFs, allowing them to position end effectors and/or sensors in a wide range of locations. This is particularly true of the humanoid form factor, where the legs, torso, and arm all work in serial to extend the vertical reach. In military settings, limbed robots could access tight spaces and elevated areas that may be challenging for human workers, enabling them to inspect machinery for signs of wear, damage, or malfunction. Their articulated arms and grippers would allow them to manipulate tools and components, performing tasks such as tightening bolts, replacing parts, or conducting routine maintenance procedures, even while under fire.

In remote or hazardous environments, such as CBRN-contaminated environments, limbed robots can be deployed to perform maintenance tasks without exposing human workers to dangerous conditions. Their ability to traverse uneven terrain and navigate obstacles makes them well-suited for inspecting and repairing infrastructure (e.g., in forward operating bases) in challenging locations.

Furthermore, these robots can be equipped with specialized tools and equipment tailored to specific maintenance tasks, such as welding torches, cutting tools, or sensors for detecting leaks or structural weaknesses. Autonomous or semi-autonomous capabilities allow them to carry out routine maintenance efficiently, reducing downtime and improving overall operational efficiency.

3.11 Robot-Augmented Protection

Employing a limbed robot for augmented protection on the battlefield offers a unique approach to enhancing the protection of infantry units and military assets. Through advanced sensor technology and real-time communication systems, robots may be able to predict, detect, and intercept threats before they can reach friendly forces. This could contribute to a form of Formation Based Layered Defense.

One advantage of using limbed robots for this kind of mission is their ability to move in any direction. Traditional wheeled and tracked platforms can only move forward/back and rotate; they cannot move laterally. The ability to move in any direction affords a significant agility advantage in highly dynamic situations.

Additionally, the robot's mobility allows it to adapt to changing battlefield conditions, including the introduction of new rubble and craters. Despite such dynamic obstacles, the robot could position itself strategically to provide maximum protection where needed most. This might aid the human Warfighter in moving across an open battlefield to overtake an enemy stronghold, as one example. Integration with UAVs or surveillance systems could further enhance situational awareness, enabling the robot to anticipate and respond to threats proactively. By acting as augmented protection, the limbed robot becomes an invaluable asset for safeguarding troops and assets on the battlefield, enhancing overall mission effectiveness and minimizing casualties.

Finally, a limbed robot could potentially reduce the armor's required mass, and therefore the overall size, weight, and power (SWaP) required for the mission. The ability to swiftly direct or redirect armor means that the mass could be focused only where it is needed. The reduction of planning times for such a vision is already a reality,⁶⁶ though actuation times remain a significant challenge.

3.12 Engineering Support

Army combat engineers "help Soldiers navigate while on combat missions by clearing barriers . . . constructing obstacles, as well as defense and fighting positions."⁶⁷ Limbed robotic systems could significantly contribute to achieving these goals through their ability to interact with and reshape their environment. Future limbed systems will have the capacity to construct ad hoc bridges facilitating the movement of troops and equipment over rivers and other bodies of water, deemed wet gap crossing. They could remove barriers crossing roads, whether natural or constructed, maintaining Soldier standoff from potential threats embedded within those barriers.⁵ They could further construct similar barriers to

slow down or limit enemy mobility. They could even dig fighting positions such as trenches or foxholes to create more advantageous terrain.

Each of these example tasks can be challenging under the most favorable of conditions. To perform them during active combat scenarios only increases the level of difficulty and danger. Utilizing limbed robots in an engineering support role could afford opportunities to achieve critical objectives requiring manipulation of the world to reshape the battlespace while reducing human exposure to potential threats.

3.13 Medical Assistance

Finally, limbed robots could be very helpful for casualty evacuation and other forms of medical assistance. Sometimes conducted by helicopter under fire, wounded Soldiers must be evacuated to the nearest care facility to receive urgent treatment. This operation can be frantic and highly time sensitive.

Robots as a general class are not subject to the sometimes-paralytic emotions that humans face in such circumstances. Limbed robots have the added advantage of being able to manipulate within an enormous workspace. They could quickly disembark, pick up and secure the casualty, and re-board the helicopter. They may even be able to do this without requiring the helicopter to fully land on the ground, opening the possibility to perform casualty evacuation on rough terrain. Further, dexterous hands could even begin first aid treatment while in the field and/or enroute to the hospital.

Limbed robots could also serve as field assistants for providing limited medical care. As a human medic moves through a scene to triage the situation, limbed robots could accept simple tasks such as squeezing and releasing a bottle to serve as a field ventilator for a specific patient. Thus, the medic could move through patients more quickly while providing some level of care.

4. Challenges and Limitations

Despite their potential benefits, the widespread adoption of limbed robots for military purposes faces many challenges and current limitations. These include many technological barriers, but the power requirements, fragility, and complexity of these systems also present operational and logistical hurdles that must be overcome. Finally, limbed robots have the potential to be classified as lethal autonomous weapon systems,⁶⁸ bringing legal and ethical considerations for which there are unlikely to be easy answers. This section seeks to describe many of the

barriers that must be overcome for limbed robotics to gain adoption for real-world use in addressing the mission sets described in the previous section.

4.1 Technological Challenges

Many of the challenges to widespread use of limbed robots for military applications relate to issues that are technological. The actuators, sensors, control, batteries, computer processing, and materials that compose the physical system each require continuous improvement to bring these highly complex systems to the battlefield.

4.1.1 Actuation and Hardware

Limbed robots by their very nature have many DoFs. Each DoF adds complexity on multiple levels. Planning becomes more difficult; the number of potential failure points increases; sensing and actuation overhead often increase. While some under-actuation can be effective, many of those DoFs need to be independently actuated to achieve the versatility sought.

