# Real-time Cooperative Behavior for Tactical Mobile Robot Teams

# Skills Impact Study for Tactical Mobile Robot Operational Units

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## 1. INTRODUCTION

This report provides a detailed study of the design of feasible human-robot interfaces for near-term deployment in a "robot unit," defined as a tightly coupled group of humans using a multiplicity of robots as tactical tools. There is a strong relationship between three phases of fielding man-machine systems of this type: system design, operator selection, and operator training (Figure 1). Here we consider all of these dimensions, developing an understanding of

- the tradeoffs between highly-trained operators versus novice operators,
- the importance of specific cognitive and intellectual reasoning abilities of potential operators, and
- the impact of system design on all of this.

Clearly, a sophisticated, well-designed system will require less training and enable a larger set of people to interact with it. The purpose of this study is to span this space of potential design and human factors issues and identify the inherent wins, losses, and trade-offs given the goal of rapidly fielding such a system.

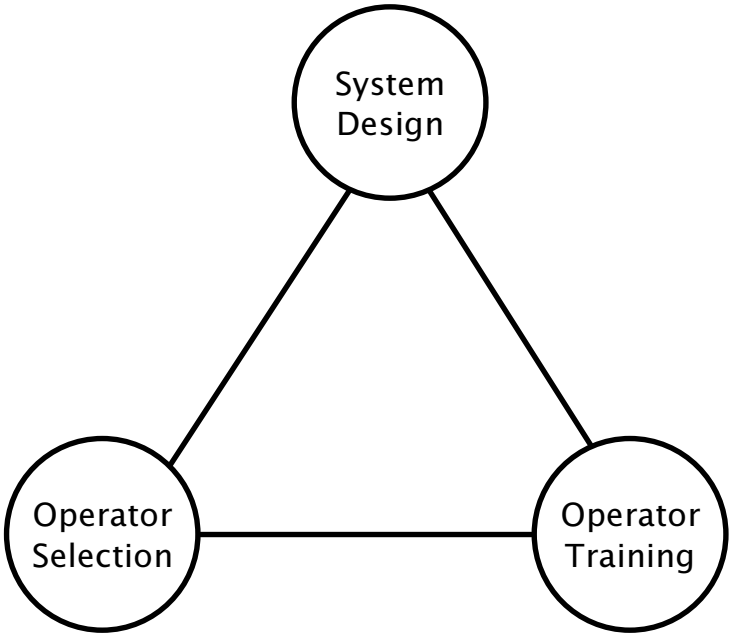


Figure 1: The implementation of a usable man-machine system requires a synergistic approach that takes into account both the hardware and the operator.

To accomplish this, we look heavily towards existing literature and studies. Thus we attempt to synthesize information from a wide range of disparate sources including published papers, military documents, and commercial sources. Visits have been taken to sites that are promising nuclei of relevant information, including:

- Oak Ridge National Laboratory (telepresence concepts, teleoperation techniques, and human factors),
- NASA Ames (human factors techniques), and
- Ft. Benning.

A guiding influence of this work is the report of the TMR Concept Development Group, "Concept Development Report For The Tactical Mobile Robotics (TMR) Program (Extract of 03/24/1999 Revision)," which is included as Appendix A of this document and will be referred to often [TMR 99]. Often, the CDG recommendations serve to constrain the problem and focus this study, and in many cases we cite evidence of the validity of the CDG opinions. In a few cases, we identify areas where some promising technologies may have escaped the attention of the CDG.

## 2. HUMAN-ROBOT INTERFACE DESIGN

This section is intended to serve military decision makers as a guide to existing technologies for human-robot interfaces that are practical for field deployment. In this context, "practical" means that the technology has been demonstrated to be reliable, somewhat ruggedized, and ideally available as commercial off-the-shelf (COTS).

The "system" being considered is the combined system of a human, one or more robots, and appropriate interface hardware and software. All robots have readily-identifiable weaknesses, as do humans. Therefore, a major point of this report is to assess the strengths and weaknesses of a human augmented with the remote resources of a robot. In order to justify the use of robots, is not sufficient to merely to note that a robot can have specialized "non-human" sensors or locomotive capabilities. It must be shown that there are reasonable methods to allow a human operator to have access through these capabilities through available technology while still maintaining awareness of local surroundings.

