

A survey on teleoperation

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A Survey on Teleoperation

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DCT 2007.155

DCT report

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1 Introduction

Teleoperation means "doing work at a distance", although by "work" we mean almost anything. What we mean by "distance" is also vague: it can refer to a physical distance, where the operator is separated from the robot by a large distance, but it can also refer to a change in scale, where for an example a surgeon may use micro-manipulator technology to conduct surgery on a microscopic level. Teleoperations comprise a robot technology where a human operator (master) controls a remote robot (slave). The system is formed by two parts, the control module, called cockpit and the telemanipulator, the slave robot at the remote location.

Traditionally teleoperation has been used in applications where normal on-board manual operation/control cannot be used or where it would be too hazardous or expensive. Typical examples are the handling of nuclear materials (dangerous), control of small models (impossible) and space and underwater exploration (too hazardous and expensive). The history of modern teleoperation began at the end of the 1940's when the first master - slave manipulator was developed in the Argonne National Laboratory for chemical and nuclear material handling [72]. After that, the development of teleoperation was fast. Adaptation of video technology and force feedback to teleoperation made the first telepresence systems possible. Computer technology brought the advanced control loops into the remote (teleoperator) end of the system, and finally brought virtual reality into teleoperation. Despite progress in the technology, the traditional idea of teleoperation was based on the idea that the human operator would at all times be available to exercise more or less direct control.

The evolution of teleoperation has generated sophisticated telepresence systems where the operator can really feel that he is present in the teleoperation site. When looking at the related research in the area of teleoperation, it may be noted that most of the research has been done in order to provide better and more effective teleoperation methods for difficult work and manipulation tasks where stereo vision and anthropomorphic manipulators with force feedback are needed in order to perform the task.

The aim of this report is to present the state-of-the-art teleoperation systems with their different applications and the control issues which have been tackled by the system control community. This report is the first chapter in the Teleman project framework, which is focused on building a teleoperation system for a generic robot. This report is organized as follows: firstly, we recall some definitions concerning telerobotics, a short history of the development of teleoperations and different applications which use teleoperated robots. In the second part, the focus is set on telepresence and the means to ensure a transparent and direct connection between the human operator and the remote environment where the slave robot performs its tasks. The third section deals with the control issues of teleoperation with an emphasis on control under communication delay problem. In the last part of this report, we conclude with the perspectives of the Teleman project.

2 Teleoperation

This section recalls first some definitions used in the telerobotics community. Afterwards we focus on the chronological development of teleoperation applications and we finish with a presentation of the different fields of application of teleoperated robots/vehicles.

2.1 Definitions

This section comprises a set of definitions which are to help the reader understand what the writer has meant with the word in this document.

Robot: "Any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a human-like manner. By extension, robotics is the engineering discipline dealing with the design, construction, and operation of robots." [10]

Autonomous robot is a robot, which is not available now, and will be extremely difficult to build in the future. Animals and humans are autonomous. To be autonomous a robot has to have consciousness, which can not be created by existing computer technology. (This is the author's own, rather pessimistic opinion.) Usually the term *autonomous robot* is used for a robot that can execute its task(s) autonomously without an operator's help.

Operator: A human operator is the person who monitors the operated machine and takes the control actions needed.

Teleoperator is the teleoperated machine (robot).

Teleoperation means "to operate a vehicle or a system over a distance" [23]. However more exact definitions are needed to separate the poking of fire from high-level supervisory control. The first teleoperation tasks such as poking fire or manipulating nuclear material can be classified as *remote operation* or *remote manipulation*. The word "remote" emphasizes that the controlled vehicle or system is at some distance from the operator. Today, in the "normal teleoperation", there is no direct visual contact with the controlled system. The visual feedback is usually made by a camera-display combination. Controlled commands are sent electrically by wire or radio/wireless. When the connection between the manipulator and operator is mechanical, the term "remote manipulation" means mechanical manipulation. In tele-manipulation, the connection is electrical.

Between the simple mechanical manipulation and high-level supervisory control, there are several systems of different technical levels included under the term teleoperation.

Mechanical manipulation: The control commands are transmitted mechanically or hydraulically to the teleoperator. Visual feedback can be direct or via a monitor.

Remote operation/control: The operator has direct visual contact most of the time with the controlled target. Control commands are sent electrically by wire or radio.

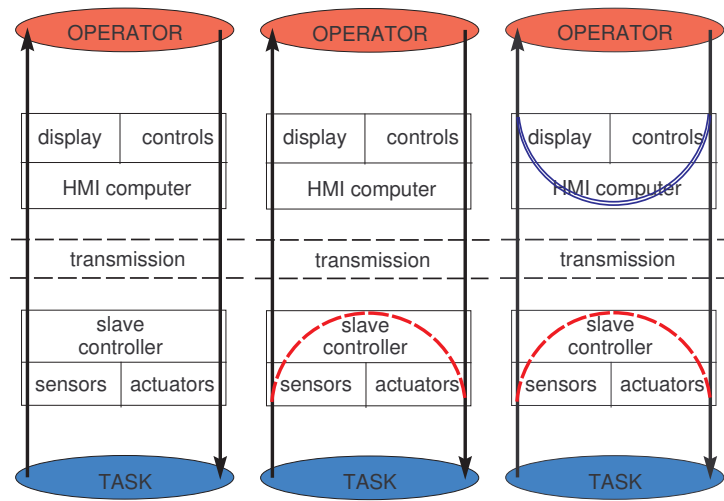


Figure 1: Teleoperation strategy

To clarify the wide concept of "teleoperation", the applications are classified into three classes:

1. *Closed loop control (Direct teleoperation)*: The operator controls the actuators of the teleoperator by direct (analog) signals and gets real-time feedback. This is possible only when the delays in the control loop are minimal. A typical example of this is a radio controlled car.
2. *Coordinated teleoperation*: The operator again controls the actuators, but now there is some internal control loop in the teleoperator (the dotted line in figure 1). However, there is no autonomy included in the remote side. The remote loops are used only to close those control loops that the operator is unable to control because of the delay. A typical example of this is a teleoperator for whom the speed control has a remote loop and, instead of controlling the throttle position, the operator gives a speed set point. Digital closed loop control systems almost always fall into this category.
3. *Supervisory control*: Most of the control part is to be found on the teleoperator side. The teleoperator can now perform part of the tasks more or less autonomously, while the operator mainly monitors and gives high-level commands. The term "task based teleoperation" is sometimes used here. In figure 1, the double loop (on the operator side) demonstrates feedback from the Human-Machine Interface (HMI). This can be a virtual model, estimated parameters, etc.

