Platforms for Rescue Operations

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Executive Summary

This document reports the results of a survey study about robotic platforms to be used in rescue and emergency response operations.

The study was commissioned by NIROS, the Swedish National Center for Innovative Rescue and Safety Systems) (Nationellt Centrum för Innovativa Räddnings- Och Säkerhetssystem) located in Karslkoga, Sweden. It was carried out by the AASS Mobile Robotics Laboratory at the Department of Technology of the University of Örebro, Sweden. A companion report, produced by the AASS Learning Systems Lab, discusses the sensors that can be used on robotic rescue platforms.

This document is structured into two main parts. In the first part, we discuss the main locomotion modes that characterize robotics platforms, and survey many of the existing platforms which have been developed around the world. In the second part, we analyze the different modes of operation of a robotic platform. These modes differ in the balance between operator control and robot autonomy.

This report ends with a summary of the current state of practice in this field, and with some projections about likely future developments.

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Introduction

1.1 Objectives

This document reports the results of a survey study about robotic platforms to be used in rescue and emergency response operations. This study was carried out by the AASS Mobile Robotics Lab at the Department of Technology of the University of Örebro, Sweden. A companion report, produced by the AASS Learning Systems Lab, discusses the sensors that can be used on robotic rescue platforms.

The objective of this study was to get a wide and representative picture of the field of rescue robotics, with a special focus on the physical platforms and their modes of operation. This report discusses both some general principles and guidelines that have emerged from this study, and a number of specific platforms.

This survey does not have the ambition to be complete, and it could not be, since there is much work done in this domain which is not made easily available to the public. Our priority has been breath in coverage rather than completeness. We believe that the technological solutions and case studies that we present are enough to provide a fair understanding of the state of the art in this field.

1.2 Structure

This study is structured into two main parts.

The first part summarizes the main locomotion modes that characterize robotics platforms, and surveys many of the existing platforms which have been developed world-wide. Platforms are classified in three categories according to their main intended use: fire fighting robots, robots for manipulation in hazardous environments, and robots for search and rescue operations after a disaster.

The second part analyzes the different modes of operation of robotic platforms. Effective human-robot interface is essential in order to maximize the usability and effectiveness of robotic platforms, and this is especially true in the case of emergency response operations due to the often extreme conditions. Modes of operations differ in the balance between need for tight operator control and ability of the platform to perform autonomously. We discuss different options which cover the full range of possible modes, from pure tele-operation to fully autonomous robot operation.

This report ends with a summary of the current state of practice in this field, and with some projections about likely future developments.

1.3 Sources

The following are the main sources from which we have extracted the material used to perform this study, and which can be consulted to obtain further information.

- Proceedings of the 2003 and 2004 editions of the IEEE International Workshops on Safety, Security, and Rescue Robotics.
- Proceeding, website and information material from the 2003 and 2004 editions of the "Urban Search and Rescue Robot Competitions", organized by the RoboCup Federation, and by the American Association for Artificial Intelligence.
- Website of the International Rescue Systems Institute: `www.rescuesystem.org`.

- CLAWAR-2 (European Thematic Network on Climbing and Walking Robots) public reports.
- Specific information regarding most of the individual projects described in this report was extracted from scientific papers and web-sites relative to those projects, cited in the corresponding text.

In addition, a number of people contributed to this report by providing material and information, including Robin Murphy, Adam Jacoff, and Satoshi Tadokoro. Their contribution is gratefully acknowledged.

Chapter 2

Physical Platforms

Experience with robots at disaster sites suggests that useful emergency response robots must have several characteristics. From the practical mechanical point of view, they must possess basic mechanical durability, very high mobility in complex terrain, simple manipulation capabilities, and the ability to recover from errors and/or failures (such as toppling). Size is also an important factor: as we discuss below, search and rescue robots are more or less suited to certain tasks and environments depending on their size.

Furthermore, mobile robots must be able to gather large amount of sensory information, which is then processed and presented to remote human operators in the correct geometrical context. The communication system is an important parameter here: radio communication is usually preferred to cable in order to improve the range, mobility and autonomy of the robot. However, radio communication may be lost depending on the environment structure and on the amount of radio interferences in the environment. Ideally, the robot should be able to adaptively allocate its resources on the fly as it encounters evolving situations. All of these operations rely heavily upon coordination and planning techniques that take sensing into account.

Finally, energetic considerations should be taken into account for rescue robots that are expected to operate out of the reach of human operators for a long time. Many current rescue robots draw their power from a cable. This reduces the range of operation of the robot, makes mobility more limited since the cable must be pulled by the robot, and often requires an additional human operator to manage the tether. This operator must work in proximity of the robot, which often means to stay in a potentially dangerous area.

In what follows, we survey some of the existing platforms for emergency response and rescue operations. They mainly fall into three categories: platforms for fire fighting, and platforms for remote manipulation, and platforms for post-accident search and rescue. Before we start our survey, however, we provide a short reminder about the main forms of locomotion.

2.1 Types of Locomotion

We distinguish five main forms of locomotion for rescue platforms: wheeled, tracked, legged, airborne, and serpentine. These are illustrated in Figure 2.1.

The large majority of existing platforms for rescue operations use wheeled or tracked locomotion, including almost all of the commercially available platforms. Only a very limited number of platforms rely on other forms of locomotion, including legged, serpentine, airborne, or hybrid (e.g., wheeled plus tracked, or wheeled plus legged). This later type of platforms are, however, usually in an experimental and laboratory stage of development.

2.1.1 Wheeled, Tracked and Legged Platforms

These are the most common types of locomotions for mobile robotic platforms. The relative advantages and disadvantages of these three forms are straightforward. Wheels provide fast motion on flat and smooth surfaces, but they are inadequate for rough or uneven surfaces. Tracked locomotion is slower but it allows a robot to operate on a wide variety of rough, uneven and slippery terrains, and to some extent

Figure 2.1: Different types of locomotion. All robots are developed by the International Rescue System Institute (www.rescuesystem.org)

to negotiate steps and stairs. Legged locomotion is potentially the most versatile form of locomotion, able to negotiate many different types of situations, but it is slow, relative fragile, and very hard to control.

2.1.2 Airborne Platforms

The advantages offered by Unmanned Airborne Vehicles (UAV) are numerous and accrue most noticeably in certain mission areas, commonly categorized as “the dull, the dirty, and the dangerous”. Many studies have pointed out the importance of UAVs to the future of the military services. A great deal less attention has been paid to the possible civilian applications of these vehicles. However, there is a great potential for UAVs in rescue operations. UAVs can quickly and systematically search a very large area to locate victims of an accident or a natural disaster. They can then visually lock onto objects at the site or stranded victims to guide rescue forces to the scene. They can help focus the efforts of search and rescue crews to the rescue operation instead of the time consuming search operation. They can be more readily deployed in weather conditions that would normally prevent human piloted search and rescue. Finally, they can be sacrificed in very dangerous conditions to save human lives. Prime examples include flying close to a forest fire to look for stranded individuals, searching in contaminated areas, and identifying potential radioactive leaks after a nuclear reactor accident.

2.1.3 Serpentine Platforms

Serpentine mechanisms have many more degrees of freedom than conventional robots, while at the same time have a small cross-sectional area. These many degrees of freedom enable hyper-redundant mechanisms to thread through tightly packed volumes reaching locations otherwise inaccessible to conventional robots and people, while at the same time, not disturbing the surrounding areas. This is critical in search and rescue operations where large pieces of debris become fragile make-shift support structures.

Serpentine robots also offer unique forms of mobility particularly well-suited to confined areas. Consider their biological counterparts: snakes and worms. Snakes lost their legs in evolution because the legs got in the way when crawling through narrow passageways. Likewise, serpentine mechanisms can maneuver through narrow crawl spaces and then up a vent, etc. Just like their biological counterparts, these highly articulated mechanisms can also perform a variety of tasks – manipulation (spider monkeys and elephant trunks), locomotion (snakes and worms), shoring (teams of ants), inspections etc. – albeit not as well as a specialized mechanism for one task but sufficiently well for a variety. Finally, as their name suggests, hyper-redundant robots are redundant, so if one actuator fails, the mission can still achieve its goals.

2.2 Fire Fighting

2.2.1 CNII-RTC “Fireman”

Developed by the State Scientific Center Central Research and Design Institute for Robotics and Technical Cybernetics (CNII-RTC) in St. Petersburg, Russia.

Tele-operated via cable or radio connection. Equipped with a set of cameras and infrared sensors, and a small-size foam-making machine for fire-fighting. High maneuverability and cross-country ability, motion on the flights of steps. Can be used for fire inspection of premises, underground communication tunnels, visual inspection of the seats of the fire, putting out the fire by means of foam or water.

A few prototypes have been assigned to fire-fighting municipal services, airport security services, special-purpose technical centers of the State Committee for Extraordinary Situations.

More information: `www.neva.ru/CNII-RTC/fireman.html`.

