48. Robotics in Hazardous Applications

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Robotics researchers have worked hard to realize a long-awaited vision: machines carrying people from burning buildings or tunneling through collapsed rock falls to reach trapped miners. In this chapter we review progress. Researchers still have many challenges ahead of them but there has been remarkable progress in some areas. Hazardous environments present special challenges for the accomplishment of desired tasks depending on the nature and magnitude of the hazards. Hazards may be present in the form of radiological or toxicity dangers to potential explosions. Technology that specialized engineering companies can develop and sell without active help from researchers marks the frontier of feasibility. Just inside this border lie teleoperated robots for explosive ordnance disposal (EOD) and for underwater engineering work. Even with the typical tenfold reduction in manipulation performance imposed by the limits of today's *telepresence* and teleoperation technology, robots usually offer a more cost-effective solution. Most hazardous applications lie far beyond the frontier, although researchers managed to establish some limited inroads by the turn of the 21st century. Fire fighting, rescue operations, removing high-level nuclear contamination, reactor decommissioning, tunneling through rock falls, and most landmine and unexploded ordnance problems still present many unsolved problems.

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48.1 Operation in Hazardous Environments: The Need for a Robotics Solution

Hazardous environments present special challenges for the accomplishment of desired tasks depending on the nature and magnitude of the hazards. Hazards may be present in the form of radiological or toxicity dangers to potential explosions. When the magnitudes of hazards reach the point that human exposure would either represent a direct threat to life or long-term health consequences, some form of remote operations that separate humans from the hazards must be employed. An extensive example of such operations is environments involving nuclear radiation; in fact many of the technical roots of modern robotics technology can be traced back to nuclear remote handling manipulators and support systems. Remote handling and operations concepts using engineered systems that allow humans to work effectively from a safe environment have evolved over the years. Today, such remotely operated systems are used widely in many areas and recently they have become rou-

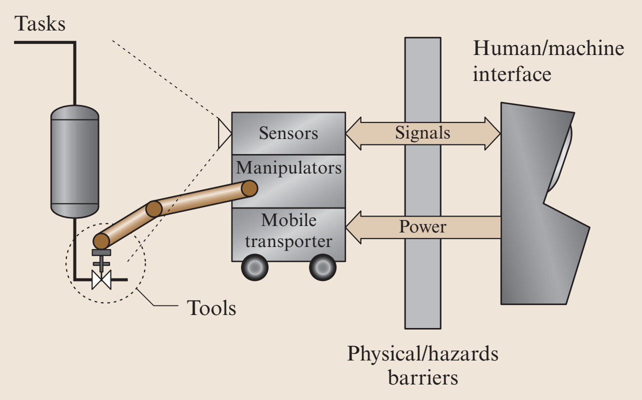

Fig. 48.1 Basic subsystems of a remote handling system

tinely used in explosives disposal, security operations, and handling of dangerous biological materials.

A remote handling system will generally involve subsystems for mobility, manipulation, tooling, sensing, and human–machine interfacing (Fig. 48.1). Nominal operations involve the collective workings of these subsystems to accomplish remote operational goals. Any remote handling system will eventually experience some aspect of off-nominal operation that may be the result of unexpected environmental events or system malfunctions. The fundamental idea is to connect the human operator to the remote environment via a power and signal infrastructure that allows effective operation in the remote environment: mechanized devices and sensor systems that allow the human's perception and action capabilities to be *projected* into the hazardous environment to perform remote operations. The more realistic this projection, the more natural and effective the human remote control will be.

Because of their inherent complexity and the very nature of remote operations, operator training is a major challenge that requires the use of simulations and cold testing facilities that provide operators with comprehensive and realistic training. Such training will typically encompass all aspects of nominal and anticipated off-nominal operations.

Remote handling systems themselves will eventually experience equipment failures. Remote maintenance/operation of failed remote maintenance systems must be an integral part of their basic design and operational features. Hardware/software features must be provided for the analysis of, recovery from, and correction of problems.

Robotics researchers have worked hard to realize a long-awaited vision: machines carrying people from burning buildings or tunneling through collapsed rock falls to reach trapped miners. In this chapter we review progress. Researchers still have many challenges ahead of them but there has been remarkable progress in some areas.

Technology that specialized engineering companies can develop and sell without active help from researchers

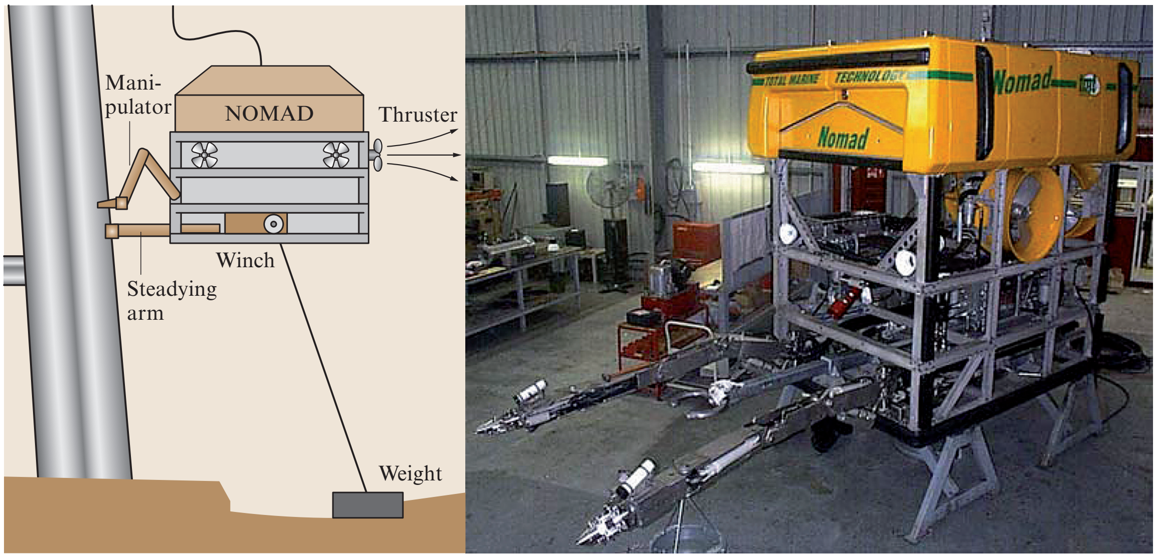

Fig. 48.2 NOMAD remotely operated vehicle for underwater engineering work (Total Marine Systems Pty Ltd, Fremantle, Australia)

marks the frontier of feasibility. Just inside this border lie teleoperated robots for explosive ordnance disposal (EOD) [48.1, 2] and for underwater engineering work. The necessity for people to wear protective suits in these situations limits their endurance and dexterity. Even with the typical tenfold reduction in manipulation performance imposed by the limits of today's *telepresence* and teleoperation technology, robots usually offer a more cost-effective solution. Figure 48.2 illustrates the elegant simplicity of the NOMAD remotely operated vehicle (ROV) that pulls itself deeper with a simple electric winch. It can be left in place overnight or during rough weather. Free-swimming robots are much more complicated and expensive and have to be hauled out of the water when not under active control.

Limited autonomy or autonomous operation for a restricted time can relieve operator fatigue and allows unmanned aerial vehicles (UAVs) to fly extended reconnaissance missions with occasional precision weapon delivery. Such missions would be too hazardous or too politically sensitive for manned aircraft.

Most hazardous applications lie far beyond the frontier, although researchers managed to establish some limited inroads by the turn of the 21st century. Fire fighting, rescue operations, removing high-level nuclear contamination [48.3], reactor decommissioning, tunneling through rock falls, and most landmine and unexploded ordnance problems still present many unsolved problems. Attempts to use first-generation mine rescue robots reported in the press in 2000 and 2001 merely created distractions for the people who regularly have to risk their lives saving their trapped colleagues (e.g., the Australian Numbat robot [48.4]).

48.2 Applications

Applications of robotic systems in hazardous environments encompass an extremely wide spectrum. The solutions for these different environments are equally diverse. In general such applications involve unique challenges associated with the uncertainty and unstructured nature of the associated tasks. In this discussion, two application areas that are very different have been selected to give the reader a deeper sense of technology evolution, accomplishments, and remaining challenges. Landmine eradication, sometimes referred to as demining, is a current application domain with humanitarian importance and extremely difficult and dangerous outdoor conditions. Hazardous materials and operations is a decades-old problem area that has had a strong influences on many aspects of robot manipulation and mobility research and development.

48.2.1 Eradicating Landmines

Efforts to construct a practical robotic device to help with landmine clearance have met with only limited success. While remote control technology has enabled some existing machines and vehicles to be used in hazardous situations, we are still a long way from achieving reliable robotic mine clearance. It is instructive to understand why many expectations have turned out to be hopelessly optimistic.

Landmines, a simple type of victim-activated explosive device, were used extensively in Europe and North Africa during the Second World War between 1939 and 1945. Extensive clearance operations in 1945 and 1946 removed nearly all of the landmines then in use ([48.5], part 1, pp. 15–25).

Landmines were used extensively in subsequent decades. Along with antipersonnel cluster bombs, they caused extensive civilian and military casualties in Vietnam and Cambodia from the 1960s onwards. However, it was not until their widespread use in Afghanistan, Angola, Cambodia, and several other countries in the 1980s that they were recognized as a major humanitarian problem. Landmines blocked aid efforts needed to rebuild communities following civil conflicts.

The Red Cross and the International Campaign to Ban Landmines (ICBL) successfully promoted a ban on the use of landmines that came into effect in 1997 as the Ottawa Treaty. The knowledge that thousands of children were losing their legs, even their lives, motivated hundreds of researchers to develop new technologies to help eliminate this threat. By 2000 ICBL estimated that over 80 countries were affected by landmines and other explosive remnants of war such as cluster bombs. Although many countries that have not signed the Ottawa Treaty still have extensive stocks of landmines, the treaty has been effective in restricting the use of landmines as much through peer pressure as enforcement. A few countries and several nonstate actors continue to deploy landmines according to recent reports. However, explosive remnants of war such as cluster bombs and other munitions have become, yet again, an increasing problem in Iraq and Afghanistan.

There are several basic types of landmines and unexploded ordnance (UXO) that continue to cause problems in many countries.

