A REVIEW OF TELEOPERATION SYSTEM CONTROL

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ABSTRACT

This work presents a survey of control methods applied to teleoperation systems. Although the topic is kept general, emphasis in the review is placed on force-reflecting manual controllers, which experience time delays, and suffer stability problems. Various theoretical and experimental methods that have been developed over the years are presented and the more promising ones are outlined for further study, and development of efficient, real-time control software, which is the ultimate goal of the current work.

1.0 INTRODUCTION: DEFINITION

Teleoperation has enjoyed a rich history and has led both to many practical applications and to a broad vision of interaction with environments far removed from the user. In order to understand teleoperation clearly, we first provide some of the basic terms and concepts, which appear in articles related to teleoperation [4, 8, 9, 10, 29, 33, 37].

Teleoperator is a machine that enables a human operator to move about, sense and mechanically manipulate objects at a distance [10]. Most generally any tool, which extends a person's mechanical action beyond her reach, is a teleoperator.

Telerobot is a subclass of a teleoperator. It is a robot that accepts instructions from a distance, generally from a human operator and performs live actions at a distant environment through the use of sensors or other control mechanisms. Usually it has sensors and effectors for manipulation and/or mobility, plus a means for the human operator to communicate with both.

Teleoperation is a means to operate a robot using human intelligence, which requires the availability of adequate human-machine interface. A teleoperation system usually consists of two robot manipulators that are connected in such a way as to allow the human operator control one of the manipulators, which is called the master arm, to generate commands that map to the remote manipulator, which is called the slave arm.

Figure 1 illustrates the information flow in a teleoperation system [25].

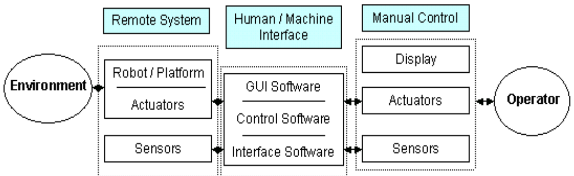

Fig. 1 Information flow in a teleoperation system [25]

The main function of the teleoperation system is to assist the operator to perform and accomplish complex, uncertain tasks in hazardous and less structured environments, such as space, nuclear plants, battlefield, surveillance, and underwater operations [24, 34, 42].

Telemanipulation is a scheme in which a slave robot arm, which is usually in a remote or dangerous environment, tracks the motion of a master manipulator. In general, telemanipulation is divided into two strongly coupled processes: the interaction between the operator and the master device; and the interaction between the remote slave device and its environment [39].

Telepresence. In 1987 Sheridan described telepresence as the "ideal of sensing sufficient information, and communicating this to the human in a sufficiently natural way that she feels herself to be physically present at the remote site." Sheridan also called telepresence a "compelling illusion" and "a subjective sensation."

In the field of robotics, telepresence generally refers to a remotely controlled system that combines the use of computer vision, computer graphics and virtual reality [29].

Telepresence systems are usually viewed as composed of three parts: A capture system to record and represent the information from the remote site; a network transmission system and a display system to make the local user feel as if she were somehow present in the remote scene [11].

2.0 APPLICATION AREAS OF TELEOPERATION

Within the last two decades, different teleoperation systems have been developed to allow human operators to execute tasks in remote or hazardous environments, in a variety of applications ranging from space to underwater, nuclear plants, battlefields, surveillance, and so on [16, 17]. Teleoperation system tasks are distinguished by the continuous interaction between the human operators, teleoperator system and the environment.

With the development of Internet and other related technologies, the application of teleoperation becomes much wider and more indispensable than before.

2.1 Space

Teleoperation has been used in space applications very frequently. Most of the deep space probes have been telerobots, which had relatively simple, straightforward, but reliable controls, having low-bandwidth capability to receive pictures and other sensory data, and the ability to be reprogrammed in space.

In 1993 the German space agency DLR successfully demonstrated the first space telerobot, the "Rotex" experiment, on the NASA Space Shuttle. This experiment showed that the ability of a computer to control a telerobot in space, and also showed that space telemanipulation can be controlled from earth through a time delay.