To achieve desired functionality, actuators must continue to improve. SWaP, as well as cost, are all driven in large part by the actuators needed to output the desired forces and torques on the world. Innovative ways to increase torque while decreasing SWaP demands will drive realistic dynamic function while also reducing energy demands and increasing endurance.

Another way to improve endurance is to transform chemical energy directly into mechanical energy. Actuators that mimic biological muscles are exploiting the superior energy density of hydrocarbons. Even with an efficiency of 5%–10%, they could outperform brushless motors and lithium-ion batteries. Computing and sensing elements are likely to require electrical power in the long-term, which implies multiple energy storage materials and conversion technologies onboard a single robot. Furthermore, electric motors are already very efficient and power dense. One of the major challenges in permanent magnetic motors is saturation in the iron core and heat dissipation. Without room temperature superconductors, engineers are forced to use air cooling and liquid cooling to prevent motors from being damaged. Other motor designs, including axial flux and iron-less motors, help with efficiency. Motors with higher torque and lower speed have larger diameters, which can lead to excessive inertia and enlarged joints that may limit the robot's kinematics. Newer robots are incorporating mechanical energy storage devices such as springs to exploit gait resonance for efficient locomotion. Likewise, clutches and other braking mechanisms are being explored to reduce idle (standing) power consumption while increasing joint stiffness. Limbed robots are advancing at a rapid pace due to advancements in actuators, energy storage, and perception.

Over the next decade, limbed robots need to make significant improvements toward the performance and endurance of biology.

Hardware will also need to be significantly more ruggedized to be robust to the harsh, chaotic environments posed by military settings. High DoF systems pose numerous points of potential failure, and thus numerous opportunities for enemy disruption. Hardening systems for reliable use across a broad spectrum of environments and scenarios will be a critical challenge to overcome before realistic widespread adoption is possible.

4.1.2 Sensing

Limbed platforms rely on an array of sensors for proprioception (information on the robot's internal state) and exteroception (information acquired from the robot's environment).⁶⁹ Locomotion requires position, velocity, and torque sensing to control movement through feedback. Multi-axis accelerometers and gyrometers are outfitted on the body to offset noise and drift errors to provide complete and more accurate movement tracking. Exteroceptive sensors can provide real-time information about the environment and terrain. Examples include tactile sensing, GPS, inclinometer, electrooptical, temperature, humidity, acoustic, biochemical, lidar, electromagnetic, and communications. Load cells are exteroceptive sensors that can be outfitted on the feet, end-effectors, or body to record force or pressure and to detect slip. They are often noncompliant, limiting their placement options. Sensors can be active (emit energy to the environment, then measure the environmental reaction) or passive (measure ambient environmental energy entering the sensor).

Sensors currently require a substantial number of wires and connections to transfer and receive data. In the future, a single input and output is desired to reduce weight, power requirements, and electrical/mechanical complexity. Stretchable and flexible sensors are also desired to improve sensor resilience while lowering SWaP requirements and to achieve physical compliance. The formation of sensing capabilities such as skin could improve feedback for manipulation tasks, but also could be useful for sensing stable footholds while traversing challenging surfaces such as loose rock, soft soils, and slippery surfaces. Further, it could support multi-contact locomotion such as Army crawling.

While increased sensor density, fidelity, and modalities facilitate advanced function, they come with the potential cost of data overload.⁷⁰ More data means more data processing, which can drive time, power, and heat generation. Advanced methods of filtering, data fusion, and data processing via edge computing will be

required as more sensory data are brought to bear.⁷¹ More sensors and processing also exacerbate the cost challenge.

4.1.3 Behavior Development

Despite continual advancements in control theory and AI, many limitations remain to moving effectively over complex terrains and performing dexterous, whole-body manipulation tasks. Legged robots have many more DoFs than wheeled and tracked robots, making sophisticated control algorithms necessary for basic tasks. In addition, legged robots must be able to move in a variety of terrains, some of which are quite complex. Terrain slope, friction, and stiffness can vary significantly from one stride to the next. There is some generality in certain motion controllers for walking and running on simple, uniform terrains, but most current controllers are designed for a specific robot morphology operating on a specific terrain. AI can be used in simulation and on hardware to train robots to perform locomotion and manipulation tasks in many different environments using techniques such as reinforcement learning. However, these models still typically need many hours of training in each specific scenario, which takes a large computational overhead. Even after training, better, more consistent methods are needed for overcoming the sim-to-real gap and deploy effective behaviors on real-world robots.

Like locomotion in complex terrains, manipulation is an extremely difficult controls problem. A control strategy must account for objects with unknown shape, size, friction, and stiffness. Contact dynamics are extremely important in manipulation tasks. In addition, present-day robots typically rely on visual sensors to perceive and localize objects. By contrast, humans can blindly reach into a pocket and easily understand what objects are in it. Researchers are just beginning to use AI to train robots to perform more general manipulation tasks in simulation and on hardware. Like locomotion control algorithms, training these models often takes huge overhead in time and compute, and often leads to highly specific, brittle solutions. Transferring skills learned in simulation to the real world remains a substantial challenge for which we have not yet found general solutions.

