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ROBOTICS APPLICATIONS IN MAINTENANCE AND REPAIR

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1. INTRODUCTION AND BACKGROUND

Maintenance is the process that preserves or restores a desired state of a system or facility. The maintenance process includes three major activities: inspection, planned maintenance, and disturbance handling (where *disturbances* are unplanned system states). Inspection is the activity in which information about state is monitored to allow prediction or early detection of disturbances. Planned maintenance is the activity in which elements of the system are modified or replaced according to a pre-determined schedule, with the aim of avoiding or reducing the frequency of disturbances. Disturbance handling is the activity in which elements of the system are modified or replaced to restore the desired state, following a disturbance.

Maintenance is a task that has some important differences from tasks commonly selected for industrial robots. First, maintenance often requires access to environments that are more dynamic and less predictable than is the case for many robotic applications. Second, tasks may be less predictable in maintenance, both in terms of the nature of tasks and the frequency of maintenance or latency between tasks. Finally, the cost benefits of robotic maintenance may be different from that of other robotic applications. In general, robots typically pay for themselves over their entire operational life; however, robots used in maintenance, particularly in the nuclear industry, may pay for themselves in a single application. This is particularly true if robots allow a facility to avoid shutdown and to continue operating even during maintenance.

2. APPLICATION EXAMPLES AND TECHNIQUES

Robots, whether teleoperated, under supervisory control, or autonomous, have been used in a variety of applications in maintenance and repair. The following subsections describe many of these systems, focusing primarily on applications for which working robot prototypes have been developed.

2.1. Nuclear Industry

In the nuclear industry, teleoperators have been well-utilized in the maintenance role for more than 4 decades. Several features of maintenance make it a good application for teleoperators in this arena. First is the low frequency of the operation, which calls for a general-purpose system capable of doing an array of maintenance tasks. Second, maintenance and repair require high levels of dexterity. Third, the complexity of these tasks may be unpredictable because of the uncertain impact of a failure. For these reasons, the choice for this role is often between a human and a teleoperator. Thus, when the environment is hazardous, a teleoperator is usually the best selection. If humans in protective clothing can perform the same job, the benefits of having teleoperators continuously at the work site need to be weighed against the cost of suiting up and transporting humans to and from the work site. While humans are likely to be able to complete tasks more quickly than teleoperators, using teleoperators can: (1) shorten mean time to repair by reducing the response time to failures, (2) reduce health risks, (3) improve safety, and (4) improve availability by allowing maintenance to take place during operations, instead of halting operations.

As an example of the importance of maintenance for nuclear industry robotics, the proceedings of the 1995 American Nuclear Society topical meeting on robotics and remote handling included 124 papers, nearly a quarter of which were devoted to some aspect of maintenance. The 1997 meeting included 150 papers, where more than 40% dealt with some aspect of maintenance. Furthermore, if one considers environmental recovery operations as a form of maintenance, then a much larger proportion of papers at both meetings were maintenance-related.

Vertut & Coiffet (1985) listed the following applications of teleoperated robots in nuclear maintenance: (1) operation and maintenance of industrial nuclear facilities and laboratories, (2) maintenance in nuclear reactors, (3) decommissioning and dismantling nuclear facilities, and (4) emergency intervention. Our exploration of robotics for nuclear-related maintenance will follow these categories.

Operation and maintenance of industrial nuclear facilities and laboratories. Guidelines for applying teleoperators in the remote maintenance role exist (e.g., Burgess *et al.*, 1988). Unfortunately, there is an historic tendency to ignore the importance of designing for robotic maintenance and lessons learned by past experiences with remote maintenance (Vertut & Coiffet, 1985). Nuclear facilities do not necessarily need to be designed for robotic operations for robots to be successfully deployed within them. However, designing a facility to accommodate robotic maintenance greatly improves efficiency. Chesser (1988) reports on an extensive maintenance demonstration carried out using a teleoperator to dismantle and re-assemble components built for robotic maintenance. Reprocessing spent nuclear fuel requires a complex chemical process plant. To demonstrate the ability of a state-of-the-art teleoperator to replace equipment modules in such a plant, Chesser conducted a demonstration disassembly and re-assembly of a prototype chemical process rack using the Oak Ridge National Laboratory's Advanced Servomanipulator (ASM). Figure 1 shows the ASM, which is also remotely maintainable because of its modular design. Using standard tools (impact wrenches, ratchet wrenches, and a torque wrench), ASM operators were able to dismantle the rack, including tubing jumpers, instruments, motors, tanks, etc. As an adjunct to this demonstration, another teleoperator was used to disassemble and re-assemble the ASM to show its remote maintainability.