While interfaces for teleoperated and teleautonomous control are getting more attention and becoming increasingly more sophisticated, the primary emphasis of existing systems is concentrated on non-man-portable systems, such as multi-operator control stations for high-value UAVs and elaborate mission control centers for space robotics. The field is considerably narrowed when dealing with the targeted application of an single dismounted soldier controlling multiple platforms.

### *2.1 Wearable Computing and Augmented Reality*

A complete robot OCU suitable for field deployment in tactical situations has much in common with what is generally called a "wearable computer." To emphasize just how closely the model of wearable computing fits the TMR requirement, consider the criteria given by Mann as a basic definition of the subject [Mann 97]. Here he states that a wearable computer is:

"1. **eudaemonic:** the apparatus is subsumed into the 'eudaemonic space' of the wearer (e.g. it may be worn, or otherwise situated in a manner that makes it part of what the user considers 'himself' or 'herself,' and in a manner that others also regard it as part of the user . . .). It is sufficient that the interface be eudaemonic (e.g. some of the compute power can be remote);

"2. **existential:** the apparatus is controlled by the wearer. This control need not require conscious thought, but the locus of control must be such that it is entirely within the wearer's domain . . . . Furthermore, the apparatus provides the wearer with the ability to make its operation completely private and secure when desired. In addition to the obvious privacy afforded by its eudaemonic nature (e.g. securely attached to the body so that it might be less likely to be stolen when working in close quarters with adversaries), the output can be made private when desired by, for example, using a screen that cannot be read by others looking over the wearer's shoulder;

"3. **constant:** (constancy of both operation and interaction):

- Operational constancy: it is always active while worn. . . .
- Interactional constancy: one or more output channels (e.g. screen/viewfinder) are known (e.g. visible) to the user at all times, not just when the computer is being interacted with in a deliberate manner. In this way, context switching time to mentally engage with the apparatus is near zero."

While Mann generally considers the above criteria in the context of a civilian user, enhancing the security and freedom of the individual, the applicability to a military user is clear. In agreement with the principles described in Section 6.2 of the TMR CDG [TMR 99] ("Human Robot Interface"), Mann also states [Mann 98] that essential qualities of a wearable computer include that it be

1. **unmonopolizing** of the user's attention,
2. **unrestrictive** to the user,
3. **observable** by the user: "It can get your attention continuously if you want it to,"
4. **controllable** by the user: ("Responsive"),
5. **attentive** to the environment, and
6. **communicative** to others.

The single greatest difference between a generic wearable computer and a TMR OCU is that the OCU is specialized to act as a remote teleoperation "console," and as such may require specialized input devices for robot control and specialized output devices for robot sensor visualization. In a word, a TMR OCU requires some degree of *teleimmersion* or *telexistence*, a computer user's experience of being part of a remote environment. Wearable computers developed to date sometimes include some capabilities related to either teleimmersion or ordinary *immersion* (a virtual environment rather than a remote environment), but this is essentially an application-dependent characteristic.

We must be careful to define our concept of teleimmersion in the OCU context, since immersion (and similarly, teleimmersion) can imply a monopolizing user interface. At the extreme end of the teleimmersion scale is *virtual reality*, a poor model for what a TMR operator should experience, since by definition it is overwhelmingly distractive. But it can be useful for an operator to **at will** step in and out of an environment that embodies some of the qualities of *augmented reality* and *mediated reality*. (Later we discuss some of the reasons for this, including improved ability to perform remote driving and manipulation operations.)

*Augmented reality* refers to the enhancement of the actual perceived environment with information that has been obtained by other means. A heads-up display in an aircraft or other vehicle is a common example, where graphical and textual information about location, altitude, and vehicle status are made available while still allowing the pilot to see the local surroundings. Any soldier carrying wireless voice communications equipment is essentially experiencing a basic form of audio-augmented reality, enhancing the visual experiences of the local environment with useful information from other military personnel (and generally augmenting **their** "reality" with return communication, as well).

*Mediated reality* acts as a filter on the perceived environment, blocking extraneous information and focusing user attention on important stimuli. In the TMR OCU scenario, we can imagine multiple operators in close proximity to each other and a support HMMWV, all potentially exposed to enemy fire. So an approach based on mediated reality would attempt to block out some of the activity of the other operators and support personnel while focusing operator attention on the following important information:

- status of the robots under the operator's control,
- warnings and other pertinent information from sentries providing protective support for the robot unit,
- high-level status of robot teams under control of other operators, and
- operator's own perceptions of local threats (sniper fire, aircraft activity, etc.).