4.1.4 Run Time/Energy Storage

Another challenge is how long the robot can operate. Limbed robots, as currently designed, often require a great deal of energy even to stand still. The many DoFs and mass demand large energy expenditures, limiting run time. Biology continues to serve as the gold standard for power and energy in the design of limbed robots. The onboard energy available in modern limbed robots is approximately two orders of magnitude less than what biology provides. Consider the Ghost Robotics Vision 60 quadruped weighing 27 kg (twice the battery configuration) providing 1 kWh

(3.6 MJ) for 3.5 h walking endurance. This energy storage works out to approximately 142 Wh (0.5 MJ)/kg. If we assume an 80%–90% brushless motor and controller conversion efficiency, then there are 3 MJ available for this 27-kg robot (0.11 MJ/kg). Now consider an 80-kg male human with 15% fat content and a conversion efficiency of 25%. Body fat as a specific energy of 39.5 MJ/kg, therefore the human example provides a specific energy of 9.8 MJ/kg (after conversion). This ratio of 89:1 exemplifies why endurance remains a major challenge even with the recent advances in lithium-ion battery technology. This crude example ignores the energy needed for perception and compute, which only exacerbates the difference.

In the near future, energy storage is expected to double in chemical batteries while longer term, this increase could be much greater. It is unlikely that batteries will reach the energy density of hydrocarbons, which is why hydrogen fuel cells, solid oxide fuel cells, and even nuclear batteries are of particular interest. In the meantime, the limbed robotics community will be faced with typical endurance lasting 2–4 h on relatively benign terrain. This is far short of what is needed for many military missions. A 96-h continuous military operation without resupply is an ambitious target, though it is unclear how many of those hours the robot would need to be active, or to what degree it needs to exert itself. Design of a limbed robotic system must be approached with the same mentality as unmanned aerial systems, where the mission duration, payload, computation, range, etc., must all be well integrated into the platform to reduce weight and enable longer endurance and range.

4.1.5 Computer Processing

Computer processing capacity is an essential element for intelligent systems. Filtering and making sense of sensory data, fusing information across sensory modalities, performing path planning and collision avoidance calculations, reasoning about dynamics of objects in the world through time, and many more functions require computer chips such as GPUs. The complexity involved with controlling robotic limbs only adds to the computational demands of most robots. Recent advancements in machine learning and generative AI are being used to create robots that can learn to use their limbs to perform autonomous behaviors while also conversing using natural language. The demands from these industries apply even more pressure on chip manufacturers and rare materials to produce them, presenting a possible scarcity problem down the road. Further, the use of ever-more processing power onboard the robot increases heat, cost, and energy usage.

4.1.6 Materials

Current limbed platforms are relatively heavy and would be challenging for a single Soldier to carry and field when considering current load limits. Material developments will play a pivotal role in the deployment of limbed robotic systems as SWaP constraints currently limit the endurance and deployment of these platforms. Lighter and stronger materials⁷² will enable greater endurance and/or increased payload potential and ease burden. Elastic, flexible, and soft materials can be applied as a “fat layer” to promote safe human–robot interaction, store energy when compressed or stretched, insulate the robot from extreme temperature, and help absorb shock and damage. This fat layer can also be inflated (e.g., via air) to act as a cushion and decrease density, enabling legged robots to swim and efficiently traverse wet-gap crossings.

New sensor architectures and stretchable soft sensors with multimodal functionality and embedded sensing systems may provide valuable feedback in the form of “skin” for determining optimal gaits, obstacle detection/avoidance, object manipulation, detection of slip events during manipulation tasks, and characterization of terrain and environment. In addition to tactile sensing, skins can also be used for adaptive optoelectronic cloaking, electromagnetic radiation shielding, and conformal antennas.

Limbbed robots made of biodegradable components including transient electronics and devices that can disintegrate over a period of stable operation when exposed to ultraviolet light, thermal energy, or water⁷³ will be important as robots continue to proliferate.⁷⁴ Biodegradable robots would also lower the environmental impact as well as eliminate the need for Soldiers to recover robots.

4.1.7 Attritability: Cost and Security

Limbbed robots are extremely complex systems requiring enormous upfront effort to design, manufacture, assemble, and program. Because of this, most highly capable limbed systems with reasonable payload capacities cost six figures to acquire and maintain today. If a small number of low-cost munitions can easily remove a high-cost limbed asset from the battlefield, at some point economics will diminish the will to continue fighting. Therefore, reducing the cost of limbed systems such that they can serve as Attritable Robotic Autonomous Systems must be considered as another technological challenge to be surmounted. Uncrewed, reusable, multimission capable systems that are relatively inexpensive and able to be planned for expenditure will be much more readily used than expensive equipment for which Soldiers are held accountable if lost.

In addition to cost, security in the event of loss will also be an important factor. Systems that are damaged and recovered by the enemy must not present information security risks, either through accessibility of onboard data or as an access point to our network. They should also not be capable of repurposing for enemy use. Ideally, this would include any weapons capabilities or false flag recognition carrying trojan horses in the form of malware or physical threats.

4.2 Operational Challenges

Beyond the technology onboard the physical robot, adoption of limbed systems for military applications will also face operational challenges that must be overcome. Communications and bandwidth, human–machine interfacing, teaming, and trust will all need to be considered as part of the development process.

4.2.1 Bandwidth and Communications

Because limbed robots are more complex than most other form factors, they may require more information transfer to control them. This could include information transferred from the robot to the OCU in the form of video, point clouds, state information, and contact and force information from, for example, skin sensors. It may also include command information from the OCU to the robot in the form of audible instructions, map information, or other forms. Distributed information, such as video from other robots, may further reduce available communications bandwidth. Thoughtful consideration must be taken to control assumptions about bandwidth availability, especially when multiple heterogeneous systems are in use in proximity. The development of robust, autonomous behaviors can reduce the need to communicate high-fidelity data, relying more on the robot than on the operator to identify objects, understand the surroundings, and perform operations independently.