Particle accelerators are another type of nuclear facility sometimes maintained robotically. The CERN laboratory seems to have produced the largest body of experience in remote maintenance (Horne *et al.*; 1991). That program features integrated use of a variety of remote devices, including inspection and surveillance systems, dexterous manipulators, and mobile robots. The CERN application has some characteristics common to nuclear applications: (1) diverse array of maintenance tasks, (2) unpredictability of tasks and occurrences, (3) environment dangerous for humans, and (4) large facility size and, hence, a need for mobility. The evolving response to these factors depends on flexibility and versatility of robotic systems and their users. There is also a trend toward providing computer assistance during teleoperation to improve overall performance (Horne *et al.*, 1991).

Maintenance in nuclear reactors. Nuclear reactors are even less likely to be designed for robotic maintenance than industrial nuclear facilities, thus leading to the frequent requirement for innovative approaches to gaining access to trouble spots. This, along with limitations on size imposed by reactor designs and the resulting long lead times necessary for purpose-built robots has limited the use of robots in this arena in the past (Glass *et al.*, 1996). However, increasingly stringent limits on worker exposure to ionizing radiation and exposure reductions possible with robotic maintenance may increase robot use in the future (Lovett, 1991). For experimental fusion reactors, a remote maintenance philosophy seems to be an important part of design; see, for example, MacDonald *et al.* (1991).

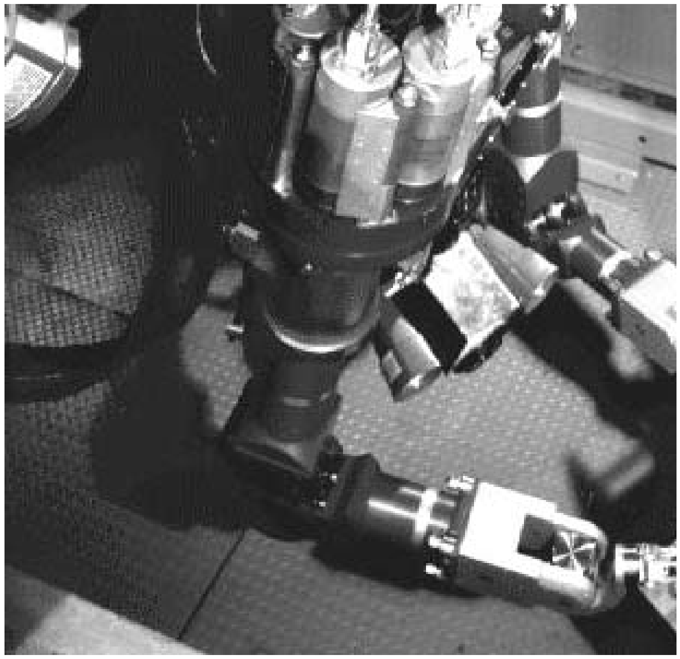


Figure 1. Advanced servomanipulator (ASM), designed for maintaining chemical process racks and itself remotely maintainable.

Several programs are addressing the difficulties of maintenance in nuclear reactors. For example, a preliminary analysis of tasks required in nuclear power plant maintenance and robot requirements for meeting these needs has been completed (Tsukune *et al*., 1994). A modular approach has been proposed to reduce costs incurred by customized robot designs (Glass *et al*., 1996) and problems in handling tools and fixtures designed solely for human use have been addressed by the development of more dexterous robot grippers (Ali, Puffer, & Roman, 1994).

Decommissioning and Dismantling Nuclear Facilities. In the United States, this topic is currently receiving much attention within the Department of Energy community. At the time of this writing, the first completely robotic decommissioning effort is being conducted at the Argonne National Laboratory. Two systems --- a pair of dexterous manipulator arms and a vehicle with a manipulator --- are being used to dismantle the CP-5 (Chicago Pile number 5) reactor. Development work in support of this effort is described in Noakes, Haley, & Willis (1997). Hazardous waste site remediation is a related topic that is also the target of development work within the DOE. Underground storage tank remediation using robotics is currently being done by the Oak Ridge National Laboratory (Randolph *et al*., 1997) and Pacific Northwest Laboratories (Kiebel, Carteret, and Niebuhr, 1997). Figure 2 is a photograph of robotic devices deployed to retrieve waste at the Oak Ridge National Laboratory. Detailed task analyses of underground storage tank remediation illustrate the complexity of this task (Draper, 1993a,b). In this application, the unpredictability inherent in the mission makes it a prime candidate for the application of teleoperated robots, with automation generally limited to providing assistance to the operator under specific conditions. As an example of the unpredictability in this arena, a quarry remediation conducted at Oak Ridge started with an estimate that approximately 2500 objects would be retrieved; in fact, more than 17,000 items were removed from the quarry by robotic systems.