This is a key point: mediated reality should be **better** than reality. Instead of concerning ourselves with how an OCU may impair the operator's ability to deal with other "non-robot-related" activities, we must turn the problem back on itself and strive make the operator's situational awareness **better** than it would be **without** the OCU.

Wearable computing is often considered to be a subset of *ubiquitous computing*, the notion of having computers literally everywhere, in even the simplest devices. Curiously, some consider ubiquitous computing to be the opposite of virtual reality, by virtue of the fact that placing computers in a user's world is the opposite of placing the user in a computer's world. But clearly that is a limited viewpoint – the worlds can mix in almost any proportion, and a TMR OCU represents such a mix.

Most existing COTS wearable technology does not address the teleoperation issues, instead focusing primarily on data entry and database access applications including inventory, maintenance, inspection, medical treatment, cartography, and journalism (Figure 2). Some of these applications are described at the web site of a leading vendor of wearable computers, Xybernaut (www.xybernaut.com).

Figure 2: Emerging applications of COTS wearable computers, including (left to right) cartography, journalism, and inspection/maintenance. ( © Copyright 1999 Xybernaut Corporation and subject to use restrictions at http://www.xybernaut.com.)

Of slightly greater interest are applications related to "location-aware" access of data, such as those projects pursued by the Nexus group at the University of Stuttgart (http://inf.informatik.uni-stuttgart.de/ipvr/vs/projekte/nexus/), the Future Computing Environments and Wearables groups at Georgia Tech (http://www.cc.gatech.edu/gvu/fce/index.html, http://wearables.gatech.edu), the Wearable Computing and Vision and Modeling groups at MIT (http://www-white.media.mit.edu/vismod), http://wearables.www.media.mit.edu/projects/wearables), the Wearable Computing Systems group at Carnegie Mellon (http://www.cs.cmu.edu/afs/cs/project/vuman/www/frontpage.html), and others. Location awareness can be on a large scale, as in aids for a tourist exploring an unknown city with the aid of a wearable computer that displays information relative to GPS position (Figure 3a), or on a local scale, as in the use of a *pose estimation* sensor (e.g., a head tracker) to determine where a user is looking so that his view may be annotated (Figure 3b). Both of these are examples of augmented reality, and both may be relevant to a TMR OCU.

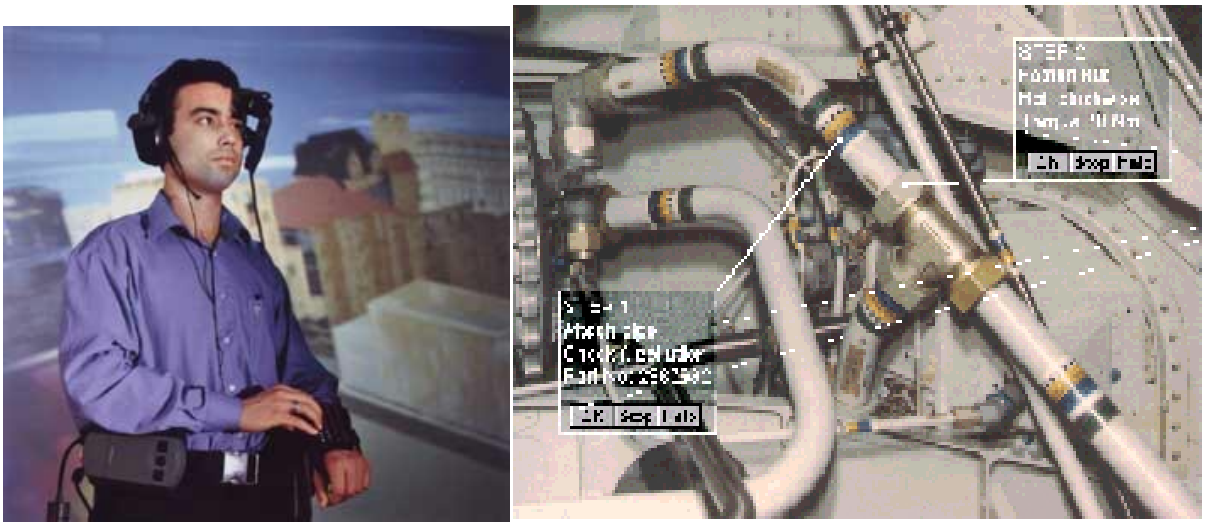

Figure 3: Applications of location awareness for wearable computers. a) A tourist accessing location dependent data in an unknown city, and b) Machinery annotated with information relative to the user's view. ( © Copyright 1999 Xybernaut Corporation and subject to use restrictions at http://www.xybernaut.com.)