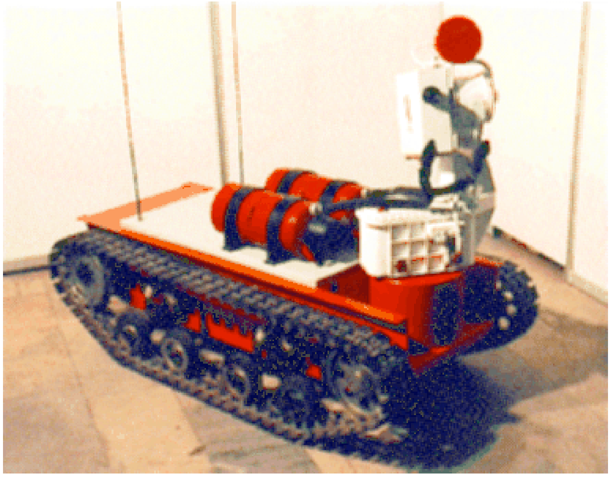


Figure 2.2: The Fireman robot

Figure 2.3: The PXZ-A robot

2.2.2 Shanghai Beian "PXZ-A"

Developed by Shanghai Beian industrial Ltd, Shangai, China. Wheeled vehicle, tele-operated via a cable connection. Six-wheel drive, providing a good cross-country performance and good terrain adaptability. It can run on muddy, rugged road surfaces and can cross 250mm perpendicular obstacles and 30 degree slopes.

The platform can spray water and foam. It can be used for extinguishing a fire, cooling, washing and disinfecting chemically polluted areas (inaccessible by fire brigade vehicles and personnel) at high-temperature, high radiant heat, or easily collapsible sites in petrochemical complexes, tank farms, large depots, architectures, etc.

The operator maneuvers the movement of the vehicle bodies through a base control panel. He utilizes water contained in the water tank on the vehicle body and water supplied by the water pump or by the hose connected to the rear, to spurt water for self-protection. Also he controls the sideways rotation and the elevating and lowering movement of the monitor to adjust the falling points of the jetting extinguishant.

More information: `www.china-fire.com/beian/robot.htm`.

Figure 2.4: The Rainbow-5 robot (left) and its little brother JetFighter (right)

2.2.3 Tokyo “Rainbow 5”

Developed by the Tokyo Fire Fighters Department, Tokyo, Japan. Wheeled locomotion, tele-operated via cable or radio connection. Rainbow 5 was designed to fight fires too big for firemen to approach, like a burning petrochemical complex or an airplane in flames. It can also get close to burning objects that might explode. It has four video cameras to transmit images of the fire, and in one minute it can spray five tons of water or three tons of smothering foam.

The Tokyo Fire Department started using robots in 1986. Rainbow 5 was the first one. After it, the Tokyo Fire Department has put seven other types of robots into service, including Jet Fighter (right in Figure 2.4), a small robot for action in manholes and places too small for a human fire fighter to go.

More information: `http://www.tfpc.com/`.

2.2.4 Rechners “Luf-60”

Developed by Rechners GmbH, Ludesch, Austria. Tracked locomotion, tele-operated via cable or radio communication. It includes a powerful blower that can spray small water (or foam) particles up to a distance of 60 meters, up to 500 liters/minute. It can be used to help in fighting fires in tunnels, garages, underground stations, and

Figure 2.5: The Luf-60 robot

closed places. The platform is powerful enough to climb stairs and to push blocking automobiles. All the controls can be manually overridden in case of loss of electronic control.

The Luf-60 has been successfully tested and used in tunnels and buildings. In March 2003, it has been demonstrated to many European fire departments in a simulated fire in a tunnel. Figure 2.6 shows the Luf-60 robot in action in this tunnel (left) and extinguishing a burning vehicle (right).

More information: `http://www.rechners.com/`.

Figure 2.6: The Luf-60 robot in action

Figure 2.7: The Altus II robot

2.2.5 NASA "Altus"

The Altus II is a robot airplane developed by NASA in conjunction with General Atomics Aeronautical Systems Inc (GAAS). It a variant of the Predator drone similarly designed by GAAS for the US Air Force, and it was originally designed for high-altitude, long-duration scientific sampling missions. It can fly for up to 24 hours.

The plane is remotely piloted via a radio link, and needs a crew of several expert people to be operated. The plane sends video and thermal images through a satellite link and onto the Internet, where fire-fighters can access it to make minute-by-minute decisions. The images are geo-registered: this allows the system to create accurate imagery to be used by disaster managers, who can trust it move resources around. In addition to fires, these images can help in managing floods, hurricanes and earthquakes.

Compared to other airborne robots used to observe fires, Altus II can fly higher and therefore view a larger area. Also, previous robots did not have the ability to deliver the images via radio, but they had to land and to unload the images for interpretation and delivery to command posts.

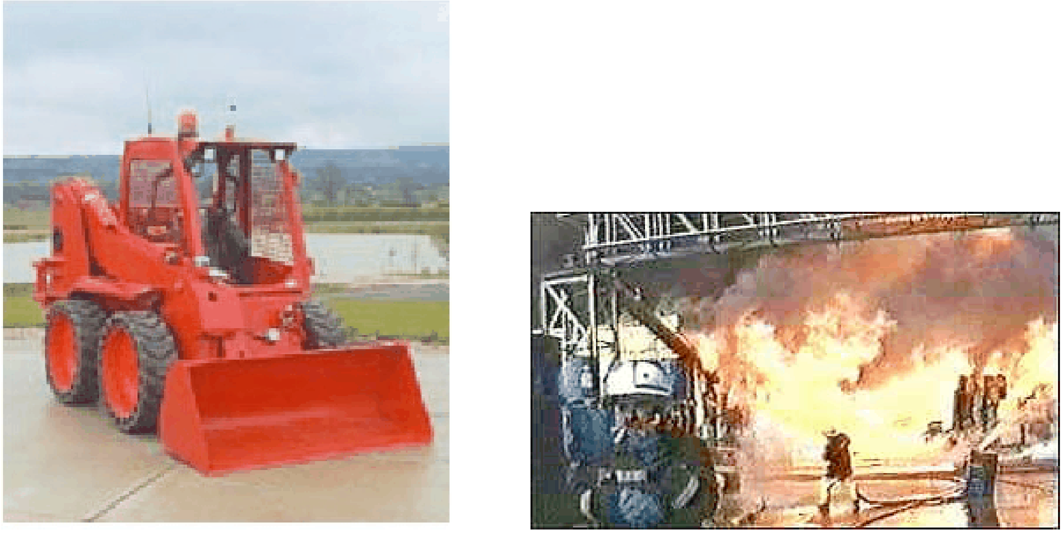


Figure 2.8: The FireSpy robot, static (left) and in action (right)

More information:
`http://www.nasaexplores.com/show2_articlea.php?id=01-091`.

2.2.6 QuinetiQ “FireSpy”

FireSpy is a tracked robot developed by QuinetiQ, UK, based on a JCB vehicle which has been modified to withstand temperatures of up to 800◦C. It is controlled remotely through a cable. It has a video camera and infrared camera providing live streams to the operator, and it has a grabbing arm in front. The main purpose of this robot is to remove dangerous items from a fire affected site.

Although based on a simple technology, this platform was successfully used in a firefighting operation at a Bradford chemicals factory in 1992, where a large amount of a highly explosive chemicals (600 tons of acrylo-nitryl) had to be removed from the danger area — see Figure 2.8 (right).

More information:
`http://www.qinetiq.com/news_room/newsreleases/2002/2nd_quarter/qinet`

2.3 Manipulation in Hazardous Environments

2.3.1 Telerob “tEODor”

The tEODor remote manipulator vehicle is part of array of products for emergency response called TEL 600, developed and commercialized by Telerob GmbH, Ostfildern, DE (part of the Rheinmetal Group). The tEODor robot is mainly use for observation and bomb disposal (EOD, Explosive Ordnance Disposal). It is teleoperated with either cable or radio connection, can operate under ambient temperature conditions ranging from -20° C to $+60^\circ$ C, and can mount a number of special tools and devices depending on the task.

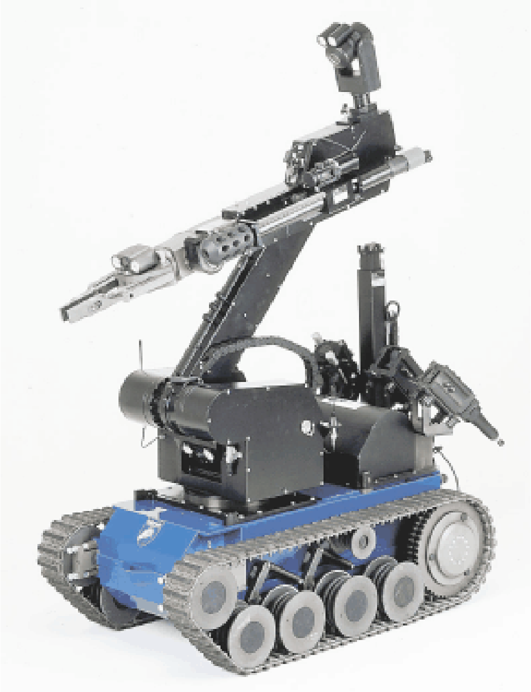


Figure 2.9: The tEODor robot

More information: `http://www.telerob.com`.

2.3.2 IPA/BASF “Safety Guard”

The Safety Guard is a robot developed by the Fraunhofer Institute Production technology and automation (IPA) in Stuttgart, DE, in cooperation with BASF Aktiengesellschaft in Ludwigshafen, DE. It is based on a teODOr platform by Telerob.