Emergency intervention. The most famous case of emergency intervention in the nuclear arena in the United States is the accident at Three Mile Island (TMI-2). Merchant & Tarpinian (1985) and Bengal (1985) provide overviews of robotic programs developed for recovery operations at TMI-2. The accident is illustrative of principles of emergency intervention by robots. First, the event was unpredictable. Robotic systems were not available to perform reconnaissance or inspection for some time afterward. Robots on-site could have significantly reduced post-accident personnel exposure (Merchant & Tarpinian, 1985). Second, the accident created an environment very hostile to people and, at the same time, hostile to autonomous robots. Obstructions routinely present in buildings designed for human access are already difficult for robots to negotiate; the effects of the accident were to render access more difficult by introducing even less structured and unknown obstructions. Lesser-known interventions have also been carried out, and Chester (1985) briefly describes some of these.

Figure 2. Robotic devices deployed to retrieve waste at Oak Ridge National Laboratory.

2.2. Highways

In the developed world, highways are a critical component of the transportation network. The volume of traffic on the roadways has been steadily increasing for many years as society becomes more and more mobile. However, the funding to maintain these roadways has not been keeping pace with the traffic volume. The result is deteriorating roadways that cannot be adequately maintained. Conventional techniques to road repair lead to traffic congestion, delays, and dangers for the workers and the motorists. Robotic solutions to highway maintenance applications are attractive due to their potential for increasing the safety of the highway worker, reducing delays in traffic flow, increasing productivity, reducing labor costs, and increasing quality of the repairs.

Application areas to which robotics can be applied in this area include (Ravani and West, 1991):

- highway integrity management (crack sealing, pothole repair)
- highway marking management (pavement marker replacement, paint re-striping)
- highway debris management (litter bag pickup, on road refuse collection, hazardous spill cleanup, snow removal)
- highway signing management (sign and guide marker washing, roadway advisory)
- highway landscaping management (vegetation control, irrigation control)
- highway work zone management (automatic warning system, lightweight movable barriers, automatic cone placement and retrieval)

Although relatively few implementations in highway maintenance and repair have been attempted, some successful prototypes have been developed (Zhou and West, 1991). The California Department of Transportation (Caltrans), together with the University of California at Davis (UC Davis) are developing a number of prototypes for highway maintenance under the Automated Highway Maintenance Technology (AHMT) program. Efforts are underway to develop systems for crack sealing, placement of raised highway pavement markers, paint striping, retrieving bagged garbage, pavement distress data collection, and cone dispensing. One result of this effort is a robotic system, ACSM, for automatic crack sealing along roadways (Winters *et al*., 1994). Shown in Figure 3, this machine senses, prepares, and seals cracks and joints along the highway. Sensing of cracks along the entire width of a lane is performed using two-line scan cameras at the front of the vehicle. Sealing operations occur at the rear of the vehicle using an inverted, slide-mounted SCARA robot. A laser range finder at the tooling verifies the presence of the cracks and provides guidance for the sealing operation. The vehicle is able to perform this operation moving at about 1.6 to 3.2 km/hr (1-2 miles per hour). Other crack sealing prototypes have been developed at Carnegie Mellon University (Hendrickson *et al.*, 1991) and at the University of Texas at Austin (Haas, 1996).

Earlier prototypes for highway maintenance date back to the 1980s (Skibniewski and Hendrickson, 1990). Researchers at Tyndall AFB developed a rapid runway repair (RRR) telerobotic system for repairing craters in runways (Nease, 1991). The objective of this work was to safely restore pavement surfaces after enemy attack to ensure subsequent future successful aircraft operations. The system was based upon a John Deere multipurpose excavator enhanced for telerobotic operation. The system used a 4 DOF joystick system using position and rate control, plus force feedback for human remote control. The resulting machine could dig, scrape, compact, break pavement, and change tools under preprogrammed, onboard control. Carnegie Mellon University also developed a robotic excavator prototype, called REX, which used topography and a computer-generated map of buried objects to generate and execute appropriate trajectories for the mission. The system used an elbow-type manipulator coupled with a master arm for manipulator setup and error recovery.