Ideally, the core elements of a TMR OCU would be interchangeable with any standard-issue wearable computer which is ultimately developed for military use. Such concepts typically include a computer, power supply, voice radio, GPS, display, and input devices. As will be shown, the major differences are likely to be in the display and input devices.

In some of the more relevant research involving wearable computers, Barfield [Barfield98] considered the effectiveness of augmented reality (AR) displays in aiding an operator in the performance of a manufacturing assembly task. The researchers compared four methods of conveying the assembly instructions to the operator:

- printed instructions,
- conventional computer-aided instructions,
- information graphics on an opaque AR display, and
- information graphics on a transparent AR display.

In the Barfield study, the test subjects were given the task of assembling a computer motherboard, admittedly a significant extrapolation of a typical TMR task. They were given training on the insertion process for various components prior to undergoing trials in which the metrics measured were 1) time of assembly and 2) number of errors. This was followed by a questionnaire to assess user preferences. The final results showed lowest execution times for the transparent AR display, followed by the opaque AR display, computer-aided instructions, and printed instructions. Errors were lower with AR displays in general. Certainly this supports the notion of using AR technology to facilitate the operation of a TMR OCU, but it does not address the effectiveness of wearable technology for teleoperation. Another Barfield study briefly described in the same report supported the use of force feedback in the understanding of statics and dynamics.

The usefulness of AR as an effective model for providing information to the warfighter has not been unnoticed by the military. As noted in COTS Journal [Ciufo 00]:

". . . the trouble with immersive HMDs is that they block out the real world and prevent the operator from reacting to real events while immersed in the virtual world. Whereas this downside can be overcome by piping in real-world video on top of the virtual environment, information overload sets in, and the operator can quickly become disoriented. A better approach is augmented reality (AR) technologies that allow viewing the real world with superimposed virtual objects.

"The U.S. military is using AR in a big way. HMDs are used by pilots to supplement the traditional heads-up display (HUD) in platforms ranging from the F-15 and F/A-18 to the new Joint Strike Fighter and Comanche helicopter. Armored vehicle drivers and commanders will use HMDs with "head-out" views of the real world while still viewing vehicle instruments and weapons systems. Battlefield soldiers have a digital view of the battlefield, the locations of 'friendlies' and opposing forces (OPFOR), and remote viewing capabilities around corners or in anti-laser 'eye-safe' mode. And both medics and mechanics can call up on-the-spot documentation for ready access to on-site documentation."

A key issue in the near-term deployment of robot units is the ruggedness of available equipment. This report deals primarily with COTS equipment and some devices that are only slightly past the proof-of-concept stage. In that respect, ruggedness is evaluated in terms of the potential for ruggedization. This results in three possible classifications for a component or system: 1) ruggedized (suitable for military use as is), 2) ruggedizable (a clear path for ruggedization exists, using mature technology at reasonable cost), or 3) questionable (fragility exists, and there is no obvious solution at this time). "Questionable" technologies will not be utilized in the proposed robot units.

It is probable that TMR operators will often perform their supervisory tasks within close proximity to a support vehicle. In such cases, it is still important that the operator remain unencumbered and able to react to the local situation, but it opens up possibilities for non-wearable devices that can remain resident on the support vehicle. These devices will be considered here, with appropriate notation of their limitations for man-portable applications.

## *2.2 Input Device Technologies*

This section describes a wide range of input device technologies in the context of a TMR OCU. The evaluation of these devices with regard to wearable computers, teleoperation, or teleimmersion has resulted mainly from the experiences at major centers of advanced users.

### *2.2.1 Pose Estimation Sensors*

*Pose estimation* sensors are devices that measure some relationship of one or more of an operator's appendages to the operator or a reference frame. Typically, this relates to the operators head, hands, or fingers, but in some of the more immersive versions it may include virtually the entire body. In general, the pose estimation sensors used for research in immersive environments are too cumbersome to be practical for a wearable TMR OCU. But some feasible alternatives exist, including head position sensors and gloves, which will be described in the following sections.

Pose estimation sensors tend to be analog in their response characteristics, providing some degree of continuous control. In most of the available literature on robotic teleoperation, there is little mention of using discrete "cursor-key" type control. The MPRS program demonstrated some effective operation of teleoperated (not teleautonomous) robots with keys on a pendant device [Laird 00], but it requires the dedicated use of both hands. This sort of operation, including the adjustment of speed with a rotary potentiometer, can be suitable for dedicated control of a single machine, but is less desirable for TMR.

