Introduction
Although servo-driven teleoperators have been around since the 1950s for handling dangerous nuclear materials remotely, teleoperators never branched out successfully into other applications. With the virtual freeze on new nuclear power plant construction during the past 20 years, teleoperators have remained largely obscure. Few people outside of the nuclear industry have ever seen or handled a teleoperator.

Yet, perhaps sparked by fresh notions that recast robots as human collaborators, known as “cobots” (Wannasuphoprasit et al., 1998), or because of the recent surge in interest in haptic devices for minimally invasive surgery (Akhil, 1998) and more general uses (Massie, 1998), teleoperators may have fresh hope for growth over the next decade. But, these opportunities may remain elusive unless engineers improve the slave half of teleoperator systems.

This paper discusses the drawbacks of conventional slave implementations that rely on force-torque sensors. By highlighting the natural symmetry of a teleoperator system, the authors suggest an alternative design methodology that improves performance while enabling teleoperators to manipulate objects even larger than the slave.

What is a teleoperator?
A teleoperator is a machine that allows a human operator to manipulate objects remotely. It often facilitates collaboration between people and robots to perform functions that neither could perform alone.

As illustrated in Figure 1, a teleoperator consists of three parts:

1. a master, which a human grasps and manipulates;
2. a slave, which manipulates objects in order to perform a task; and
3. a controller, which couples and communicates movements and forces between the master and slave. Wherever possible, the person is given audio and visual feedback from the task, usually through a live video feed.

No matter how complex the master mechanism, the human operator interacts with it solely by grasping a handle or stylus located at the endtip of the master device. Similarly, the slave interacts with its environment only through a tool or gripper located at its endtip.
The objective of the teleoperator system is to communicate motions and forces between these two endtips. Except in whole-arm haptics, described at the end of this paper, the supporting structures serve no purpose other than supporting the role of the endtips.

Consider the kinematic relationship between the master and slave, which dictates the structural requirements. Teleoperators support up to six degrees of freedom, not including an optional gripper or tool at the slave and tool trigger at the master; and a person may control a pair of masters—one with each hand. In a teleoperator system, kinematics of the corresponding master and slave may be identical, scaled, or totally different as long as the number of master degrees of freedom at least equal the number to be controlled in the slave. There is no restriction on the use of revolute (rotational) or prismatic (sliding) joints assembled in any combination of serial or parallel linkages. The controller then reconciles any differences in kinematic structure (Bejczy and Salisbury, 1980).

Teleoperators combine the best aspects of robots and people. The slave of a teleoperator serves functions similar to an autonomous robot, except that it is controlled by real-time human manipulation rather than by a computer. Robots, even aided by advanced artificial intelligence, are not capable of human-level judgement or intuition. Even at a motor-skills level, no control algorithm exists which can manage the complex motion-and-force interactions, known as haptic interactions, which people manage subconsciously while performing everyday tasks.

Of course high-performance robots have their advantages over humans as well. For example, robots do not require sleep. No matter how extreme the temperature, pressure, radiation, etc., they feel no pain or suffering. Furthermore by specializing their design, robots can be scaled from microscopic to the size of buildings. Compared to people, robots can be cleaner, stronger, faster, and more precise. With the tremendous power of computer technology, robots also have an enormous and perpetual memory and flawlessly perform millions of calculations per second.

Recognizing the complementary skills of robots and people, the best teleoperator design strives to combine the best characteristics of each into a system.

### Independent roots of teleoperator masters and robot slaves

Given that the components of teleoperator masters commonly include kinematic linkages, position sensors, and motors, it may be surprising that teleoperator masters were developed in relative isolation from conventional robot designs, which comprise the same components. Yet, the design objectives and resulting performance characteristics between masters and robots could not be more different.