Telepresence (tele-existence): If a sufficient amount of sensor information (vision, sound, force) is brought from the teleoperator site to the operator, then he feels physically present on the site.

Virtual presence (or Virtual reality): It is similar to telepresence, except the environment where the operator feels to be present (and the sensor information) is

artificially generated by a computer (blue line from figure 1).

Augmented presence (or Augmented reality): It is a combination of real world sensor information and virtual reality. A typical example of this is a real camera image with additional computer generated virtual information.

2.2 History

The poking of fire might have been one of the first general teleoperation tasks in the history of mankind. To be exact, the poking of fire is tele or remote manipulation, which was the earliest type of teleoperation. This task is also a good example with which to demonstrate the difference between teleoperation and tool utilization. A human hand is a perfect tool for setting the firewood better and, in fact, usually the unfired wood is set by hand in the fireplace. After the fire has been set, the environment is so hostile that a more adequate tool must be used in order to protect the hand. Tools make it possible to perform a task like cutting (a knife), or to improve work like digging (a spade).

The first modern master - slave teleoperators were mechanical pantographs. The group working under R. Goertz developed these manipulators in the late 1940's at the Argonne National Laboratory, where it was developed for the first nuclear reactor [72]. The need was obvious. The radioactive nuclear material has to be manipulated safely. The nuclear material was placed in a "hot cell" where the operator could manipulate it outside the cell by remote handling. The visual contact with the target was through a protective window and/or a mirror.

The mechanical manipulators were soon replaced by electro mechanical servos. In 1954, Goertz's team developed the first electro mechanical manipulator with feedback servo control. After this, the teleoperation of manipulators and vehicles extended rapidly to new branches where the advantages of teleoperation techniques could be utilized.

One of the first areas where teleoperation techniques were utilized was deep-sea exploration. The deep oceans are even today regarded as so hostile that most of the deep-sea operations are made with teleoperated submarines. These submarines are called - even today - Remote Operated Vehicles (ROV), though the term could be equally well understood as referring to ground, or even flying, vehicles. Often ROVs are equipped with telemanipulators in order to perform underwater work tasks. Teleoperation is also typically used for space and military applications. In both cases, the environment is hostile for humans, while in space applications there is the additional point that the extra equipment needed for the human pilot is more expensive than a sophisticated teleoperation system.

2.3 Applications

2.3.1 Space Applications

The space is a very appropriate environment for teleoperation applications. The physical presence of a human to operate a vehicle in space requires many resources (Moon/Mars exploration) or is totally impossible (Sun exploration), therefore it is more efficient to use teleoperated vehicles (figure 2). The space applications are divided into different groups:

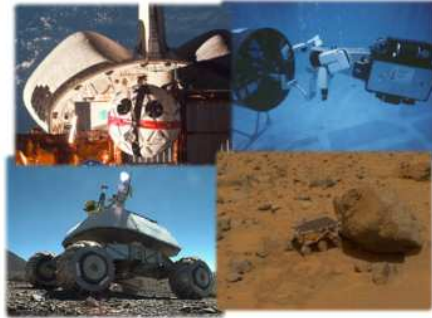


Figure 2: Space Applications for Teleoperation, courtesy NASA (<http://www.nasa.gov/>)

1. Space exploration robots

In the human quest to explore the Moon, Mars or the Solar system, the need for exploration vehicles is undeniable as a first step for gathering information. The exploration vehicles can be classified as:

- Landing robots (e.g. Sojourner(NASA), Rocky I-IV(NASA), Lunakhod 1(Russia))
- Exploration probes (e.g. Voyager(NASA))
- Deep Space Observers (e.g. Hubble Observatory)

2. Satellites

Satellite communication, reliable weather forecast and GPS positioning are only some of the satellite applications which respond to human needs.

3. Outer-space robot arms

On the International Space Station some robot arms have been build to perform different tasks outside the station without the hazards of a human being working in the outer-space.

2.3.2 Military/Defensive Applications

Just like for space exploration, military applications include recon missions. Gathering information about an enemy is a very common task for a military operation. Of course, the recon missions are also the riskiest. In order to avoid the loss of humans, teleoperated recon vehicles have been deployed. Different kinds of environments have led to build a large variety of teleoperated vehicles, both air and ground vehicles.

The modern Unmanned Air Vehicles (UAV's) like the US Air Force Predator (figure 3) are remotely piloted by radio or by satellite links. They can also have the capability to fly autonomously with the help of GPS and inertial navigation.

Unmanned Ground Vehicles (UGV's) have also a wide application field in military operation: reconnaissance, route clearing, land-mine detection. The newest models like SARGE (figure 4) are equipped with vehicle localization (GPS, Inertial navigation) and supervisory control to improve the performance. Military UGV's are often supplied with the state of the art teleoperation equipment (like stereovision telepresence) to provide the best possible feedback in fast and dangerous



Figure 3: Unmanned Air Vehicle. Predator, courtesy US Air Force (<http://www.airforce-technology.com/projects/predator/>)



Figure 4: Unmanned Ground Vehicle. The Surveillance And Reconnaissance Ground Equipment(SARGE), courtesy Sandia National Laboratories (<http://www.sandia.gov/isrc/SARGE.html>)

operations.

Other military applications consist in clearing land-mine fields. A teleoperated



Figure 5: Land-mine field clearing vehicle. Scanjack, courtesy Scanjack AB (<http://www.scanjack.com/>)

mine dismantling machine called Scanjack (figure 5) has been produced in collaboration with the Swedish army and is used to clear mine-fields with the UN peace keeping forces.



Figure 6: Bomb deactivating robot, courtesy PoliceOne (<http://www.policeone.com/>)

2.3.3 Security Applications

Similar to the military applications, the security field presents some teleoperation systems. On the one hand, with the rising number of terrorist actions, most police departments have created bomb squads for deactivating bombs. A very useful equipment is the "Terrobot" ([17, 32]), a teleoperated vehicle with robot arms and tools for deactivating a bomb.

On the other hand, another security application is surveillance. Two of the best known security teleoperated robots are:



Figure 7: Rotundus, courtesy Rotundus AB (<http://www.rotundus.se/>)

- Rotundus (Figure 7) is a spherical robot without external feet or wheels which moves through the balance of a weight inside the sphere. It has two surveillance cameras behind shielded glass areas and can attend speeds of up to 70km/h (much more than a running human).
- Secom (Figure 8) is a robot produced for Tokio police department. It can be used for surveillance and for stopping a person it can spray a cloud of gas.

