Research article

Fault-tolerant teleoperation systems design

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Abstract

Purpose – The objective of this study is to enhance the usage of teleoperation fields, such as in nuclear site decommissioning or nuclear waste disposal, by designing a stable, dependable and fault-tolerant teleoperation system in the face of "extraordinary" conditions. These "extraordinary" conditions can be classified as variable time delays in communications lines, usage of different robotic systems, component failures and changes in the system parameters during task execution.

Design/methodology/approach – This paper first gives a review of teleoperation systems developed earlier. Later, fault tolerance is proposed for use in teleoperation systems at the processor, actuator, sub-system, and system levels. Position/force control algorithms are recommended to address stability issues when there is a loss in communications. Various other controls are also introduced to overcome the instability experienced when there is a time delay in the communications line.

Findings – Finally, this work summarizes the teleoperation system architecture and controller design options in terms of a flowchart to help in the conceptual design of such systems.

Originality/value – The impact of these new designs and algorithms will be to expand the limits and boundaries of teleoperation and a widening of its utilization area. Enhanced operation of these systems will improve system reliability and even encourage their use in more critical and diverse applications.

Keywords Robotics, Fault tolerance, Remote control systems

Paper type Case study

1. Introduction

Teleoperation is a robotics application wherein a master and a slave system interact with each other and the environment. Master system is often a joystick or a duplicate of the slave system that is driven by the operator. Slave system is the robot that is located at a remote site and controlled by the commands sent by the master. Depending on the information flow, teleoperation systems are usually called unilateral or bilateral. These concepts are further explained in the paper.

Many researchers have studied teleoperation and the related stability problem for decades. Ultimately several researchers have proposed an algorithm called the wave variable technique to stabilize bilateral controllers that experience time delays. Current studies focus on the variable time-delayed teleoperation. Although the wave variable technique guarantees stability for the constant time-delayed teleoperation, the system may experience instability when the time delay varies. Studies to resolve this problem focus on adaptive algorithms.

One of our contributions to teleoperation studies is the implementation of a position/force controller for the slave side to have a finer manipulation. Since, the slave system is always in interaction with the environment, it is often a necessity to have control over the force that is exerted on the environment. The human operator is alerted with the help of the force-feedback provided by the slave. By this way, control over the force exerted to the environment is accomplished in conventional teleoperation systems. A position/force controller at the slave side will enable the regulation of the force exerted even when the time lag is large. Thus, neither the objects the slave robot is working on, nor the slave robot will be damaged under excessive amounts of force. This leads us to a fault-tolerant system.

The master and slave robot systems are also thought of to be fault-tolerant as individual systems. Both of the systems are designed to complete the task even when there is a failure in one of the components, e.g. the actuators. Even if the task completion is not physically possible, the system performance will degrade gracefully in the presence of unexpected component failures.

2. Overview of some teleoperation systems

Robotic interfaces can provide access to environments that are hazardous, remote, or require interactions at a smaller or larger scale. For example, teleoperated nuclear waste handling systems can keep operators at a safe distance from hazardous material. For space applications, teleoperation systems allow for remote control of such activities as satellite capture and repair. This reduces substantially the risk to humans and the costs associated with manned missions.

Japan's National Institute of Advanced Industrial Science & Technology has concentrated on space robot teleoperation technology to achieve effective ground-based control of

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manual manipulations in orbit (Goshozono *et al.*, 2004). Similar studies are carried out for ground-space teleoperation at Kyoto University of Japan (Imaida *et al.*, 2004).

Telesurgery is another application where remote control is required. Cavusoglu (2000) has researched telesurgery and surgical simulations. Butner and Ghodoussi (2003) worked on transforming a surgical robot for human telesurgery. Sitti (2003) investigated teleoperated nanomanipulation.

Nevertheless, few systems have progressed beyond a laboratory setting. Current telemanipulation systems rely heavily on visual feedback and experienced operators. For example, telemanipulators attached to remote-operated undersea vehicles are position-controlled. They use a miniature replica of the slave arm and they have a visual feedback (Bennet and Needles, 1997).