Beyond bandwidth, adversarial jamming, environmental barriers, and limited range may prevent assured, continuous communication with systems. We may even wish to minimize communications to reduce our signature and limit enemy monitoring or targeting. System robustness to comms loss will be an additional challenge to overcome. The ability to understand mission goals and autonomously perform operations that advance the team toward satisfying those goals will be a highly desirable long-term aim as forms of AI continue to mature.

4.2.2 Human–Machine Interface

Due to the complexity of limbed robots, human–machine interfaces pose an additional challenge, especially when considering the desire for a common

controller. Standard controllers have too few buttons to rapidly access the full capability of the platform. Further, while operators have traditionally sought “full control” of robots, joint-by-joint control can lead to increased operation times and nonintuitive function; such control ceases to be sensible for high-DoF systems. Trying to control even a 12-DoF quadrupedal robot joint-by-joint would be excruciatingly slow and mentally burdensome; in addition, there is a good chance the robot would fall over. Inverse kinematic control of a robotic arm allows the operator to focus on moving the end effector, with individual joint planning occurring automatically to achieve the commanded trajectory of the hand. For quadrupeds, this type of control goes one step further, allowing the operator to control the motion of the body while individual limbs move automatically through a gait cycle. In advanced cases, specific step placement is also determined automatically for use on highly rugged or cluttered terrain. Through training/experience, operators learn to trust this form of automation.

To achieve situational awareness, the most common human–machine interface is a monitor or set of monitors showing video feeds. Operators can often choose which feed is highlighted, view multiple feeds through tiling, and/or scroll through feeds using a menu system. This could even be extended to include multiple robots. Newer approaches on the horizon are utilizing AR or VR goggles, providing a more immersive experience. These can be combined with audio inputs that include directionality. While they provide better situational awareness around the robot, this may come at the cost of situational awareness where the human is located.

For manipulator control, exoskeleton-like haptic interfaces can determine joint information from the user’s arm and hand, converting those signals into appropriate commands for the robot. The joints can even exert forces on the human, providing force-feedback for more realistic motion and knowledge of the environment. Gloves can provide a sense of touch back to the operator’s hands, enhancing the ability to manipulate. If haptic feedback is not required, video or lidar-based systems can capture and map human motions into effective robot motions.

Finally, visual language action (VLA) models offer the opportunity to control robots using voice commands. This requires a large degree of autonomy for the robot to both successfully interpret the world and execute appropriate actions within it. Virtual demonstration of intended actions in simulation with human approval prior to execution may help facilitate generally acceptable functionality and trust.

4.2.3 Teaming

In a military environment, a limbed robot with arms and legs can be used in teaming scenarios to augment the capabilities of human Soldiers and enhance overall

mission safety and success. Future limbed robots are expected to have mobility and agility comparable to the human element and are anticipated to be integrable within military formations. The robot element can reduce human exposure by being the front line of attack and receiving the brunt of the enemy's force first. As the level of autonomy advances, limbed robots could eventually be used to conduct missions as its own forcing squad. The front-line robotic force could engage the enemy or transmit real-time critical information back to human operators, providing valuable situational awareness while limiting Soldiers' risk.

Limbbed robots have a unique capability set that can provide opportunities to execute tasks requiring force sharing. One space to observe this task domain could be in setting up a forward base of operations, where many large, awkward, or heavy objects and equipment must be moved from a transport vehicle to their appropriate and functional locations (e.g., moving a portable generator, pitching a large tent, carrying unwieldy boxes). This task domain, which is being explored in academic literature, generalizes beyond Army applications, but such shared tasks are critical for Army operations.

In addition to force sharing tasks, teaming with limbed robotics can provide support for various maintenance and repair tasks. Certain mechanical repairs and maintenance are achieved by holding an item in place, while using a tool to conduct an action, and needing focused light or a camera perspective on a small area. It is easy to see with this example that more than two hands might be needed. Although limbed robotic teaming is not the only way to achieve such shared workspace tasks (e.g., static clamps or a flashlight clipped to a nearby surface if available), leveraging a limbed robotic teammate has the potential to complete shared workspace tasks more efficiently by dynamically adjusting complementary actions, which would also reduce injury risks in robot–Soldier teaming situations.

To facilitate these sorts of teaming behaviors, future robots will need to understand commander's intent. Clearly understanding shared goals is a critical step for a team to achieve its objective. Further, the ability to understand and predict the actions of teammates will help the robot adapt its role and performance to best support the mission. Bidirectional communication, including the ability to ask clarifying questions, using natural language processing and generative AI will be an important capability milestone that is rapidly maturing.

Limbbed robot teaming is not explicitly restricted to force sharing or shared workspace tasks, but this synchronized and collocated action domain is likely a near-term eventuality with the recent advancements emerging in the consumer and commercial space (e.g., Boston Dynamics, Toyota, Tesla, Ghost). Therefore, the

Army of 2040 will likely be playing catch-up if limbed robotic teaming is not developed for specific Army applications before 2030.

4.2.4 Trust and Training

As with any robotic system, trust is a critical (but often misunderstood) requirement for effective integration into a team, no matter the level of human control or autonomy. It follows the foundational research showing the importance of trust calibration (increase or decrease) over time. Legged systems should focus in on the critical sub-factors of trust.⁷⁵ The human–animal trust literature identifies the predominant factors that can be applied to this particular area of robotics.⁷⁶ However, the importance of each factor is dependent on the potential robotic benefit and defined task allocation of the Soldier–robot team. Robotic benefits can replace, multiply, augment, or extend a physical benefit (e.g., carrying payload) or cognitive benefit (e.g., ISR) to the Soldiers where teaming is defined through task interdependence (i.e., requires both to partner to complete the task), pooled interdependence (i.e., separate tasks with combined output), sequential interdependence (i.e., task order dependent on other team members), or reciprocal interdependence.³⁷ Figure 4 depicts some of the factors that are most important for trust building on human–animal relationships.⁷⁶