Antipersonnel (AP) blast mines, made predominantly of plastic with small metal firing pins and detonator cases, typically contain between 20 g and 100 g of explosive (Fig. 48.3). These mines only cause extensive injuries when they detonate within a few centimetres of a person. Typically they lie buried just below the ground surface and are activated when the victim steps on top of the mine. Shattered fragments of bone pass through the flesh of the leg at high velocity. If the victim survives long enough to reach hospital, amputation above or below the knee usually saves his or her life but the victim will need prosthetic legs, replaced at regular intervals.

Antipersonnel fragmentation mines contain similar quantities of explosive with a thick metal case that breaks into high-velocity fragments when the mine explodes just above the ground surface. Older fragmentation mines were mounted on posts; more recent varieties lie buried but jump into the air when activated and explode at waist height, killing or seriously wounding victims up to 200 m away. These mines are much easier to detect so they are often protected by nearby antipersonnel blast mines to deter theft.

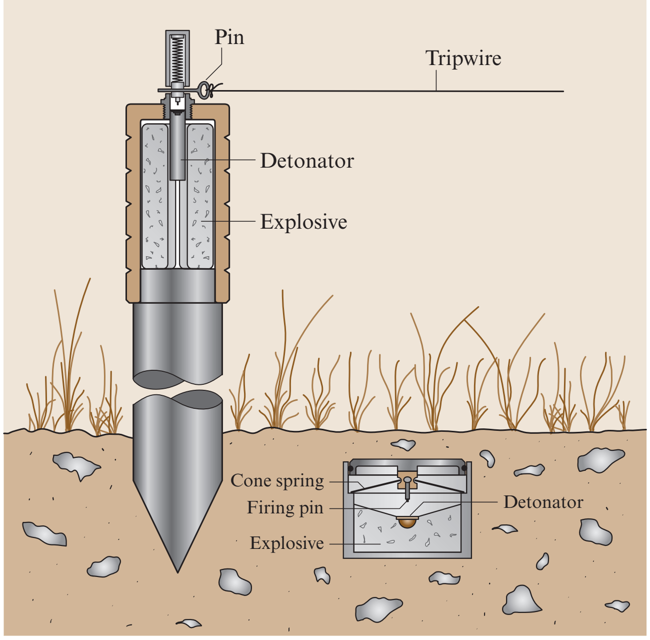

Fig. 48.3 Antipersonnel fragmentation mine (*left*) and buried blast mine (*right*)

Antivehicle (AV) or antitank mines (AT), made predominantly of plastic with small metal firing pins and detonator cases, are large versions of the AP blast mine and typically contain 5–10 kg of explosive. Some have a thick metal plate on top that can penetrate 50 cm of armor plate on the underside of a tank. These mines cause significant damage even to mine-resistant vehicles which have blast-resistant hulls, offset wheels, and additional protection for occupants.

Air-dispersed munitions such as cluster bombs (CBs) were not intended to be victim-activated. Several hundred are released from a single canister and they are designed to explode on impact with the ground. Typically between 5% and 25% failed to explode immediately and lie in a partially triggered state either on or just below the ground surface. Some will detonate in response to electromagnetic fields from metal detectors, and others will detonate with the slightest movement. Most explode like powerful fragmentation mines with a lethal radius of up to 200 m.

Improvised explosive devices (IEDs), often in the form of roadside bombs, are increasingly used by insurgent groups fighting organized military forces (asymmetric warfare). They are often made from large UXOs fitted with remote controlled detonators. Ironically the UXO is often unintentionally donated by the same organized military forces who become the targets of these devices.

Evolution of Landmine Clearance Techniques

Removing landmines is difficult. It is important to distinguish between humanitarian mine clearance and military mine clearance methods (sometimes called *breeching*). Military mine clearance has to work fast, in all conditions (even under fire), and therefore it is unrealistic to aim for 100% clearance. In humanitarian operations there is less time pressure and work can be suspended in unfavorable conditions, and the aim is 100% clearance. Recent political expectations of low casualties often demand very high clearance standards even in military operations.

Humanitarian mine clearance typically starts years, perhaps decades, after the mines were laid. The mines lie buried or hidden from view. They deter people from entering the land so vegetation often grows thickly. Drainage systems rapidly become clogged, denying access in wet conditions.

The traditional *manual* method for removing landmines has been to use a metal detector to locate metal

Fig. 48.4 Typical ruined house overgrown by vegetation in a village in northern Croatia, possibly containing mines or booby traps. The entire village population was forced to leave in 1991 and the houses were looted and intentionally severely damaged. Vegetation problems like this must be taken into account in considering practical mine and UXO clearance devices. August 1999 (photo J. Trevelyan)

fragments close to the ground surface and then to carefully check each metal fragment to see if it is associated with a mine or explosive device. Any tripwires and vegetation have to be removed, with great care, before a metal detector can be used. In many areas deminers have to investigate hundreds or thousands of metal fragments for every mine found. Manual mine clearance also requires careful organization and marking of the ground to ensure safety and thorough clearance. Currently it is still the method that guarantees the lowest risk of residual mine contamination but it is expensive, typically costing US\$1–\$5 /m^2.

Armored mine clearance machines using hammers mounted on the end of rapidly spinning chains (flails) first appeared in the 1940s but have not been able to neutralize mines with sufficient reliability for most humanitarian applications [48.6].

In the late 1990s commercial mine clearance organizations operating in thick vegetation in Bosnia Herzegovina and Croatia realized that flails spinning just above the ground could rapidly remove vegetation and trip wires to prepare the ground for manual clearance, often assisted by mine detection dogs. Clearance costs have been reduced by up to 80% (particularly in thick vegetation) using different combinations of machines, detection dogs, and manual clearance.

Ground milling machines use metal drums studded with hard cutters that shred buried objects. They require more power than flails but can operate with greater levels of reliability. Both flails and ground milling machines have been extensively used in Croatia to recover large areas of formerly productive agricultural land. Both kinds of machines can withstand a limited number of AT and moderate-size UXO explosions before main bearings and other components need to be replaced.

Naturally, machines operate best on flat or gently sloping ground, which is also the land that is most valu-

Fig. 48.5 Flail machine using hammers on the ends of spinning chains to clear vegetation and tripwires. This machine will also detonate a proportion of buried mines (*inset*) (photos Scanjack AB, Sweden)

able for agriculture and human habitation. Thick forest and mountainous terrain still requires traditional manual clearance and in most countries will not be cleared of mines for a long time, if ever.

Mechanized clearance methods continue to evolve with improvements to machines and techniques. Machines can be used for survey, risk assessment, and risk reduction tasks to help determine the need for more expensive manual clearance methods. Mine action programs are gradually shifting from an emphasis on total clearance in the 1990s to one of progressive prioritized risk reduction involving a series of measures including high-security fences, mechanized survey and risk reduction methods, and selective manual clearance ([48.5], part 4). Protective measures applied to agricultural machinery offer cheaper alternatives in low-AT-risk areas [48.7].

Evolution of Demining Research Priorities

Technological development in landmine clearance from within the demining community has mainly been driven by the search for improved productivity. Many of the comments in this section are based on numerous discussions with experienced demining personnel who have tried new technologies in the field. References have been cited where further detailed written information is available.

In the mid-1990s there was the expectation that, with sufficient research, advanced technology detectors could replace eddy-current metal detector technology that had been in use since the 1940s. Metal detectors also react to metal fragments in the ground. A detector that could confirm the presence of explosive, it was thought, would save having to investigate all these false alarms. The most promising line of research seemed to be data fusion: combining signals from a metal detector, ground-penetrating radar, infrared detectors, thermal neutron detectors, and even acoustic detectors. Astute observers at research conferences have pointed out that these signals were often well correlated, even in the presence of false alarms: producing a reliable detector was going to be hard work. Their forecasts turned out to be very accurate. Only one such detector is currently in operation: the handheld standoff mine detection system (HSTAMIDS) detector used by US military forces in Afghanistan employs a combination of ground-penetrating radar and eddy-current metal detection. Little information on its effectiveness has been released and no independent trials have been reported. Experienced research groups report that ground-penetrating radar requires accurate alignment of the detector with the ground surface (to eliminate ground surface returns) and also with the target center point to enable the target to be characterized reliably. If the principal metal component of the landmine coincides with its geometric center, a common feature of minimum metal mines, the metal detector can be used for alignment. However this is not always the case and one cannot guarantee the absence of other metal fragments near the mine. Ground-penetrating radar provides confusing returns in very dry or very wet conditions and is also susceptible to false alarm indications from underground discontinuities such as stones, sticks, animal burrows etc. Publishers mostly downplay these difficulties and prefer only to report positive results, not false negatives. These issues only emerge from discussions with developers who have seriously evaluated technology in field conditions.

The major performance improvements in sensing have been obtained by compensating eddy-current metal detectors for soil magnetization, enabling them to work in a much wider range of soil conditions. Improvements in sensitivity can help with minimum metal mines but can also result in a large number of false alarms from smaller metal fragments. Metal detector arrays have been fitted to vehicles to speed up clearance of paved areas and roads [48.8].

By the late 1990s slow progress with sensors had become more apparent and research priorities after 2000 gradually turned to mine detection dogs and large demining machines.

The Afghanistan Mine Action Center (MACA) started using mine detection dogs around 1993 but it was not until 1998 that this program was running effectively. There were several difficulties. The first challenge was that close association between humans and dogs was socially unacceptable in Afghanistan. The second challenge was to devise ways to use dogs and manual mine clearance in an effective combination providing reliable clearance with high productivity. This was much the greater challenge, but by 1998 the cost of clearance using dogs was around one-third the cost of manual clearance. It was then that the problems started to appear: the occasional missed mine that could not be explained by lack of organization or failure to follow procedures. At the same time, carefully controlled trials of mine detection dogs in Bosnia had returned highly variable results. On several occasions dogs had walked past blocks of trinitrotoluene (TNT) lying almost visible in the ground. Yet, at the same time, a number of commercial demining agencies were routinely declaring land free of mines using similar dogs. In late 1999 the Bosnian Mine Action Center ran a carefully controlled test in which around 80% of the dogs failed to achieve the required performance standard. The results were hotly contested at the time and the international community organized a systematic trial of mine detection dogs through the Geneva International Center for Humanitarian Demining (GICHD).