Commercial robot designs come from the industrial machine-tool industry, where the endtip of a mill cutter or lathe tool is guided precisely along predetermined paths. Every aspect of the design of machine tools and their control systems aims to enforce precision by rejecting all disturbances, such as the cutting forces generated at the workpiece. The need to maintain precision while plowing through metal workpieces leads to heavy, rigid, powerful moving components driven by powerful motors.

Other design artifacts tend to increase motor power even further. Maintaining precision motions subjected to reversing loads requires minimal transmission backlash between the drive motors and the driven joints. In geared drive mechanisms, backlash is reduced or eliminated by applying one of several design techniques, each of which increases Coulomb friction. Though undesired, Coulomb friction, unlike backlash, can be eliminated in the controller.

Application of velocity control overcomes the adverse effects of Coulomb friction. A velocity sensor is attached directly to the motor shaft. Since this sensor is colocated, in control-theory parlance (Hollars and Canon, 1985), the gain can be set extremely high in

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**Figure 1** Telerobotic system

![Telerobotic system](image-url)
order to reject any friction disturbance in the mechanism as well as the force disturbances from the workpiece. Yet more powerful motors are required to overcome friction without saturating the high gain. Even in robots rated only for human-scale payloads, the safety hazard introduced by these powerful motors requires fences and light curtains that isolate people from robots.

Now consider the design requirements of masters. To begin with, a master, by its very definition, must maintain direct contact with people, so isolation from people is not a viable safety solution. Furthermore, rather than reject contact forces as unwanted disturbances as robots do, the master must sense and react to them as its sole input from the human operator! Therefore, when servo-driven teleoperators were developed, engineers were forced to acknowledge that masters and robots have opposing design objectives. Unlike robot design, joint friction and inertia were minimized in a master design so that a person could move its endtip freely. This characteristic, called backdrivability, is described later in this paper.

Yet, since high stiffness and low backlash remained important in the master, new drive types were enlisted to replace gears. Notably stiff steel-tape and steel-cable tension-element drives (Vertut and Coiffet, 1986) removed the friction-backlash trade-off. Until recently, tension-element limitations, such as strength and bandwidth, made them unsuitable in the design of industrial robots. However, recent breakthroughs in tension-element drives, described in this paper, may support the design of slaves that share the beneficial qualities of masters without significant strength or bandwidth penalties.

Master-slave symmetry

The terms master and slave conjure notions of harsh slavery in human history. The master enforced absolute obedience over the slave while rejecting all feedback from the slave. The asymmetric arrangement is simple to comprehend, though not as effective as more symmetric relationships supported by collaboration and task-related feedback.

Similarly, for the teleoperator designer an asymmetric arrangement is easier to comprehend and implement, but far from optimal. True to the notions of master and slave, many teleoperator designs enforce motion on the slave without any channel for force-torque feedback to the master.

The loss of functionality in the absence of force feedback is self-evident. Recall the numb feeling in your mouth from the dentist’s novocaine injection. Now imagine the same numb sensation applied to your hands before you attempt to screw the lid onto a food jar. The task might be possible, but without the force feedback that supports your dexterous human motor control, it is certainly not effective.

It is likely that the earliest teleoperators were sticks. Sticks are symmetric teleoperators and, in spite of their simplicity, extraordinarily useful. Prehistoric man certainly used sticks to avoid burnt fingers while retrieving dinner from a fire or to escape bee stings while extracting comb honey from a hive. The stick embodies:

1. the master, held end of the stick;
2. the slave, task end of the stick; and
3. the controller, middle of the stick, which communicates trajectories and forces/torques between the master and slave ends of the stick.

By selecting a stick that is lighter than the person’s hand and stiffer than the person’s wrist and arm joints, the dynamics of the stick become superbly transparent. Furthermore, the stick teleoperator is equally adept at communicating force and position in either direction. That is, if the slave touches an energetic environment, such as engaging a combatant in battle, the force and position effects are communicated instantly in reverse, delivering time-critical information to the master which may not be immediately visible.