The Safety Guard is a tele-operated Manipulator designed and constructed for assistance during or after technical faults in major technical plants. The following activities are included in it’s wide operation spectrum:

- survey scene of accident,
- detect possible explosives,
- search missing persons in concealed areas,
- transport material to scene of accident,
- active fire-fighting,
- seal-off leakages, and
- emergency pressure release of pressurized tanks.

In order to carry out these tasks, the vehicle carries a range of multi-use tools and gadgets in an on-board case. If required, the maintenance robot can be delivered with a trailer containing further tools, which can also be remotely used by the manipulator arm. In addition, the platform can carry many sensors for information gathering, including a video camera, an infrared camera, air reading and analysing sensors, temperature reading (room, body, column or storage tank) at different heights. It has both cable- and radio-based information links.

The platform has the ability to turn on the spot, to overcome pipelines (Tank dams) or hoses which are on the ground, and to open laboratory cubicles. It does not have the ability to climb steps. However, it fit for lifting using an elevator, crane or forklift truck, and it can therefore by brought into position (correct level) by other means.

Figure 2.10: The Safety Guard variant of the tEODor robot built by IPA/BASF, performing two different tasks involving hazardous manipulation

The manipulator has a sophisticated software allowing both direct and functional remote operation. Work is under way to increase the autonomous capabilities, including: navigation assistance to aid obstacle recognition and overcome obstacles, Sensor control for operations in difficult to reach areas, with restricted view (smoke product releases), and management of energy supply and information transfer.

More information:
`http://www.basf.de/en/ueber/dienste/wfw/innov/manipulator.htm?id=V00-Dz6fI5eCxbsf3Ci`.

2.3.3 CMU "Pioneer"

Pioneer is a remote reconnaissance system which was explicitly built for structural analysis of the shelter of the Chernobyl Unit 4 reactor unit. The Pioneer project is sponsored by the US Department of Energy and NASA and is a collaboration between Carnegie Mellon University, the University of Iowa, NASA, Lawrence Livermore National Laboratory, and several private companies.

The major components of the Pioneer system are

- a tele-operated mobile robot for deploying sensor and sampling payloads,
- a mapper for creating photorealistic 3D models of the building interior,

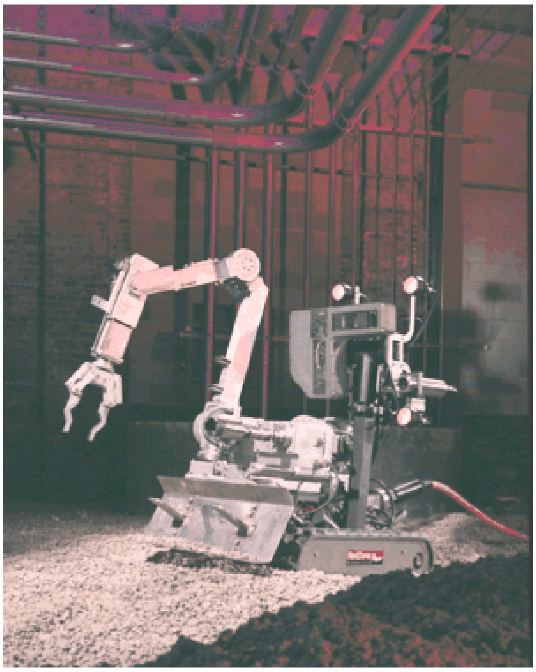
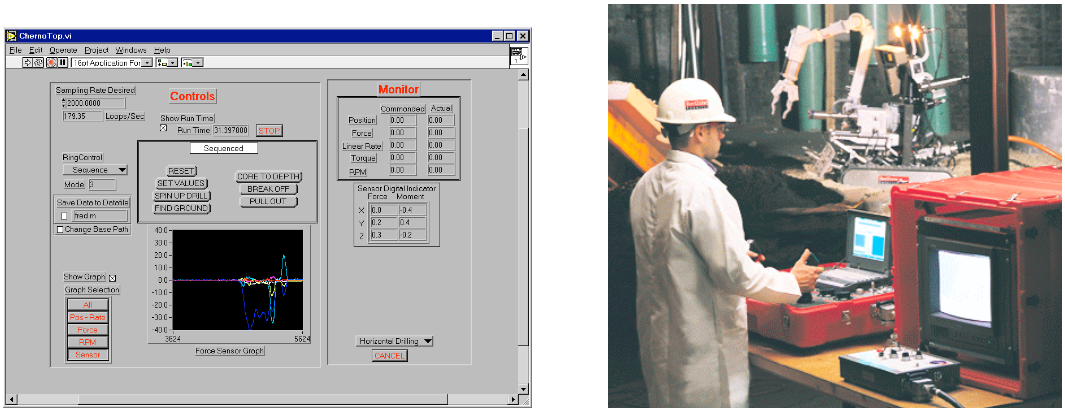


Figure 2.11: The Pioneer robot

- a coreborer for cutting and retrieving samples of structural materials, and
- a suite of radiation and other environmental sensors.

The Pioneer robot is a radiation-hardened mobile diagnostic unit, shown in Figure 2.11. It is a track-driven machine similar to a small bulldozer that is electrically powered and remotely operated via a 100 meter long umbilical. Tracked locomotion is well suited for driving over and through rubble; the robot's wide footprint provides ample stability and platform capacity to deploy payloads. A six axis manipulator allows positioning of sensors and tools.

In order to allow the Pioneer to help in assessing the structural integrity of the Unit-4 building, it has been equipped with a remotely operated concrete sampling drill. The drill has been designed to cut and retrieve cylindrical samples of floors and walls that can be subsequently analyzed for strength and brittleness. Material hardness can be estimated based on the resistance and deflection measured by the drill sensors. Structural information from Pioneer's concrete sampler can be valu-



Sampling Rate Desired 2000.0000

179.35 Loops/Sec

Show Run Time ☒

Run Time 31.397000

RingControl Sequence

Mode 3

Save Data to Datafile ☐ fred.m

☐ Change Base Path

	Commanded	Actual
Position	0.00	0.00
Force	0.00	0.00
Linear Rate	0.00	0.00
Torque	0.00	0.00
RPM	0.00	0.00

Sensor Digital Indicator

	Force	Moment
X	0.0	-0.4
Y	0.2	0.4
Z	0.3	-0.2

Figure 2.12: The operator console of the Pioneer robot (left), and an operator using it (right)

able for assessing the building's structural integrity and correlating it to radiation and other environmental parameters. The controller for Pioneer's drill is based on NASA technology for sampling materials on asteroids and comets.

Intrinsic to the robot is a suite of radiation detectors, temperature probes and humidity sensors, as well as a radiation hardened color video camera for inspection and remote viewing. A ruggedized, portable control console provides the means to operate the robot from safe locations and is connected by a 400 meter cable to five sealed enclosures that house power supplies, control electronics, and the vehicle umbilical termination. The operator's console is shown in Figure 2.12.

From the point of view of software, one of the highlights of the Pioneer system is an advanced 3D digital reconstruction software intended to faithfully capture both the appearance and geometry of the Unit 4 interior using stereo videography. A custom, radiation resistant imager consisting of three black & white cameras with folded optics is deployed on Pioneer's sensor mast and positioned by a pan and tilt unit under computer control. Images that it acquires are processed to generate surface meshes that are texture-mapped with a frame of color video. Pioneer's mapper is derived from stereo vision and 3D rendering developed by NASA for Mars Pathfinder, and modeling software developed by DOE for decommissioning nuclear facilities.

More information: `http://www.frc.ri.cmu.edu/projects/pioneer/`.

2.4 Search and Rescue

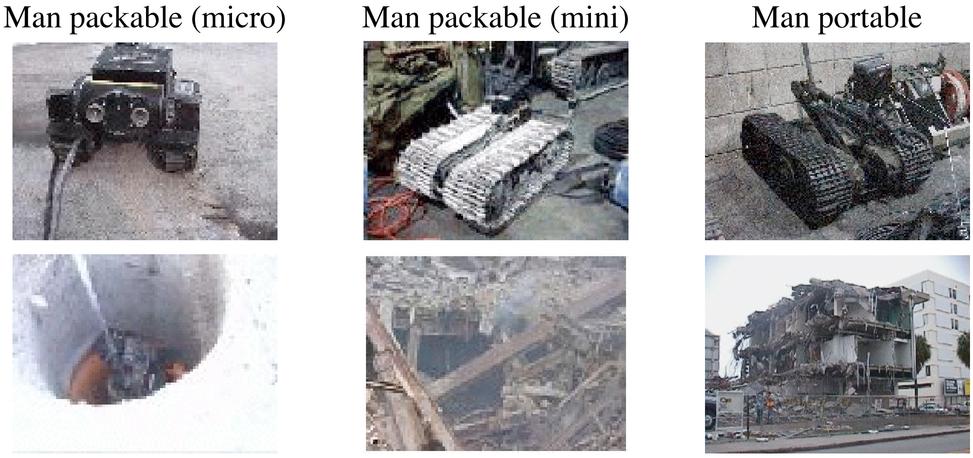
Robot platforms could potentially be used for a variety of tasks in search and rescue operations, including: delivery of food and medicals to buried survivors, rubble removal, victim transportation, and inspection of voids in the rubble pile. Until today, most robotic platforms have been used for the last task, exploring voids which are not accessible to humans because of their size or because of the extreme danger.