Japan has made noteworthy progress on teleoperator development. The Japan Experiment Module (JEM) is an integral part of Space Station Freedom. JEM includes a long teleoperator operating from a "porch." Figure 2 shows this teleoperator that was on the Japanese Experiment Module for Space Station Freedom.

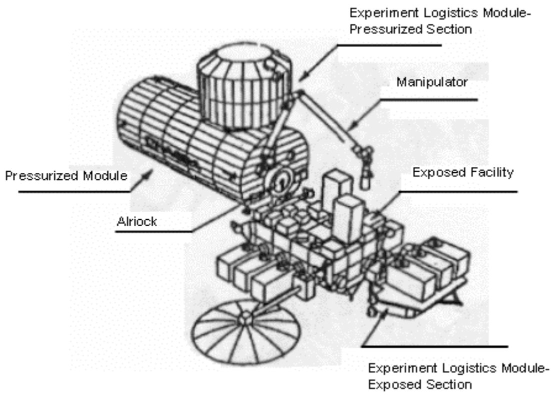

Fig. 2 Teleoperator on JEM [9]

Planetary surface telerobots have also been developed with mixed success. After the first American Surveyor mission in 1967, others such as the Russian Lunakhods in 1969 and 1980, and the American Viking missions to Mars in 1976 have been attempted. The Mars Pathfinder space probe sent back the panoramic color images of Mars' surface in 1997. NASA is planning to send another probe to Mars to explore that planet. Also, the Space Shuttle manipulator on the shuttle has been controlled by two three-degree-of-freedom joysticks from within the shuttle.

2.2 Undersea

In the area of undersea applications, teleoperation is used in offshore oil exploration, inspection and maintenance on drill-heads, oil platforms and pipelines, geological surveys, and classified navy tasks. Americans, British, Japanese have led in this area.

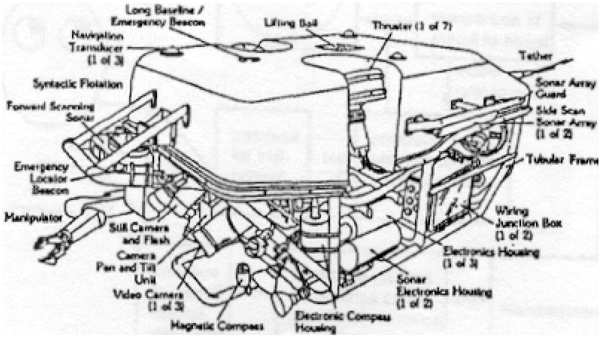

Fig. 3 Undersea vehicle Jason [9]

Figure 3 depicts an undersea vehicle Jason that was controlled remotely to locate Titanic. This system was developed as Argo-Jason project at the Woods Hole Oceanographic Institute and named after Jason and his Argonauts of Greek mythology [13].

2.3 Toxic waste cleanup

In toxic waste cleanup, teleoperation has the un-substitutable function, especially in nuclear plants. Presence of radioactive materials and leakage make the environment dangerous for humans, and all tasks in this environment lend itself to teleoperation. Although the main concept of remote control and teleoperation remains the same, size of the system may vary considerably depending on the size of the task. Remotely controlled systems may vary from pipe crawlers to trucks with hydraulically operated manipulators that can carry several thousand pounds of payload.

2.4 Other applications

Today teleoperators find their way into more and different applications; they become accepted as the normal and mundane way of doing tasks. In medicine, CAT and MRI imaging [26, 27], teleoperation is now being used to guide robotic devices in order to machine the heads of femurs and other bone structures for much tighter and surer fitting of prosthetic joint implants than was possible with manual drilling.

The modern and advanced teleoperators and telerobotic devices are applied in hazardous environments including those that are hazardous to humans (nuclear reactors), those where humans adversely affect the environment (clean rooms), and those which are impossible for humans to be situated in (deep space exploration).

We believe that teleoperation systems will be used in more and more different environments with the development of new and effective technologies.