By 2001 it was apparent that there had been little scientific research on the fundamental physiological mechanisms that enable dogs to locate sources of explosive vapor. Dogs had been able to find mines using explosives (such as high melting point explosives (HMX)) with vapor pressure far below measurable detection thresholds. The mechanism by which TNT vapor and its breakdown products reach the ground surface was the subject of considerable scientific debate. By 2003 a systematic trial in Afghanistan, scientific studies at SANDIA Laboratories in the USA and in Scandinavia, explosive trace detection studies with dogs at Auburn University, and several other investigations provided some insight into this problem for the first time [48.9]. However, the precise physiological mechanisms for canine explosive detection remain unclear, especially for lower-vapor-pressure explosives. We do not know for sure whether dogs are reacting to vapor, minute particles of explosive suspended in the air, biochemical breakdown products, or a combination.

In 2003 a US company, NOMADICS, demonstrated the FIDO detector, the first that could reliably measure the presence of TNT vapor with greater sensitivity than a highly trained dog. However field trials showed that TNT vapor could be detected everywhere in a mine contaminated area. An explosive vapor sensor was just the beginning of the story and warns of a complex task ahead.

By 2004 the international community realized that the early confidence in a breakthrough resulting from advanced sensor technology, demining machinery, and mine detection dogs had been misplaced. GICHD commissioned the first serious study of manual demining to see whether productivity improvements could be made. A systematic series of trials were conducted in Africa to determine the effectiveness of several innovations such as magnets and rakes. The final report, issued in 2005, revealed that greatly improved productivity was possible but would depend more on improving contracting arrangements, management, and training than technology.

The New York attacks in September 2001 have fundamentally changed research priorities. Removing unexploded ordnance, particularly cluster bombs, became the top priority for the next 12 months in Afghanistan (Fig. 48.6). Since then the deteriorating security and political situation in Afghanistan has focused mine clearance agencies more on maintaining security for their own workforce than trying to improve productivity and safety.

Fig. 48.6 Unexploded BLU-97 cluster bombs in Afghanistan early in 2002. Two of the small yellow canisters with parachutes still attached lie visible in the foreground. Others lie in the houses in the distance. Some may lie up to 40 cm below the ground surface. Some can detonate when a metal detector or mobile phone is used nearby. These devices have a kill radius of 200 m and can sometimes be set off by a strong gust of wind. They readily attract the curiosity of children (photo G. Zahachewsky and N. Spencer)

Resistance to the US and international occupation of Iraq and the easy availability of explosives both from former Iraqi armed forces and unexploded ordnance from US military operations led to the proliferation of improvised explosive devices (IEDs) to attack organized military forces and police. These have now become the main threat and the focus for much of the funding, and operational and research expertise formerly available to support mine clearance operations. This development has also placed ordnance disposal teams at the front line for the first time, rather than working in well-protected secure areas. Iraqi insurgent groups attack ordnance disposal teams both because they are attempting to disarm some of the insurgents' most effective weapons and also because they remove the main sources of explosives available to insurgent groups.

Improvised explosive devices, when detected, are often investigated and neutralized using remotely operated robots. While there are nondestructive methods to neutralize IEDs, the fastest method usually involves placing a small demolition charge on the device. Operational details remain confidential to reduce the risk that IEDs will be modified to defeat current neutralization methods.

Paradoxically it is this development that has enabled robotics to make a greater contribution to


Fig. 48.7 Bozena teleoperated demining vehicle (Way Industry, Slovakia)

the problem by contributing improvements in remote manipulation technology. These improvements come more in the form of low-cost commercial off-the-shelf components (mobile platform, motors, TV cameras etc.) than from fundamental research advances. Improvements are still being made: improved remote manipulation, blast survivability, operator interface improvements, and mobility improvements have all contributed significantly to performance and reduced operating costs.

Advances in Demining Robotics Research

In a brief survey it is not possible to mention every contribution. We have attempted to provide a sample of research reports that illustrate the main achievements and we present brief technical discussions on mobility and manipulation dexterity.

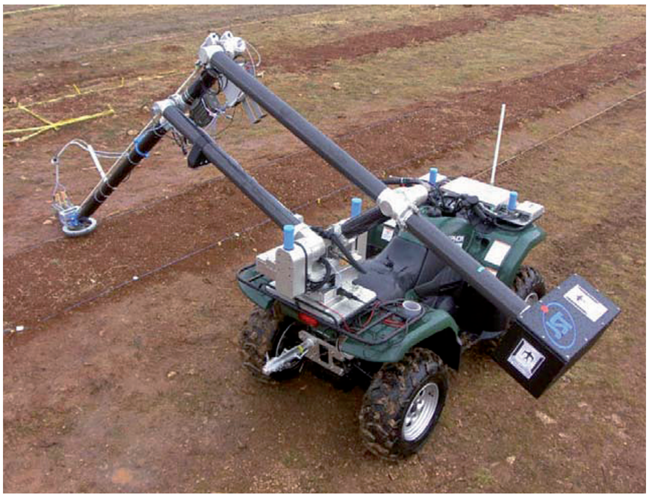
Fig. 48.8 Gryphon experimental robot on trial in Croatia (Photo S. Hirose) [48.10]

Teleoperation remains the only robotics technology that has been used in practical application in field conditions [48.11, 12]. Robotics research has not yet been able to make a significant contribution to mine and unexploded clearance work. However, the problems posed by landmine clearance have stimulated new research results that could have other applications.

Robotics researchers started their efforts in the early 1990s, for example, Stephan Havlik and *James Trevelyan* independently proposed suspended cable robots to work in minefields [48.13]. However, both have later argued in favor of alternative solutions [48.11, 14].

Nicoud [48.15] wrote one of the first surveys exploring the possibility of using robotics technology for landmine clearance. Developments in robotics research since the mid 1990s have been motivated both by a genuine desire to help combat a serious humanitarian issue and also by a desire to find a justification for more fundamental research. However, most researchers still have not learned lessons from the field such as the need to remove vegetation and the variety of situations in which deminers find themselves [48.16].

One of the most prolific research areas justified in part by humanitarian demining problems has been path planning for autonomous agents [48.17]. Probabilistic approaches were explored by [48.18]. Some researchers have proposed multiple robot solutions, even *swarms* of robots [48.19] and so-called *immune systems* [48.20]. Autonomous search and mapping algorithms have also been explored [48.21], including even three-dimensional search techniques for locating underground chemical sources [48.22].

Landmine clearance has also stimulated developments in autonomous robot vehicles, with many examples in the literature [48.23]. Tracked vehicles have been proposed for working in rubble and built environments [48.24]. Walking vehicles have been proposed, particularly for difficult terrain in countries like Bosnia and Afghanistan [48.25] even to the extent of examining how damaged robots with missing legs could extricate themselves from a mined area [48.26].

The desire to keep human operators away from the risk of handling unexploded ordnance has stimulated research on artificial hands and telemanipulation [48.27]. Purely mechanical devices have also been explored [48.28]. Several researchers have provided detailed results of tests with manipulators mounted on autonomous vehicles [48.10].

Robotics solutions have also been proposed partly to overcome the limitations of handheld sensors such as ground-penetrating radar. A robot manipulator can control the motion of the sensor so much more precisely, opening the possibility of synthetic aperture techniques for both metal detection and radar [48.29].

Military research agencies in the United States, Australia, Britain, and Canada devoted large research budgets to the problem of road clearance after military casualties in Somalia and Bosnia. Insurgent forces had demonstrated that they could bring organized military forces to a complete standstill overnight simply by laying antivehicle mines in a few road potholes. With most roads in poor condition there was no easy way to detect that the mines had been laid. Insurgents would typically use mines to stop leading vehicles in a convoy in order to increase the effectiveness of an ambush.

Most research teams proposed one or more vehicles carrying multiple sensors including ground-penetrating radar, metal detector arrays, passive and active infrared, and even some acoustic arrays. Some sensor arrangements were designed to look forward sufficiently far to allow the carrier vehicle to stop before reaching a mine. Others were to be carried by lightweight remotely controlled lead vehicles. Military planners calculated that search speeds of approximately 30 km per hour would be required to be able to check roads daily in time for supply convoys to use the roads in daylight hours. Many different arrangements have been reported [48.30]. Other teams proposed teleoperated devices for landmine and explosive ordnance detection and neutralization but few anticipated the requirement to operate under armed attack. Typical requirements envisaged secure rear area mine clearance in combat situations and peace-keeping on roads and tracks [48.31] or force protection roles [48.32]. Most of these efforts were initiated in the late 1990s but by 2005 it had become apparent to military planners that vehicle protection rather than mine detection was a more practical solution. Much of today's vehicle protection technology originated in southern Africa with further development in Australia, the UK, and other countries, stimulated in part by South African expatriates.

One way to reduce the distance between researchers and field problems, at least in terms of geographic distance, has been to promote research in landmine-affected countries such as Sri Lanka and Colombia [48.33]. However this is not easy. Most countries affected by landmines have been disrupted by social conflict and destabilization that led to the military conflicts in which landmines were used. This makes it difficult for local people to create sufficient economic and physical security for researchers to pursue their work.

Future Prospects For Robotic Demining

What are the challenges for robotics researchers working on landmine clearance and other hazardous applications in the future?

We need further advances in mechatronics design, sensing, and accurate understanding of the problems to be solved using robots.

The best starting point for research is to witness people undertaking hazardous work in several different situations. Nuclear accidents, mine disasters, and burning buildings are usually off-limits to researchers. However, mine clearance operations are readily accessible in many countries. It is unfortunate that many researchers think a visit would be far too hazardous and, as a direct result, have failed to appreciate the practical difficulties involved. Photographs taken at mine clearance operations are available to provide researchers with a web site for reference purposes, partly in answer to this need to understand the practical realities [48.34].

One of the main motivations for robotics researchers has been the perception that mine clearance is a hazardous occupation and that it would be more preferable for robots to be exposed to minefield risks than human beings [48.35]. While mine clearance is certainly a hazardous occupation it is not necessarily dangerous. Accident records show that mine clearance in Afghanistan in 1998 resulted in about half the rate of injury of the United States forestry industry and about one third the rate of injury for the United States building construction industry per 100 000 working hours. Mine clearance agencies use advanced techniques to improve safety when possible [48.36]. In terms of deaths, demining is considerably less hazardous than mining, construction of building foundations, and especially offshore drilling rigs ([48.37], pp. 11–14).