The first and most famous search and rescue operation to date has been the use of several robots to explore the rubble pile at "ground zero" at the World Trade Center after the September 11 event. The operation was carried out by the "Center for Robot Assisted Search and Rescue" (CRASAR) at the University of South Florida, FL, USA, under the direction of Prof. Robin Murphy. The CRASAR has since been very active in other robot assisted search and rescue operations – see `http://crasar.csee.usf.edu`.

The critical aspect that distinguish different robot platforms to be used for search and rescue operations is their size, since this determines the type of void that can be explored. The following classification has been proposed by Prof. Murphy:

Robot size	Type of void to explore
Man packable (micro)	sub-human (pipes, ventilation holes)
Man packable (mini)	confined space (voids in muck pile)
Man portable	semi-structured (partially collapsed building)

Man packable micro robots typically have the size of a shoe-box and are tethered. They are especially practical for exploring vertical spaces, e.g., holes. Man packable mini robots typically have the size of a backpack, and use on-board power and wireless radio communication. Most of them are tracked and are able to negotiate uneven surfaces and climb stairs. Portable robots have typically the size of a lawnmower, and use on-board power and wireless radio communication. Many have a manipulator and can carry a richer set of sensors than the other two classes of robots. They can be used for rapid handling of materials in hazardous situations. Larger robots can be used for extrication and rubble removal, and they belong to the



Man packable (micro) Man packable (mini) Man portable

Figure 2.13: Types of search and rescue robots, and the corresponding type of void that they are suited to explore

category "Manipulation in Hazardous Environments" which was described in the previous section.

Figure 2.13 show examples of the above three classes of robots, and the corresponding classes of voids.

In the rest of this Section, we describe some of the existing robot platforms which have been developed for search and rescue operations.

2.4.1 NASA "Urban"

The Urban Robot platform has been developed at the Nasa Jet Propulsion Laboratory in the USA. It is a novel chassis populated with several different cameras and sensors that are controlled by state of the art software. This combination creates a robot that can autonomously operate in widely varying terrain and can investigate different environments that are dangerous to people. Urban is shown in Figure 2.14.

The size and weight of Urban allow it to be carried to any location to be deployed. It can also be used to investigate areas to difficult for humans like culverts and tunnels.

The basic chassis is a tracked vehicle that is able to provide fast movement over

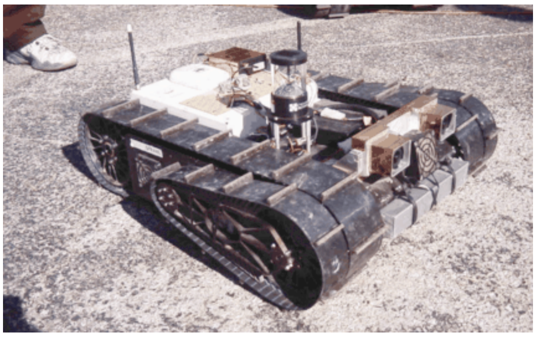
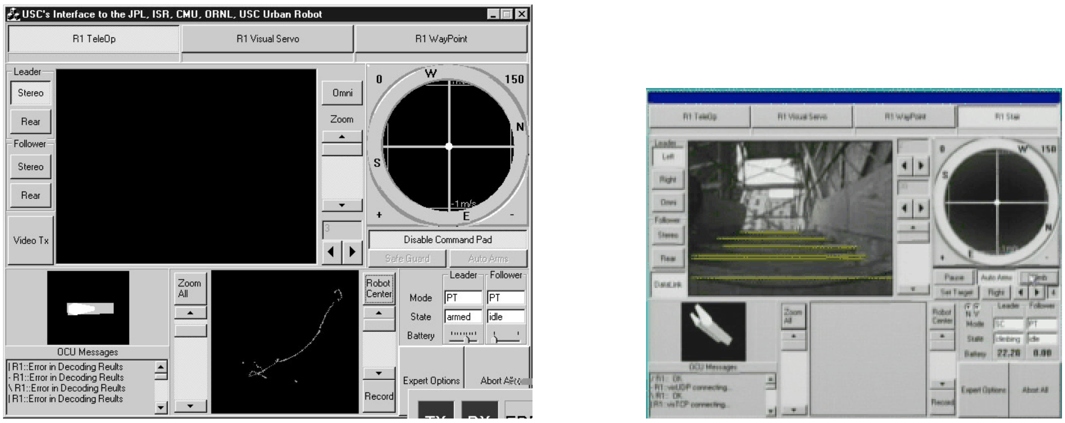


Figure 2.14: The Urban robot

rough terrain, and to traverse many different obstacles and barriers and handle varying terrain. The chassis is populated with many sensors and two processors for vision processing and robot control. The sensors include: stereo cameras, an Omnicam, three-axis gyros and accelerometers, digital compass, and a high-precision GPS. In the future the robot will also carry a night-vision camera and a two-axis scanning laser range-finder.

The robot's arms can rotate 360 degrees and they make the body very adaptable. They are used to help the robot mount obstacles or stairs and they can flip the robot over if it's inverted. An autonomous stair-climbing behavior is used to take the robot up multiple flights of stairs without any user control. This is accomplished with a combination of on-board sensors and vision algorithms to sense where the stairs are and which direction the robot should go to drive up the center of the stairs. Figure 2.15 shows Urban climbing a stairs, and entering a tunnel.

Figure 2.15: The Urban robot climbing a stairs (left) and entering a tunnel (right)



Mode: Leader PT, Follower PT
State: Leader armed, Follower idle

| R1::Error in Decoding Reults
- R1::Error in Decoding Reults
\ R1::Error in Decoding Reults
| R1::Error in Decoding Reults

Mode: Leader SC, Follower PT
State: Leader climbing, Follower idle
Battery: Leader 22.20, Follower 0.00

Figure 2.16: The operator interface of the Urban robot, in stand-by mode (left) and during a stair climbing (right)

Urban also has a vision-based obstacle avoidance system that steers the robot away from objects in it's path. This behavior is used to automatically maneuver around obstacles and to assist while the operator is driving.

The Operator Control Unit is a graphical user interface developed by the University of Southern California that runs on a laptop or wearable computer. It is used to control Urban by sending commands to run different behaviors or to remote control the robot if necessary. It also provides feedback to the user about the surrounding environment, the robot's position, the tilt and roll of the robot's body, and what Urban is seeing. The operator interface is shown in Figure 2.16.

More information: `http://robotics.jpl.nasa.gov/tasks/tmr/`.

2.4.2 SPAWAR "NUGV"

The NUGV (Novel Unmanned Ground Vehicle) has been designed and built by ACEi, Valencia, CA, under contract from the Space and Naval Warfare Systems Center (SPAWAR) in San Diego, CA, USA. It is a six degree of freedom, sensor-rich small mobile robot designed to test methods to improve mobility in this class of robots. It belongs to the "man packable mini" class.

This platform has not been used for search and rescue operations yet. However, its

Figure 2.17: The NUGV robot

has a great potential in that it has the ability to change its conformation while in motion and thus adapt to a range of physical obstacles and barriers in the environment. Figure 2.18 shows several different configurations.

The NUGV is composed of three pods: a center pod plus two identical lateral drive pods each connected to an end of the center pod via an "L" shaped axle. Each of the three pods contains sensors of the internal and external environments, batteries, two motors with transmissions, radios, computers and associated electronics. A local RF network provides communication among the pods and with the OCU. The lateral

(a) (b) (c)

Figure 2.18: Different configurations of the NUGV robot. (a) Fitting between a narrow gap. (b) Climbing a stairs. (c) Bipedal balancing

Figure 2.19: The operator interface of the NUGV robot

tracked pods are capable of independent motion. The NUGV's improved mobility is achieved using a combination of lateral pod track rotations (2-dof), lateral pod tilt rotations (2-dof), and lateral pod camber rotations (2-dof).

The NUGV operator interface displays motor currents, battery voltages, some sensor values, and video from one of four cameras selected by the operator. The OCU runs from any laptop and is reconfigurable. Figure 2.19 shows an example. The NUGV may be tele-operated, or released to operate under local reactive control, or operated with a combination of tele-operation and local reactive control.

More information: `http://www.nosc.mil/robots/land/nugv/nugv.html`.

2.4.3 iRobot "PackBot"

PackBot is a family of robots developed and commercialized by the iRobot company. They are compact tracked vehicle weighing about 20 Kg that have a self-righting capability using a pair of flippers.

The EOD model of PackBot has a lightweight OmniReach manipulator system that can reach as far as 2 meters in any direction. It belongs to the "portable" category.

Figure 2.20: The PackBot EOD robot

The PackBot robots were designed mainly to conduct military and law enforcement operations, but their characteristics make them suitable candidates for search and rescue operations as well.

More information: `http://www.irobot.com/`.

2.4.4 University of Tokyo “Khoga”

Khoga is a snake-like robot developed at the Matsuno Laboratory of the University of Electro Communications in Tokyo, Japan.

This snake-like robot is about 2 meter long and it can move by rotating the four screw-driving-like units attached on its body. The robot can move laterally, forward or forward-turn. The robot can get into narrow places and its long, thin body disperses weight to prevent collapse of damaged structures. It can be used to find trapped survivors under earthquake rubble. The Khoga robot can be dismantled

Figure 2.21: The Khoga robot

into about 10 parts for transport to disaster sites. It is radio-controlled, and it has a built-in camera.