3.0 MAIN PROBLEM IN TELEOPERATION CONTROL: TIME DELAY

Time delay occurs in every electro-mechanical system. In most cases it is not noticeable, but in other cases it can render the system unstable.
An idealized teleoperator causes a tool (telerobot) to move in space, matching exactly the motions of an operator. All forces imposed on the tool should be accurately reflected back to the operator.

Assume that ideal teleoperation can be achieved and that it is possible to cause the system to behave as a zero mass, infinitely rigid, tool with no viscous damping. If all forces are reflected back to the operator, this must include the force of impact. Any physical device must obey Newton's laws, and thus perfect force reflection means perfect transfer of momentum from slave to master on contact. This kind of teleoperator should be the perfect teleoperator.

However, the master will have much lower impedance than the slave, the operator's muscle stiffness is low and the human hand has little mass compared to a large industrial manipulator. Also, the physical separation of master and slave, which may cover vast distances, is another factor. Therefore, time delay is an inevitable factor in teleoperation.

In the case of teleoperation over the Internet, time delay can have even a more pronounced effect on remote control and cannot be ignored [15]. Almost by definition, a teleoperation system experiences time delays during communications between the local (controller) and remote site (system controlled). Untreated, even small delays may lead to instability due to unwanted power generation in the communications. Moreover, stable force reflecting teleoperators can be designed and shaped to act as simple virtual tools when they are exposed to large delays.

In an experiment carried out at MIT's Nonlinear Systems Laboratory, researchers tested and recorded trans-continental round-trip time delays when they tried to send data between MIT and California, a distance roughly 4,000 kilometers. Figure 4 shows this experiment's results [15]. From the figure, we can extract an approximate range for time delays, which seem to lie between 0.8 to 1.8 seconds according to this experimental data. Of course, depending on the route, day, time, and traffic, this delay value can change.

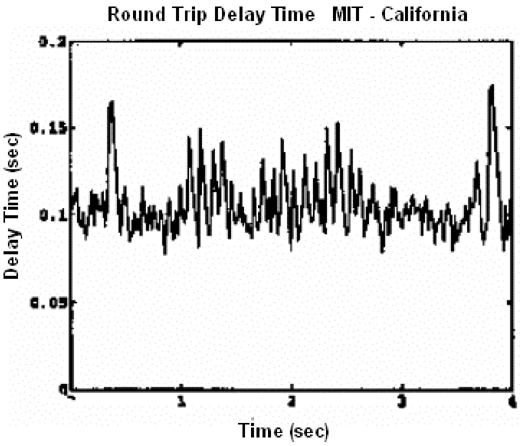

Fig. 4 Observed round-trip delay times between MIT and California when 50 data sets per second transferred [15]

4.0 FORCE-REFLECTING MANUAL CONTROLLERS

A force-reflecting manual controller (FRMC), or joystick, is one of the devices that can be used to control remote systems in teleoperation. Among those available devices, such as joystick, mouse, switchbox, keyboard and touch-screen, the joystick is usually a better control device than others because the operators can identify better with the task. The joystick should be able to reflect forces that are experienced at the remote site; this kind of system is known as a force-reflecting manual controller [10, 17, 21, 28, 29].

Basically, there have two major types of force-reflecting manual controllers: one uses a serial-structured design, and the other utilizes parallel-structured design. Both have some advantages and disadvantages when they are applied to a teleoperation system. The relative merits of these two kinds of controllers are given in [15] in detail. Some of these two types of controllers are briefly listed below.

4.1 Serial-structured force-reflecting manual controllers

In 1977, Teleoperator System Corporation developed a bilateral force-reflecting servo master-slave manipulator called SM-229. SM-229 was the first member of a family of force-reflecting electric master-slave manipulators designed for production and it was designed to be maintainable by the users [12].

In 1980, Jet Propulsion Laboratory (JPL) and Stanford Research Institute (SRI) developed a universal, bilateral force-reflecting 6-DOF manual controller [3].