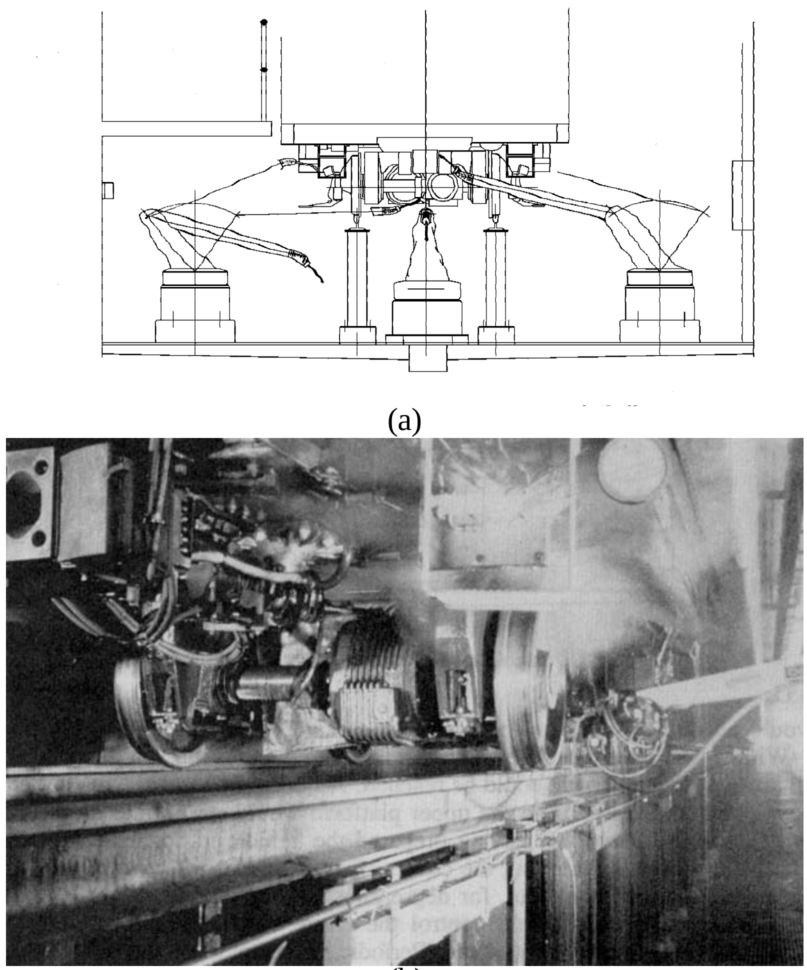
Automated pavement distress data collection vehicles have also been developed (Zhou and West, 1991). The vehicle built by Komatsu Ltd., of Japan, uses scanning lasers to examine a road surface's condition, measuring information regarding crack formation, wheel rutting, and longitudinal unevenness. The vehicle can travel at speeds up to 60km/hr, evaluating roads up to 4 meters wide with ruts and potholes up to 0.25 meters deep.

Figure 3. Automated Crack Sealing Machine developed by UC Davis.

The French Petroleum Studies Company developed an automatic cone dispenser that can dispense and remove up to two rows of warning cones, for a total of 240 cones. The system operates at about 15 km/hr. The Technique Special de Securite Company developed a mobile lane separator that can place and remove concrete road marker blocks at speeds up to 30 km/hr. Systems for automatic grading have been developed by Spectra-Physics of Dayton, Ohio, and by Agtek Co. of California. These systems use laser guides to controls the height of the grading blades, thus relieving the human operator from the need to perform manual positioning and control of the blades.

2.3. Railways

The railroad industry has recognized the economic benefits of automation, which has lead to the development of a number of robotic solutions to maintenance and repair applications in the industry. The railway maintenance shops are the most common location of robots, which perform activities such as welding, grinding, cleaning, and painting (Martland, 1987). A Toronto Transit Commission project led to the design of an automated system for cleaning the undersides of subway cars (Wiercienski and Leek, 1990). Shown in Figure 4, this system involved the use of three industrial painting robots mounted on either side and under the subway vehicle being cleaned. An operator located remotely would begin the cleaning operations after preparing the vehicle in advance. The entire system would be controlled by a master computer that supervised the three individual robot controllers. A robot-mounted vision system would be use to correct the robots' positions along their tracks. This system is expected to yield dramatic improvements in working conditions and work quality over the previous human worker approach.



(a)

(b)

Figure 4. Robot system developed for the Toronto Transit Commission for cleaning the undersides of subway cars. Figure (a) shows the schematic layout of the robots under the railcar, while Figure (b) shows the robot in operation (one robot manipulator can be seen at the right side of the photograph).

Another robotic system developed by the railway industry is the RMS-2 rail grinding system (Anonymous, 1986). Developed by Speno Rail Services Co., this system has automated capabilities to sense the existing condition of the surface of the rails. Up to 99 patterns are stored that correspond to rail contour patterns. An integrated onboard computer system is used to generate onboard grinder controls for finishing the rail to the appropriate, pre-determined rail contour. The RMS-2 has 120 stones for grinding spread along the underside of five of the twelve railway cars that make up the system. The system is capable of grinding rails at speeds up to 6 miles per hour.

2.4. Power Line Maintenance

Many common maintenance operations on overhead transmission lines are performed by human operators on live lines. Examples of these tasks include replacing ceramic insulators that support conductor wire and opening and reclosing the circuit between poles. These tasks are very dangerous for the human workers, due to risks from falling from high places and the risk of electric shock. Obtaining skilled workers to perform these tasks is quite difficult due to the high training and labor requirements of the job. Performing the maintenance while the lines are de-energized would alleviate some of the risks, but would also create other problems with a society that demands interruption-free service from electric power companies.