More information: `http://www.hi.mce.uec.ac.jp/matsuno-lab/`.

Other examples of snake-like robots designed for search and rescue operations are: the Moira robot, developed at Kyoto University; and the elephant trunk like robot Snoopy, developed at Carnegie Mellon University. These are portrayed in Figures 2.22 and— 2.23, respectively.

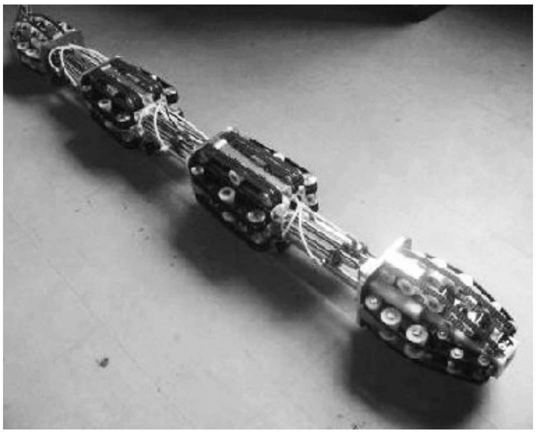


Figure 2.22: The Moira robot

Figure 2.23: The Snoopy robot (left), and a detail of its camera (right)

Chapter 3

Modes of Operation

3.1 Degrees of Autonomy

The traditional way to remotely operate a robot is for an operator to observe the robot's environment, either directly or via a remote camera, and to command its motor via some sort of joystick. Over the years, much progress has been made in endowing the robot with advanced functionalities that simplify the operation. Typically, these functionalities provide the operator with a more abstract interface to the robot by adding some "autonomous" capabilities to the robot.

Today there is an emerging consensus that the robot can operate under different "degrees of autonomy", ranging from pure tele-operation by part of the operator to full autonomous operation by part of the robot. There is also some consensus in the field that the most interesting configurations, especially for rescue systems, are somewhere in between these extremes. In this report, then, we will consider the following modes of operation.

- Tele-operation: the operator has full control;
- Tele-autonomy: the operator gives abstract-level commands and has access to pre-interpreted sensor data;

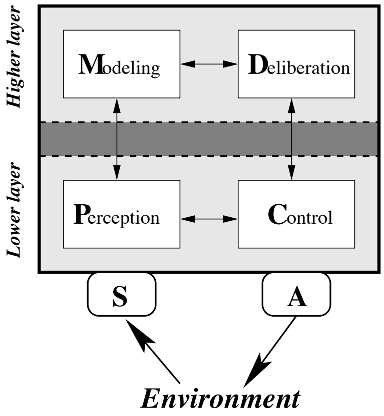


Figure 3.1: An abstract architecture for an "intelligent robotic agent".

- Shared autonomy: the robot and the operator are seen as "on-pair" partners in performing a joint task;
- Full autonomy: the robot performs the task entirely by its own, without any human assistance.

In what follows, we shall discuss each mode of operation, and provide a few example of the most interesting ones.

For the purpose of our discussion, we see a robotic system as comprising a set of functionalities organized in some way, for instance, in a generic two-layer hybrid architecture like the one shown in Figure 3.1. In these architectures, the top layer implements higher cognitive processes for world modeling (M) and for planning and deliberation (D). The bottom layer implements sensori-motor processes for sensing and perception (P) and for motion control (C), which are connected to a set of sensors (S) and actuators (A). We also see a human operator as an agent able to provide the same four functionalities. As we shall see, this will allow us to describe the different modes of operation as different ways to distribute the above functionalities between the two partners involved in the task: the robot and the operator.

3.2 Tele-Operation

Tele-operation is the oldest and still dominant way of interaction between a human operator and a (remote) robotic device. In terms of the architectural view adopted in this chapter, the “robot+operator” system is as depicted in Figure 3.2. The Sensors and Actuators reside on the robotic platform, usually complemented by some basic software that takes care of pre-processing of the sensor data (e.g., image compression) and of low-level control of the actuators (e.g., motor servos). All the other functions of the distributed “robot+operator” system are performed by the human operator. Namely, the human operator is in charge of: the perceptual interpretation of sensor data; the integration of this data to form a mental model of the environment and of the current situation; the formation of plans and decisions as to the next actions to be performed by the robot; and the actual control of the robot’s actuators, usually via a joystick interface.

This mode of operation relies on visual contact between the operator and the robot’s environment, either directly or through video transmissions, as shown in Figure 3.3. As it can be expected given the above list of functions which are delegated to the operator, tele-operating a robot is often a formidable task, complicated by the limited view from the video camera. Under such conditions, a human tele-operator must exercise extreme care, especially in obstacle-cluttered environments. Loss of

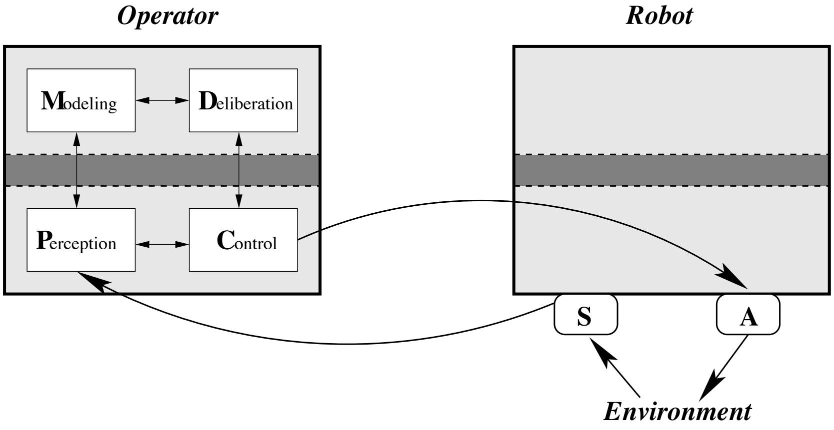


Figure 3.2: Robot-operator interaction in tele-operation.

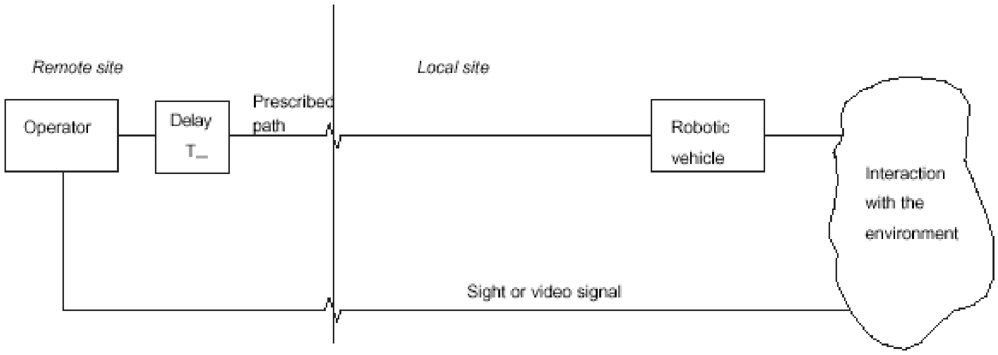


Figure 3.3: The control loop in tele-operation passes through the operator.

situational awareness, poor depth judgment, and failure to detect obstacles are common occurrences. Unpredictable time delays and occasional loss of communication are also common problems when tele-operating a robot via a radio link, especially in the type of environments encountered in rescue situations. Consequently, the actual traveling and operational speed of the vehicle might be very slow. When dust, smoke, or steam inhibit vision-based guidance, conventional tele-operated activity might have to be ruled out altogether.

Another important limitation of tele-operation from the point of view of rescue robotics is the cognitive overload of the operator. A great amount of the operator's attention is taken away by the need to perform the basic tasks needed for the robot's safe navigation, like watching out for obstacle, making sure that the robot is in a safe posture, and controlling its motors. This reduces the cognitive resources available to the operator to attend to the main task, that is, to analyze the data collected by the robot in order to assess the situation, e.g., to detect possible victims, and to decide a course of action. For this reason, in robotic rescue operations usually two operators are assigned to control each robot: one takes care of the navigation, and one concentrates on the analysis of the data collected by the cameras, microphones, and the other sensors on the robot. (As noted in the previous chapter, a third operator is often needed to perform "tether wrangling" if the robot must use a cable for energy and/or data transmission.)

Notwithstanding the above limitations, tele-operation is the most basic way to interact with a robot, and the only available one in most existing robots. For instance, most EOD (bomb disposal) robots are operated by giving the desired angles of each one of the joints of the manipulator. In more recent systems, the burden of tele-operation is somehow reduced by including more sophisticated software in the robot. For instance, many current robotic manipulators allows the operator to control the robot in work space rather than in joint space, that is, to give the desired Cartesian coordinates of the tool rather than the set of joint angles. In some sophisticated cases, the images provided to operator are enhanced in some way, for instance, by overlaying additional information using techniques from the field of augmented reality.

In general, a vast body or research is currently being performed in the field to develop more advanced ways of human-robot interaction for remote robot operation. We shall survey some of these in the rest of this chapter.