Another motivation for research is to reduce deaths and injuries among local people who have to live with the daily threat of landmines and unexploded ordnance. Again, there are misperceptions of risk. The incidence of death and injury from mine explosions is often very small compared with disease, for example. The main priorities for local people tend to be improvements for water and food supplies, education, sanitation and physical security: landmine clearance is usually a much lower priority and it is often hard to justify significant local resources.

It is also important that robotics researchers intending to contribute to the solution of this problem understand the relatively small size of humanitarian demining operations, which have been funded from a combined international humanitarian aid budget of approximately US$400 million. These programs spend an estimated $20 million annually on all equipment needs. The market for specialized humanitarian demining detectors is therefore very small and manufacturers cannot afford research and development specifically to support humanitarian demining solutions [48.38]. Adapting technology developed for other purposes, such as military equipment or civil engineering construction machinery, is more likely to be feasible.

The last 10 years has seen significant improvement in mine clearance techniques but progress is still slow and robotics may well provide the final solution in the long term. There is plenty of time to develop robotic techniques that could ultimately provide the only cost-effective method for removing this menace.

48.2.2 Hazardous Materials Handling and Operations

The oldest application of robotics-related technology to hazardous environments is various aspects of remote nuclear operations dating back to the beginning of serious work on atomic physics in the early 1940s. This section discusses hazardous materials and operations in the context of nuclear applications and some extrapolations to other domains. These applications run the spectrum from low- to high-fidelity manipulation and multiple mobility modes.

Many variations of remote handling systems have been in use since man has attempted to cope with hazardous environments. In the 1940s, research in atomic physics led to a new era in remote handling as scientists sought to explore the nature of materials involving ionizing radiation. As experiments became more complex, mechanical manipulator systems were created which allowed operators to perform increasingly complex tasks safely behind thick biological shielding. These mechanical systems then evolved into electrical systems that allowed larger work volumes to be considered. Incredible engineering achievement occurred in a 15 year period within the Remote Control Division of the Argonne National Laboratory. Even though this era represented tremendous technical achievement, it went further in illustrating the intrinsic complexity of remote operations. The equivalent work performance achieved with sophisticated teleoperated remote systems is poor in comparison to what human workers can achieve with direct contact operations and common tools. Typically, this form of teleoperation (i. e., manual control over a physical distance or barrier) is ten to hundreds of times slower than conventional contact operations. Remote operations are extremely expensive and time consuming and have been the continual target of engineering improvements over the years.

Many research and development efforts have focused on different avenues for improving the work efficiency of teleoperated remote operations. These efforts have included the development of better manipulators, control stations, control algorithms, etc., all intended to enhance reliability and maintainability. In the late 1960s and early 1970s, as digital electronics became more cost effective, interest began to emerge in the integration of automation with teleoperation as a scheme to effectively increase remote operations work efficiency. It was around this time that industrial robot concepts were also introduced. Combining selective automation of specific subtasks with traditional teleoperation offers the potential to reduce labor requirements and to improve the quality of repetitive task executions. This integration of automation with teleoperation became the foundation of what is now termed *telerobotics*. From the 1970s until today, telerobotics has been an active area of research and development in many different domains that include nuclear, space, and military applications. Unlike manufacturing automation, remote operations in hazardous and unstructured work task environments necessitate human-in-the-loop control, or teleoperation, as a backstop to assure safe operations. Teleoperation related to hazardous materials and operations, in the most general sense, involve mobility and the use of manipulators to handle objects and tools to accomplish useful work in predominantly unstructured and uncertain environments.

Over the years, there have been numerous papers, books, and reports written concerning technical challenges, issues, and solutions. Readers will find *Vertut* [48.39] and *Slutski* [48.40] provide comprehensive and general information about manipulators and systems. The performance and design of effective teleoperated systems are strong functions of human factors and *Kraiss* [48.41] and *Johnsen* and *Corliss* [48.42] provide good discussions of key principles. Finally, control system hierarchies and structures are explained in depth by *Sheridan* [48.43].

Past Perspectives

Initially, science and experiments involving dangerous radiation levels were accomplished through the innovative use of shielding walls, long-handled tools, and mirrors. As the tasks became more difficult, mechanical arms that could do a better job in emulating human motions were pursued. These ideas represented schemes whereby human sensing and handling capabilities could be more completely *projected* into the remote work environment [48.44]. One of the first challenges that the Argonne group tackled was the development of the mechanical master–slave manipulator. The basic concept was to create a mechanism that would have a master controller side where an operator could provide position and orientation commands to a slave-side mechanism/linkage system that would *replicate* motions and forces in the remote work area. It was felt that force reflection to and from the master and slave systems was essential for the operator's sensory awareness of the task execution. Experimentation has repeatedly verified the significance of both kinesthetic and tactile feedback in performing more complicated tasks [48.45].

Today, master–slave manipulator (MSMs) are used around the world in nuclear, biological, and other types of hazardous remote experimentation and operations. The remote work efficiency of a dual-arm MSM with shielded-window viewing is around 5–10 times slower than equivalent contact operations. Because the master and slave sections of MSM's are mechanically coupled through the metal-tape drive transmission, the physical separation that can exist between the safe operating area and the hazardous remote work area is limited to a maximum of approximately 10 m. Because of this characteristic and their kinematics, MSMs are restrictive in many applications and often have constrained the physical design of remote cells. The Argonne group and others recognized that it would be much better to have the equivalent of a fly-by-wire MSM in which the physical separation of the master and slave could be larger. This need led to the development of electrical master–slave manipulators (EMSs) that are commonly called electrical servomanipulators [48.46, 47]. Research and Development on the EMS began in the late 1940s and continued into the early 1950s.

The Argonne group was at that time limited by the available electrical control technology. Nonetheless, they made noteworthy progress toward integrated systems, as depicted in Fig. 48.9. The prototype system shown is a dual-arm anthropomorphic system with head-aiming remote television viewing and bilateral force reflection. After the Argonne Remote Control Division was disbanded, limited research and development occurred until the 1970s when commercial nuclear power growth was driving a number of research programs in the US, West Germany, France, and Japan. During this time, the programs in the US and France were focused on electrical servomanipulator systems which incorporated emerging microprocessor technology. The Central Research Laboratories model M2 system, shown in Fig. 48.10, was jointly developed with the Oak Ridge National Laboratory and was the first force reflecting servomanipulator system to use distributed digital

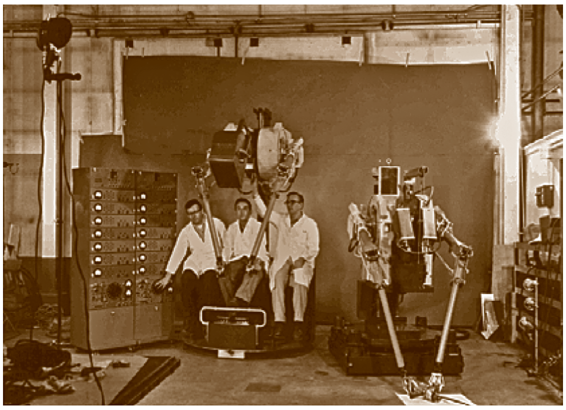
Fig. 48.9 An integrated electrical master–slave manipulator system (courtesy of Oak Ridge National Laboratory)

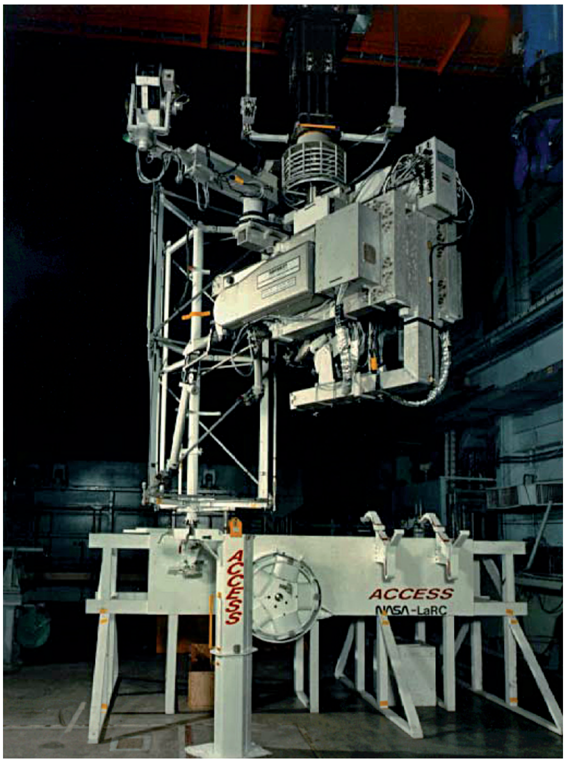

Fig. 48.10 CRL Model M2 manipulator system performing space truss assembly (courtesy of Oak Ridge National Laboratory)

Fig. 48.11 Advanced servomanipulator system (courtesy of Oak Ridge National Laboratory)

electronics to implement position–position force reflection with multiplexed serial communications between the master and slave. The model M2 system was used over the years to explore remote operations for military, space, and nuclear applications.

The development of the advanced servomanipulator (ASM) followed the M2 in an effort to improve the remote maintainability of the manipulators themselves. This work was one of the earliest modular robotics efforts. The motivation for this work was to reduce maintenance technician radiation exposure and to increase the overall availability of the remote maintenance system. The ASM was designed from the beginning to provide a foundation for telerobotics in addition to effective teleoperation [48.48] (Fig. 48.11).

At the time of the M2 and ASM developments, Jean Vertut and his colleagues in the Commission de Energie Atomique (CEA) focused their research on the development of telerobotic functionality for their MA-23 electrical servomanipulator systems. This research appears to include some of the earliest experimental demonstrations of telerobotic functions [48.39]. They called their concept computer-assisted teleoperation and it included both operator assists and robotic teach/playback functions. Operator assists included software jigs and fixtures designed for the improvement of the remote operation of tools such as saws, drills, etc.

In the 1980s and 1990s as nuclear power activities began to decline, nuclear remote operations technology was migrated into other areas such as space and the military. Nuclear remote operations experience with teleoperation influenced the Space Shuttle remote manipulator system and the short-lived Flight Telerobotic Servicer program.

In the mid 1990s, substantial interest developed in the application of remote handling systems to deal with problems in hazardous site/facility remediation, such as those associated with defunct nuclear facilities in the US and in Eastern Europe. The intrinsic complexity of remote clean up operations continues to drive research and development in all aspects of teleoperated and telerobotic systems. Challenges and accomplishments in this application area are discussed in the next section.