Electric power companies have therefore been investigating the use of robotic systems for live-line power line maintenance since the mid-eighties. In particular, power companies in Japan, Spain, and the United States have developed teleoperated and semi-autonomous approaches to this problem. One of the first systems developed was the TOMCAT (Teleoperator for Operations, Maintenance, and Construction using Advanced Technology), developed as part of an Electric Power Research Institute (Palo Alto, California) program. The basic TOMCAT concept was first demonstrated by Philadelphia Electric in 1979 (Dunlap, 1986), with subsequent development continuing in the 80's, leading to a system prototype. The TOMCAT system consisted of an insulated bucket truck, a Kraft seven-function manipulator that was bolted to the end of the truck boom, a television viewing system for human supervisory control, and requisite control and power supplies. The operator control components were mounted on the back of the bucket truck, and included a manipulator master with no force feedback.

A more recent robotic system for live-line maintenance has been developed by Kyushu Electric Power Co., Inc., in Fukuoka, Japan (Yano, *et al.*, 1995). The system configuration schematic for the dual-arm robot system they developed is shown in Figure 5. The earlier phases of this work involved the development of a two-manipulator telerobotic system; subsequent phases are incorporating more autonomy to evolve from a basic master-slave configuration to a human-robot cooperative system. Laser sensors are used onboard the robot to help with position control. In the current system, the human works from a control station on the supporting truck, rather than on the elevated boom, which nearly eliminates the risk of injury due to falls.

Other related work in this area includes the ROBTET teleoperated system for live-line maintenance developed by researchers in Spain (Aracil *et al.*, 1995) and the robot for automatic washing and brushing of polluted electric insulators (Yi and Jiansheng, 1993) developed in China.

2.5. Aircraft Servicing

Aircraft servicing applications may benefit from robotic maintenance in several areas. The size of modern multi-engine jets makes inspection and coating removal and application particularly attractive in terms of improving quality and efficiency. As examples, Siegel, Kaufman, & Alberts (1993) describe concepts for automating skin inspections, and Birch & Trego (1995) and Baker *et al.* (1996) describe stripping and painting concepts. Automated stripping and painting systems are already in place at a few U.S. Air Force bases. A robotic assistant for re-arming tactical fighter aircraft is being developed at the Oak Ridge National Laboratory for the U.S. Air Force.

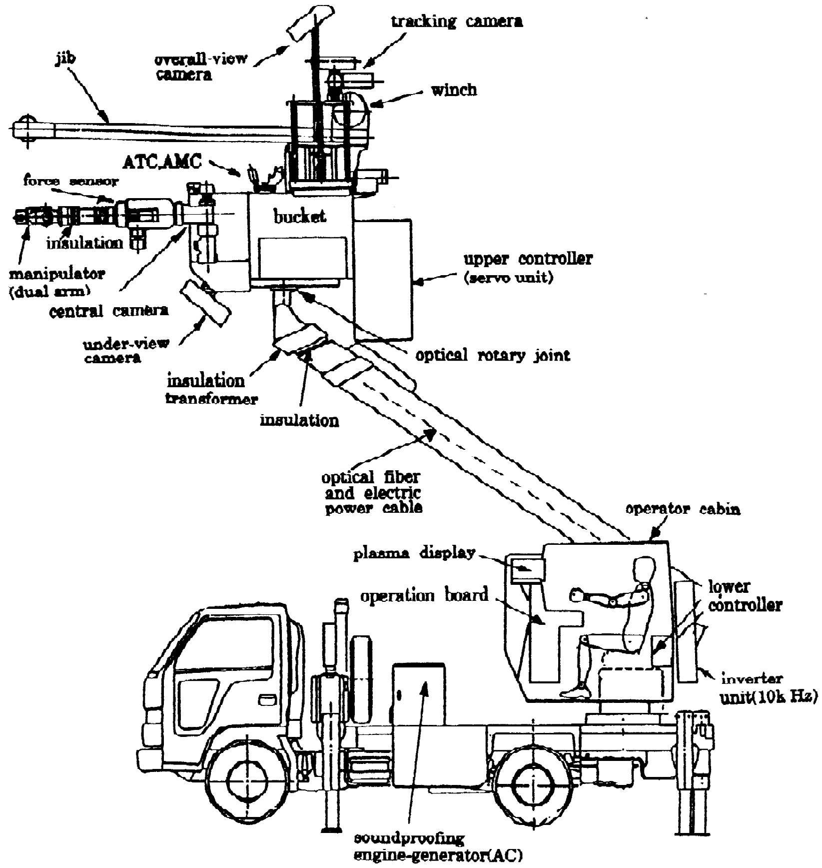


Figure 5. Dual-arm robot for live-line maintenance developed by Kyushu Electric Power Co.