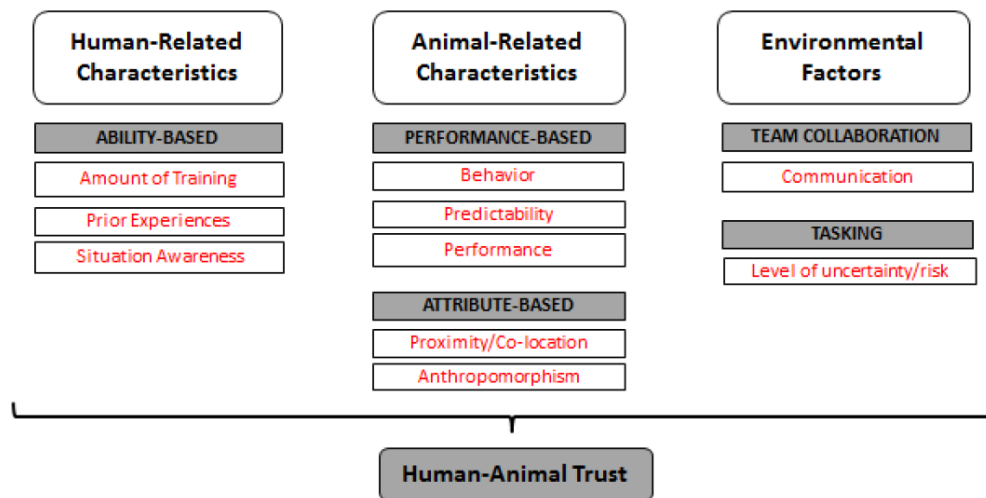


Figure 4. Identified factors associated with trust in human–animal interactions.⁷⁶

Just as trust is built among human teams through training, the same should be true of human–machine relationships. Operator training time is fundamental for the operator to learn how to use the robot, the bounds of its capabilities, and improve speed. It is also critical to building trust in procedures and tools for performing the various tasks required. As robot autonomy increases, training will become even more important for building trust, so that operators or handlers can better

understand how a robot is likely to go about its commanded task and predict its probability of success. Robot performance needs to be robust not only for assured operation during a mission, but also for frequent training activities that must occur to develop and maintain strong team performance.

4.3 Logistical Challenges

Just as support for human Soldiers is heavily reliant on logistical support to provide the necessary food, water, and equipment, limbed robots will also require logistical support. The challenges associated with providing logistical support need to be considered as limbed robots are developed, because solutions to logistical challenges may affect the overall composition of the desired product.

4.3.1 Energy Sustainment

Run-time is paramount. With limbed systems, the cost of transport is greater than that of conventional wheeled vehicles, therefore recharge time and distance to recharge are more sensitive to ensure maximum time on task. Hot swappable batteries offer minimal downtime; however, such mechanisms are fragile to environmental conditions (e.g., ice, mud, dust, and debris). Conversely, integrated batteries overcome this issue provided that the battery supports high-speed charging via wireless power or robust electrical connection. It is also beneficial for the robot to remain powered during energy resupply so that it may execute mission planning algorithms while also maintaining situational awareness. Long endurance missions should occur without human intervention, leveraging autonomous behaviors for energy resupply.

The Army presently derives most of its electrical energy from liquid fuel generators. This could be extended to supply robot energy needs, including ideas such as charging off the vehicles transporting the robots, but it necessitates assured fuel resupply, which is not always possible. Alternative energy sources including solar, foraging biomass from the environment, or parasitic induction from existing power line infrastructure could be advantageous far-term solutions to these challenges. Solutions to challenges associated with using other forms of energy such as nuclear or fuel cells should also continue to be explored as part of an energy source diversification strategy.

4.3.2 Maintenance

As with all highly complex systems, limbed robots will require maintenance. Their highly capable nature will make them natural targets on the battlefield, further driving anticipated maintenance needs. The ability to service the robots will pose

challenges. Maintenance workers will need to be highly skilled and trained to service the numerous potential failure modes. The number of specialized parts necessary to perform the repairs might be quite large. To the extent possible, system design should consider the number of specialized parts, tools required, and procedure time necessary to perform maintenance activities. Standardized, easily swappable limbs may be one way to reduce downtime and challenges associated with continuing maintenance.

4.4 Social/Legal Challenges

Even if effective autonomous limbed robots were to be fully realized, their use in military contexts may face social, ethical, and legal challenges. Numerous science fiction movies have highlighted potential dangers of autonomous robots with the capacity to kill (e.g., *Terminator*), even when designers have attempted to make them incapable of harming humans (e.g., *iRobot, 2001: A Space Odyssey*).^{77,78} Global discussions continue around the possible banning of autonomous weapons. It is unclear what the social consequences of using such devices might be, especially if other countries adopt legal bans. Responsible development and use of limbed robots will remain an ever-present imperative for both ethical and practical reasons.

5. Conclusions

In conclusion, limbed robots offer significant potential to shape the future of warfare, providing military forces with novel capabilities and strategic advantages on the battlefield while significantly reducing Soldier risk. By leveraging their mobility, versatility, and human-like capabilities, these robots can enhance situational awareness and increase the decision space through expanded environmental access, leading to more effective and efficient military operations. Further, leveraging manipulation capabilities of limbed robotic systems affords opportunities to reshape the battlespace while maintaining Soldier standoff. Advancements in robotics and AI technologies, including improvements in sensor capabilities, autonomy, and human–robot interaction, will enhance the performance and effectiveness of limbed robots on the battlefield. Ethical frameworks and international regulations, informed by multidisciplinary perspectives and stakeholder engagement, will ensure the responsible and ethical use of limbed robots in military contexts, minimizing the risks of unintended consequences. Through continued research, innovation, collaboration, and cross-organization coordination, limbed robots can continue to evolve into indispensable assets for modern military operations, providing transformational overmatch opportunities and shaping the future of warfare in the 21st century and beyond.