Hazardous Site Clean Up Applications

Robotic and remote systems have been used in assessing the status of sites contaminated with hazardous materials. These surveys are essential in planning and executing subsequent clean up operations. Such systems have been used most extensively in nuclear waste sites around the world because remote techniques are more common in many nuclear operations. There has been some use of robotic survey systems in chemical and biological hazard situations as well.

Survey Systems. Numerous robotic survey systems have been developed and used. The basic idea is to integrate a sensor suite, appropriate for the contaminants of interest, with a suitable mobile platform that incorporates remote and/or autonomous driving functions and requisite navigation and control functions. The desired output of the survey process is a *precise* map of contaminant locations and concentrations. Such systems have been developed for both outside and inside operations.

It was common practice in many industries for a number of decades to bury hazardous wastes in earthen trenches in isolated burial sites. Usually, useful records of what materials were buried at what locations either did not exist or were not accurate. In fact, the general conditions of such buried waste sites are often unknown to the extent that human entrance is not allowed. As a result, the first step toward remediation is to quantitatively

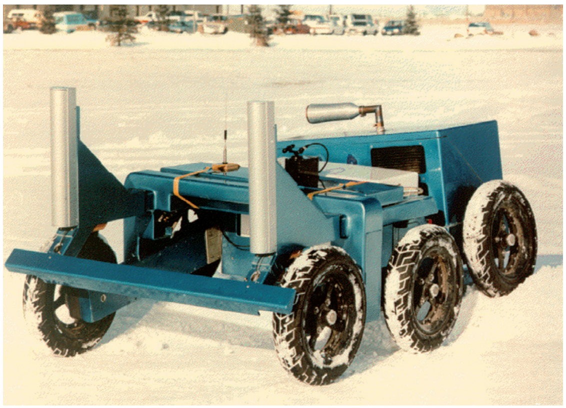

Fig. 48.12 Prototype buried waste survey robot (courtesy of Los Alamos National Laboratory)

Fig. 48.13 Mobile characterization system (courtesy of Oak Ridge National Laboratory)

assess the physical and hazard conditions of the site. The mobile robot shown in Fig. 48.12 is an example of a survey system used to evaluate nuclear waste buried waste sites. The robot's location is monitored with Global Positioning System (GPS). The suite of sensors includes eddy-current probes and ground-penetrating radar that reveal density contours, radiation detectors, and gas emissions monitors. This system was an initial prototype that could be operated from a remote driving station or operated in autonomous programmed trajectory mode. The system was controlled using a radio communication link. Its unique feature is that it was designed with minimal use of ferromagnetic materials to minimize interference with the magnetic subsurface sensors.

The mobile characterization system shown in Fig. 48.13 is a similar concept for radiation survey of floored areas. This particular system uses a Cybermotion commercial mobile platform, triangulation of optical fiducial markers for localization, and operates primarily in a full autonomous mode. The objective in this application is to reduce labor costs and eliminate error-prone tedious human operations.

Excavation Systems. The actual remediation of buried wastes ultimately leads to digging and object-handling type operations. Various types of systems involving integrated mobility and manipulation-like functions have been developed. One of the most popular and low-cost approaches has been to retrofit conventional excavation equipment with sensor and actuators that allow remote and robotics operations. Such systems have been used in explosive ordnance disposal also. The system shown in Fig. 48.14 is called the teleoperated small emplacement excavator (TSEE) and is a prototype remotely operable backhoe for such applications. The unit included a multicamera remote viewing system that is the primary basis for teleoperation. Radio and tether communica-

Fig. 48.14 Remotely operated excavator (courtesy of Oak Ridge National Laboratory)

tions connections are used to allow the human operators to be displaced up to several miles from the hazardous operations.

Deactivation and Decommissioning Systems. In recent years, one of the most complex forms of hazardous operations is the deactivation and decommissioning (D&D) of defunct facilities where nuclear radiation or toxicity hazards preclude human presence. D&D can be thought of as remote demolition for the most part. Some operations are crude such as knocking down building structures and debris removal. Other operations may involve careful disassembly of equipment and devices, size reduction and packaging of handling/storage. These operations are essentially the inverse of remote maintenance and require the dexterous use of tools and handling of objects. Tools include saws, hydraulic shears, impact wrenches, and the like. Planning and situational awareness are very important in demolition-type operations because the physical layout and stability of the basic environment is changing during the process. Effective remote viewing (adjustable multiview capabilities) and acoustic sensing are essential. Audio feedback from the remote environment provides the human operator with the ability to monitor the normalcy of tooling operations such as sawing. D&D applications require manipulators that are both dexterous and massive. Experience has shown that payload capacities on the order of 100 kg are needed to deal with debris handling, typically with manipulators of the type shown in Fig. 48.15. Figure 48.16 is a frame view from one of the remote viewing cameras used to operate a similar system that was used to D&D an old experimental nuclear reactor. A manipulator is being used to teleoperate a conventional circular saw to segment a large-diameter aluminum tank. This operator view of the remote environment provides a realistic perception of the task environment lighting conditions and complexity.

In recent years, numerous remote manipulation systems for nuclear applications have been developed around industrial robots. These systems are augmented with sensors and master controller arrangements to facilitate teleoperation. This approach offers significant cost savings and the level of teleoperation performance achievable in complex task environments has steadily increased [48.49–53].

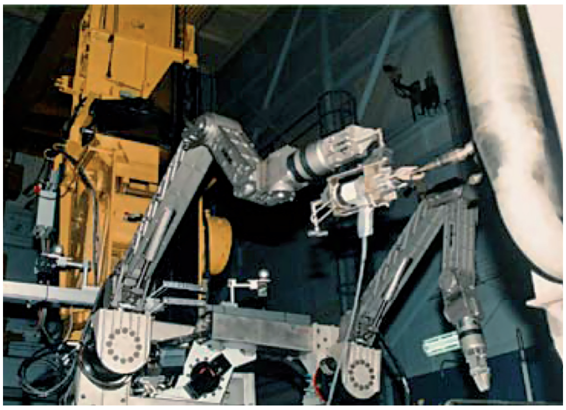

Fig. 48.15 Dual-arm D&D manipulator system (courtesy of Oak Ridge National Laboratory)

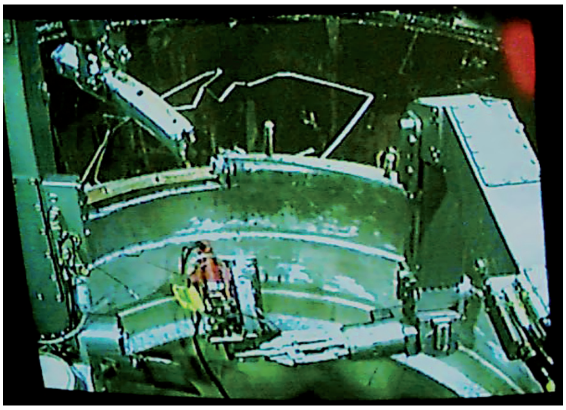

Fig. 48.16 Operator's view of a remote sawing task (courtesy of Oak Ridge National Laboratory)

48.3 Enabling Technologies

There are a number of technology issues that are key to the design and implementation of mobile robots that can operate effectively in different types of hazardous environments. A few of them are touched upon here to give the reader additional insight into the foundational aspects of this class of robots.

48.3.1 Mobility Issues

Hazardous application such as fire fighting, EOD, and demining naturally include uneven ground in indoor and outdoor environments where a normal wheel-type robot cannot easily operate. It is critical to have a mobile mechanism with a good negotiability in uneven ground conditions. Most mobile mechanisms are classified into wheel type [48.54–57], track type [48.58–63], and leg type [48.64]. For negotiability in uneven ground, the wheel and track types need additional linkages with ground adaptation. There are two kinds of this adaptation: active and passive adaptation. Active adaptation uses an additional actuator to alter the linkage's motion while in passive ones the linkage motion is controlled by the ground conditions and gravity effects.

Stability Conditions

Stability should be considered in the design process to prevent rollover on uneven ground including stairways, steps, and natural terrain. Stability can be investigated in terms of three parameters: *center of mass, supporting area, and stability margin*. Stability requires that the center of mass remains inside of the supporting area, as shown in Fig. 48.17. The supporting area is a polygon built by the edges connecting each projection point on the horizontal plane. A conventional vehicle has limitations in rugged terrain due to a fixed center of mass with respect to the body coordinates. The center of mass greatly affects the stability margin (the minimum length between the center of mass and edges of a supporting area). If the center of mass is located out of the supporting area, rollover occurs. The stability margin of a conventional vehicle is mainly determined by the inclination of landform. Many vehicles are designed to have a low center of mass, thereby obtaining a large stability margin on a slope. Furthermore, a vehicle is often designed to have multiple bodies to overcome this limitation. For a multiple-link mechanism, the center of mass varies and the relative motion of links when traveling over the landform also alters the supporting area.

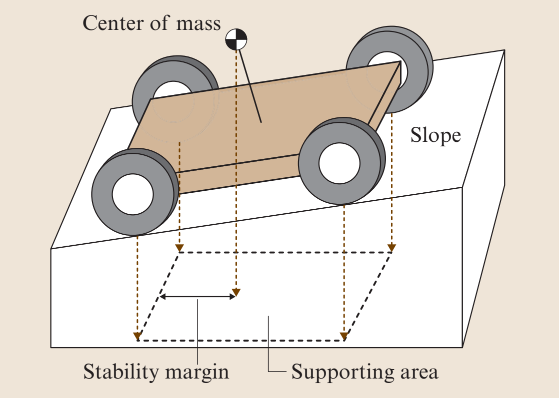

Fig. 48.17 Stability condition

Active Adaptation Mechanisms

An active adaptation mechanism uses an additional actuator to generate motion of the adaptation linkage on rugged ground. Although additional actuators and linkages are required, the adaptation mechanism can overcome variously shaped rugged landforms.

It is known that a vehicle can negotiate an obstacle which is smaller than radius of a wheel. One may think that a vehicle which has large wheels can pass over rough terrain like a monster truck. However, most applications require a small vehicle to drive between obstacles.