2.6. Underwater Facilities

Teleoperated robots are widely used to maintain facilities beneath the surface of the ocean, mainly in service of the offshore oil industry. Specific applications include repairing communications cables, pipelines, well heads, and platforms. Teleoperators have also been deployed to clean marine growth from power plant cooling systems (Edahiro, 1985), to inspect and clean steam generators (Trovato & Ruggieri, 1991), perform underwater construction (Yemington, 1991), and to inspect and repair water conveyance tunnels (Heffron, 1990). While these efforts do not have the visibility of robotics work in industrial, space, or nuclear applications, it is an arena in which robotics and remote control technology are widely used. It is perhaps the most common venue for everyday use of teleoperated robots. One publication lists 63 companies involved in building remotely operated vehicles or manipulators for sub-sea work and 180 different, commercially available, remotely controlled systems (Gallimore & Madsen, 1994). The remotely operated systems range from towed sensor arrays to submersibles with dexterous manipulators to large construction machinery.

2.7. Coke Ovens

Another example of robotics used in maintenance and repair operations is a robot developed by Sumitomo Metal Industries, Ltd., Japan, for repairing the chamber wall of a coke oven (Sakai *et al*, 1988). Damages to coke ovens occur over years of operations due to repeated cycles of chamber door opening and coke pushing, which induce damaging changes in temperature. The result is cracks, joint separations, and chamber wall abrasion, which can lead to gas leakage, air pollution, and structural flaws in the ovens. Thus, the effective repair of coke ovens is needed to extend the life of the ovens and to allow for stable operation.

Especially challenging maintenance operations involve the repair of the central portion of the oven. This type of repair is very difficult due to the inaccessibility of the area, the high temperature, and the predominance of narrow cracks. Any technology for repair in this area must involve high heat resistance components and mechanisms for external observation, resulting in repairs of high quality and durability. The solution to this repair problem was the development of a heat-resistant robot, shown in Figure 6, that can autonomously perform individual crack repair, while being given high-level guidance through a human-machine interface. Of special benefit to the industry is the ability to perform these repairs without disturbing oven operation or incurring a large firebrick temperature drop.

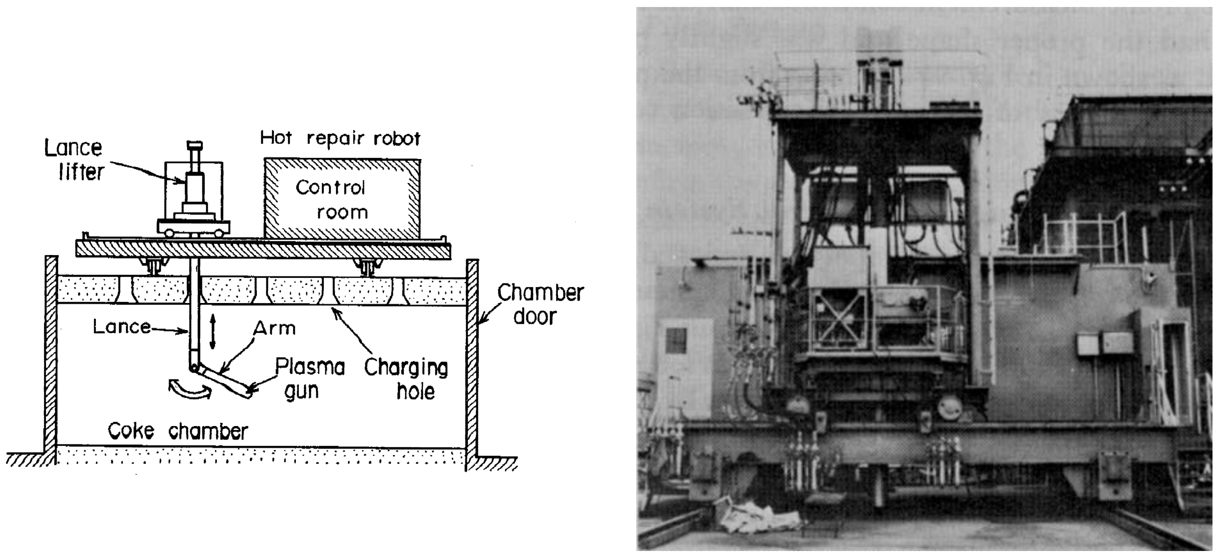


Figure 6. Hot Repair Robot developed by Sumitomo Metal Industries, Ltd., Japan, for repairing cracks and joints in the chamber wall of coke ovens during hot operation.

2.8. Summary of Robotics Applications In Maintenance and Repair

In this chapter, we have reviewed the primary application areas in which robotics is used for maintenance and repair. Some of these application areas have a significant ongoing effort in robotic development and usage, while others have received relatively little attention thus far. Table 1 provides a summary of these application areas, noting the importance of robotics to the maintenance tasks of inspection, planned maintenance, and disturbance handling.