If the stick slave is mobile, such as the end of a blind person’s cane while walking, then a static environment behaves like an energetic environment with respect to the slave’s forward and swooping motions. Even the texture of an object is sensed by sliding the end of a stick across its surface. The texture itself drives the slave end up and down perpendicular to the surface and the generated forces and motions are communicated back to the master.

Of course, while the symmetry of the stick dynamics may be excellent, the stick’s dexterity is not, especially for wrist rotations at the tip of the stick. Furthermore, the stick requires that the person and the task share the
same environment. Unfortunately, in most teleoperator applications, the person and task must be separated. Examples include protecting a person from harmful hazardous materials, protecting a clean-room environment from relatively dirty people, and bridging thousands of kilometers between a surgical specialist and patient.

Neither a stick nor any direct mechanical-only linkage is practical in the majority of circumstances, so the slave is replaced by a robot, which enables remote control through electric, optic, or radio communication signals. In asymmetric systems, where the master does not require force feedback, a simple backdrivable mechanism with joint position sensors is the most common master design. In force-feedback systems, the master also includes servos to simulate the forces and torques measured by the remote slave. The scope of this paper is limited to teleoperators that attempt to measure forces at the slave and feed them back to the master.

In the ideal servo-driven teleoperator, motions and forces flow unimpeded, though perhaps scaled, between the master and the slave, blurring distinction between the two. Figure 2 illustrates this force-feedback symmetry for one axis. Implicit in this system, as with many advanced control algorithms, is joint torque control. However, slaves based on conventional robots are not capable of direct joint torque control because of Coulomb friction.

**Figure 2** Single axis teleoperator with joint-torque-controllable slave

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**Improved methods for designing slaves**

Unlike master devices and teleoperator controllers that are designed specifically for their ultimate purpose in teleoperator systems, slaves suffer from legacy robot designs that are better suited to the machine-tool industry than to teleoperators.

**Conventional robots retrofitted with force-torque sensors**

Measuring joint or tool forces-torques is easy, but the strategy of controlling the joint torques indirectly through velocity commands based on force-torque sensors is very difficult. The difficulty is unrelated to the quality of commercially available force-torque sensors, which are durable, precise, and responsive. In the most common implementation, a multi-axis force-torque sensor is placed between the tool-plate of the robot wrist and the tool or gripper itself. Less common are single-axis torque sensors designed into each joint, enabling detection of structural collisions but requiring that each sensor support the rest of the structure. The force-torque measurements are important for researchers attempting to understand the complex interactions occurring at the tool or gripper of a robot.

But, when applying forces against hard surfaces, the rate of change of force can be extraordinarily high. Consider the case of a collision with a hard surface. The measured impact force rises quickly to a high value, perhaps even saturating the sensor. The sensor reports the increase in force with kilohertz bandwidth. The controller, also operating with kilohertz bandwidth, begins commanding the corresponding joints to decrease forward velocity. But most robot arms of human scale operate in the single-hertz range, so within a few milliseconds the end of the arm careens beyond any desired contact force. So now the control law generates velocity commands to reverse joint directions, all the while the endtip of the arm continues increasing the forces and torques across the sensor. By the time the arm tip has responded, the velocity-controlled motors are now moving at high velocity in the wrong direction. Eventually, the velocity reverses once more and drives the endtip back into the surface, beginning the cycle over again.

In fact, when the arm is moving through air, it is a stable system; and when it is in contact with the surface it is a different system
that is linearly unstable. This piecewise linear system creates a nonlinear pattern known as limit cycling and will continue to chatter against the surface indefinitely. The problem is predicted by colocation theory (Hollars and Canon, 1985). There are only two ways to prevent the limit cycling from occurring in such a system. The first is to contact softer surfaces, and the second is to reduce gain and accept a visibly sluggish system. A better solution is to design slaves with the inherent capability of controlling joint torques directly, without added sensors.