The quality of a teleoperation experience is often referred to as "telepresence." Ideally, the information from the remote environment (visual, aural, haptic, etc.) is displayed in such a way that the operator "feels" as if he/she is actually present at the remote environment. Presumably, with a greater level of telepresence, an untrained operator can perform tasks as easily as if he/she were at the remote location. The appropriate level of telepresence required for satisfactory performance is still an area of ongoing research.

The first telemanipulation systems, developed in the mid-1940s, provided a direct physical connection with the "remote" environment through mechanical linkages. In 1950s, the linkage connections were replaced with electric servomotors allowing for a much greater distance between master and slave system. Research has shown that providing the operator with force feedback can improve task performance (Massimino and Sheridan, 1994).

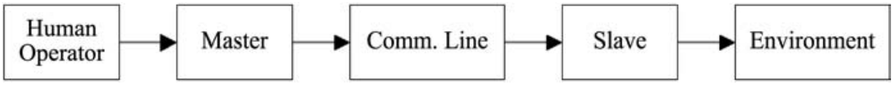
Different from these teleoperation studies, the following teleoperation system has a fault-tolerant design. The joystick, built at the Robotics and Automation Laboratory at Florida International University (FIU), Miami, Florida, has two uncoupled degrees of freedom (DOF) and uses a gimbal-based design (Batsomboon *et al.*, 2000). In the gimbal-based design, both DOFs are composed of revolute joints. Each joint is designed to be bedded between two servomotors to establish a base for fault-tolerant teleoperator design.

2.1 Unilateral teleoperation

In unilateral teleoperation, the information flow is in one direction, or in short, unidirectional. Master system that is driven by the human operator sends the necessary inputs (e.g. position, and/or velocity) through the communications line to drive the slave system. No information is sent back to the master system or the human operator during this type of manipulation. Instead, in most of the cases, the slave system has a local closed-loop control system which uses the feedback signals within this control system Figure 1.

There seems to be a lack of applications of this type of teleoperation in the literature. The reason for this might be that this type of control is not significantly different than any classical control application. Although the human operator sends the command signals to the slave system, actually all the monitoring is accomplished in the control system of the slave.

Figure 1 Basic blocks of a unilateral teleoperation system



2.2 Bilateral teleoperation

The basic blocks of a bilateral teleoperation system consist of a human operator interacting with the environment through a teleoperator system as shown in Figure 2. The teleoperator system consists of a master and a slave with the communication link between them. Master devices vary from a one degree-of-freedom joystick to glove-based interfaces with many DOF (Griffin, 2003). The slave robotic device may vary from a one-degree-of-freedom "manipulator" to a complex system with a dexterous robot hand attached to a multi degree-of-freedom arm even to multiple slave robots (Lee and Spong, 2005). Both sides of the teleoperation system typically have some type of local control operating on position, velocity, and/or force. The master and slave systems may be controlled by the same computer or by dedicated computers separated by hundreds of miles.

A common type of teleoperation architecture is one in which the master system sends position or velocity commands to a slave system. Force or torque information induced from interactions with the environment is fed back to the master system (by the slave system). This type of two-channel (one communication link in each direction) architecture, as shown in Figure 3, is often referred to as "position-force" architecture. Another type is the four-channel teleoperation, as shown in Figure 4, where both positions (or velocities) and forces are transmitted between the master and slave (Lawrence, 1993).

It appears that some researchers chose to work with the four-channel model (Lawrence, 1993; Fite *et al.*, 2004) while others chose to work with the two-channel model because the information flow was sufficient enough for a stable teleoperation. These researchers also introduced the wave variable technique for stability even under time delays (Niemeyer, 1996; Niemeyer and Slotine, 1997; Munir and Book, 2003; Anderson and Spong, 1989; Chopra *et al.*, 2003).

3. Fault tolerance in teleoperation

A fault tolerant system is one that can identify a failure, isolate the failure and provide a means of recovery. Teleoperation robots are designated to work in deep-sea operations, space missions, nuclear cleanup, and any remote operations. Because these robots are in situations that are hazardous for humans or remote from the human operators, a robot failure can be very expensive. In these critical missions, robotic systems must be fault tolerant.