	Maintenance Task		
Application Area	*Inspection*	*Planned Maintenance*	*Disturbance Handling*
Nuclear Industry	Growing area, especially as new facility designs incorporate remote maintenance philosophy	Well-established field, with several decades of successful robotic applications.	Much current activity related to decontamination, decommissioning, and dismantling.
Highways	Relatively new area with few current prototypes, except as packaged with crack sealing and pothole repair systems.	Relatively new area, with quickly growing interest and a huge potential impact. Several ongoing efforts should result in a number of new robot prototypes in the next 5 years.	Of significant interest, particularly for highway integrity management. A number of successful prototype systems are gradually making way into routine use. Several new efforts underway.
Railways	Few current systems, and little ongoing activity.	Most common area of railway robotics, but with little new activity.	Little current use.

Power Line Maintenance	Little current use.	Interest is increasing, especially for robotic techniques that work on live power lines.	Greatest area of current use, with much potential growth due to technology advances and need to remove humans from highly dangerous tasks.
Aircraft Servicing	Steadily growing area, due to recent advances in automated inspection technologies.	Steadily growing area, especially for automated stripping and painting.	Little current use.
Underwater Facilities	Steady progress over the last two decades, with continued advances.	Of increasing importance, with several new prototype systems under development.	Of increasing importance, with several new prototype systems under development.
Coke Ovens	Little current use.	Little current use.	Fair amount of activity in late 1980’s. Relatively little new work in this area.

Table 1. Summary of robotics applications in maintenance and repair.

3. DESIGN CONSIDERATIONS AND EMERGING TRENDS

Several years ago Jordan (1963) observed that "[people] are flexible but cannot be depended upon to perform in a consistent manner whereas machines can be depended upon to perform consistently but they have no flexibility whatsoever." The three decades of development in robotics and artificial intelligence that have passed since he wrote have greatly improved the flexibility of machines but have not abrogated his observation. As Ruoff (1994) pointed out, "Robots have limited intelligence and ability to perceive. To compensate, applications have . . . relied either on human presence in the control loop or on the imposing of significant order on tasks." The applicability of autonomous robots, supervised robots, and teleoperated robots to maintenance and repair applications is especially dependent upon two aspects of the work environment --- variability and accessibility. Autonomous robots still cannot function well in many dynamic, and thus variable, environments, so these applications tend to require either completely human or teleoperator solutions. Of course, environments with low human accessibility (because of physical constraints or danger) are usually good candidates for robotic solutions. Where accessibility is low but variability is high, teleoperators are usually best.

Until additional significant progress is made in autonomous systems, human involvement with robotic systems must increase with environmental variability. Figure 7 illustrates this principle: where variability is low, autonomous robots are efficient and human involvement is at the level of strategic decision making. Where variability is high, human sensing and decision making are more important and the human user must take more responsibility. At the lowest level, the human is responsible for executing movements; this is the region of true teleoperation. Telerobots, which combine autonomous sub-task completion capabilities with human-in-the-loop control, may help teleoperators to be more efficient or autonomous robots to be more capable of dealing with variability. The left-hand side of Figure 7 illustrates the relationship between environmental variability and human input responsibility for various types of robotic systems. The right-hand side maps maintenance and repair tasks onto these ideas. Inspection tasks are most often carried out under routine conditions and may be performed with an autonomous robot for many applications. Planned maintenance may be somewhat less structured and thus requires more interaction with the environment, in terms of manipulating task elements. Therefore, it may be necessary to deploy a telerobot or teleoperator to complete these tasks. Disturbance handling is by nature unpredictable.

Therefore, in general, this maintenance task is much more likely to require human-in-the-loop control.

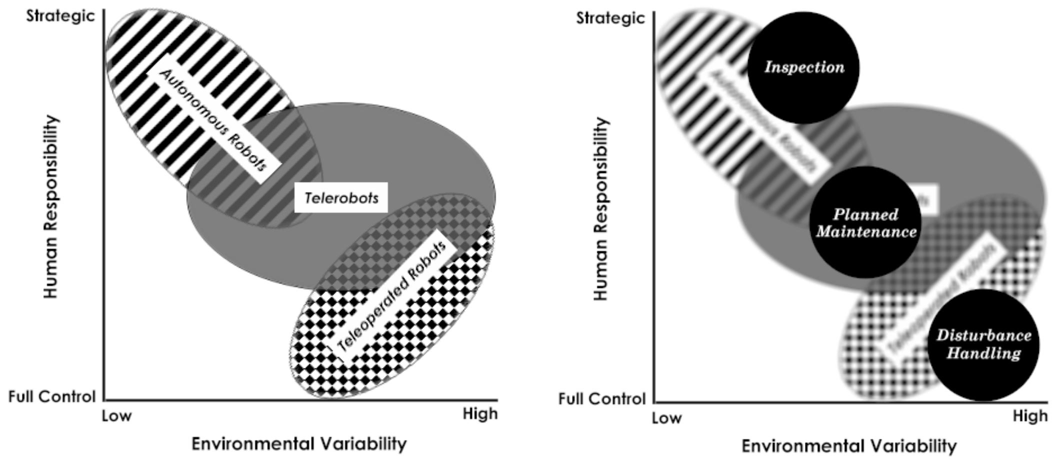


Figure 7. Application of autonomous robots, telerobots, and teleoperated robots to robotic maintenance and repair tasks.