**New performance parameters**

Improved design for teleoperator slaves begins with the realization that, in a force-reflecting system, the slave is not just an output device - it must also reflect torque commands back to the master. We base our design methodology on the natural symmetry of the teleoperator system. This design strategy requires a new set of performance goals, including backdrivability, bandwidth, and force fidelity.

**Backdrivability**

Backdrivability is the measure of how accurately a force or motion that is applied at the output end of a mechanical transmission is reproduced at the input end. In a mechanical robot-like linkage, good backdrivability means that a person can grab the endtip of the linkage and move it around effortlessly.

The dictionary does not define backdrivability, and only a handful of engineers use the term. But good backdrivability is essential in the design of devices that can sense forces inherently without resorting to destabilizing force-torque sensor strategies.

Most motorized mechanical transmissions are designed to carry power in only the forward direction, from an energetic power source at the input to a passive, power-absorbing load at the output. However, if the flow of power switches direction, so that an energetic environment at the output drives the input, then power flows in the backwards direction.

Consider the example illustrated in Figure 3 and Figure 4, where the left crank provides input power to the worm of a simple, single-stage transmission; and the output, represented by the right crank, is driven by the mating 50-tooth worm gear. Generally the output drives a power-absorbing load or cutting tool, but the crank in this illustration highlights the possibility of backdriving the transmission.

The single-pitch worm must rotate 50 times for one complete rotation of its mating 50-tooth worm gear, so the transmission ratio is 50:1. The transmission allows a relatively small motor to multiply its torque by 50X while reducing its speed 50X. Since motors operate most efficiently at fast speeds and low torque relative to the typical speed and load requirements of robots, virtually every commercial-robot joint employs a speed reducer.

While torque and speed are changed by the value of the transmission ratio, it is interesting to note that the inertia changes by the square of the transmission ratio, 2500X in this example.

When backdriving the output, the transmission ratio will amplify the perceived input friction torque (usually motor friction) by 50X and the perceived input inertia (usually motor rotor inertia) by 2500X, diminishing the ease of moving the output crank. Furthermore, depending on the value of the coefficient of friction between the worm and the
worm gear, the friction can easily be magnified to infinity, so that no matter how much torque is applied at the output, it will never drive the input – this infinite friction results in complete nonbackdrivability.

While people quickly learn by experience which robots have good, bad, or no backdrivability, the quantitative details become messy. Coulomb (dry) friction, velocity-dependent (viscous or damping) friction, and inertia all combine to degrade backdrivability. Coulomb friction depends on the sign of the velocity, viscous friction depends on the sign and magnitude of velocity, and the inertia depends on the acceleration.

For a drive to produce good backdrivability, dry friction, viscous friction, and inertia of the input (which will be dramatically magnified through the transmission) must be carefully minimized in the mechanical design.

**Bandwidth**

Bandwidth is a characteristic of the responsiveness of a mechanism; the higher the bandwidth of a mechanism, the more accurately it can follow a rapidly changing input. It is important for master design because the master’s mechanism should be able to follow the human operator’s hand motions, reading them as position commands for the slave. In a force-reflecting system it is important in another sense; the master and slave should be able to reproduce quickly changing force-torque signals from the teleoperator controller faithfully and without instability.

The overall bandwidth of a system is driven by its least responsive subsystem, which traditionally has been the slave mechanism. The bandwidth of a slave is usually worse than that of the master or controls not only because of legacy from robot designs, but also because the slave is often asked to magnify the user’s force and motion ranges. Higher force requirements and greater reach both increase inertia, while greater reach reduces stiffness. Therefore any desire to scale up the slave must be weighed cautiously against reduced responsiveness.

For any linear mechanical system that can be modelled as a set of springs and masses, the bandwidth takes the form of the square root of the stiffness over inertia. To maximize bandwidth, the mechanical system should be as stiff and light as possible. And since inertias increase as distance squared, the greatest effort to reduce mass should focus on the endtip. Dominant compliances generally occur at the joints, so the design effort should focus on implementing the stiffest possible mechanical transmission stiffness by using high-speed transmission elements with speed reduction only at the driven joint wherever possible.