A deformable wheel or its equivalent mechanism can be adopted: insufficiently inflated wheels, as shown in Fig. 48.18a, adapt to irregular terrain by deformation of wheels. However, their size should be big enough to negotiate rough terrain, so this concept still has size limitations. Their equivalent mechanisms are relatively compact and yet they need sophisticated articulation mechanisms, as shown in Fig. 48.18b. Two wheels are attached to a link that rotates about a main body. Therefore, revolution and rotation of wheels are made as shown in Fig. 48.18b. If rotation is provided by actuators at the main body (i. e., an active mechanism), the vehicle has an equivalent wheel whose radius is equal to that of the rotation. The vehicle in Fig. 48.18b can pass a sill via carriage rotation, although the radius of a wheel is smaller than the height of the sill.

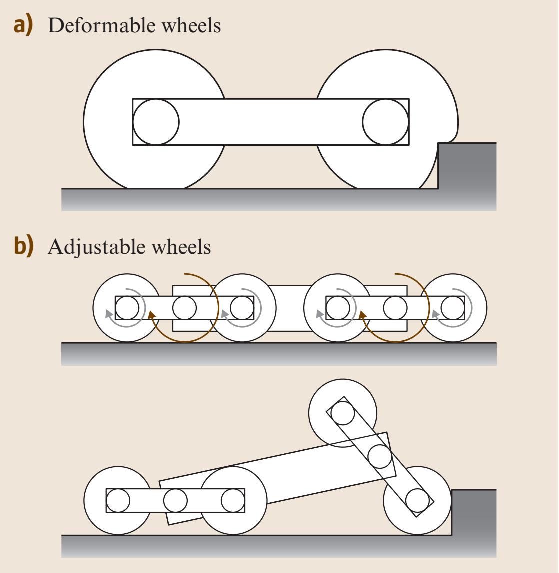

Fig. 48.18a,b Wheel configurations **(a)** deformable wheels, **(b)** adjustable wheels

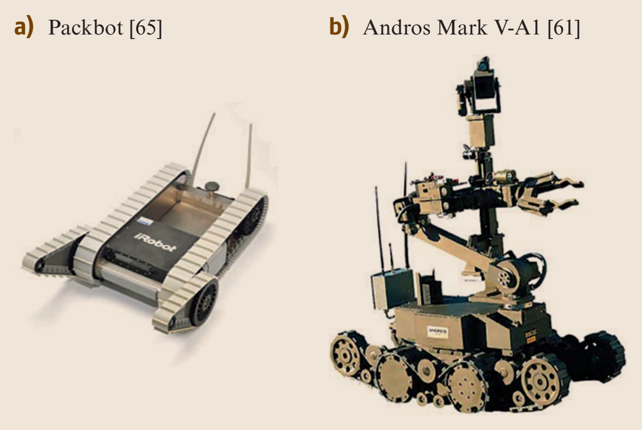
a) Packbot [65] **b)** Andros Mark V-A1 [61]

Fig. 48.19a,b Mobile robots with active adaptation mechanisms **(a)** Packbot [48.65], **(b)** Andros Mark V-A1 [48.61]

a) Deformable wheels

b) Adjustable wheels

Fig. 48.20a,b Mobile platforms with passive adaptation:**(a)** Soleo-Shrimp [48.57] and **(b)** Robhaz-dt3

Many track-type mechanisms have multiple linkage structures with active adaptation [48.60–63, 65]. When traveling over uneven ground, these mechanisms can negotiate rugged ground by changing the configuration of multiple track mechanisms, for example, typical multiple-tracked robots with active adaptation such as *Andros* [48.61] and *Packbot* [48.65], as shown in Fig. 48.19a and b, commonly uses a small active additional track called a flipper. By using the flipper when spinning on the ground the robot reduces undesired friction torque between the ground and the track by lifting up the flippers. When climbing up stairs, touching the flippers down to the ground can increase the stability by enlarging the supporting area. Snake-like robots use active interconnecting joints [48.62] and have the potential for mobility and manipulation.

Passive Mechanisms

Passive adaptation mechanisms do not use any additional actuators; rather they simply utilize the gravity effect to generate adaptation to irregular ground. This approach is less adaptive but enables the operator to drive the robot easily because he (or she) does not have to take care of controlling the adaptation mechanism. Passive mechanisms usually include various kinds of passive linkages activated by irregular ground conditions.

For the wheeled vehicle shown in Fig. 48.18b, a passive mechanism can be designed in which no additional actuators are needed, for example, when a wheel meets a sill whose height is greater than the radius of a wheel, it will become stuck. Then high torque is exerted at the wheel since the stall torque is usually greater than the normal rotation torque of the wheel. In this case, a closed linkage without any actuator except the driving wheels can generate a passive motion to climb over the sill [48.55], for example, a smart mobile robot with passive adaptation called Soleo-Shrimp (depicted in Fig. 48.20a) can climb up an obstacle by lowering the instant center of rotation of the passive four-bar linkage when coming into contact with the vertical surface of the obstacle [48.57].

Similarly, multiple bodies with tracked and chained passive joints can also adapt to irregular landforms. The track type is inherently insensitive to the unevenness of ground. Thus passively chained multiple-tracked bodies can provide greater reliability and better capabilities in ground adaptation. For example, a mobile robot with a passively chained double-tracked mechanism called Robhaz (shown in Fig. 48.20b) is a practical design with

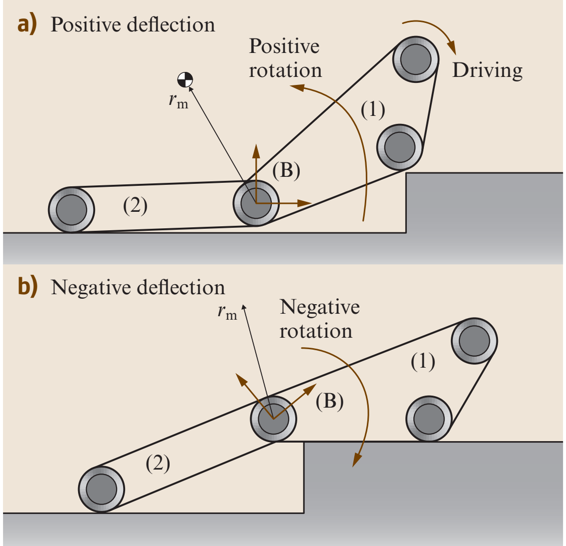

Fig. 48.21a,b Passive adaptation of double-tracked mechanism: **(a)** positive deflection and **(b)** negative deflection

simply adapted multiple tracked bodies with passive joints [48.63]. As depicted in Fig. 48.20, two tracks of the Robhaz rotate positively or and negatively according to the contact situation between the track and the stair surface. Based on this behavior, in terms of the lower center of mass (Fig. 48.21a) and the supporting area (Fig. 48.21b) better stability in stair climbing than that of a single-tracked vehicle can be achieved.

48.3.2 Manipulator Design and Control for Hazardous Object Handling

Manipulation is essential for EOD missions. Generally, EOD missions have two phases: (1) approach, and (2) object manipulation to achieve ordnance neutralization. The second phase is generally controlled by teleoperation. Both the human's careful control and innate intelligence, plus appropriate manipulator design and control, are needed for such dangerous tasks.

Design Requirements

Unlike industrial manipulators, the design of manipulators for many robots in hazardous environments does not require very fast movement. Instead, high payload, lightweight, and compactness are more important. Therefore, many manipulator designers locate actuators and reducers, which typically have high weight and large volume, on the base or lower links. This reduces the weight of the moving parts of the manipulator and offers better stability and dynamic control properties. Consequently, they have a thin profile, as shown in Fig. 48.22a,b. This characteristic is usually associated with explosive ordnance disposal-type robots that require access to congested areas and normal human living spaces. Mobile robots used in other hazardous environments can be much larger, depending on the specific applications. Refer to Sect. 51.2.2 for examples.

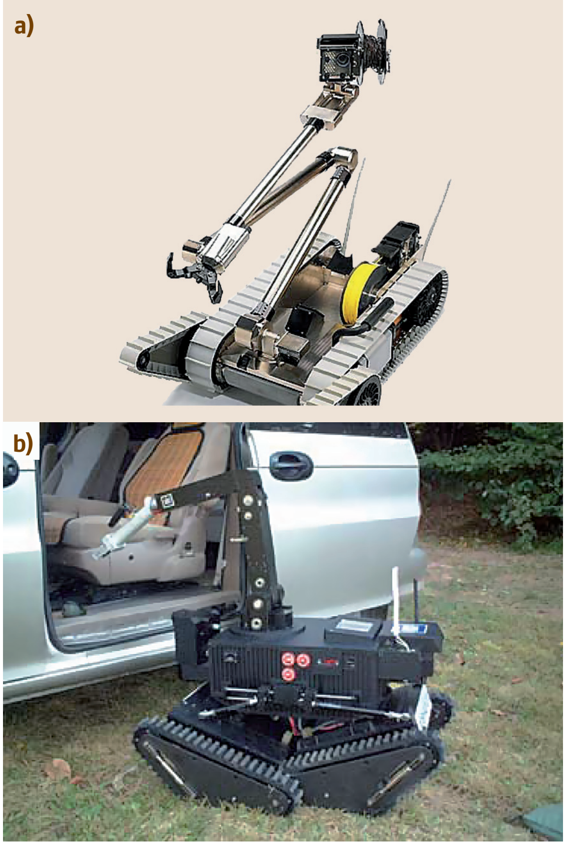

Fig. 48.22a,b Hazardous application robots with manipulator: **(a)** Packbot with manipulator and **(b)** Robhaz-dt2 with manipulator

48.3.3 Control for Hazardous Tasks

In most cases, the operator does not have much information about the environment around the robot and the manipulator. He may have very limited vision, and unexpected collisions between the manipulator and obstacles can easily happen, even if he (or she) tries to be very careful. The robot should be able to handle these risks by appropriate design of the manipulator and good control algorithms. There are several ways to solve these problems.

Proximity sensors that detect objects around the robot and/or mounted on the manipulator can be used to avoid a collision before it occurs [48.66]. However using many proximity sensors necessitates large wiring bundles and complex manipulator design. Force control is also a good way to handle collisions. When a collision occurs, the manipulator can move away from the collision point by using force/torque sensor data. Often a six-axis force sensor attached at the end-effector of the manipulator is used for the force control [48.67]. Many researchers have developed stiffness/compliance/impedance control methods for a manipulator with a force sensor. However, this method can only handle a limited collision zone – only the end-effector or the manipulator *hand* – because the sensor cannot sense contact with intermediate links, while a collision could occur at any point on the manipulator. For this reason, some manipulators use joint torque sensors at all of their joints [48.68]. When using a joint torque sensor, contact at any point on the manipulator can be sensed, however, gravity compensation and errors in the transformation from the joints to the Cartesian space introduce further difficulties.