Fault tolerance is increasingly seen as an important feature in modern autonomous or industrial robots. The ability to detect and tolerate failures allows robots to effectively cope with internal failures and continue performing designated tasks without the need for immediate human intervention. This is crucial in teleoperation applications because the slave system is usually unreachable to the human operator to be fixed at a time of failure.

Figure 2 Basic blocks of a bilateral teleoperation system

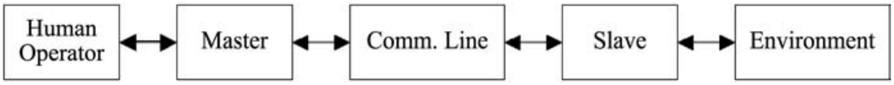
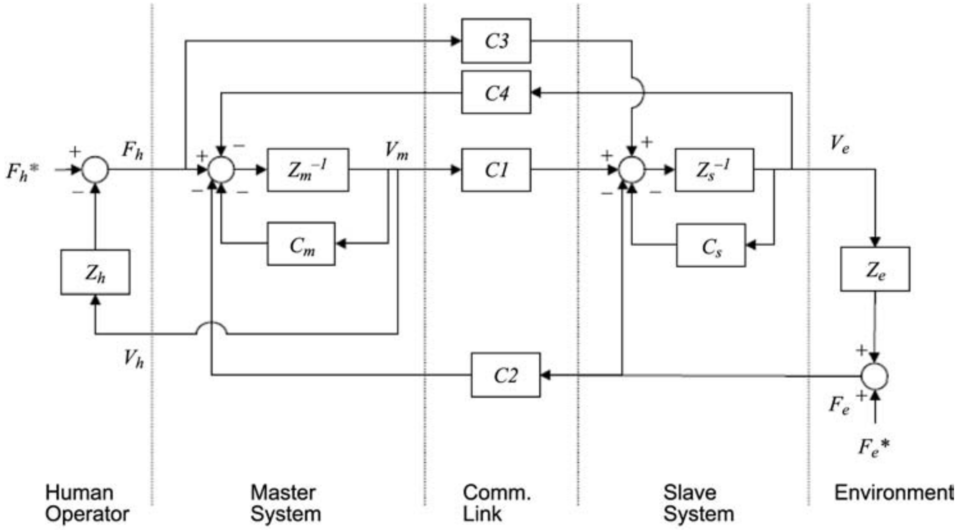
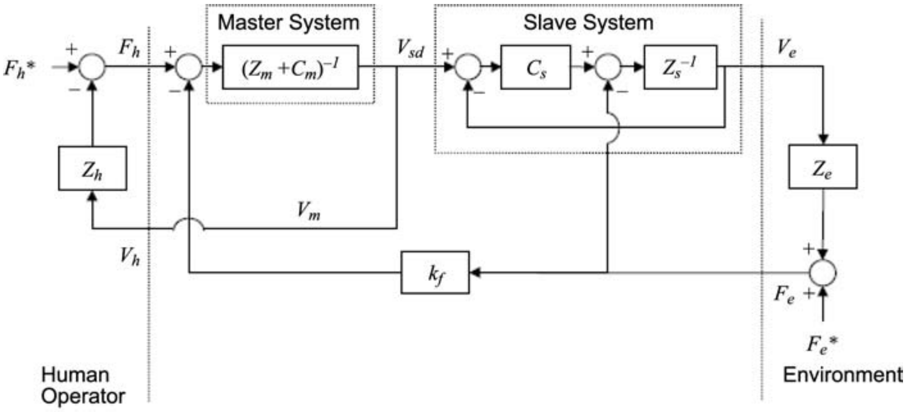


Figure 3 Two-channel architecture for bilateral teleoperation



Source: Lawrence (1993)

Figure 4 Block diagram representing the general four-channel single degree-of-freedom



Source: Lawrence (1993)

3.1 Computer and sensor fault tolerance

A common method used to provide fault tolerance in computer systems or sensor systems is triple modular redundancy (TMR) (Visinsky *et al.*, 1991; Nelson, 1990) in which three processors or sensors all work on the same problem and compare their results. When one of the processors or sensors is faulty and its outcome does not agree with the results of the other two processors or sensors, the faulty processor or sensor is voted out of the final decision and the correct result is passed on to the rest of the system. A shortcoming of this process is that only one faulty processor or sensor can be tolerated by this system.