**Force fidelity**

Force fidelity is synonymous with dynamic range of force controllability. In either case, it is defined as a dimensionless ratio of the largest controllable force divided by the smallest controllable force. With robots, payload is an important factor. But, in force-reflecting applications, force capacity is meaningless without reference to force sensitivity. The high end of dynamic range is typically limited by actuator saturation in the mechanism and is generally a function of the size of the manipulator. The low end of dynamic range is typically limited by dry friction and any other hard nonlinearities in the drive mechanisms. A match in dynamic range between master and slave is optimal, since excess dynamic range at either device is wasted.

**Dexterity**

The dexterity of the system is limited or extended in three ways:

1. The number of independent degrees of freedom of the master or the slave, whichever has the least. Six degrees is normally considered the maximum.
2. The range of each joint, measured in degrees of arc for revolute joints.
3. The kinematic similarity and workspace overlap between the human operator, the master, and slave, which should match as closely as possible.

It is interesting to note that many teleoperator designs support the maximum number of six. Six is special because six unique numbers define the position and orientation of any rigid object within a given coordinate frame. If a structure has exactly six independent degrees of freedom, then the structural motions required to support a given endpoint motion are well defined. If a structure were to have seven independent degrees of freedom to control only six, then the structure is defined to be kinematically redundant, and solutions for the required kinematic structure become underconstrained. Only ten years ago, suitable methods for working with kinematically
redundant structures were not well developed. Today, a backdrivable arm can exploit the redundancy in real-world tasks (Leeser and Townsend, 1997) where it becomes an asset rather than a liability.

Example - the whole-arm manipulator (WAM)

Design strategies that maximize the performance parameters recommended in this paper were first proposed to guide the design of the whole-arm manipulator (WAM) at the Massachusetts Institute of Technology in 1988 (Townsend, 1988). The name “whole-arm” reflects the extended design goal that the arm be able to control forces and torques robustly along all of the outer link surfaces—not just a gripper or tool at the endtip. “Whole-arm” also reflects the freedom for a human controller, treating the device as a master, to manipulate any intermediate structure independently of the endtip by exploiting redundancy in the kinematics.

Borrowing elements from earlier master designs

While the WAM design project introduced new technology, its roots are based in preexisting master design methodology, most importantly the reliance on tension-element drives (Vertut and Coiffet, 1986). Properly implemented tension-element drives have no backlash-versus-friction trade-off, making them unique among common mechanical power-transmission drive types, such as gears, cycloidal reducers, harmonic reducers, hydraulics, pneumatics, etc. In tension-element drives, backlash simply does not exist; and the only sources of friction come from:
(1) ball bearings; and
(2) the rolling and unrolling of stainless-steel the cable or tape across hardened cylinders.

In gears and the valve designs of hydraulic and pneumatic drives, backlash and friction can be reduced in tandem only by manufacturing component and housing parts with better and better precision, which pushes fabrication costs ever higher.

Robots with planar SCARA kinematics may be driven by either cables or tapes. However, for more complex kinematic geometries, cables are chosen over steel tape, since the steel tape edges fail quickly when bent or twisted out of plane. A symmetric steel cables have no preferred bending plane and so bend equally well about any combination of arbitrarily aligned axes.

But before the WAM innovations were developed, cable drives had two technical hurdles preventing their use in slaves and robots:
(1) Axial cable compliance limited the bandwidth. Reduced bandwidth not only degraded master performance but barred the use of cables in slaves. The compliance prevented the servo drive from guiding the endtip through precise motions in the face of unexpected disturbances. Nevertheless, master designs still relied on cables for the valuable simultaneous elimination of backlash and near-elimination of friction.
(2) Lack of any cabled equivalent to the geared bevel prevented application of cable drives to one of the most important robot mechanisms, the differential. To keep the kinematic algebra tractable, spherical joints are made from independent axes that intersect mutually through a common point at right angles. A differential implements these kinematics while allowing motors to remain remote.