3.3 Tele-Autonomy

The "Tele-autonomy" paradigm started to emerge in the early 90's (e.g., [2]. The basic idea is to endow the robot with some limited capabilities for local autonomous perception and navigation, in order to reduce the cognitive burden of the operator. In terms of the "robot+operator" system, the situation is as depicted in Figure 3.4. Some (or all) of the Perception and Control functionalities are implemented in the remote robot. This allows the robot to follow the general directions prescribed by an operator, by taking care of the low-level details like attitude control or obstacle negotiation. In this way, the operators can focus most of their attention on the high-level Modeling and Deliberation tasks, and only give abstract commands to the robot. The operator can, for instance, click on a position in the image where the robot should navigate, or where it should point-and-zoom the camera. If the robot encounters an obstacle, for example, it autonomously avoids collision with that obstacle while trying to match the prescribed direction as closely as possible.

This mode of operation can be seen as composed of two nested control loops, as shown in Figure 3.5. The internal loop is of a sampled-data type and operates at a constant sampling frequency $f = 1/T$. Compared to conventional tele-operation, the internal loop causes only a minor delay in the entire operation of our system if the sampling period is small. On the other hand, the performance of the system

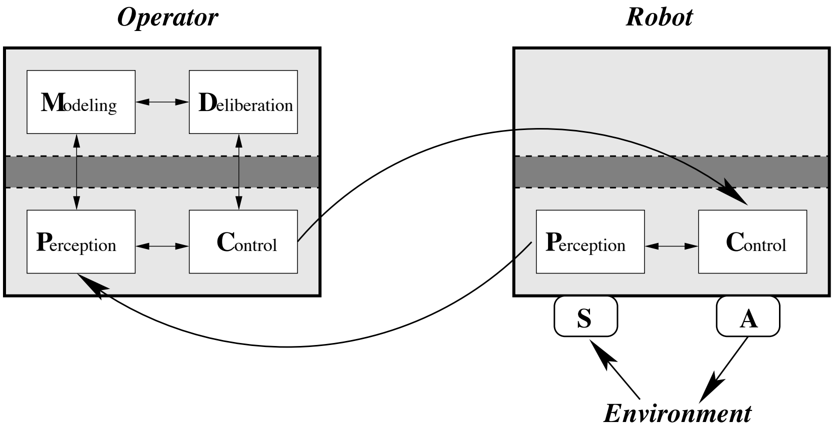


Figure 3.4: Robot-operator interaction in tele-autonomy.

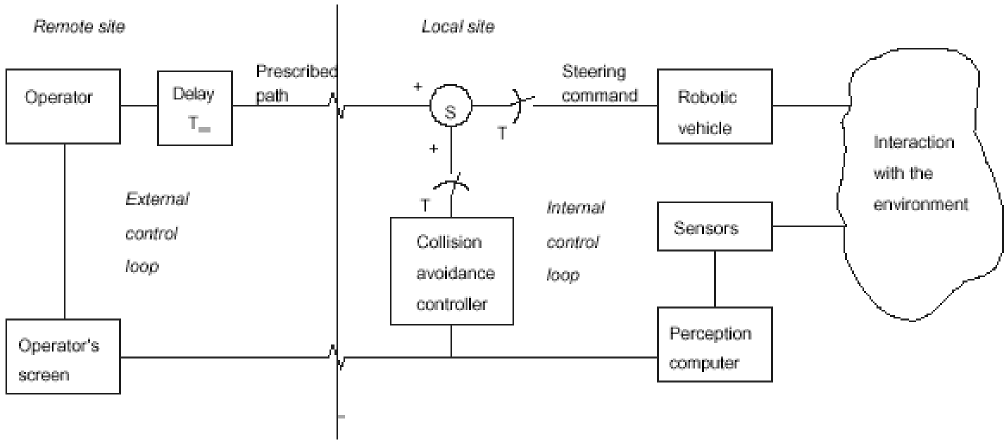


Figure 3.5: Tele-autonomy is characterized by two nested control loops.

would be degraded if T was large. Using a version of Shannon's sampling theorem, we may define the boundary condition for tele-autonomous operation as follows: Tele-autonomous operation can be implemented when the sampling frequency of the autonomous loop is greater than $1/T_d$, where T_d is the sum of the operator's delay (due to decision making and response time) and the communication delay. This in turn tells us that the amount of functionalities that can conveniently be embedded in the autonomous loop depends on the time T_d.

An early example of tele-autonomy is described in [1]. This approach, named tele-robotics, is designed for remotely operated manipulators and was tested on a PUMA robot. The tele-robotics concept also couples human commands with computer reasoning in a shared control architecture. The operator commands are communicated to a map and a sensor-based constraint analyzer. Based on knowledge of the environment acquired by a vision system and of the manipulator properties, the analyzer examines the consequences of the operator commands and determines appropriate perturbations, which are communicated to the robot controller.

Tele-autonomy comes in many varieties, depending on which functions are incorporated in the autonomous loop inside the robotic platform, and to what extent. Relevant insights to build tele-autonomy systems can come from several domains. In supervisory control, an operator divides a problem into a sequence of tasks which the robot must achieve on its own [10]. Sensor fusion displays combine information from multiple sensors or data sources into a single, integrated view [5]. More recently, vehicle tele-operation systems have emphasized the use of multi-modal operator interfaces and supervisory control [3]. Cooperative tele-operation tries to improve tele-operation by supplying expert assistance [8].

In general, tele-autonomy has several advantages compared with full tele-operation, including:

- It reduces the reaction time to events which are critical to the robot safety, like collision avoidance or posture control, thus increasing the robot's survivability.
- It guarantees that a reaction to the above events will be provided even in case of communication delays of losses.
- It does not require constant visual contact on the part of the operator.
- It may provide the operator with more abstract and richer information about the environment, and about the position of the robot in the environment, thus simplifying the tasks of perceptual interpretation and situation assessment.
- It releases the operators from low-level navigation concerns, allowing them to concentrate on the inspection task.

The most notable disadvantage of this mode of operation is that the operator might find it difficult to release some control to the vehicle. The success of this mode of operation critically depends on the design of the robot's autonomous behaviors and of the operator interface. The development of fully satisfactory solutions is still an active area of research in this field. In order to illustrate this research, in the following we briefly describe two state-of-the-art systems.

3.3.1 The PdaDriver at CMU

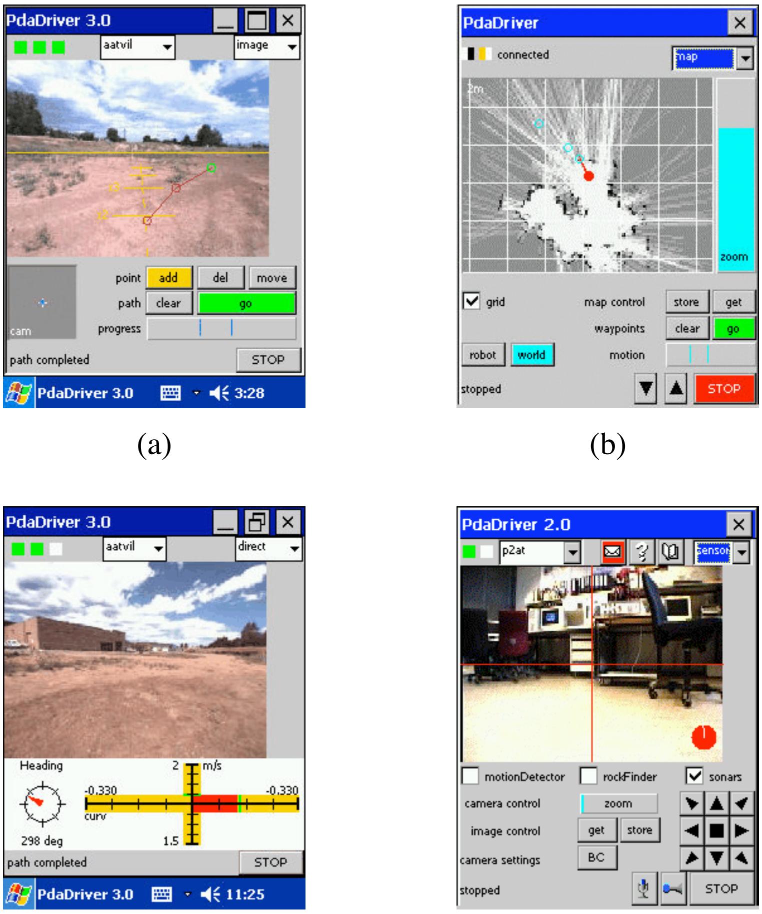
PdaDriver [3] is a Personal Digital Assistant (PDA) interface for vehicle tele-operation developed in a cooperation between Carnegie Mellon University (Pittsburg, PA,

Figure 3.6: The PdaDriver

USA) and the École Polytechnique Fédérale de Lausanne (Switzerland). Although the PdaDriver is not reported to have been used in rescue operations yet, we mention it here since we believe that it would provide an effective operator interface for rescue robotic platforms.

PdaDriver was designed to be easy-to-use, easy-to-deploy and to function even when communication links are low-bandwidth and high-latency. PdaDriver uses multiple control modes, sensor fusion displays, and safeguarded tele-operation to enable efficient remote driving any-where and anytime. The PdaDriver has been originally implemented using a WindowsCE Palm-size PC and Personal Java, shown in Figure 3.6, but other versions have later been developed. The PdaDriver provides relative position, rate, and way-point (image and map) control modes.