The stability of telerobotic systems, particularly when force feedback or reflection is involved, remains a critical issue. Systems involving significant data communication time delays are even more difficult. National Aeronautics and Space Administration (NASA) groups have studied stability and bandwidth issues numerous times over the years; one of the more recent studies is provided by *Uebel* et al. [48.69]. Energy methods have been applied to this problem, resulting in new ideas entitled *passivity* control that show promise for enhanced stability and performance [48.4, 70].

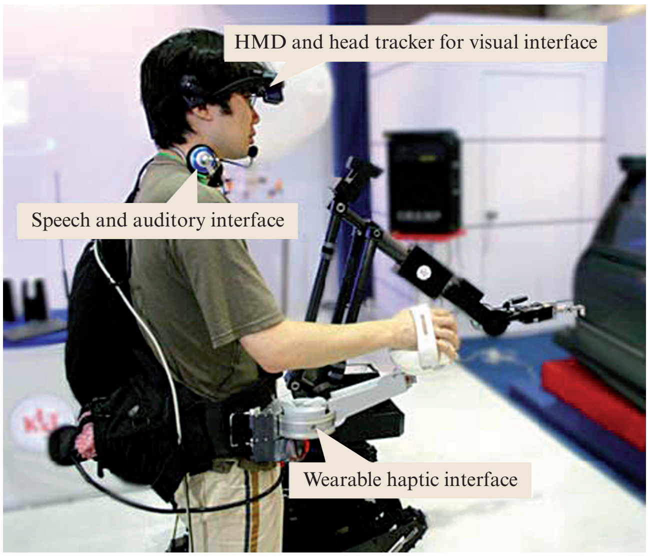

Fig. 48.23 Appearance of proposed wearable multimodal user interface

Master Controllers for Teleoperated Manipulation

In teleoperation, the robot is designed to be a faithful slave to deal with a dangerous task while the operator uses a control interface to direct the slave from a safe location. The user interface usually provides a means for

- sending position commands to the manipulator
- providing contact force feedback or force reflection to the user

Ideally, the design goal of a user interface is to make it *transparent*, so the operator feels as if he or she is directly manipulating the object handled by the slave manipulator. To achieve this transparency, there are several design issues

- Simplicity:
  - All indicators are unified as one scene.
  - All input button and joystick are integrated into one haptic device.
- Intuitiveness:
  - High-level command by speech recognition.
  - Human-friendly feedback such as graphical displays and human voice.
  - Motion command matching between the haptic device and the slave in Cartesian space.
- Portability:
  - Small/lightweight and human-friendly design for wearability
  - Tetherless operation without communication lines and additional power.

An example of wearable multimodal user interface is provided by [48.71], as shown in Fig. 48.23. The operator wears a head-mounted display (HMD), head tracker, and headset to interact with the slave. A six-degree-of-freedom haptic master is attached on his waist together with the standalone controller, and the operator grips its handle to telemanipulate in Cartesian space. All the control hardware including the batteries are packed into one backpack, so that the user can walk around to gain a better view during teleoperation. It includes radiofrequency (RF) and wireless local-area network (LAN) modules enabling completely wireless communication. It is composed of major three interfaces.

Speech and Auditory Interfaces

An operator usually sends two types of commands to the robot: selection and continuous motion commands. For example, the selection between mobile and manipulation mode, the reset of the robot arm and mobile base, the on/off and reset of pan–tilt motors, speed selection for the mobile platform, selection among installed cameras are defined in the selection commands. It is convenient if the operator can issue these commands by speaking to the controller. When the operator says a word that has been predefined as a command, the speech interface can sense that word and, if the speech recognition system successfully recognizes it, the recognized command pops up on the HMD for confirmation. Finally, the operator decides whether to execute or cancel the command with a confirmation button on the haptic master.

The auditory interface synthesizes the human voice using a speech synthesis engine. It can warn of the approach of an obstacle by sound, or reveal the distance and direction to a laser-designated object nearby.

Wearable Haptic Interfaces

A wearable haptic device is shown in Fig. 48.23. The base linkage is designed as a serial RRP mechanism to measure a translation, and an RRR z–y–z rotation mechanism is attached at the end of the base linkage.

Figure 48.24 shows a wearable haptic master device for teleoperation of mobility and manipulation systems. It has six degrees of freedom for motion input and three degrees of freedom for force feedback.

To achieve a compact design and reduce its weight, a tendon-driven mechanism is designed into each joint.

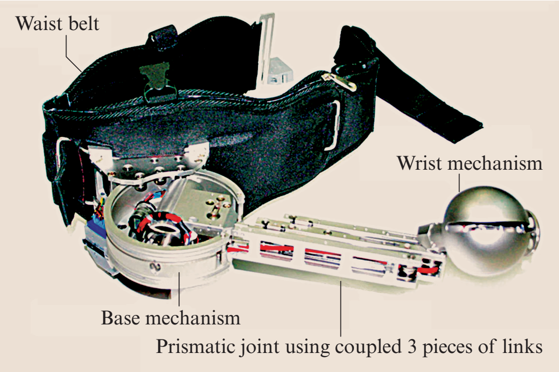

Fig. 48.24 Picture of wearable haptic device

Due to weight constraints, only three actuators are installed for force feedback, and each actuator is specially designed to fit the joint. Because a passive actuator is better than an active actuator with respect to power density (power per unit volume or weight), small magnetorheological (MR) brakes have been developed. They are installed at each joint of the base linkage for force feedback. Also a compact brake drive with current feedback capability has been designed, which reduces the response time of the MR brake. The controller is packed into a bag that is attached to the back side of the waist. Because it includes brake driver module, satellite controller, wireless LAN module, and battery, it can operate without cable connections.

Visual Interfaces

The visual interface integrates the robot's view, the status of sensed data, and the status of speech commands. Since the slave includes a stereoscopic camera, the user sees a three-dimensional view on the head-mounted display (HMD). The operator wears the head tracker and it generates a pan/tilt command from the two-degree-of-freedom head motion. In the integrated system, head tracker data is used to command the direction of the remote viewing camera, thus the user easily

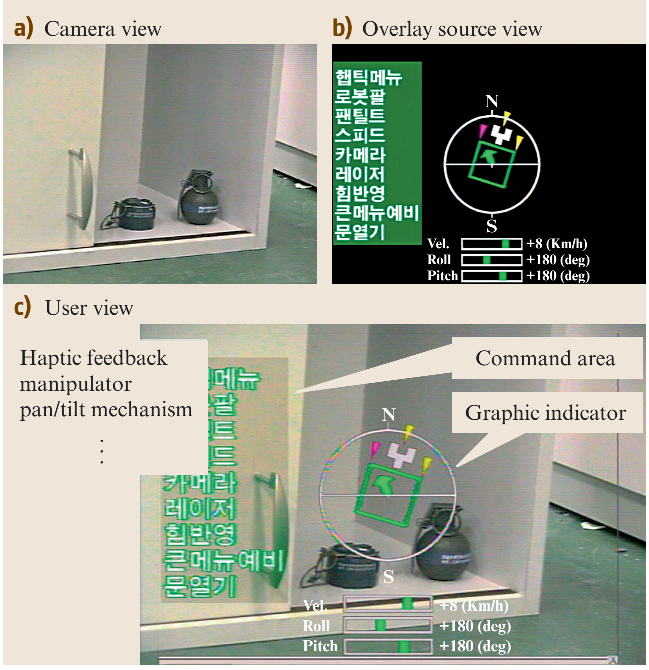

Fig. 48.25a–c Appearance of integrated visual interface: (**a**) camera view (**b**) overlay source view (**c**) user view

looks around the environment of the robot, as shown in Fig. 48.25.

Moreover, the head tracker is useful to indicate an object as a target. The operator moves his head and looks at a target to get information of direction and distance, then triggers a laser displacement sensor that is placed in parallel with the pan–tilt camera. The vision information is sent via a RF channel while the sensed data is fed back via an independent wireless LAN channel to reduce the data communication traffic. A source for video overlay is prepared with the reported data, as shown Fig. 48.25. The recognized speech command is highlighted on the left for confirmation. When an ultrasonic sensor detects an obstacle, it shows a round robot icon in the middle of the scene. Other useful and important information (i. e., velocity, heading direction, view direction, arm posture, etc.) are shown by bar graphs. These are overlaid on the remote video source pictures and unified into a single scene. Finally the operator sees the stereoscopic picture and the status of the robot at a glance on the immersive HMD. The overlaid view is shown in Fig. 48.25c.

48.3.4 Data Communications

Robots used in hazardous environments are almost always mobile so that they can move about an area of interest with flexibility. The combination of mobility and intrinsic operation across a physical or hazard barrier introduces unique problems with respect to bidirectional data communications (refer to Fig. 48.1). Communications from the operator location to the robot is necessary to achieve remote control or teleoperation. Communications from the robot to the operator are essential to connect the operator's perceptive skills into the remote environment. The transmission of the electrical and/or optical signals comprising such data communications can be quite complex due to a host of factors such as penetration of physical barriers, signal transport delays, signal attenuation, and data throughput requirements. As summarized in Table 48.1, data throughput requirements are dominated by the feedback of visual imagery or remote camera views from the mobile system. Channel capacity necessary for audio feedback and control are small in comparison. If the mobile system involves precision manipulation with force feedback, bidirectional data channels on the order of 1 Mb/s are required.

For a mobile robot with high-fidelity manipulation, multichannel remote viewing, and other sensors, on the order of hundreds of megabytes per second are required for the data communications path from the remote environment to the operator station while on the order of ten megabytes per second are needed for the bidirectional control link. Communications at these data rates are straightforward with the use of retrievable hardwired cabling or tethers. Tethered systems complicate mobility and reliability significantly. Tethers that combine signal and power conductors are difficult to pay out even with servo-controlled deployment/retrieval reels and are often snagged on obstacles such as debris. Free-space radio or microwave signal transmissions at these rates in the cluttered environments often associated with hazardous robots are much more difficult and require specially designed systems. Data throughput requirements can be reduced through data compression and reduced frame rate schemes with effective results in many cases.