Beyond technical drawbacks, cables have suffered for decades from an unfairly bad reputation. While cable transmissions can be, and usually are, designed for long, reliable life; budding machine designers often use cables for small demonstration mechanisms because they are cheap and easier to implement than gears or hydraulics. By contrast, cables used in large mechanisms, such as cranes, elevators, tramways, and cable cars require (and have the capital to pay for) professional engineers with experience in the design of reliable mechanical-cable drives.

For example, consider the ill-conceived application of bicycle-brake guide sheathes to clutch cables in some automobiles. Owing to the capstan effect of sheathed cables, friction is an exponential function of the included cable angle. Even slight variations in installation technique can trigger a doubling in included angle, causing friction and resulting wear to increase by orders of magnitude.
WAM innovations remove limitations of cable drives

The WAM design embraced the benefits of cable drives while developing innovative solutions for the two drawbacks of cable-drive designs discussed in the previous section. The now-patented solutions were developed at MIT in support of the WAM project.

The most serious problem was cable compliance, because this reduced the performance of both master and slave. To solve this problem, the WAM designers simply moved the “gearhead” to the opposite end of the transmission. By implementing the speed reduction with cables instead of gears, the increase in weight of the joint was negligible. The result was dramatic because the speed reducer amplifies compliance by the square of the transmission ratio. From the previous worm-gear transmission example the compliance increases by 2500X. Simply moving the speed reducer to the opposite end of the cable transmission, pictured in Figure 5, would increase stiffness by 2500X. A detailed proof of this technique may be found in Townsend (1988). The speed reducer location change completely removes the stiffness barrier to using cable drives in slaves and robots, while dramatically benefiting new master designs.

The second technical challenge that had barred cable drives for use in slave designs was the lack of a cabled equivalent to the bevel gear and differential mechanism. Separate groups at MIT, IBM, and University of Utah had considered a number of possible solutions during the 1980s. It is interesting to note that the correct solution, shown in Figure 6, was also by far the simplest concept proposed by any of the groups. Yet the MIT engineers who sketched it initially rejected the idea as physically impossible. Only after months of deep frustration did someone actually make a prototype. Not only is it feasible, but it has few parts, outstanding strength and stiffness, zero-backlash, near-zero friction, and is intrinsically tolerant to fabrication variances, which leads to low manufacturing costs in production quantities.

Figure 7 illustrates details of the differential. Four cables are required; two for each of the two separate bevel actions. The top and bottom cables drive the left input bevel; and the middle two cables drive the right input bevel. On each bevel input pulleys, two of the cylinder surfaces never support a cable. The input bevels are manufactured identically, each with four cylinders for reduced manufacturing and inventory costs.
Unlike gears, the input and output pulleys never touch. The geometries are simple concentric circles; not at all like gears, which must be indexed and hobbed to generate each gear tooth during manufacture. The cables spread the load evenly around the pulley surfaces, creating a symmetric radial pressure. Therefore, the pulley structures can be extremely thin (0.2mm), like an eggshell, and still support several hundred kilograms of cable tension. By comparison, each individual tooth of a bevel gear must be designed to support the total transmitted torque through shear and moment loading concentrated at one point on the circumference, which requires a thick and rigid hub.

The biggest drawback of cables is a fundamentally limited roll rotation of about 340-degrees, which bars their general use in power trains, but suits them nicely for robotic joints.

**WAM design**

The original WAM arm has four revolute degrees of freedom (without a wrist): three intersecting joints at the base and one distal joint located 0.6 meters from the base. The two non-zero-length, cylindrical links have a combined reach of one meter and mass of 4kg (including the distal joint). The mass of the arm including base and motors is 35kg. All four joint axes have a range of three-quarters of a revolution.