From this survey of robotic systems for maintenance and repair, some trends in robotic maintenance in recent years can be identified. These trends include:

- ***Computer control/monitoring/assistance:*** increasing integration of computer control over subsystems and sub-tasks, for monitoring user inputs and evaluating their appropriateness and for user assistance. As an example, Volpe (1994) describes using model-based artificial forces to enhance collision avoidance. By monitoring the position of a manipulator relative to a model of the remote work site, a repulsive force can be generated by the control system to resist movement into areas where collisions are possible or even to push the manipulator away from surfaces or features.

- ***Virtual reality:*** increasing integration of virtual reality interfaces into teleoperated systems. Virtual reality systems (VR) and teleoperators may be considered members of a super-set called Synthetic Environments Technology (Durlach and Mavor, 1995). They differ only in that a user interacts with a remote, *computer-generated* world in VR but a remote, *real* world in teleoperation. Therefore, it should be no surprise that VR techniques are being adopted for teleoperation. However, application of VR to autonomous robotics is also likely to increase in the future for programming and for monitoring robot operations. This may be limited to providing a virtual view of the workspace and manipulator or may be present in the form of graphical preview control. In the latter, the user completes the task in the virtual world as a means of programming the robot. The latter is inherently less efficient than real-time control but proponents claim potentially greater safety and ease-of-use for graphical preview control (e.g., Small and McDonald, 1997), although there are no data supporting that opinion. Milgram, Yin, and Grodski (1997) provide examples of what may be termed an "augmented reality" interface for teleoperation, in which video from a remote site is combined with partial computer models of the site.

- ***Increasing sensor integration:*** use of larger numbers of sensors and multi-sensor integration, toward the goal of allowing autonomous robots to function more effectively in environments too variable for effective modeling. For example, Dudek and Freedman (1996) demonstrated how two different types of sensors, a sonar array and a laser range finder, can provide more accurate information about a work site than either type alone.

- ***Responsiveness vs. payload:*** sacrificing responsiveness (the ability of a manipulator to re-create a user's trajectories and impedance in time and space) for payload in manipulators. Telerobotic manipulators developed since about 1985 seem to be increasingly less responsive but more powerful.

Table 2 provides some comments on how these trends may affect each of the three maintenance tasks in future applications. These are necessarily speculative, but give some guidance for the development of robotic technology in maintenance for the near and intermediate future.

	Maintenance Task		
Trend	*Inspection*	*Planned Maintenance*	*Disturbance Handling*
Computer control/ monitoring/ assistance	Will make inspections more autonomous and at the same time more effective. Robots are more capable of accurately monitoring position and measuring sensory input than humans are (although humans better at pattern recognition).	Will assist in scheduling and reduce human involvement in tasks that can be sufficiently ordered. It is possible to remove much of the tedium from remote tasks by automating tasks or sub-tasks.	Most likely to improve record-keeping and to help assure quality by assisting operators in quality-critical subtasks. Also may allow oversight of user actions, which may improve safety.
Virtual reality	Graphical overlays of expected task configuration will be helpful. Multiple sensor "views" can be integrated to provide more information.	May assist in robot navigation by providing displays to enhance user situation awareness. May be used to display robot progress through planned maintenance tasks without on-site video. May be used to display information about maintenance campaigns (as opposed to tasks).	Forms of computer-assisted teleoperation may be beneficial; integrating graphics and video could provide information about expected state, which could help with diagnosis. Could allow on-line guidance for operators.
Increasing sensor integration	Will make it possible to perform inspections in multi-sensor fashion, and develop a picture of inspected items that integrates several sensors, including energy not sensed by humans.	Arrays of sensors may provide more complete information about a component and aid in assuring the effectiveness of planned maintenance.	Arrays of sensors may provide more complete information about a disturbance and aid in diagnosis and remediation.
Responsiveness vs. payload	Not likely to have much impact.	May allow larger parts to be replaced but may make replacement more difficult under human control.	May allow application to a wider range of disturbances but may reduce efficiency.

Table 2. Emerging trends and their potential impact on the robotics activities of inspection, planned maintenance, and disturbance handling.

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