The TMR voting scheme can be expanded by adding more redundancy in terms of processors or sensors. NASA Space Shuttle uses five redundant general purpose computers (GPCs) in an expanded TMR voting scheme (Sklaroff, 1976). There are four computers that are exact duplicates and work redundantly to perform the same tasks given the same input data. By comparing the output commands, the four computers vote on the results and can detect up to two flight-critical computer failures. After two failures, the two computers remaining in this redundant set use comparison and self-test methods to tolerate a third failure (Sklaroff, 1976). The fifth computer runs the Backup Flight Software and generally performs non-flight-critical functions. Because it is programmed on a different system than the other four computers (Norman, 1987), the fifth computer could be used as a backup if the failure is due to an architectural design flaw in the main GPCs.

3.2 Redundancy-based robotic fault tolerance

Fault tolerance for the mechanical aspect of robots previously has concentrated on algorithms that rely on duplicated parts for their fault tolerant abilities. Generally, these schemes concentrate on faults in one specific part of the robot such as a motor, sensor or joint failure. Tesar *et al.* (1990) has explored methods of duplicating actuators in a robot joint. The two actuators in a joint must be able to work together to provide one output velocity for the joint. If one of the motors breaks, the other one takes over the faulty motor's functions while adjusting to any transients introduced into the system by the failed motor. When the robot is performing a time-critical or delicate task, fault tolerance must allow the robot to get a run-away motor under control quickly before any damage to the environment or the robot occurs. This is vital in teleoperation cases where the slave manipulator is at a remote and unreachable site carrying out critical tasks.

Redundancy, providing the advantage of fault tolerance has also led to adding extra parallel structures, such as a backup arm or leg (Tesar *et al.*, 1990). This allows many different reconfiguration possibilities when failure occurs. Redundant components offer an obvious solution to the reconfiguration problem by providing a backup if one of the components fails. As in TMR with computers and sensor systems, redundancy may also give the robot system multiple components to check and vote between. This improves fault detection.

3.3 Kinematic fault tolerance

Today robots are built with the advantage of being kinematically redundant. Kinematic redundancy means that the robot has more degrees of freedom or motions than necessary to position and orient the end-effector which allows the robot to choose between multiple joint configurations for a given end-effector position in the robot workspace. This redundancy is used to create fault-tolerant algorithms that use the alternate configurations in positioning a robot with failed joints. These algorithms would not require the addition of extra motors, sensors or other components to the robot. They would use the existing structure to provide fault tolerance within the existing physical limitations.

Maciejewski (1990) has quantified the effect of joint failure on the remaining dexterity of a kinematically redundant manipulator. He calculated an optimal initial configuration of redundant arms to maximize the fault tolerance while minimizing the degradation of the system in the event of a failure.

An aspect of fault tolerance that should be taken into account occurs when a robot is in a singular configuration, which may trigger a false alarm for failure. A configuration is considered singular if the robot is fully extended or folded in on itself in such a way as to hinder motion in one direction without rapid changes in one or more joint positions. The joint velocities of a manipulator may become extremely high, when the robot must move through one of these singularities. Fault detection routines might interpret these jumps in the joint velocities as failures in the robot and erroneously shut down a fault-free system. The optimal damped least-squares technique used in the singularity robust inverse algorithm described in Deo (1992) ensures feasible joint velocities with minimum end-effector deviation from the specified trajectory. The inverse kinematics scheme helps the manipulator to avoid drastic joint motions at or near singular configurations and eliminates false alarms for fault detection.