Table 48.1 Example data communications requirements

Type	Single channel	Typical system
Standard black-and-white remote television: 600×400 pixels 30 frames/s 12 bit gray scale	≈ 10 Mb/s per viewing channel	30–50 Mb/s for 3–5 channels
Color remote television: red, blue, and green = 3× black and white	≈ 30 Mb/s per viewing channel	90–150 Mb/s for 3–5 channels
Control 12 bit resolution input and output 200 Hz sampling rate	≈ 4.8 kb/s per control channel	48 kb/s - ten control servo channels
Audio feedback 15 kHz signal capture 12 bits resolution	≈ 180 kb/s per audio channel	540 kb/s - three remote microphones

48.3.5 Energetics

Another key challenge in fielding mobile robots in hazardous environments is in the area of energetics including power supply, consumption, conversion, and management. The specifics of the given environment often restrict the types of power supply/conversion that are permissible, for example, the use of combustible fuels and internal combustion engines is seldom allowed within nuclear facilities but are entirely acceptable in demining and most outdoors operations. The most common power systems used today are electrochemical batteries and electric motor drives. The power and energy density map [48.72] given in Fig. 48.26 shows the fundamental situation for mobile robots used in hazardous environments. For perspective, a small passenger automobile is estimated to need a minimum of 200 Wh/km to meet road demands, which in turn translates into 500 Wh/kg. This is why hybrid electric vehicles that combine spark ignition engines with battery-powered electric motors are becoming popular. A large mobile robot with dual manipulators operating in the payload range of hundreds of kg would have power requirements similar to these and would be well above the 100–200 Wh/kg range that batteries can provide. A force-reflecting six-degree-of-freedom robot manipulator with a 20 kg payload will have a peak power consumption on the order of 10 kW. If a particular application domain is amenable to the use of spark ignition engines, the order of magnitude power density compared with any type of battery-powered system makes implementation feasible. If pure battery power is necessary, then considerable attention must be given to the design, including state of charge monitoring and mission provisions for recharging. In the future, emerging fuel-cell technology may provide better solutions for mobile robot power systems.

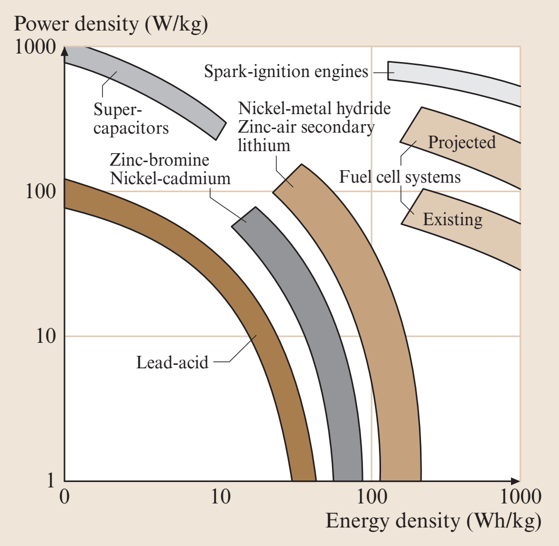

Fig. 48.26 Power and energy density for various power storage and supply systems

48.3.6 System Architectures for Real-Time Mission Control

Because of the intrinsic nature of hazardous environments where uncertainty and lack of geometric structure are prevalent in the task environment, shared control architectures are commonly used. The degree of human interaction runs the gamut from pure teleoperation (manual control) to high-level intelligent control operations (autonomous). For example, most low-cost EOD type robots utilize simple manual control architectures, while at the other end of the spectrum, the MARS Rover robots operate as autonomous agents responding to mission-level commands from human operators on the earth. The basic architectures for real-time mission control are summarized in Fig. 48.27 [48.73]. Also, see *Sheridan* for a comprehensive discussion of architecture principles and design [48.43]. Between the manual and autonomous control exist combinations of computer assistance and semiautonomous (i. e., selective and in situ task automation) functions intended to improve remote work performance by either reducing operator workload or allocating tasks more suitable for computer control to autonomous execution. It is important to recognize that, as one moves from manual control toward autonomous control, the data throughput rates for communication and control are reduced because high-level commands are comparatively small packets of information while force-reflection manual control of a manipulator, for example, requires visual feedback and high-bandwidth control interconnection of the slave and master controller. The data communication bandwidth available has great bearing on the type of architecture that must be used. Untethered undersea applications usually require semiautonomous architectures because of the bandwidth limitations of acoustic communications links.

As intelligent systems research advances, it is expected that, for hazardous situations, robots will employ semiautonomous and autonomous architectures to a greater degree as a fundamental approach to overall performance optimization. Operators will be able to choose the control mode based on the task needs

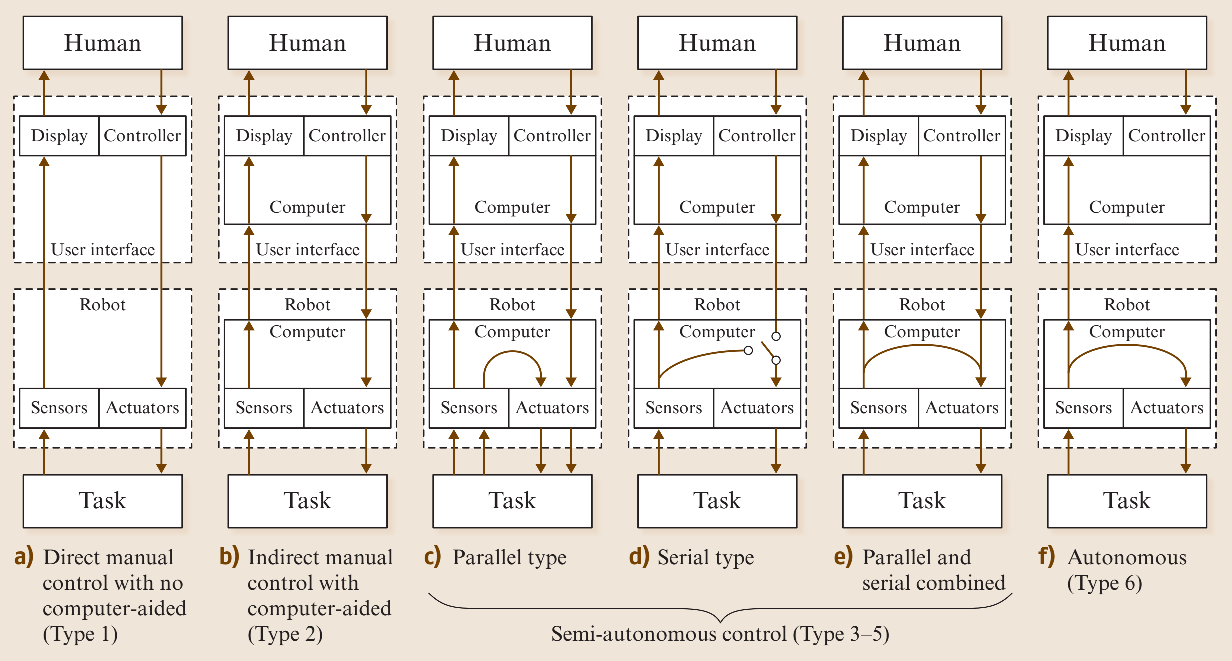

Fig. 48.27a–f System control architectures

and the likelihood that autonomous execution can be reliably achieved. In this human-centered way, task execution mode will be matched to best achievable performance.

48.4 Conclusions and Further Reading

If we are to learn anything from the experience of the last decade we must appreciate that robotics research is just one step in the development of tools that extend human capabilities. This search for improved tools is as old as humanity itself so great patience is required [48.74].

Researchers need to make significant advances on four different fronts: mechatronics design, sensing, machine intelligence, and problem understanding.

- Mechatronics designers have to trade gains in precision, dexterity, mobility, and strength for losses in endurance and reliability. We are mostly well short of biological (e.g., human) capabilities except for high-precision applications. Machines have much the same environmental tolerance as people. Machines need special precautions against heat and cold outside the temperature range of 0–35 °C, and operation beyond −60 °C or +60 °C is usually impractical. Dust, radiation, low or zero air pressure, fumes, biological agents, even insects can be fatal for machines without special design features, which may result in performance reductions. Maintenance or repair work may necessitate decontamination before people can work on the machinery.
- While electronic sensors can go far beyond biological capabilities, hazardous applications still present problems far beyond present capabilities as we have seen in the case of landmine applications. Radiation levels that are lethal for humans can also quickly kill electronic sensors. Extreme heat or cold limits performance, as can contamination, and even insects.
- Advances in usable machine intelligence have been much more difficult than many expected. The only real progress has been achieved with capabilities often associated with clever people: logic, mathematical manipulation, and playing games. Even the least intelligent animals have capabilities that still defy present-day understanding. However, teleoper-

ation and supervisory control can make up for this deficit in the medium term. Shortcomings in machine intelligence represent less of a barrier than the other three fronts.
- Understanding the intended application and economic factors has proved to be equally important for researchers. Early applications rely on exploiting particular opportunities with specific applications to generate confidence that inspires others to persevere with more difficult problems. Failures in understanding, particularly with economic factors, undermines confidence, and leads to disappointment and disillusioned researchers. Attempts to develop landmine clearance robots provides a useful case study that illustrates some of the difficulties in developing robots for hazardous applications.

There is no question that future teleoperators will become hybrid telerobotic systems that allow seamless transfer between manual and autonomous operations. Specific tasks will be selectively automated by operators for the purposes of enhancing quality and/or reducing subtask execution times. Early systems will continue to incorporate high levels of human interactivity to accommodate the limitations of current intelligent systems technology. Low-cost embedded computational power will continue to track Moore's Law, making real-time execution of complex control algorithms and virtual-reality-like graphics engines (which are really useful) routine. Robust machine learning that allows human task execution skills to be captured through learning by observation will become realizable. Through micro-electrical mechanical systems (MEMS) and engineering miniaturization, all types of sensors particularly imaging sensors will be more powerful and less costly. In the next decade, telerobots for hazardous environments will become smarter and their relationship with their human operators will become more cooperative and less interactive. Human operators will supervise the operation of multiple telerobots. However, telerobots will remain subordinate and the need to assure human-takeover capabilities through teleoperation will always be present.

Readers are directed to the selection of references provided in this chapter for further reading.

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