The 7-DOF electrical Force Reflecting EXoskeleton Master was developed for research at Wright-Patterson Air Force Base [7]. The system could provide an operator 25 N of force feedback at the handgrip using cables to transmit forces to the user's hand.

Two versions of PER-Force, 3 DOF and 6 DOF, have been produced by the Cybernet System Corporation. The 3-DOF version consists of three 30 oz-in brushless DC motors. It is capable of reflecting a maximum force of 9 pounds and yet the joystick unit weighs only 4.5 pounds. Figure 5 shows the 6-DOF force-reflecting manual controller which was developed by CSC.

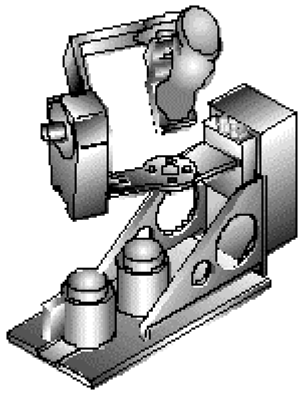

Fig. 5 6-DOF Force-reflecting manual controller

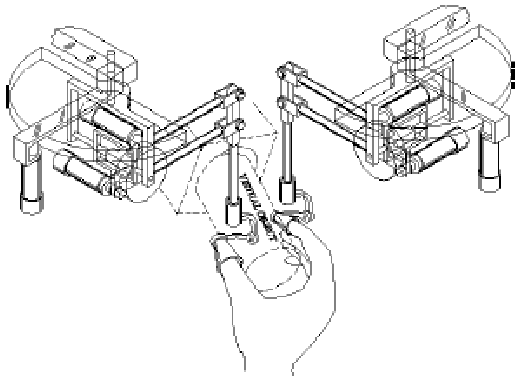

Fig. 6 PHANToM System [5]

The Personal Haptic Interface Mechanism, PHANToM (Figure 6), is the three-DOF "thimble-gimbal" desktop device that provides a force-reflecting interface between a human operator and a computer [5]. The system, which has been developed at MIT's Artificial Intelligence Laboratory, enables the operator to manipulate and feel virtual objects. PHANToM consists of three DC brushed motors with encoders and the human finger.

4.2 Parallel-structured force-reflecting manual controllers

The Stewart platform shown in Figure 7 was first introduced by Stewart as studied in detail in [3]. It has six degrees of freedom and uses all six actuated prismatic joints. The prismatic actuators are usually not backdrivable, but with the addition of a load cell in the actuators, the Stewart platform can be made backdrivable and able to provide force feedback.

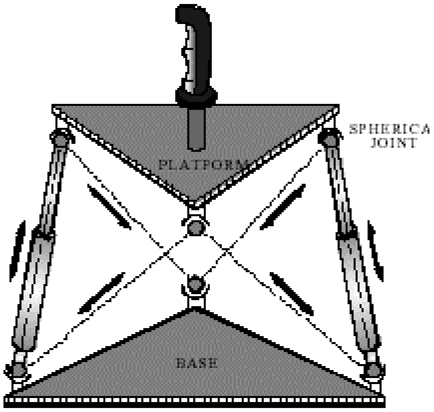

Fig. 7 Stewart platform [10]

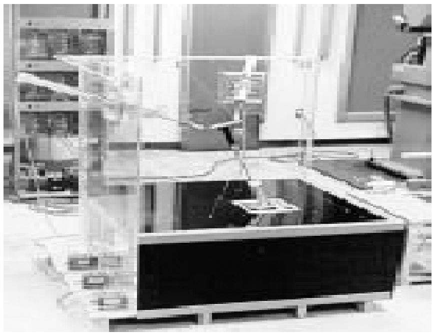

Fig. 8 Nine-string six-DOF manual controller [10]

Nine-string, six-DOF manual controller (Figure 8) has been developed at the University of Texas at Austin [1]. The system is capable of reflecting forces up to ten pounds by using nine actuators to control nine string tensions.

Space Interface Device for Artificial Reality (SPIDAR) system used stringed force-feedback interface as the 6-DOF Texas Nine-String manual controller, but it was simpler and more compact [7]. SPIDAR was developed by Ishii and Sato in Tokyo.