2.3.4 Underwater Vehicles

As mentioned before, underwater operations were one of the first mobile applications where teleoperation techniques were adopted. Today these ROV's probably represent the largest commercial market for mobile vehicle teleoperation. ROV's are used in surveying, inspections, oceanography and different simple manipulation and work tasks, which were traditionally performed by divers. ROV's are



Figure 8: Secom Robot X, courtesy Secom (<http://www.secom.co.jp/>)

generally tethered to a surface ship and controlled using video monitors and joysticks. The most recent system can also perform some autonomous tasks such as station keeping or track following (figure 9).

Submersible ROV's are normally classified into categories based on their size, weight, ability or power. Some common ratings are:



Figure 9: Submersible Victor, courtesy French Research Institute for Exploitation of the Sea (<http://www.ifremer.fr/>)

- Micro - typically Micro class ROV's are very small in size and weight. Today's Micro Class ROV's can weigh less than 3 kg. These ROV's are used as an alternative to a diver, specifically in places where a diver might not be able to physically enter such as a sewer, pipeline or small cavity.
- Mini - typically Mini Class ROV's weigh in around 15 kg. Mini Class ROV's are also used as a diver alternative. One person may be able to transport the complete ROV system out with him/her on a small boat, deploy it and complete the job without outside help. Occasionally both Micro and Mini classes are referred to as "eyeball" class to differentiate them from ROV's that may be able to perform intervention tasks.
- General - typically less than 5 HP (propulsion); occasionally small three finger manipulators grippers have been installed. These ROV's may be able to carry a sonar unit and are usually used on light survey applications. Typically

the maximum working depth is less than 1000 metres though one has been developed to go as deep as 7000 m.

- Light Workclass - typically less than 50 HP (propulsion). These ROVs may be able to carry some manipulators. Their chassis may be made from polymers such as polyethylene rather than the conventional stainless steel or aluminium alloys. They typically have a maximum working depth less than 2000 m.
- Heavy Workclass - typically less than 220 HP (propulsion) with an ability to carry at least two manipulators. They have a working depth up to 3500 m.
- Trenching/Burial - typically more than 200 HP (propulsion) and not usually greater than 500 HP (while some do exceed that) with an ability to carry a cable laying sled and work at depths up to 6000 m in some cases.

2.3.5 Telerobotics in Forestry and Mining Applications



Figure 10: The Centauroid Robot Work Partner, courtesy Helsinki University of Technology (<http://automation.tkk.fi/WorkPartner>)

The use of heavy equipments in forestry and mining and the hazards of falling trees, rough terrain and caving in mine galleries have imposed the use of teleoperated robots. The Helsinki University of Technology has produced Work Partner (figure 10), a robot which can perform forestry tasks. It is a dedicated centauroid (centaur-like) which a very well-developed human-machine interface. A vast range of tests have been done on this platform to identify also the operator's response from a psychologic point of view.

The mining applications considered for teleoperation are:



Figure 11: Mine Exploration Robot. Groundhogbot, courtesy The Robotics Institute, Carnegie Mellon University (<http://www.ri.cmu.edu/>)



Figure 12: Mine Rescue Robot. Cave Crawler, courtesy The Robotics Institute, Carnegie Mellon University (<http://www.ri.cmu.edu/>)

- Excavating machines. The tunneling and drilling machines can be operated from surface without the presence of a human being close by. For a full mine automation, a system of conveyer belts and railway wagons is needed, but nevertheless an integrated system as such can be exploited directly from a command center on the surface.
- Exploration robots. Searching for seams of precious ore can be a risky business, therefore Carnegie-Mellon Robotics Institute has produced Groundhogbot (figure 11), which can explore and take rock samples from the mine most secluded corners.
- Rescue robots. Mine accidents with cave in galleries and human workers trapped inside need a quick response. The rescue teams have to use a robot to check where are the trapped humans and if they are injured. Similar type of robot can be used for rescuing people in earth-quake damaged buildings. Cave Crawler (figure 12) is a teleoperated robot which can also retrieve an injured person from a mine.

2.3.6 Telesurgery

Technology is revolutionizing the medical field with the creation of robotic devices and complex imaging. Though these developments have made operations much less invasive, robotic systems have their own disadvantages that prevent them from replacing surgeons.

Both computer-assisted and robotic surgeries have similarities when it comes to preoperative planning and registration. Because a surgeon can use computer simulation to run a practice session of the robotic surgery beforehand, there is a close tie between these two categories and this may explain why some people often confuse them as interchangeable. However, their main distinctions lie in the intraoperative phase of the procedure: robotic surgeries may use a large degree of computer assistance, but computer-assisted surgeries do not use robots.

Computer-assisted surgery (CAS), also known as image-guided surgery, surgical navigation, and 3D computer surgery, is any computer-based procedure that uses technologies such as 3D imaging and real-time sensing in the planning, execution and follow-up of surgical procedures. CAS allows for better visualization and targeting of sites as well as improved diagnostic capabilities, giving it a significant advantage over conventional techniques. Robotic surgery, on the other hand, requires the use of a surgical robot, which may or may not involve the direct role

of a surgeon during the procedure. A robot is defined as a computerized system with a motorized construction (usually an arm) capable of interacting with the environment. In its most basic form, it contains sensors, which provide feedback data on the robot's current situation, and a system to process this information so that the next action can be determined. One key advantage of robotic surgery over computer-assisted is its accuracy and ability to repeat identical motions.

One of the best known surgical systems is the da Vinci Robot (figure 13). It can



Figure 13: Da Vinci Surgical System, courtesy da Vinci Surgery (<http://www.davincisurgery.com>)

perform a variety of laparoscopic surgeries which involves scaling the surgeon's actions over a very small communication-delay. Even though this application has become quite common now-a-days, another type of teleoperation, involving surgery is on an experimental stage: telesurgery over distance. In 2001, a team of surgeons from Johns Hopkins University in Baltimore (US) operated on 17 patients at Rome's Policlinico Casilino University (Italy). In seven of the 17 procedures, the telesurgical connection was stopped and the operations were continued only from the primary site. Two of the 17 were converted to open surgery and during one of the kidney-related procedures problems developed with a manual control for a robotic device. Therefore not all the cases were fully teleoperated and the presence of a surgeon on site is needed in case unexpected problems arise. Nevertheless, with the robotic surgery development from the last years, we can envisaged in a not so far future that a surgeon on one location can operate on a patient from another location and afterwards switch to another patient on a different location and so on.