3.4 Control algorithms for fault tolerance

Fault-tolerant control of a robotic system under the failure of its components is not an easy task. The goal is to have a robust control over the system with a minimum recovery time in the face of disturbances caused by the component failures so that the system continues to work on the given task (Sreevijayan and Tosunoglu, 1994). Researchers examined various control algorithms for fault-tolerant control. These control algorithms could be listed as computed-torque method, sliding-mode controller, adaptive techniques, and fuzzy logic controller.

4. Teleoperation control techniques

4.1 Control techniques between the master and the slave

Niemeyer (1996) in his dissertation, suggests that passivity is not only sufficient, but also necessary for the stability of teleoperation systems and presents a passive P.D. controller for a teleoperation system modeled with no time delays Figure 5.

However, in real-time teleoperation systems, there will always be some transport delay for the information transport between the master and the slave. Niemeyer (1996) presented the results for the instability due to time delays using the P.D. controller in the teleoperation system.

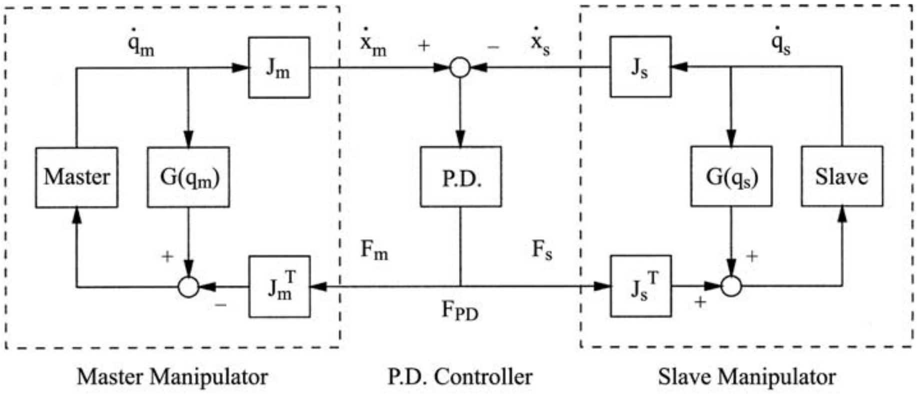
Munir and Book (2003), listed the controllers for the time-delayed systems as Smith predictors, observer-based design, and sliding-mode controller. Other than the listed controllers, Cho and Park (2002) worked with impedance controllers for bilateral teleoperation. Smith proposed a control scheme that allowed a high loop gain for better accuracy Figure 6.

Watanabe and Ito (1981) proposed an observer for a linear feedback control law of multivariable systems with multiple delays in controls and outputs. The observer-based design overcomes the fact that the Smith predictors ignore the initial state of both the process and the delay element. Thus, if the initial condition is not zero, the actual delayed output of the process cannot be exactly predicted. They proposed an observer, which can estimate the system state as a linear function of the controls and outputs.

Park and Cho also developed a sliding-mode controller for bilateral teleoperation with variable time delays. They used the sliding-mode controller for the slave side and an impedance controller for the master side. Since, sliding-mode control is robust to variations in model parameters, they suggested that the method could be used successfully to compensate for the effects of variable time delays. They also proposed a modified sliding-mode controller whose nonlinear gain can be set to compensate for the effects of variable time delays. Later, Cho and Park, 2002 suggested impedance controllers on both sides of the teleoperation system Figure 7.

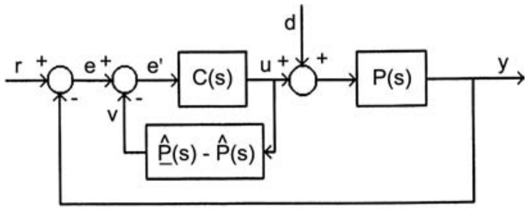
A common shortcoming of force-feedback teleoperation is the instability that the system undergoes when it experiences time delays in communication lines between the master and the slave. The magnitude of this time delay may be in the order of seconds, minutes, hours or even days depending on the task of the teleoperation. This problem has been researched prior to Anderson and Spong (1989), but they were perhaps the first to use the wave variable method to control bilateral controllers. Also, Niemeyer (1996), Niemeyer and Slotine (1997) and Munir and Book (2003) have implemented this method to teleoperation systems. Effects of the time delay in teleoperation systems are reported as a result of a study at FIU as well (Dede *et al.*, 2004). Current studies are on variable time-delayed