PdaDriver provides four different modes to interact with the remote platform, illustrated in Figure 3.7. In *image-based mode* the operator is shown live images from a camera located on the robot. They can pan and tilt the camera by clicking in the gray camera control box. Yellow lines shown on the image indicate the projected horizon line and robot width. The operator drives the robot by clicking a series of way-points on the image and then pressing the go button. As the robot moves, the progress bar displays the robot's progress. This image-based way-point driving



path completed

connected

stopped

path completed

stopped

(a) (b)

(c) (d)

Figure 3.7: The four PdaDriver interaction modes. (a) Image-based mode. (b) Map-based mode. (c) Direct mode. (d) Sensor mode.

method is well suited for unstructured or unknown terrain as well as for cluttered environments.

In *map-based mode*, the operator is shown a map (an occupancy grid constructed by histogramming sonar range data) registered to either robot (local) or global (world) coordinates. As in the video mode, the operator drives the robot by clicking a series of way-points on the image and then pressing the go button. As the robot moves, the motion status bar displays the robot's progress. This mode helps to maintain situational awareness and is useful for long-distance movements.

In *direct mode* the operator has direct rate control, mimicking a 2-axis joystick. The operator controls the robot's forward and backward speed by clicking on the vertical axis. Clicking on the horizontal axis controls the robot's rotation. A compass continually displays the robot's absolute heading.

The final mode is *sensor mode*. Unlike the other modes, this mode is not used to generate motion commands. Instead, it is designed for configuring robot sensors and perception modules. For instance, in this mode the operator can control the robot's camera and sonar array, or decide to enable (or disable) specific perception modules like the MotionDetector and RockFinder.

PdaDriver has been tested on field trials in a variety of environments, both indoor and outdoor. Since remote driving is performed in a safeguarded, semi-autonomous manner, continuous operator attention is not required and the robot moves as fast as it deems safe. Anecdotal evidence from both novice and expert users suggests that the PdaDriver has high usability, robustness, and performance. Furthermore, users reported that the interface enabled them to maintain situational awareness, to quickly generate commands, and to understand at a glance what the robot was doing.

3.3.2 The DDT project in Japan

The DDT (DaiDaiToku) project is part of special program for "Earthquake Disaster Mitigation in Urban Areas" launched in 2002 in Japan by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The DDT project focuses on the "Development of Advanced Robots and Information Systems for Disaster Response". Its objective is technology development of effective information collection for disaster response at urban large-scale earthquakes by applying robotics and related technologies.

This project focuses on robotic and intelligent technologies for support of human-body search, information collection and distribution in emergency response (including search and rescue) to large-scale earthquake disasters. The project does not focus just on the development of a robotic platform, but it takes a comprehensive approach to the entire problem of disaster management, as illustrated in Figure 3.8. The project is managed by the International Rescue System Institute (IRS), a non-

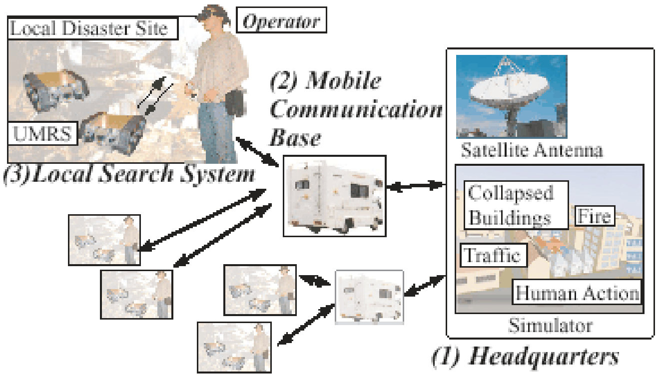


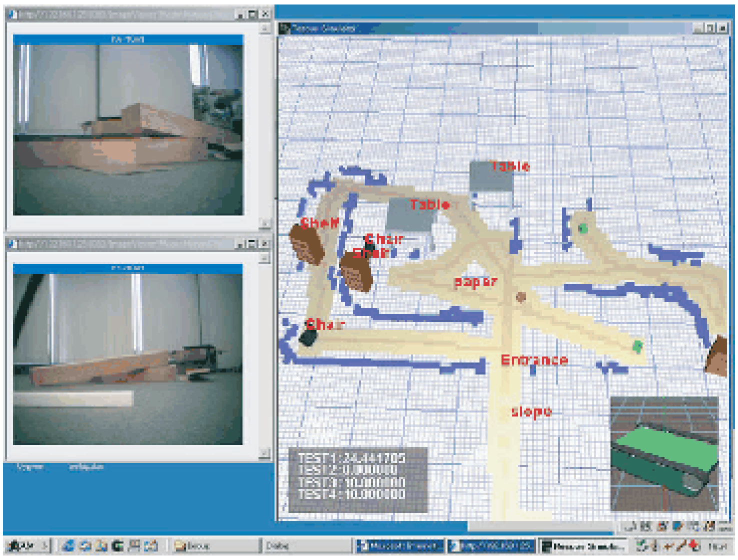
Figure 3.8: The concept of advanced robots and information systems for disaster response developed in the DDT project.

profit organization [7]. The main research centers are the Kawasaki Laboratory in the Tokyo area, and the Kobe Laboratory in the Kansai area.

The DDT project explicitly targets the development of tele-autonomy. The project aims at having several robots that move with some degree of local autonomously under the guidance of a few human operators. Local autonomy here is the key to enable operators to control multiple robots.

Figure 3.9 shows the operator interface to a UMRS robot, one of the platforms used in the DDT project. The operator can control forward/backward and rotational movements using the keyboard or the mouse. The interface provides a live camera view, a map view, and a diagnostic of the posture and conditions of the platform.

The map view shows the result of an autonomous map building performed by the robot. This map gives information about traversable and non-traversable areas, e.g., debris. In addition, entities of interest can be manually identified and selected in the camera image by the operator, and placed in the map. Typical entities can be visual landmarks, like desks or doors, or victims. This facilitates the later localization of these entities by the rescue team.



```
TEST1 : 24.441705
TEST2 : 0.000000
TEST3 : 10.000000
TEST4 : 10.000000
```

Figure 3.9: The operator interface developed in the DDT project.

3.3.3 The GasBot Project at the University of Örebro

At the Center for Applied Autonomous Sensor Systems (AASS) of the University of Örebro, Sweden, we have performed an initial study toward the realization of a robotic system for assisting fire-fighting and rescue services. The system implements the concept of tele-autonomy between the robot and the human operator: the mobile robot performs local navigation, sensing and mapping, while the operator interprets the sensor data and provides strategic navigation goals.

The aim of this pre-study was to evaluate the use of mobile robots as *remote amplifiers of the perception capabilities* of field personnel. This refers to the safe and reliable collection and communication of information at different levels of abstraction, which is relevant for the successful execution of a task. Target tasks include fire-fighting, search and rescue, and inspection of human-unfriendly sites. Easy, reliable, and task-dependent means of human-robot interaction were identified as crucial aspects to enable the field deployment of mobile robots.

The most important reason for a human-in-the-loop, as opposed to a fully autonomous robot, in this project was psychological: the system should be perceived and accepted as a "trusted partner" by the rescue personnel. Two preferred interaction modes with such a partner have been identified by the field personnel: given a view from a camera and a view of an online local map of the environment, (i) point-and-click on the map or in the image to indicate locations where the robot should go, and (ii) point-and-click on interesting objects seen in the camera image to include them in the map. By "online local map" we mean a map of the space around the path traveled by the robot, built by the robot itself.

The main components currently implemented in this system are as follows.

- Map Builder. It incrementally builds a map (occupancy grid) of the environment from laser data. At the same time, it estimates the robot's position in this map using a multi-level relaxation algorithm [6].
- Path Planner. It takes navigation goals from the user by point-and-clicking on the map. It plans a path across the free space, and regularly updates this path as new parts of the environment (obstacles) are detected by the robot and included into the map.
- Path Follower. It moves the robot along the planned path, and reactively adapts to new or dynamic obstacles. The integration of path following and reactive obstacle avoidance is achieved using fuzzy-logic behaviors [9]. The controller can be overridden by the operator using a virtual joystick.
- Video Streamer. It shows the images taken by the camera. The user can point-and-click on locations to visit or on objects to be included in the map. An image interpretation layer will be added in the future to detect and highlight possible objects of interest for the user, and suggest possible identifications.

The user is presented with the interface shown in Figure 3.10. The leftmost window represents the robot, in top view, and the sensor readings in the vicinity of the robot. This view is robot-centric: the robot is fixed at the center of the window, and the sensor readings give an outline of the environment around it. This view makes it easier to joystick the robot around if the operator wishes to take full control.

The middle window displays the current map built by the robot, in world-centered coordinates. The map is built incrementally as the robot acquires more sensor data.