2.3.7 Telepresence Robots

Telepresence in the context of telepresence application means replacing the human presence with a robot which is operated by the human operator from another location. The typical example for telepresence applications is teleconference. A few robotic teleconference systems are available on the market already:

- HeadThere Giraffe Telepresence Robot (figure 14). It is a robot with a telescopic arm on which a display with a camera is situated. One of the interesting features of this robot is that the display can be tilted and therefore change the perspective of the teleoperator.
- Pebbles Teleconferencing Robot (figure 15).

Other applications for telepresence are to be envisaged for nursing/caring and education. The population in First World countries is getting older, therefore a bigger



Figure 14: HeadThere Giraffe Telepresence Robot, courtesy HeadThere (<http://www.headthere.com/>)



Figure 15: Pebbles Teleconferencing Robot, courtesy Telbotics (<http://www.telbotics.com/>)

need exists for nurses and helping hands. In order to supply the presence of a nurse close to a patient a possibility would be to use a telepresence robot; moreover a nurse could operate a few robots simultaneously. On the other hand, the presence of a teacher can be replaced by a robot operated by the teacher from another location. Such a device could be helpful in hospitals where child-patients could still follow the classes or in remote areas scarcely populated such as the Australian desert.

3 Telepresence

Telepresence simply means that the operator feels that he is present at the teleoperator site. Already the simple camera-monitor combination creates some level of presence, but usually a more sophisticated system is used in order to call it telepresence. The typical ways to create telepresence are cameras that follow the operator's head movements, stereovision, sound feedback, force feedback and tactile sensing. To provide a perfect telepresence, all human senses should be transmitted from the teleoperator site to the operator site. A good example of multi-sense telepresence is presented by Caldwell [13]. His system provides both hearing and vision in stereo mode, head tracking, tactile, force, temperature and even pain feedback.

The vision, hearing and touch sense are relatively easy to transmit, but smell and taste are more complicated. Fortunately, these two senses are rarely important in machine teleoperation.

3.1 Vision

Humans get more than 90% of their perception information via vision. The human vision sensors - eyes - are very complex opto-mechanical systems. They allow stereovision, focusing, fast pointing, and a very wide field of view. The human field of view is 180 degrees horizontally and 120 degrees vertically. The focused area is only a few degrees, but movements and other interesting targets can be noticed from the whole field. It is extremely difficult to manufacture a teleoperation system that can imitate human vision and provide the operator with the same amount of information as he could get in the teleoperator place.

In most visual feedback configurations, from simple monitors to complex telepresence systems, the field of view is reduced because of the camera and monitor technology used. In all mono-vision systems, the perception of distances is limited because of the lack of depth view. In most cases, there is no need to build up a complex telepresence system. The simple vision feedback with static camera and monitor is enough for most cases. In the learning process the operator will also compensate for the limitations in visual feedback such as e.g delays.

In some cases, an advanced form of telepresence is needed. To create such presence, a human operator has to be cheated into feeling that he is present in the teleoperator place. To "cheat" a person is primarily to cheat his or hers vision - "to see is to believe". It was Goertz who first showed that when the monitor is fixed relative to the operator's head, and the pan and tilt movements of the head drive the pan and tilt of the camera, the operator feels as if he were present at the location of the camera. Already, the head mounted display with tracked pan and tilt provides clear telepresence for the operator. If the roll, and even the eye movements [63], is tracked, the feeling is even more real.

Tachi was amongst the first who developed a high performance hardware system for telepresence (Tachi called it "tele-existence") experiments ([69]). His system had a very fast 3 DoF head tracking which - together with a high class HMD - provided a very good feeling of presence [<http://www.star.t.u-tokyo.ac.jp/>].

3.2 Hearing

The total range of human hearing is between 16 - 20000 Hz. The smallest audible intensity depends on the frequency; the minimum is between 1000 and 6000Hz

and increases for lower and higher frequencies. In the control of a heavy work vehicle, the noise of the machine is usually so high that the driver uses hearing protectors, and can in general observe only the sounds of his vehicle. Despite damping, these sounds are extremely valuable for the driver. In [59], a teleoperation experiment with a mine drill machine is described. In this experiment, it seems that the "operator could operate the drill by hearing almost only the sounds of the machine" ([68]).

In teleoperation, the electrical transmission of sounds also makes it possible to tune the intensity, and filter the non-informative noise away. It is difficult to create a telepresence without sounds.

3.3 Touch

Human touch sensors - mechanoreceptors - are activated by touch, i.e. by pressure on the tissues. These sensors are located throughout the human body. They sense the positions and movements of joints, tension in muscles and touch on the skin. These tactile sensors can be divided into two basic classes [18]:

1. tactile information, referring to the sense of contact with the object, mediated by the responses of low-threshold mechanoreceptors innervating the skin (say, the finger pad) within and around the contact region;
2. kinesthetic information, referring to the sense of position and motion of limbs along with the associated forces conveyed by the sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, together with neural signals derived from motor commands. Touch is needed in all kinds of work where the human being is mechanically interfacing with tools and environment - practically in every work except thinking. However, in case of tools or machines, like heavy work vehicles, touch is not focused on the actual task but the control equipment of the machine. In some teleoperation tasks like manipulation, the feedback of touch can help the operator to a remarkable degree. Touch feedback can be divided in two types: force feedback and haptic feedback.

3.3.1 Force feedback (kinesthetic information)

Force feedback means that the force generated by the teleoperator, usually a manipulator, is fed back to the operator in order to generate a real response in gripping and manipulation tasks. Among mechanical manipulators, this feature was built-in because it was the force of the operator that was using the manipulator. When hydraulic and electrical servos replaced the direct mechanical contact, force feedback was no longer used. Now the feedback was generated artificially by measuring the force from the actuator of the robot and generating it with an additional actuator to the control equipment. In manipulation tasks, force feedback is essential for a good telepresence. Force feedback can also be used in virtual environments to generate the feeling of presence.