Figure 5 Master and slave systems that are connected with a P.D. controller mimicking a spring and damper



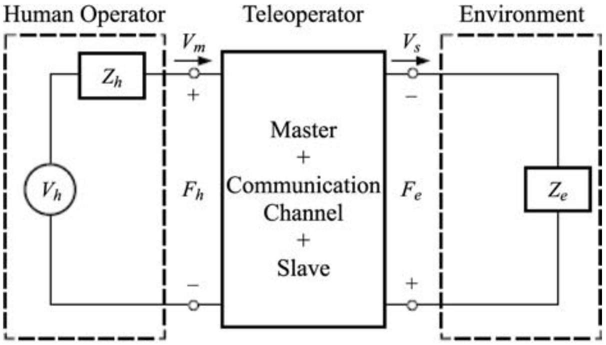
Source: Niemeyer (1996)

Figure 6 Feedback control system with the Smith predictor



Source: Niemeyer (1996)

Figure 7 Basic sketch of impedance controller (Z being the impedance term) for bilateral teleoperation systems



Source: Cho and Park (2002)

teleoperation as reported in (Munir and Book, 2003; Chopra *et al.*, 2003). Although the wave variable technique guarantees stability for constant time-delayed teleoperation, the system experiences instability when the time delay varies.

The block diagram in Figure 8 shows the wave variable technique in terms of the scattering transformation – a mapping between the velocity and force signals, and the wave variables (Niemeyer, 1996).

4.2 Slave robot controllers

Although fault tolerance secures telemanipulation to continue against failures in actuators, sensors, links and processors, it cannot yet secure the system in the face of a communication loss. Heartbeat signals may be used in teleoperation systems to detect the loss of communication (Innovative Technology, 2001). The critical issue is to secure the system after the communication loss is detected. Securing the system means that the least amount of damage is to occur on the slave side and the environment or the work piece that it is operating on.

In our research, position/force control algorithms are used as a parallel control algorithm that is to be activated at a time of communication loss. The reason for using these algorithms is not solely for monitoring the position or velocity of the slave side, but also for monitoring the force applied by the slave system. While the communication is active, the human operator at the slave side does the force monitoring by the help of force feedback. As the communication line breaks down, or in other words, control over the force on the slave is lost, an automatic force control is required. This is where the position/force controller is activated.

Widely used algorithms in the literature of position/force controllers are stiffness, impedance, admittance, hybrid position/force, and hybrid impedance controllers (Dede, 2003). Among these, in this study hybrid position/force controller and the admittance controller are examined. The designers that do not want to develop a teleoperation system with this type of communications loss compensation may use customary controls; such as PD, PID, etc.

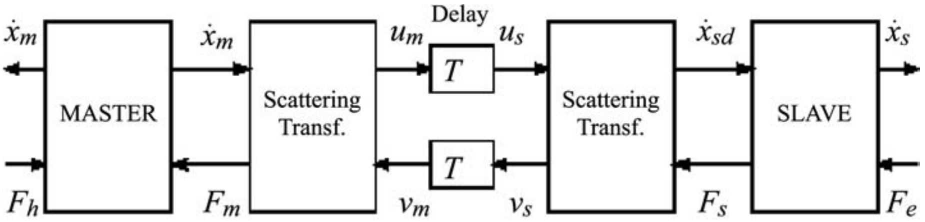
4.2.1 Admittance controller

Admittance control specifies a force setpoint, and the setpoint is tracked by a force compensator. In contrast with a pure position control which rejects disturbance forces in order to track a given reference motion trajectory, the force compensator attempts to comply with the environmental interaction and react quickly to contact forces by rapidly modifying the reference motion trajectory (Dede, 2003; Seraji, 1994) (Figure 9).