#### 2.2.1.1 Gloves

While human operators are adaptable to a variety of devices using different types of muscular action, the need for continuous control appears to be obvious. The CDG advocates the use of gloves for sending commands. In this context, it is possible to consider discrete commands (through the recognition of specific gestures) or continuous control (through the recognition of degrees of finger extension, for example). In the survey of hardware included here, no consideration is given to gloves which are part of large suits or systems which are clearly impractical for TMR, nor to "toy" devices that are not comparable in performance and durability.

Pioneering virtual reality research was performed with the DataGlove from VPL Research, whose technology has since been purchased by Sun Microsystems. The fiber optic sensors used in these gloves were reported to be fragile and subject to calibration problems, and they are no longer available. Sun is apparently more interested in the virtual reality software developed by VPL Research than their hardware, and none of the original VPL devices are in production. But back in 1987 when they first produced the DataGlove, VPL Research licensed Nissho Electronics as their sole distributor and technical partner in Japan. Nissho apparently still produces their version, the SuperGlove (http://www.tradepia.or.jp/nevc/advanced/vr/vr5-1e.htm), but there is little reported research activity with this device. Supposedly, some of the calibration problems were addressed by including a quick 3-step calibration process in hardware, but unfortunately this requires a bulky control box, adding to the difficulties in using a glove that is not especially flexible and therefore a bit cumbersome. The SuperGlove has a total of ten sensors and provides an RS-232 interface, but requires the control box for the interface.

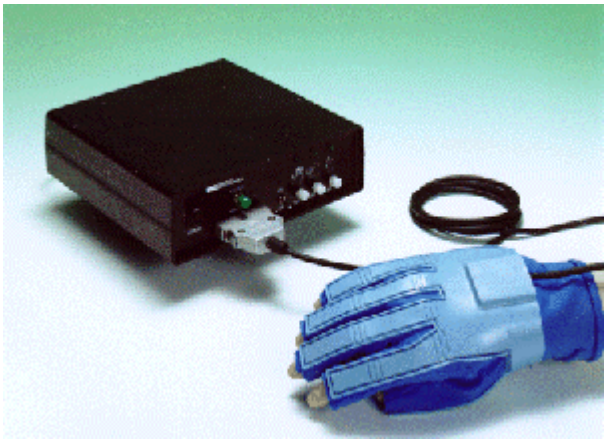

Figure 4: SuperGlove from Nissho Electronics.

The glove that is generally acknowledged as superior by researchers in the field is the CyberGlove® from Virtual Technologies (http://www.virtex.com/products/hw_products/cyberglove.html). It is available as an 18-sensor model or a 22-sensor model, with

- two bend sensors on each finger (including thumb),
- four abduction (side-to-side finger motion) sensors,
- sensors measuring thumb crossover, palm arch, wrist flexion and wrist abduction, and
- sensors to measure the flexion of the distal joints on the four fingers (22-sensor model only).

The CyberGlove is lightweight and flexible, and should be satisfactory for TMR applications from the standpoint of allowing the operator's hand(s) to still be usable for handling a weapon, radio, etc. The standard interface is an RS-232 serial connection, which is suitable for a variety of potential OCU controllers. The COTS version requires an external enclosure for the interface electronics.

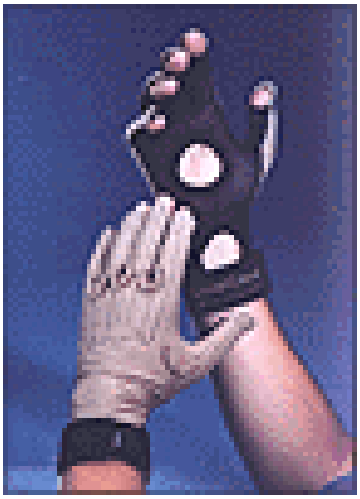

Figure 5: CyberGlove from Virtual Technologies.

A less expensive glove, the Fifth Dimension Technologies (http://www.5dt.com) DataGlove, is available in 5-sensor and 14-sensor configurations, but is bulkier. It is an instrumented glove for finger flexion and extension measurement, and it includes a 3DOF sensor for hand orientation (see below). Earlier versions included a flexor strip for elbow or knee flexion measurement, which may a potentially useful feature. Like the CyberGlove, the DataGlove uses an RS-232 serial interface.