3.3.2 Haptic feedback (tactile information)

In a wide sense, both force and tactile feedback come under the term "haptic feedback". In teleoperation, the main difference between a haptic interface and a force

feedback interface is the touch point. In force feedback, the muscular (kinesthetic) sensors give the response to the operator. In the haptic feedback, the tactile skin sensors have the main role. Usually in haptic interfaces, the tactile sensing of the robot manipulator is fed back to the fingers of the operator. But it can also be the vibration of the vehicle that is fed back to the human skin.

3.4 Virtual and Augmented Reality

In the early 1990s, [70] developed a virtual reality interface for a scanning tunneling microscope allowing users to "touch and feel" a surface at a microscopic level. In addition, users were allowed to make controlled modifications, such as sculpting, at an atomic scale. In another example, researchers use haptics to emulate the feel of piloting a teleoperated vehicle directly. [7] developed a system to relay forces and torques experienced by a teleoperated vehicle back on the user's controller. This allowed those piloting the vehicle to experience the same sensations that they would be exposed to inside the vehicle.

Remote controlled devices are used as an interface for a wide range of applications. [35] presents Internet accessible telepresence systems for a remote controlled vehicle. A camera was mounted on the front of the remote-controlled (RC) car, giving the user a first-person perspective of the surroundings. [44] combined the small RC car perspective with a virtual environment, creating an augmented teleoperated system. These systems combine the advantages of viewpoint and remote control, while superimposing additional information, such as dimensions, to enhance the users' situation awareness.

Image processing and object recognition are other vital components of teleoperation systems. Krueger (1983) was an early pioneer in the field of virtual reality and human computer interaction systems in the 1960s and 1970s [42]. His work focused on systems in which user actions could be interpreted directly without the user communicating through a physical interface. His most recognized work, Videoplace, used innovated techniques to gather user information. The user was placed in front of a screen with back-lighting, allowing a computer vision system to acquire user actions. From this interface, Krueger defined over 50 different types of interaction paradigms for the user to explore.

Since the 1970s, machine vision has progressed steadily towards real-time processing aided by increased computer performance. [16] tracked individual colors in order to follow the movement of objects on a desk space.

Objects tracked in the real world can also be used as an interface to the virtual world. Hiroshi and Ulmer of the MIT Media Laboratory coined the term "tangible bits", to describe these types of systems. As stated by [33], "'tangible bits' is an attempt to bridge the gap between cyberspace and the physical environment by making digital information (bits) tangible. We are developing ways to make bits accessible through the physical environment."

Using this concept, [15] created an interface for athletic-tangible computer supported cooperative play, termed PingPongPlus. They utilized an overhead camera to track a ping-pong ball during a normal ping-pong match. In this system, an overhead projector projects images onto the table to augment the real world game play. Several different modes were created, in which different goals and images were displayed to enable different types of game play. Chun found that their system did not only augment reality, but translated reality by creating new game interaction paradigms for participants to interact with.

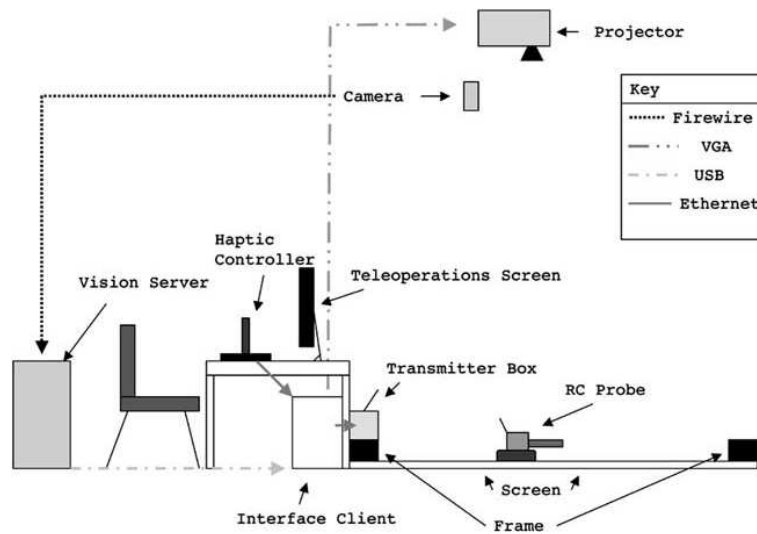


Figure 16: Virtual Bounds diagram, courtesy [57]

Other researchers, such as M. Billinghurst, have used machine vision to create augmented reality interfaces ([36, 6]). By determining the placement and orientation of real world objects (fiducials), virtual objects can be overlaid corresponding to the users perspective. Users of these systems are commonly required to wear a clear head-mounted-display in order to achieve this hybrid viewpoint. The main advantage of this augmented reality technique is that a 3D view of both the virtual and physical world is available.

Other mixed reality projects have used remote control vehicles for the purposes of gaming ([67, 49]).

In 2006, Ponto proposed an augmented reality system called Virtual Bounds which consists of overhead projectors, tracking devices, and user control units. The goal of Virtual Bounds was to create an enactive teleoperation environment which can increase the performance of the teleoperated application. In figure 16, we present the system diagram of Virtual Bounds.

4 Control Issues in Teleoperation

Designing a teleoperation system requires answering a number of issues concerning:

1. **Sensors and Actuators.** The remote slave robot must present a set of sensors and actuators; depending of the degree of telepresence, the designer wants to ensure for the human operator, corresponding actuators and sensors have to be provided in the cockpit on the master side. A large number of devices are now available as part of teleoperation systems: haptic joysticks, cyber-gloves, head-mounted displays, etc. These devices incorporate both actuators for providing the information from the remote site and sensor to encode the human control actions.
2. **Communication Media.** A large number of communication media can be used in teleoperations: transmission lines, radio wave, wireless, internet. Beside the different environments, a choice can be made between communication protocols.
3. **Time-delay Problems.** Probably the most important issue for a control engineer is the time-delay issue. We are going to focus on time-delay induced problems and their solutions through-out this chapter.

From a control point of view the main goal of teleoperation presents two aspects:

- *Stability*: the closed-loop system should be stable irrespective of the behavior of the human operator or the environmental perturbations;
- *Telepresence*: the human operator should feel as if he were present on the remote site.

A survey of the control solutions considered to ensure these aspects is presented in [34]. We recall in this section some of these control problems and their solutions mostly focused on bilateral teleoperation.

Several complications arise when studying teleoperated systems since the communication medium contributes substantially to the complexity of the system due to its dynamic nature that could distort, delay or lose samples of the signals exchanged between the operator and teleoperator systems. These issues have motivated the control theoretic research over the past decades. We are going to present the control solutions following their chronological development.