4.2.2 Hybrid position/force controller

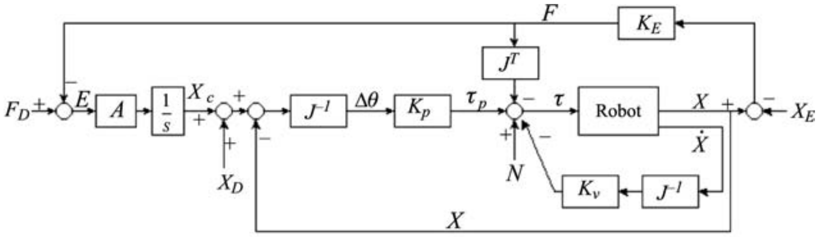
Combining position and force information into one control scheme for moving the end-effector in non-deterministic environments is called hybrid position/force control. The advantage of hybrid position/force control with respect to others is that the position and force information are analyzed independently to take advantage of well-known control techniques for each and are combined only at the final stage when both have been converted to joint torques (Fisher and Mutjaba, 1991; Dede, 2003). This means that there is not a constant relationship between the applied force and the position of the end-effector Figure 10.

Figure 8 Scattering transformation for teleoperation with constant time delay



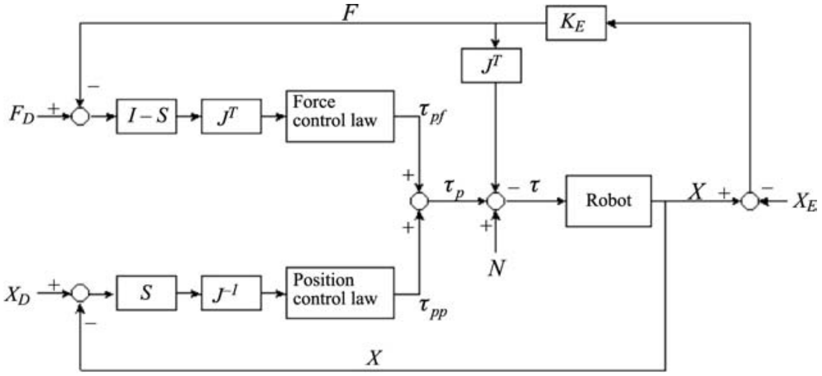
Source: Niemeyer (1996)

Figure 9 Admittance control block diagram



Source: Dede (2003)

Figure 10 Hybrid position/force control block diagram



Source: Dede (2003)

5. Teleoperation system configuration

In this paper, various teleoperation systems are introduced as well as different types of teleoperation modes and control techniques. The path to develop a teleoperation system, using the components presented, is summarized in the following flowchart. This chart provides guidance to the design engineer to decide on the critical design parameters of a teleoperation system so that the system to be developed serves its intended purpose.