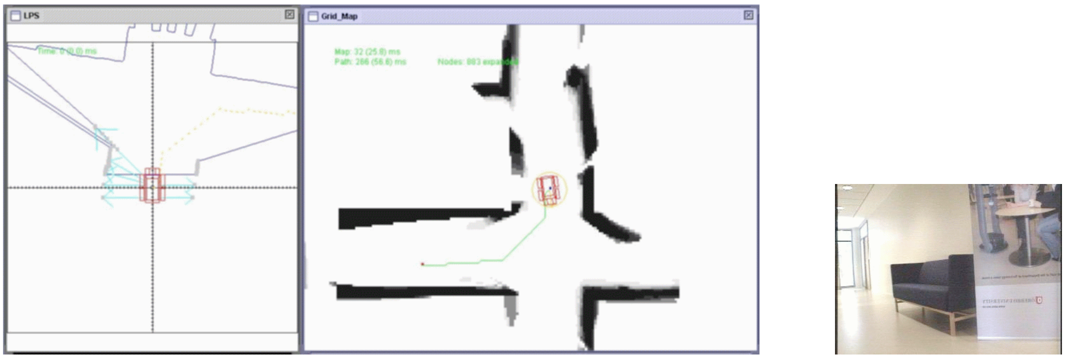


Figure 3.10: The GasBot operator interface. The leftmost window displays the sensor readings in the vicinity of the robot; the middle window displays the current environment map built by the robot; the rightmost window shows the images taken by the robot camera.

This map gives the operator a view of the shape of the environment and of the objects in it, together with the awareness of the robot's position in the environment. In this example, the robot has just explored the corridors around an intersection, and it is coming back to the intersection. The operator has clicked on a point in the left corridor (red dot) in order to instruct the robot to enter that corridor. The path planner has generated a path (in green) to that point through the free space, which the robot is following. The path is re-computed every second in order to account for new obstacles that are detected by the robot's sensors.

The rightmost window shows the images taken by the robot camera. The user can point-and-click in this window as well in order to indicate a location where the robot should go. The clicked point is translated to global world coordinates and included in the robot map, and a path to that point is computed as above. In the future, the user will be offered the possibility to click on specific objects in the image in order to put them in the global map.

The system does not include any sophisticated processes dedicated to image analysis, scene understanding, high-level decision making or planning. According to the concept of tele-autonomy, these high-level functionalities are provided by the human operator, while the remote robotic system takes care of local navigation, sensor processing, and mapping.

3.4 Shared Autonomy

As noted above, tele-operation often poses serious demands on the remote operator, and it might lead to poor performance and reduce safety of the robot. Tele-autonomy partly alleviates these problems, but factors such as poor communications and operator workload may still compromise task performance in situations.

In those cases, it might be convenient to endow the robot with even more autonomy, so that the operator perceives the robot as a "trusted remote companion". In terms of the "operator+robot" distributed system, the situation can be depicted as in Figure 3.11. We let the robot have all of the {S, A, P, C, M, D} functionalities, to some extent, so that the robot is able to perform sub-tasks in an autonomous way. We then let the operator interact with these functionalities to provide guidance and information. As a variant to this situation, the operator could also be in contact with the environment, that is, sense it and act on it directly.

This model of human-robot cooperation has received several names in the literature, including *shared autonomy*, *mixed initiative* and *collaborative control*. The main rationale, as advocated by [4], is to let the human operator and the robot collaborate to perform tasks and to achieve goals. Instead of a supervisor dictating to a subordinate, the human and the robot engage in dialog to exchange ideas and resolve differences. As an example, the following could be a dialogical interaction

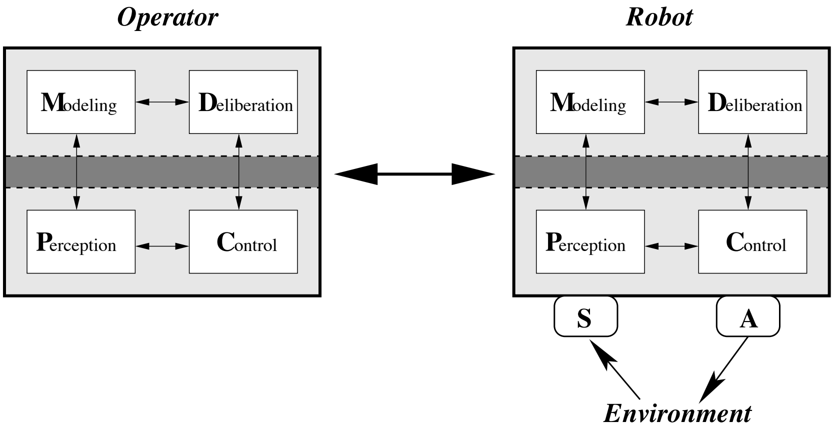


Figure 3.11: Robot-operator interaction in shared autonomy.

between a robot (rob) and an operator (opr).

Category	Direction	Message
Command	opr → rob	Go to this way-point (click on map)
Information	rob → opr	I think I'm stuck because my wheels spin
Query	opr → rob	Where are you?
Response	rob → opr	A map (shown on display)
Query	rob → opr	What object is this (image)?
Response	opr → rob	A chair (selects item from a menu)

With shared autonomy, the human is able to function as a resource for the robot, providing information and processing just like other system modules. In particular, the robot can ask the human questions as it works, to obtain assistance with cognition and perception during task execution. This enables the human to compensate for inadequacies of autonomy, but does not require time-critical nor situation-critical response. Thus, in a sense, shared autonomy emphasizes robot-human interaction rather than human-robot interaction.

Shared autonomy is a novel and potentially useful paradigm for tele-operation. It is novel because it uses dialog as a framework for coordination, to direct joint task performance and to focus attention where it is needed. It is potentially useful because it provides an efficient mechanism for adaptation, to adjust autonomy and human-robot interaction to fit situational needs and user capabilities. However, research on shared autonomy is still at an early stage, and much progress is probably needed before it can be accepted as a reliable paradigm for human-robot interaction in critical situations. Moreover, shared autonomy relies on the ability of the robot to perform non-trivial tasks with a relatively high degree of autonomy and reliability. This again is still an open research issue, especially in extremely an challenging domain like rescue operations.

3.5 Full autonomy

All the above modes of operation cover a continuous range of possible ways to share responsibility between the operator and the robot. Tele-operation is one extreme in this scale, in which control is fully in the hands of the operator. The opposite extreme is represented by full robot autonomy. In this mode of operation, the robot is a fully autonomous and independent system that performs the assigned task without any supervision by, or interaction with, the human operator. This situation is depicted in Figure 3.12. The robot has all of the $\{S, A, P, C, M, D\}$ functionalities which are needed for the performance of the task, and no interaction with the operator occurs.

Fully autonomous robot performance in non-engineered environments is still an open, and very active research issue. While a lot of progress is being made in this area, all of the current autonomous robotic systems can only provide reliable performance in a limited and constrained set of environments. Rescue missions intrinsically involve environments which are extremely harsh, non-structured, and unpredictable. Moreover, these missions are very safety-critical, and decisions often involve a large amount of technical and non-technical knowledge, as well as difficult moral judgments. For this reasons, in the opinion of this author fully autonomous robots are not suitable for rescue missions. Full autonomy will therefore not be

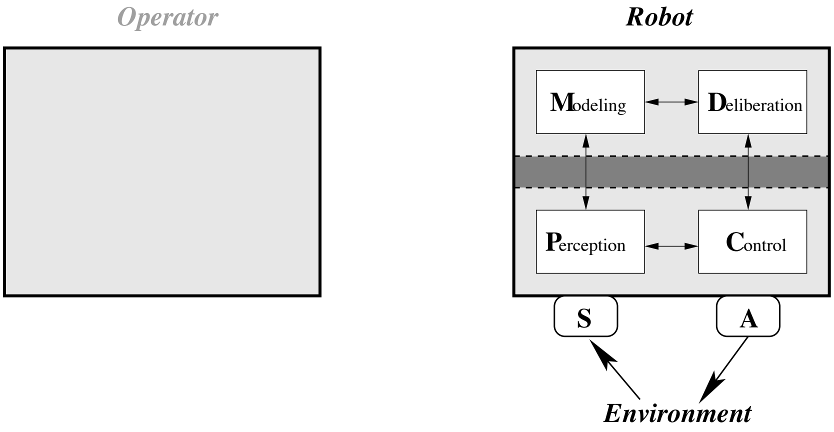


Figure 3.12: No operator-in-the-loop is considered in full autonomy.

investigated further in this report.

Chapter 4

Concluding Remarks

Robotic platforms have been used in the emergency response and rescue domains for three main categories of tasks: fire fighting, manipulation in hazardous environments, and search and rescue. In most cases, the platforms used are well adapted to the task from the mechanical point of view, and many cases are reported in which human lives have been saved thanks to the use of a remotely operated robot. The combination of the increasing technological performance and decreasing cost is likely to result in a greater demand for robots by part of rescue personnel. This in turn is likely to increase the number of commercially available systems, which today is rather limited.

Despite these positive points, our study has revealed that the existing rescue platforms are often far behind the state of the art of robotic research from the points of view of functional autonomy and of human-robot interface. One consequence of this is that each robot needs at least two human operators, even though some of them (man-packable) can be carried by just one person. The use of a tether requires even one more "tether wrangling" operator, who is often put at risk since he/she must operate in close proximity of the area where the robot has been dispatched. In the near future, it is expected that the concept of "tele-autonomy", together with better energy management, will help to eliminate the need for a umbilical connection and to reduce the operator's cognitive load. These factors are expected to bring the operators/robots ratio to 1/1, and possibly 1/many in a more distant future. Coordinated use of teams of robots under the supervision of a small number of operators is an attractive scenario for future rescue robotics.

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