4.1 Experimental Approach. Move-and-Wait

In the early 1960's, Sheridan and Ferrell [20, 65] realized some simple manipulation experiments to determine the effect of time delays on the performance of human operators in teleoperated manipulators. The objective was to quantify the total time required to accomplish a certain prespecified task. It was noticed that whenever delays were introduced in the communication loop, the operator responded by adopting a move-and-wait strategy to ensure that the task was completed. The results of these experiments showed that the completion time is linear with respect to the induced delay in the loop.

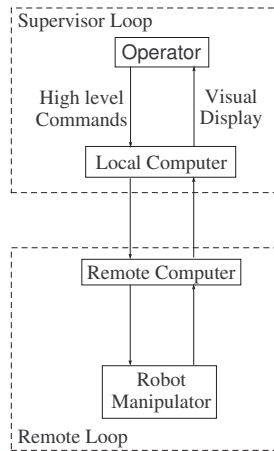


Figure 17: Supervisory control

4.2 Heuristic Approaches

4.2.1 Supervisory control

The move-and-wait strategy showed that the completion time for a task is linearly dependent on the delay factor. In order to avoid this problem, Ferrell and Sheridan proposed that the type of command issued by the operator should be of a supervisory nature [21] as in figure 17.

It was realized that supervisory control could be facilitated through developing a special programming language that contains specific instructions that could be pre-programmed or programmed online by the operator throughout the task completion. As a result of this supervisory strategy, the required communicated data for a specific task completion is reduced dramatically, and consequently the completion time is decreased. This became the new direction in research, software-based teleoperation.

4.2.2 Software-Based Teleoperation

The computing power increased constantly since the 1970's and the teleoperation research continued towards exploiting this power to achieve supervision at a higher level [22, 46, 48, 55, 61], that is, allowing the human operator to issue high level commands to the remote manipulator. In [48], a programming language that implements supervisory control was presented, along with visual and force feedback from the remote manipulator and environment.

Many extensions of supervisory control have appeared since then, such as [61] in which virtual objects are introduced to compensate for the operator's inability to visualize the whole space ahead using the slave-mounted camera due to objects blocking its view point.

4.3 2-Port Network

In the late 1980s, it was observed that a teleoperator system, comprised of a master and slave with their corresponding controllers, residing between the human operator and the environment can be modeled as a two port network [12, 28, 27, 26]. This method is particularly appealing due to its ability to study mechanical systems from an electrical network point of view for which passivity results were already established. The passivity property is particularly appealing since minimal knowledge is required about the human and environment dynamics other than being passive systems. Passivity of the latter systems guarantees passivity of the overall teleoperation system, since the interconnection of passive system is also passive.

Consider the two port network illustrated in Figure 18, with external signals being



Figure 18: Two-port Network

efforts (e_i 's) and flows (f_i 's) which correspond to voltages and currents in electric circuits or forces and velocities in mechanical systems, respectively. The behavior of this network can be captured using different matrix representations such as impedance - $Z(s)$, [58], or hybrid - $H(s)$, [28, 27]. Each of these representations is useful depending on the available signals for control.

4.3.1 Impedance Matrix

If the flows are the inputs on both sides of the two port network, then an impedance representation of the master-slave system can be utilized to relate the velocities to forces:

$$\begin{pmatrix} F_m \\ F_s \end{pmatrix} = \begin{pmatrix} z_{11}(s) & z_{12}(s) \\ z_{21}(s) & z_{22}(s) \end{pmatrix} \begin{pmatrix} \dot{x}_m \\ \dot{x}_s \end{pmatrix} \quad (1)$$

4.3.2 Hybrid Matrix

On the other hand, if the force variable is available at the slave's side, then the hybrid representation is obtained [26]:

$$\begin{pmatrix} F_m \\ -\dot{x}_s \end{pmatrix} = \begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix} \begin{pmatrix} \dot{x}_m \\ F_s \end{pmatrix} = H(s) \begin{pmatrix} \dot{x}_m \\ F_s \end{pmatrix} \quad (2)$$

where $H(s)$ is the hybrid matrix. The elements of this matrix can be interpreted as

$$H(s) = \begin{pmatrix} Z_{in} & ForceScaling \\ VelocityScaling & Z_{out}^{-1} \end{pmatrix} \quad (3)$$

The hybrid representation has become the basis for several theoretical contributions such as the scattering approach and 4-channel model, especially when time-delays are present in the communication channel.

4.4 Scattering Approach

Until 1989, solving the problem of time delays in the communication loop of a teleoperator system remained theoretically untackled and the available tools such as supervisory and preview control relied mainly on advanced computer programming tools as their strong point. The work in [1, 2] offered a theoretical approach to the delay problem, by transforming the teleoperation problem into a transmission line problem which yields a feasible solution to the delay problem.

Such a system can be viewed as an n -port network with an effort-flow pair at each port (the force-velocity pair in the case of mechanical systems). The relationship between the forces and velocities at all n ports can be represented, in the LTI case as mentioned earlier, by an impedance relationship in the frequency domain as $F(s) = Z(s)V(s)$, where $Z(s)$ is an $n \times n$ impedance matrix and V is the velocity vector. This representation, however, is not unique since an admittance relationship can be utilized or, for our current discussion, a hybrid representation of a 2-port network (2), where the effort is the force and the flow is the velocity, enters into the definition of the scattering operator.

Definition 1 [2] *The scattering operator is defined in terms of an incident wave ($f(t) + v(t)$) and a reflected wave ($f(t) - v(t)$) as $f(t) - v(t) = S(f(t) + v(t))$*

In the case of a 2-port network (2), the scattering matrix in the frequency domain can be represented in terms of the hybrid matrix by simple loop transformation

$$S(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} (H(s) - I)(H(s) + I)^{-1} \quad (4)$$

In order to guarantee passivity, the scattered wave cannot have energetic content greater than the incident wave, hence with respect to the scattering operator S :

Theorem 1 [2] *An n -port system is passive if and only if $\|S\|_\infty \leq 1$, where $\|S\|_\infty$ is the infinity norm of the corresponding scattering matrix.*

In [1], the transmission line model in the n -dimensional case that makes the channel passive is given by:

$$\begin{aligned} F_m(t) &= F_s(t - T) + Z_0(\dot{x}_m(t) - \dot{x}_s(t - T)) \\ \dot{x}_s &= \dot{x}_m(t - T) + Z_0^{-1}(F_m(t - T) - F_s(t)) \end{aligned} \quad (5)$$

with Z_0 being a matrix impedance and T the delay time on the communication line (it was supposed that the incoming and the outgoing delays are equal and constant).