The conceptual design of a three-DOF force-reflecting manual controller [21, 29], which was developed by Batsomboon, and Tosunoglu at the Robotics and Automation Laboratory, Florida International University, Miami, is shown in Figure 9. The system utilizes a direct drive setup which eliminates the need for intermediate transmission elements such as gears or belts. As a result, it has zero backlash and virtually no friction.

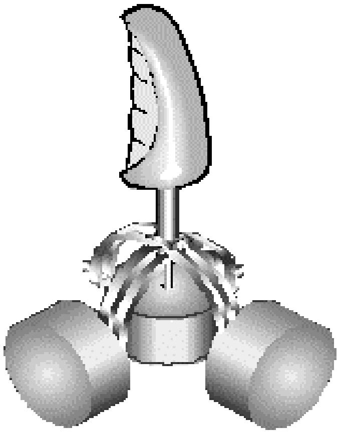

Fig. 9 FIU 3-DOF Force-reflecting manual controller design [10]

The above briefly reviewed some of the teleoperation systems that have been developed in this field to give an idea to the reader about the system as well as likely applications they will be utilized in. With this in mind, we will now move on to various control methods that can possibly be used to control such a system.

5.0 TELEOPERATOR CONTROL METHODS

Thanks to many previous works, different control schemes have been proposed in the literature for dealing with specific problems that arise in this area of telerobotics. These methods were developed for teleoperation control since early 1980s.

These control methods and schemes are based on a number of different techniques, ranging from passivity, compliance, predictive or adaptive control, variable structures, and so on [4]. Every scheme has different aspects that should be considered when designing a telemanipulation system, since the choice of the control algorithm may lead to rather different performances.

During the past few decades, after one of the earliest teleoperator systems was developed at ANL (Argonne National Laboratory), many methods appeared to control teleoperators[2, 12, 15, 23, 31, 38, 40, 43]. Based on different concepts and methods, different controllers were designed in order for the teleoperation system to perform a desired action. Depending on the system at hand, and application requirements, one (or more) of the methods may be suitable. For others, a different control method may yield the best response. Hence, there is no unique controller to remedy all requirements. Naturally, one should choose the simplest available controller which produces the desired system response.

5.1 Wave variables method

Wave variables were first introduced by Anderson and Spong [2, 6], and were later presented in a more intuitive, physically motivated, passivity-based formalism by Niemeyer and Slotine [14, 15, 19].

Wave variables present a modification or extension to the theory of passivity, which offers a robust base to approach arbitrary time delay problem[35, 36].

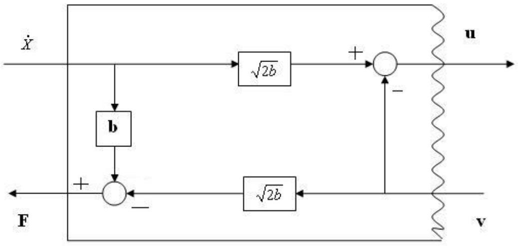

Fig. 10 The basic wave transformation relates velocity, force, right- and left-moving waves

In order to understand the wave variables, we define power flow as follows:

$$P = \dot{X}^T F = \frac{1}{2} u^T u - \frac{1}{2} v^T v$$

In our case, we assume *u* to denote the forward or right moving wave, meanwhile *v* denotes the backward or left moving wave.

The wave variables (*u, v*) can be computed from the standard power variables ($\dot{X}, F$) by the following transformation:

$$u = \frac{b\dot{X} + F}{\sqrt{2b}} \qquad v = \frac{b\dot{X} - F}{\sqrt{2b}}$$

This transformation is bijective; so that it is always unique and invertible. In practice, the wave transformation provides an interface between power and wave variables. For example, if we use the velocity $\dot{X}$ and the left moving wave *v* as inputs, the following transformation will determine the force *F* and right moving wave *u* (Figure 10).

$$F = b\dot{X} - \sqrt{2b} v$$

and

$$u = -v + \sqrt{2b}\dot{X}$$

Other combinations are also possible.