6. References

1. Fort Moore Public Affairs. Fort Moore hosts Human Machine Integration Summit. Department of the Army (US); 2023 Nov 16 [accessed 2024 Sep 10]. https://www.army.mil/article/271730/fort_moore_hosts_human_machine_integration_summit.
2. U.S. Department of the Army. The U.S. Army functional concept for movement and maneuver 2020-2040. U.S. Department of the Army; 2017. TRADOC Pamphlet No: 525-3-6.
3. Lee C-Y, Yang S, Bokser B, Manchester Z. Enhanced balance for legged robots using reaction wheels. 2023 IEEE International Conference on Robotics and Automation (ICRA); 2023. p. 9980–9987.
4. Hoeller D, Rudin N, Sako D, Hutter M. Anymal parkour: learning agile navigation for quadrupedal robots. *Sci Robot*. 2024;9(88):eadi7566.
5. Kessens C, Kaplan M, Rocks T, Osteen P, Rogers J, et al. Human-scale mobile manipulation using RoMan. *Field Robot*. 2022;2:1232–1262.
6. Atlas gets a grip [YouTube video]. Boston Dynamics. YouTube; 2023 Jan 18 [accessed 2024 Oct 10]. 1:20 min. https://www.youtube.com/watch?v=-e1_QhJ1EhQ.
7. Degraeve J, Cauwenbergh RV, Wyffels F, Waegeman T, Schrauwen B. Terrain classification for a quadruped robot. 2013 12th International Conference on Machine Learning and Applications; 2013. p. 185–190.
8. Ackerman E. Legged robots learn to hike harsh terrain. *IEEE Spectrum*; 2022 Jan 20 [accessed 2024 Oct 10]. <https://spectrum.ieee.org/legged-robots-anymal>.
9. Sathyamoorthy A, Weerakoon K, Guan T, Russell M, Conover D, et al. Vern: vegetation-aware robot navigation in dense unstructured outdoor environments. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*; 2023. p. 11233–11240.
10. Fang K, Zhu Y, Garg A, Kurenkov A, Mehta V, et al. Learning task-oriented grasping for tool manipulation from simulated self-supervision. *International J Robot Res*. 2020;39(2–3):202–216.
11. Wang J, Lin S, Hu C, Zhu Y, Zhu L. Learning semantic keypoint representations for door opening manipulation. *IEEE Robot Autom Lett*. 2020;5(4):6980–6987.

12. Newdick S, Ongole N, Chen T, Schmerling E, Cutkosky M, et al. Motion planning for a climbing robot with stochastic grasps. IEEE International Conference on Robotics and Automation (ICRA); 2023; London, UK.
13. Scalise R, Caglar E, Boots B, Kessens C. Toward self-righting and recovery in the wild: challenges and benchmarks. IEEE International Conference on Robotics and Automation (ICRA); 2024; Yokohama, Japan.
14. PackBot. Wikipedia; last updated 2024 Sep 20 [accessed 2024 Oct 23]. <https://en.wikipedia.org/wiki/PackBot>.
15. Foster-Miller TALON. Wikipedia; last updated 2024 Sep 20 [accessed 2024 Oct 23]. https://en.wikipedia.org/wiki/Foster-Miller_TALON.
16. Rhen B. Pennsylvania guard Soldiers train with new robotic system. Pennsylvania National Guard; 2022 Nov 10 [accessed 2024 Oct 23]. <https://www.nationalguard.mil/News/Article/3216047/pennsylvania-guard-soldiers-train-with-new-robotic-system>.
17. Higgins R. Army.mil. 2019 Nov 18 [accessed 2024 Oct 23]. <https://www.nationalguard.mil/News/Article/3216047/pennsylvania-guard-soldiers-train-with-new-robotic-system/>.
18. Teledyne FLIR Defense DELIVERS 1,000th MTRS Inc II (Centaur) ROBOT to U.S. Army. Teledyne FLIR LLC; 2023 June 7 [accessed 2024 Oct 23]. <https://www.flir.com/news-center/military/1000th-mtrs-system/>.
19. Boston Dynamics Spot. Boston Dynamics; c2024 [accessed 2024 Oct 23]. <https://bostondynamics.com/products/spot/>.
20. Zhu X, Hu Y, Wu G, Chen W, Bao N. Two-dimensional nanosheets-based soft electro-chemo-mechanical actuators: recent advances in design, construction, and applications. ACS Nano. 2021;15(6):9273–9298.
21. Grabowski P, Haberko J, Wasylczyk P. Photo-mechanical response dynamics of liquid crystal elastomer linear actuators. Materials. 2020;13(13):2933–2942.
22. Khaldi A, Elliot J, Smoukov S. Electro-mechanical actuator with muscle memory. J Mater Chem C. 2014;2(38):8029–8034.
23. Kitano S, Hirose S, Horigome A, Endo G. TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking. Robomech J. 2016;3(1):1–16.