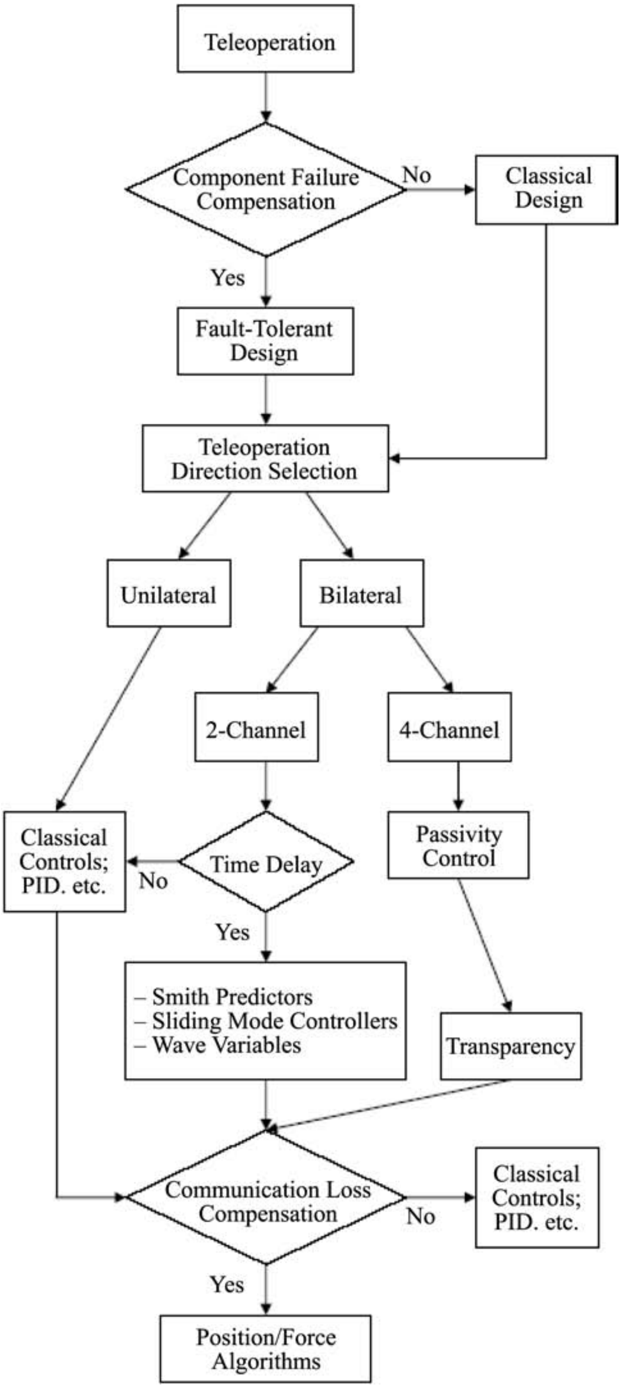
A design engineer first has to decide whether the application requires fault tolerance or not. If the task must be completed under a possible component failure, the decision should be definitely towards a fault-tolerant design. System architecture should be configured considering this decision. The next step is to select fault tolerance components to be used in the design.

The designer then selects the type of information flow between the master and the slave. He may either choose to monitor, or not to monitor the slave manipulation. By selecting a unilateral teleoperation, he chooses not to monitor; hence, the slave actions are solely monitored by its built-in control architecture. In other words, the slave runs in an open-loop fashion. Selecting bilateral teleoperation means that the actions of the slave robot are monitored by the feedback signals provided by it. The designer has to decide on the quantity of feedback signals as well. He may select to have one feedback signal by selecting two-channel, and two feedback signals by selecting four-channel teleoperation.

Later the designer needs to decide whether he wants to have control over time delays that develop in the communications line or not. He may select a wave variable controller, sliding mode controller, or another controller to have a stable teleoperation even under time delays.

The last step of configuring a teleoperation system will require the designer to decide whether or not position/force compensation will be activated on the slave side in case a communications loss occurs between the slave and master systems. If the compensation is desired, then the appropriate position/force control algorithm needs to be selected among a menu of available algorithms Figure 11.

Figure 11 Flowchart for the development of a teleoperation system



6. Conclusion

Teleoperation is a vital field of robotics that helps operations be accomplished remotely; thus, these tasks should be accomplished as fault-free as possible. We summarized various types of teleoperation systems that had been developed in earlier research. A fault-tolerant master joystick developed at FIU was introduced. Later, we classified teleoperation systems into two classes as unilateral and bilateral systems. Then, we investigated two of the main bilateral teleoperation systems as two-channel and four-channel bilateral teleoperation.

The necessity of fault tolerance in critical teleoperation tasks is also emphasized. Following this, types of fault tolerance in teleoperation systems are presented. Along with a fault-tolerant system, effective control methods to address failures are presented: the wave variable technique is explained to overcome the instabilities that the teleoperation system may experience under time delays. Position/force control algorithms are introduced for a finer manipulation on the slave side of the teleoperation system.

Briefly stated, we have addressed the path to developing a fault-tolerant and dependable teleoperation system along with a review of the relevant literature. Such a teleoperation system may be used in any of the critical/high-risk applications such as nuclear reactor maintenance, decommissioning, nuclear waste disposal, space exploration, remote medical operations, military applications, mine searching, and undersea operations.

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