MIT researchers, Niemeyer and Slotine, applied the wave variables method to force-reflecting teleoperation systems and they reported encouraging results which indicate improvement in undesirable effects of time delay.

But unfortunately wave variables are not physically measurable and are sometimes not as intuitive as simple velocity and force data. So, more research and experimentation is necessary before robust controllers can be developed.

5.2 Supervisory control method

Argentinean researchers, Garcia, Postigo and Soria, provided an approach, which they call supervisory control method [43]. It is one of hybrid control methods.

As we know, if one system includes features of both discrete events and continuous signals, it is called a hybrid system. A hybrid system should be modeled by using differential or difference equations for continuous signals, and also by using an automaton for discrete events.

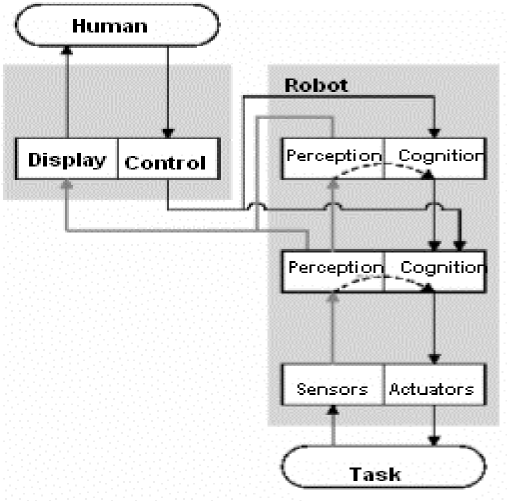

Fig. 11 Supervisory control used in teleoperation systems

The model of this kind of teleoperation system is shown in the Figure 11[43].

In 1992, Siver and Antasklis proposed a hybrid system approach as shown in Figure 12.

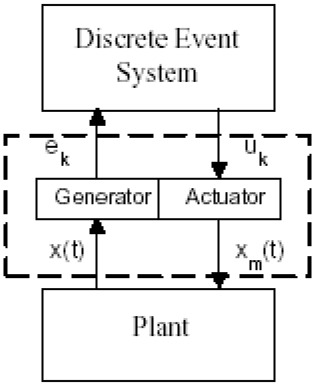

Fig. 12 Stiver's hybrid system scheme

The continuous system, usually called "the plant," has its own real-valued state space, and it can be represented with a set of differential or difference equations as

$$\dot{x}(t) = f(x(t), u(t))$$

The controller is a discrete-event system that can be modeled by a deterministic automaton. This automaton is specified by a 5-*tuple*, as

$$A = \{W, X_d, \tilde{U}, \delta, \Phi\}$$

The controller and the plant cannot be linked directly in a hybrid control system because they use different type of signals. They are connected through the generator and the actuator. The proposed supervisory strategy is illustrated in Figure 13.

The events considered in this teleoperation system are listed as follows: maximum force and/or position allowed are surpassed; communication is interrupted; return of the communication; and timeout for communication return. The events that will be implemented in the teleoperation system are related to the position signal and also to the state of the communication net. Therefore, events are generated when the position threshold is overcome.

With supervisory control, the human divides the problem into a sequence of tasks, which a robot performs on its own. Once the user gives control to the robot, the human typically assumes a monitoring role. However, the human may also intermittently control the robot by closing a command loop or she may control some variables while leaving the others to the robot.

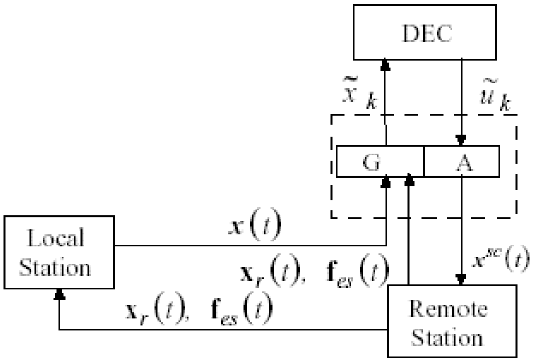

Fig. 13 Hybrid teleoperation structure

A supervisor controller is designed to modify the references sent from the local station to the remote station, when force and position thresholds are overcome or when the communication in a robot teleoperation system is interrupted. The supervisor should coordinate and execute control actions in order to increase the performance of the system when time delays are considered and when subjected to abnormal system evolution [43].