4.5 Wave Variables

A conceptually similar formulation to the scattering approach appeared in [50], the so called wave variables formulation. As seen in figure 19, instead of transmitting as reference signals the power variables \dot{x}_m and F_s the wave variables are transmitted u_m and u_s , which are given by

$$\begin{aligned} u_m(t) &= \frac{1}{\sqrt{2b}}(F_m(t) + b\dot{x}_m(t)) \\ u_s(t) &= \frac{1}{\sqrt{2b}}(F_s(t) - b\dot{x}_s(t)) \end{aligned} \quad (6)$$

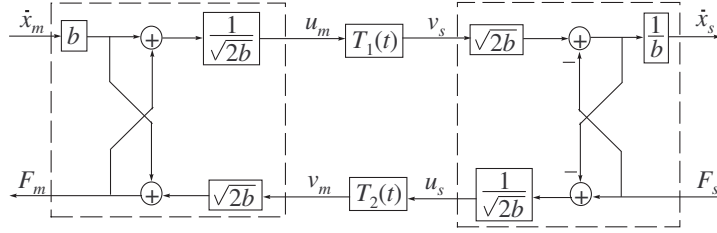


Figure 19: Wave Variables

and are identical to the scattering formulation in (5), with b being the characteristic impedance of the transmission line.

When the channel is comprised of constant time delays (T), the wave formulation results with the same control law given for the scattering approach, and the passivity analysis can be performed in time domain:

$$E(t) = \frac{1}{2} \left\{ \int_{t-T}^t (u_m^T(\tau)u_m(\tau) + u_s^T(\tau)u_s(\tau))d\tau \right\} \geq 0 \quad (7)$$

and hence, the channel is passive.

Due to the intrinsic passivity of the wave formulation, several control strategies are made possible in the wave domain, that otherwise cause the loss of passivity when performed directly in the power variables domain.

4.6 Transparency and 4-channel Control

Transparency is one of the main objectives when dealing with teleoperated systems since it provides the human with a feeling of the environment he/she is interacting with remotely. This essential objective in teleoperation can be realized whenever the input (or transmitted) impedance seen by the human operator mimics the impedance of the remote environment, i.e. $Z_t(s) = Z_e(s)$.

Lawrence [43] showed the advantages of communicating both forces and posi-

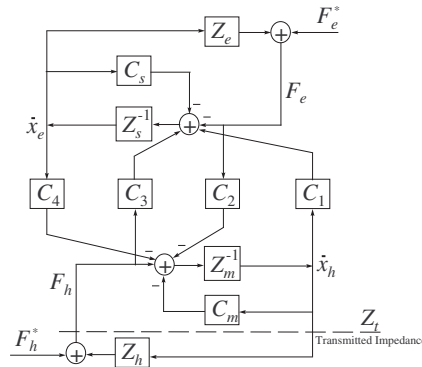


Figure 20: 4-Channel Control Architecture

tions/velocities between master and slave in order to achieve transparency. He called this architecture (figure 20) "4-channel control", denoting the four analysis variables: F_h , human force, \dot{x}_h , human velocity, F_e , environment force and \dot{x}_e , environment velocity.

In the Lawrence framework, the controller is defined as a six (in [31], there is a eight-blocks architecture) independent blocks (C_1 to C_4 plus C_m and C_s) architecture. He also suggested a certain choice of the controller transfer functions C_i , to optimize the device transparency.

4.7 Teleoperation over the Internet

Teleoperation over the internet began in the mid 1990's [25] and has been an active research area since then [8, 9, 19, 51, 73, 74]. Unlike space or undersea applications, communicating information across a packet-switched network results in randomly time-varying delays that could reach very high values and eventually lead to loss of packets. Furthermore, the need to deal with discrete-time stability arises. As a result the performance of the teleoperated system deteriorates drastically and possibly becomes unstable.

4.7.1 TCP vs. UDP

The master and slave have to transport their discrete-time information down the software layers, until the physical layer after which the data packets undergo random time-varying delays $T_{in}(t)$ and $T_{out}(t)$ the incoming and outgoing delays, respectively, which distorts the transmitted signals. A choice between using TCP (Transmission Control Protocol) or UDP (User Datagram Protocol) has to be made based on their performance; both residing at the transport layer in the ISO 7-layer reference model. On one hand, TCP provides reliable two-way communication and guarantees data delivery at the cost of retransmissions and long timeouts that are detrimental in real-time applications such as teleoperation. On the other hand, UDP does not require reception acknowledgments eliminating unnecessary waiting time, which makes it appealing for realtime applications such as teleoperation [51].

4.7.2 Information Loss

Packet loss is an inherent problem with most packet-switched networks due to several factors such as transmission time-outs, transmission errors and limited buffer size. Several reconstruction algorithms have been proposed in [62] which address the issue from a passivity perspective, that is, reconstructing lost samples while preserving passivity. Three policies can be applied in case packets are lost:

- using null packet replacement
- using previous packet
- using passive interpolation

4.7.3 Continuous to Discrete-Time

The transformation from the continuous-time signals to discrete-time signals may produce an excess energy at the interconnection port [62].

Under appropriate conditions between the continuous and discrete-time ports we have an effort equality on each time step as $e_c(t) = e_d(k), \forall t \in [kT; (k+1)T]$ and by setting

$$f_d(k) = \frac{x((k+1)T) - x(kT)}{T} \quad (8)$$

we get the following equality in the energy flow

$$E_d(N) = \sum_{k=0}^{N-1} e_d^T(k) f_d(k) = \int_0^{NT} e_c^T(\tau) f_c(\tau) d\tau = E_c(NT) \quad (9)$$

which guarantees lossless connection between the two systems independent of the sampling period.