The arm uses stiff, backdrivable, multi-stage, cabled transmissions between the compact joints and the four Moog brushless DC motors located in the base. Joint positions are inferred from 12-bit-resolution resolvers mounted on each motor shaft. Hall-effect sensors infer torques by measuring the motor-winding currents. By measuring positions and torques at the motors, the stability problems associated with noncolocated sensing are avoided.

Before the WAM arm, all speed reducers were connected directly to the rotor shaft of the motor. Since these reducers were implemented with gears and integrally attached to the end of the motor housing, they were often called gearheads. But in the radical departure described earlier, the WAM’s reducers are located at the opposite end of the power transmission, at the joint. The transmission ratios are sized so that the mechanical advantage is large but so that the backdriven motor inertia is negligible compared to a 0.1-kg payload.

A novel cabled differential allows the actuators to be placed closer to the base while maintaining backslashless, efficient, and stiff mechanical-power transmission. Even where volume would have permitted direct-drive motors, such as in the first-axis drive, relatively small motors with speed-reducing cable transmissions were used to improve torque ripple, backdriven inertia, and the effective motor constant while reducing cost and weight.

The links themselves are long and slender and covered with 3-mm-thick dense foam to tailor the contact characteristics for manipulating objects. Both links are tubular aluminum designed to absorb large local impacts with 5-mm thick walls and a small 38-mm radius of curvature (cylinder radius). In order to meet toughness constraints, the arm structure is many times stronger than it must be to lift its maximum 2-kg mass payload against gravity and many times stiffer than the servomotors driving it. The links themselves are modular so that, for example, the outer link can be replaced by a wrist and gripper.

An internal channel is provided for instrumentation and the routing of additional pneumatic or electric power lines from the base to the endtip of the distal link. The manipulator’s mounting is simple and requires two floor-mounted anchor bolts. The motor power supplies and analog current amplifiers are located three meters away in a separate electronics box.

**WAM capabilities**

In force control, even against stiff or energetic environments, the arm exhibits highly stable contact. The arm has also demonstrated the ability to identify the location and magnitude of forces applied along its outer link by measuring only motor currents.

Initial experimental results by researchers (Niemeyer and Slotine, 1989; Salisbury et al., 1989) at the Massachusetts Institute of Technology are reported in Table I. All of the experiments were performed without a wrist, end-effector, or other payload.

**Future extension to whole-arm haptics**

One of the greatest limitations of teleoperators today is that all interactions are restricted to the endtip of the master and of the slave, even though the endtip is the weakest and most compliant part of any robotic structure. However, by adding an extra structural degree...
of freedom, the functionality improves dramatically. For every endtip position there appear an infinite number of allowable kinematic postures. One of the new WAM configurations is a seven-degree-of-freedom system, pictured in Figure 8.

Some tasks requiring human haptic capability, such as the bomb search-and-disposal mission pictured in Figure 9, cannot be considered without whole-arm haptics. By allowing the human operator to grasp the master along its structure and not just at its endtip, the human can easily guide the redundancy as shown in Figure 10. Here, the human operator guides the endtip directly, while simultaneously steering the kinematic redundancy by touching near the master’s elbow with his spare hand.

Assuming the slave is likewise enhanced with kinematic redundancy, then the human operator can use some new strategies for manipulation. For example, the WAM arm has an endtip payload of only a few kilograms, but it can manipulate large objects approaching 100 kilograms through shoving, by enabling controlled physical contact all along the whole arm’s structure. Also, multiple functions can be accomplished simultaneously, for example, clearing a space on the table with the sides of links while carrying a beaker of fluid to the new spot. Finally, obstacle avoidance becomes second nature for the human operator who not only can steer the structure around obstacles, but can also navigate by sensing contacts as they occur.

References


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