5.3 Nonlinear adaptive control

A typical teleoperation system consists of a local master manipulator (master site) and a remotely located slave manipulator (slave site). The human operator controls the local master manipulator to drive the slave one to implement a given task remotely. The system must be completely "transparent" so that the human operator could feel as if she were able to manipulate the remote environment directly.

A smart control scheme based on the adaptive motion/force control has been proposed in [30]. Instead of perfect force tracking, the overall teleoperation system is assigned to behave as a free-floating mass plus linear damper specified by the control and scaling parameters [18, 41].

Hung, Marikiyo and Tuan adopted the concept of a virtual manipulator to design a nonlinear control scheme, which could guarantee the asymptotic motion (velocity/position) tracking and reasonable force tracking performance even in the situation where acceleration information, accurate dynamic parameters of manipulators as well as human operator and environment models were not available.

In the absence of friction and other disturbances, dynamic models of the master and the slave manipulators in task space are described by the following equations:

$$F_{am} + F_{mam} = M_{xm}(q_m)\ddot{X}_m + C_{xm}(q_m, \dot{q}_m)\dot{X}_m + g_{xm}(q_m)$$

$$F_{as} + F_{ext} = M_{xs}(q_s)\ddot{X}_s + C_{xs}(q_s, \dot{q}_s)\dot{X}_s + g_{xs}(q_s)$$

The subscripts *s* and *m* indicate slave and master manipulators, respectively.

For this teleoperation system, if the following performances are accomplished:

$$X_m(t) = X_s(t)$$

$$F_{man}(t) = -F_{ext}(t)$$

then the system is said to be "transparent" to human-task interface.

In the control system, the realization of criteria requires information of manipulator acceleration which is difficult to measure in practice. Moreover, there is a trade-off between motion tracking performance, force tracking performance, and system stability in controller design for a master-slave teleoperation system. In order to handle the above problem, the degree of freedom of the control design should be increased by introducing the so-called concept of "virtual master manipulator." The virtual master manipulator is described with the help of following dynamic model.

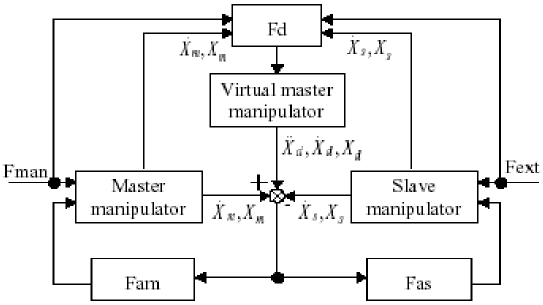

Fig. 14 Block diagram of overall system

$$F_d = M_d\ddot{X}_d + K_d\dot{X}_d + K_p X_d$$

Figure 14 shows the block diagram of the overall teleoperation system with the presence of virtual master manipulator.

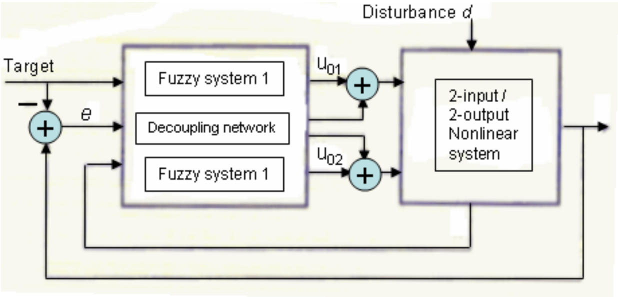

Fig. 15 Configuration of a robust nero-fuzzy control system

5.4 Robust neuro-fuzzy control

The fuzzy control method has been demonstrated to have advantages of robustness through industrial applications and theoretical analysis [22,23, 32, 40].