4.8 Other Analysis and Design Approaches in Teleoperation

Other types of analysis and design strategies have been proposed for teleoperation. In this section, we present only a few of the most important of them:

1. Shared Compliant Control. It appeared in the late 1980's [4, 29, 37, 38, 39] in order to deal with instabilities caused by delayed force reflections in bilateral teleoperation. The method consist in adding an active compliance element to close the loop around each joint of the slave robot with a low-pass filter. This creates a low stiffness joint that is felt by the human operator in the case of force feedback.
2. Virtual Internal Model. It is a concept similar to the shared compliant control, which appeared in [24]. The virtual internal model has been reapplied under delayed communication in [52]. The basic idea behind this design approach is to duplicate exactly the slave manipulator on the master side.
3. Sliding-mode Control. The application of sliding-mode control to 1-DOF delay-free teleoperated system appeared in [11] and was later extended to time-varying delayed communication in [14, 53, 54].
4. \mathcal{H}_∞ design. The concept of robust feedback linearization was applied in [47] to both the master and slave robots in order to realize the effects of parameter uncertainty, sensor noise, and external disturbances in a teleoperation setting.
5. Model Predictive Control. Due to its ability to deal with delays, model predictive control (MPC) was applied in [5] and [64] to the teleoperation problem. The two results differ in the sense that [5] considers a pre-compensated slave and a MPC controller on the master's side that provides a setpoint for the remote system to track. However, [64] considers the bilateral version of the problem where force feedback is realized and the controllers on both sides are designed for simultaneously as an outcome of the optimization problem.
6. Virtual Environment. The time delay problem in teleoperation originated the idea of virtual environment that duplicates the actual remote slave-environment setting locally, which provides the human operator with instantaneous force

feedback and an increased feeling of the remote environment, thus surpassing the delay factor. A predictive operator aid was proposed in [12] which utilizes a state predictor of the remote task resulting in local force feedback generation, or direct force feedback. However, the operator still possesses the ability to rely on delayed feedback force originating at the remote site and delayed through communication, thus indirect force feedback. A combination of both is also possible by filtering both signals resulting in a complementary force reflector. More elaborate implementations of the virtual environment concept can be found in [41, 40, 71, 76], whereas [3] presents a similar approach in a haptic interface setting.

7. Adaptive Control. In Section 4.6, we saw that a 4-channel architecture is necessary to achieve transparency between the environment and the human operator. However, it assumed perfect knowledge of the master, slave, environment and operator impedances in order to realize the fixed compensators. Hence, adaptive control has been employed as a tool to mitigate the effects of parameter uncertainty in the master and slave robots [60], uncertainty in the environment [30] or both [45, 66, 77].

4.9 Conclusions

The main control problem in teleoperated systems is the instability induced by the communication time-delay and incomplete information on both sides (master and slave). In this section, we have seen some solutions. In [75], the table 1 is presented to compare the maximal round trip delay times (sum of the time-delays on the ongoing and incoming channels) under different control strategies for which the teleoperated systems are stable. All these times are "estimated" independently of the teleoperated model (in fact the maximal time-delay depends a great deal on the specific model of the teleoperator, the variation of the time delays, the sampling time and the frequency of perturbations the system is subject to). There are some other solutions for specific teleoperator models which can perform under even greater time-delays such as [56] where the round trip time-delay was of 5-7 seconds).

The problems and the solutions considered in this report are mostly from the

Table 1: Time delay on teleoperation with force feedback, courtesy [75]

Author(s)	Delay Time for Round Trip	Feature
Anderson & Spong [1]	400ms	Scattering Theory
Niemeyer & Slotine [50]	1s	Wave Variables
Kim et al. [39]	1s	Shared Compliant Control
Kosuge et al. [40]	up to 1s	Virtual Time Delay

control engineering perspective, since some psychological problems involving the human operator are not discussed. In [68], some possible problems have been introduced, mostly induced by the telepresence. The human operator's sensors produce contradicting sensations to the brain which may lead to operator's discomfort or even states of nausea. The telepresence should consider also involving more human sensors, beside vision, hearing and touch, such as vestibular sensors.

Unfortunately, these type of devices are too expensive and are only used in simulators and not in teleoperation systems.

Some other aspects belong to the sociology such as the interaction between the human and the machine. Sometimes, the human prefers to act directly, creating some hazardous situation instead of using the teleoperated systems. One example of such a situation was the World Trade Center Attack from 2001, when even though the fire-fighters had a teleoperated system for searching the injured people in the damaged building they preferred using human fire-fighters inside the building which eventually collapsed killing besides the injured people already in the building some fire-fighters. The current systems do not provide the same dexterity that a human has, but future research might close this gap and offer some teleoperated systems closer to the human expectations.

5 Outlook on future work

As part of the project Teleman, this report presents the state-of-the-art in teleoperation systems. The perspectives of this report are closely related to this project; therefore we are going to present here the Teleman project and its goals.

The aim of the Teleman project is to develop a new high tech industry based for teleoperations. One of the main issues of this project is that the teleoperators we are aiming at are generic, meaning that they can be used in a variety of tasks.

5.1 General vs. Dedicated Robot

Although all of the other teleoperation projects are focused on specific domains, we are considering a more general approach. Some issues are to be considered when a choice is to be made concerning the degree of "generality" for this project:

- System Stability
- Performance Criteria
- Developing Time Costs
- Production Costs
- Transparency

5.2 Features

The teleoperation system must present some features. The control module where the human operator interacts with the system should present a Human-Machine Interface (HMI) with the following capabilities:

- Visual-Sound Feedback (ex. Head Mounted Display)
- Augmented Reality
- Haptic Feedback (ex. CyberGlove, Haptic arm)

On the slave side two issues are very important to be considered:

- Stability and Transparency. Most of the state-of-the-art in control strategies deals with this aspect. Different approaches are to be considered and depending on the teleoperation system we are going to choose the most appropriate to the application at hand.
- Fault Diagnosis. The slave robot should have some safety mechanisms to anticipate endangering situations. Most (semi)autonomous robots have a diagnosis tool based on an object-recognition system which allows to identify the environment bounds and objects. The teleoperator should have this capability in close connection with the augmented reality from the cockpit side so that if the human operator by mistake or from faulty communication leads the robot towards a dangerous position/state, a safety mechanism should be triggered.

5.3 Perspectives

Two possible perspectives are provided for Teleman project:

1. "General" slave robot
The slave robot can perform a variety of tasks, but only tasks connected to certain domain of activity which involve similar movements. For example a house keeping robot which uses different tools has to perform different tasks with different tools using similar movements.
2. Modular slave
A single cockpit (master) is designed to interact with different slave robots, each one designed for a specific task. In this case, an interface between the cockpit and the slave is needed so that different commands from the cockpit to be mapped to different responses of the robots.

Either possibility leads to a new research direction which has not been considered yet.

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