24. Eckert P, Ijspeert A. Benchmarking agility for multilegged terrestrial robots. *IEEE Trans Robot.* 2019;35(2):529–535.
25. Hutter M, Gehring C, Hopflinger M, Bloesch M, Siegward R. Toward combining speed, efficiency, versatility, and robustness in an autonomous quadruped. *IEEE Trans Robot.* 2014;30(6):1427–1440.
26. Bjelonic M, Sankar P, Bellicoso C, Vallery H, Hutter M. Rolling in the deep-hybrid locomotion for wheeled-legged robots using online trajectory optimization. *IEEE Robot Autom Lett.* 2020;5(2):3626–3633.
27. Amish T, Auletta J, Kessens C, Smith J, Lipton J. Johnsen-Rahbek Capstan clutch: a high torque electrostatic clutch. *IEEE International Conference on Robotics and Automation*; 2024; Yokohama, Japan.
28. Barnes M, Elliott L, Wright J, Scharine A, Chen J. Human-robot interaction design research: from teleoperations to human-agent teaming. *DEVCOM Army Research Laboratory (US)*; 2019. Report No.: ARL-TR-8770.
29. Barber D, Abich J 4th, Phillips E, Talone A, Jentsch F, et al. Field assessment of multimodal communication for dismounted human-robot teams. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*; 2015; Los Angeles, CA.
30. Bonial C, Donatelli L, Abrams M, Lukin S, Tratz S, et al. Dialogue-AMR: abstract meaning representation for dialogue. *Proceedings of the Twelfth Language Resources and Evaluation Conference*; 2020.
31. Bonial C, Foresta J, Fung N, Hayes C, Osteen P, et al. Abstract meaning representation for grounded human-robot communication. *Proceedings of the Fourth International Workshop on Designing Meaning Representations*; 2023.
32. Hayes M, Downie A. What is augmented reality? IBM; 2024 April 8. <https://www.ibm.com/topics/augmented-reality>.
33. Lowood HE. Virtual reality. *Encyclopedia Britannica*; 2024 Aug 16 [accessed 2024 Oct 23]. www.britannica.com/technology/virtual-reality/Entertainment.
34. Phillips E, Ososky S, Grove J, Jentsch F. From tools to teammates: toward the development of appropriate mental models for intelligent robots. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*; 2011; Los Angeles, CA.
35. Phillips E, Ososky S, Swigert B, Jentsch F. Human-animal teams as an analog for future human-robot teams. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*; 2012.

36. Lum H, Phillips E. Understanding human-autonomy teams through a human-animal teaming model. *Top Cogn Sci.* 2023;16(3):554–567.
37. Phillips E, Schaefer K, Billings D, Jentsch F, Hancock P. Human-animal teams as an analog for future human-robot teams: influencing design and fostering trust. *J Hum-Robot Interact.* 2016;5(1):100–125.
38. PackBot. Wikipedia; last updated 2024 Sep 20 [accessed 2024 Oct 23]. <https://en.wikipedia.org/wiki/PackBot>.
39. Foster-Miller TALON. Wikipedia; last updated 2024 Sep 20 [accessed 2024 Oct 23]. https://en.wikipedia.org/wiki/Foster-Miller_TALON.
40. Teledyne FLIR Defense DELIVERS 1,000th MTRS Inc II (Centaur) ROBOT to U.S. Army. Teledyne FLIR LLC; 2023 June 7 [accessed 2024 Oct 23]. <https://www.flir.com/news-center/military/1000th-mtrs-system/>.
41. T7™ Multi-Mission Robotic System. L3Harris; c2024 [accessed 2024 Nov 5]. <https://www.l3harris.com/all-capabilities/t7-multi-mission-robotic-system>.
42. Ghost Robotics Vision 60. Ghost Robotics; c2024 [accessed 2024 Aug 20]. <https://www.ghostrobotics.io/vision-60>.
43. Unitree Robotics Products. Unitree Robotics; c2024 [accessed 2024 Aug 20]. <https://www.unitree.com>.
44. Meet ANYmal your new inspector. ANYbotics; c2024 [accessed 2024 Aug 20]. <https://www.anybotics.com/robotics/anymal/>.
45. The new standard for industrial inspections. Boston Dynamics; c2024 [accessed 2024 Oct 23]. <https://bostondynamics.com/solutions/inspection/>.
46. Spot to the rescue. Boston Dynamics; c2024 [accessed 2024 Oct 23]. <https://bostondynamics.com/blog/spot-to-the-rescue/>.
47. Günther M, Rockenfeller R, Weihmann T, Haeufle D, Götz T, et al. Rules of nature's Formula Run: muscle mechanics during late stance is the key to explaining maximum running speed. *J Theor Biol.* 2021;523:110714.
48. Gracovetsky S, Iacono S. Energy transfers in the spinal engine. *J Biomed Eng.* 1987;9(2):99–114.
49. Atlas® and beyond: the world's most dynamic robots. Boston Dynamics; c2024 [accessed 2024 Oct 23]. <https://bostondynamics.com/atlas/>.