The control system to be analyzed should be able to transform into a perturbed Lur's system. Yi and Chung [22] presented control theoretic analysis of a fuzzy control system on the sense of Lyapunov based on the similarity between prevalent fuzzy logic controllers and the variable structure control.

In the last few years, we observe that robotic controllers take advantage of neural network learning capabilities -- as long as the dimensionality of the problem is kept at moderate levels. Urban, Beussler, and Gresser in France built a system in which they introduced a modular decomposition of the neuro-controller to confront the curse of dimensionality [20, 22].

Robot control in particular requires the processing of numerous data comprising various interactions organized into a hierarchy. In almost all of the recent works, neural networks are introduced, not as a single unit, but as specialized elements, each network contributing successively, or in a hierarchical way, to a part of the processing.

Figure 16 depicts one modular neuro-controller in a robotic end-effector positioning task.

For this controlling method, there still needs more research to complete the theory and carry out experiments in order to verify the theory.

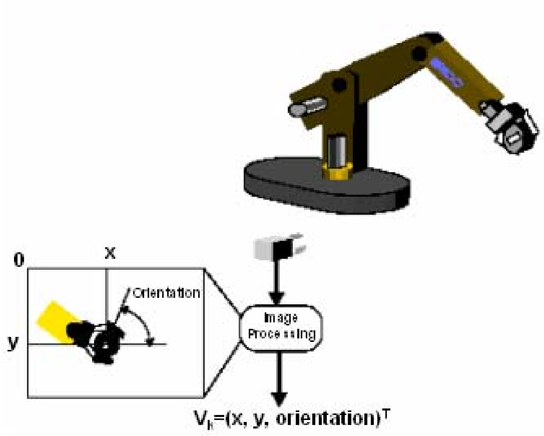

Fig. 16 Three-axis coplanar control

5.5 PID method

PID method has been used since the very beginning of teleoperation with mixed success. The acronym PID is short for *Proportional, Integral, and Derivative control.* In the PID approach, a controller monitors the error in the system (its deviation from some desired value, or *set point*) and makes corrections based on three criteria. The *Proportional* response is based on the magnitude of the observed error, the *Integral* of that error (error accumulated over time), and the *Derivative* of the error (the rate at which the error changes over time).

Here we use $e(t)$ to represent a general error function and use the following variation of the PID equation:

$$c(t) = P_e e(t) + P_I \int e(t) dtz - P_D \frac{de}{dt}$$

where

$c(t)$ is the correction factor to be applied to the system;

P_E is the adjustment coefficient for the observed error;

P_I is the adjustment coefficient for the integrated error;

P_D is the adjustment coefficient for the derivative of the error.

The above equation is a standard treatment of PID equation. We introduce a negative sign before the derivation term to reflect its role as a damping factor.

If the motion is very slow, we can get away with simple PID controllers. However, it deteriorates significantly and even cause instability if the motion is somewhat faster, -- or if some significant acceleration is involved. For instance, the space shuttle manipulator moves in a crawl but small-magnitude vibrations cannot be handled by PID-type simple controllers.

Moreover, PID controllers cannot cope with time delays; systems can become unstable if the time delays are not constant.

5.6 Other control methods

As we mentioned above, based on a number of different techniques, there are some new control methods that show us better experimental results. Intelligent control techniques [8, 40], and wave variables are among those approaches. Currently, a number of researchers work in this field which indicates that new control methods will continue emerging.

6.0 CONCLUSIONS

As we discussed and stated above, a number of force-reflecting manual controllers have been developed for different application areas. They may use serial or parallel mechanical structures, and can control remote spacecraft, manipulators, mobile platforms, aircraft, or vehicles as the particular need requires.

To efficiently control teleoperators, many different control approaches have been proposed. One particular need that still has not been effectively addressed seems to be dealing efficiently with significant time delays experienced by teleoperation systems since they can easily cause deterioration in system response as well as cause instability. Hence, a need exists for the development of more robust controllers, and their experimental verification.

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