50. Nadia humanoid project. Institute for Human and Machine Cognition Robotics; [date unknown] [accessed 2024 Oct 23]. <https://robots.ihmc.us/nadia>.
51. The humanoid robot era. Agility Robots; 2024 June 5 [accessed 2024 Oct 23]. <https://agilityrobotics.com/>.
52. Figure [homepage]. Figure; c2024 [accessed 2024 Oct 23]. <https://www.figure.ai/>.
53. Apollo general purpose humanoid robot. Apptronik; c2024 [accessed 2024 Oct 23]. <https://apptronik.com/apollo>.
54. Optimus (robot). Wikipedia; 2024 Oct 30 [accessed 2024 Oct 23]. [https://en.wikipedia.org/wiki/Optimus_\(robot\)](https://en.wikipedia.org/wiki/Optimus_(robot)).
55. Unitree robotics products. Unitree Robotics; c2024 [accessed 2024 Aug 20]. <https://www.unitree.com>.
56. Meet the future of work. Sanctuary.ai; c2024 [accessed 2024 Oct 23]. <https://sanctuary.ai/>.
57. Modebadze V. The importance of drones in modern warfare and armed conflicts. *KutBilim Sosyal Bilimler ve Sanat Dergisi*. 2021;1(2):89–98.
58. Ollero A, Tognon M, Suarez A, Lee D, Franchi A. Past, present, and future of aerial robotic manipulators. *IEEE Trans Robot*. 2021;38(1):626–645.
59. Chappell B. Hundreds of thousands of landmines remain from Korean War, but serve no purpose. NPR. 2019 Aug 27. <https://www.npr.org/2019/08/27/754811189/hundreds-of-thousands-of-landmines-remain-from-korean-war-but-serve-no-purpose>.
60. Kang J-W. The DMZ home to over 1 million landmines. *Hankyoreh*. 2019 Oct 20. https://english.hani.co.kr/arti/english_edition/e_northkorea/913843.html.
61. Headquarters, Department of the Army. Mine/countermine operations. Headquarters, Department of the Army (US); 1985. Field Manual No.: FM 20-32.
62. Jakes L. Not only for killing: drones are now detecting land mines in Ukraine. *New York Times*. 2024 Aug 24 [accessed 2024 Sep 9]. <https://www.nytimes.com/2024/08/24/world/europe/ukraine-land-mines-drones.html>.

63. Counterinsurgency operations. Defeating improvised explosive devices (IED): asymmetric threats and capability gaps. Marine Corps (US); 2014. Reference Publication No.: 3-12.1B.
64. Li T, Yan Y, Yu C, An J, Wang Y, et al. A comprehensive review of robot intelligent grasping based on tactile perception. *Robot Comput-Integrat Manuf.* 2024;90:1–25.
65. Army Applications Lab. Contractor to demonstrate robotic arm for Army. 28 MilitarySpot.com. 2021 Apr 28 [accessed 2024 Nov 5]. <https://www.militaryspot.com/news/contractor-demonstrate-robotic-arm-army>.
66. Natarajan R, Yang H, Xie Q, Oza Y, Pratim Das M, et al. Preprocessing-based kinodynamic motion planning framework for intercepting projectiles using a robot manipulator. *arXiv*; 2024 Mar 16. arXiv:2401.08022. <https://doi.org/10.48550/arXiv.2401.08022>.
67. Combat Engineer 12B [careers and jobs listing]. U.S. Army. [date unknown] [accessed 2024 Nov 18]. <https://www.goarmy.com/careers-and-jobs/mechanics-engineering/design-develop/12b-combat-engineer>.
68. Longpre S, Storm M, Shah R. Lethal autonomous weapons systems and artificial intelligence: trends, challenges, and policies. *MIT Sci Pol Rev.* 2022;3. <https://doi.org/10.38105/spr.360apm5typ>.
69. Rubio F, Valero F, Llopis-Albert C. A review of mobile robots: concepts, methods, theoretical framework, and applications. *Int J Adv Robot Syst.* 2019;16(2):1–22.
70. Kolar P, Benavidez P, Jamshidi M. Survey of datafusion techniques for laser and vision based sensor integration for autonomous navigation. *Sensors.* 2020;20.
71. Castandeo F. A review of data fusion techniques. *Sci World J.* 2013. <https://doi.org/10.1155/2013/704504>.
72. Burden S, Libby T, Jayaram K, Sponberg S, Donelan JM. Why animals can outrun robots. *Science.* 2024;9(89). <https://doi.org/10.1126/scirobotics.adi9754>.
73. Han WB, Lee JH, Shin J-W, Hwang S-W. Advanced materials and systems for biodegradable, transient electronics. *Adv Mater.* 2020;32(51). <https://doi.org/10.1002/adma.202002211>

74. Rumley E, Preninger D, Shagan Shomron A, Rothmund P, Hartmann F, et al. Biodegradable electrohydraulic actuators for sustainable soft robots. *Sci Adv.* 2023;9(12):eadf5551. <https://doi.org/10.1126/sciadv.adf5551>.
75. Lee JD, See KA. Trust in automation: designing for appropriate reliance. *Hum Factors.* 2004;46.1:50–80.
76. Billings D, Schaefer K, Chen J, Kocsis V, Barrera M, et al. Human-animal trust as an analog for human-robot trust: a review of current evidence. Army Research Laboratory (US); 2012. Report No.: ARL-TR-5949.
77. Hancock P, Billings D, Schaefer K. Can you trust your robot? *Ergon Des.* 2011;19(3):24–29. <https://doi.org/10.1177/1064804611415045>.
78. Schaefer K, Adams J, Cook J, Bardwell-Owens A, Hancock P. The future of robotic design: trends from the history of media representations. *Ergon Des.* 2015;23(1):13–19. <https://doi.org/10.1177/106480461456221>.

List of Symbols, Abbreviations, and Acronyms

AI	artificial intelligence
AR	augmented reality
ARL	Army Research Laboratory
CBRN	chemical, biological, radiological, and nuclear
CRS-H	Common Robotic System–Heavy
CRS-I	Common Robotic System–Individual
DEVCOM	U.S. Army Combat Capabilities Development Command
DoF	degree of freedom
EOD	Explosive Ordnance Disposal
GPS	global positioning system
GPU	graphics processing unit
HRI	human–robot interaction
IED	improvised explosive device
ISR	intelligence, surveillance, and reconnaissance
lidar	light detection and ranging
MTRS	Man Transportable Robotic System
OCU	operator control unit
RL	reinforcement learning
SWaP	size, weight, and power
UAV	unmanned aerial vehicle
VLA	visual language action
VR	virtual reality

1 DEFENSE TECHNICAL
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