Figure 6: Fifth Dimension Technologies DataGlove with integral orientation sensor.

For the simple detection of finger-to-finger contact, the FakeSpace PINCH™ glove is available (http://www.fakespacelabs.com/products/pinch.html). The PINCH system uses cloth gloves with electrical sensors in each fingertip. It is able to sense contact between any combination of two or more digits by detecting a completed conductive path. As with the other devices that are more commonly used in a virtual reality setting, no effort has yet been made to miniaturize the interface electronics, which are housed in a separate control box.


Figure 7: PINCH system from FakeSpace.

One additional glove is described below in section 2.2.5 in the context of muscular motion detection, and gloves for output feedback are described in section 2.3.3.1.

Most research with gloves is related to either virtual reality or gesture recognition. It is relatively clear that an "alphabet" of gestures can be trained for a given user and that the system will perform adequately well for the input of some ensemble of discrete commands. This is possible using COTS software that comes with the CyberGlove, for example, and this functionality can be useful in a TMR OCU for menu navigation, discrete command generation, etc. It is also apparent that gloves are useful in virtual reality environments. Bug it is less obvious how well they can be used for continuous control (e.g., teleoperated driving and telemanipulation). Not surprisingly, the relevant research has focused on telemanipulation, mimicking the motion of the hand with a robotic gripper. At the Dextrous Manipulator Laboratory of Stanford (http://www-cdr.stanford.edu/telemanip/) the CyberGlove has been used to control a two-fingered robotic hand that provides force feedback, under a US Navy SBIR program. In this capacity, it has been a success for manipulating objects, but the force feedback mechanism (CyberGrasp™, discussed below) is impractical for consideration when operating a TMR effector-bot.

Telemanipulation of a more dexterous hand, the UTAH/MIT hand, was done with a more awkward device that has evolved into the commercial Dexterous HandMaster (Exos, Inc.). Like it's predecessor, it is essentially an exoskeleton for the hand and is not practical for field use.

It is apparent that continuous control of a vehicle in a driving mode with glove technology (COTS or otherwise) is an unknown entity and is therefore a risk area. TMR experimentation results from Raytheon are almost certainly the best available information on the use of a glove in controlling a mobile robot. Later, there is some discussion on the use of gestures for controlling a mobile robot, which could possibly be extrapolated to consider gloves as the source of the gesture information.

#### 2.2.1.2 Orientation Trackers

Another commonly-used device in virtual reality are orientation trackers that estimate the roll, pitch, and yaw of an operator appendage, usually the head or hand/wrist. In TMR applications, this probably has more value in the context the head motion, since it is best not to constrain the hand orientation as a means of input.

The CyberTrack II (Figure 8) is similar to the the pitch/roll sensor found on the DataGlove and is also produced by Fifth Dimension Technologies, except that it incorporates a magnetic compass for yaw output as well. It is inexpensive and provides stated accuracies of +/- 2 degrees, although this must surely be degraded for the magnetic compass under most circumstances.

Figure 8: CyberTrack II.

Ascension (http://www.ascension-tech.com/) also manufactures an orientation sensor, the 3D-BIRD, shown in Figure 9. It has no external electronics unit and plugs directly into an RS-232 port. Like the CyberTrack, it is targeted for for head-tracking applications in which one needs to look around virtual environments and simulated worlds. 3D-BIRD makes up to 160 measurements per second with a latency of about 15 msec, so it is suitable for real-time tracking. Angular accuracy is given as 2.5 degrees static and 4 degrees dynamic. Its dimensions are 1.34" x 1.08" x 1.20" (3.4cm x 2.74cm x 3.05cm), and it weighs only 1.2 oz.

Figure 9: 3D-BIRD orientation tracker.

#### 2.2.1.3 Direct-contact devices

The CDG argues against using any input device that requires the dedicated use of the operator's hands, since they should be free to use a weapon, radio, or other device that may be needed to deal with other situations as they arise. In the strictest interpretation, this would preclude the use of what we here call *direct-contact devices* (of the general "joystick" class). But for obvious reasons related to ease of use, most interfaces for the direct control of manipulators or mobile robots in a visual servoing mode include some means of physically directing the machine with intuitive motions. This is usually implemented with devices such as 3D mice, joysticks, styli, steering wheels, and custom devices [Hong 99, Fong 00, Kawabata 99]. And while visual servoing by a human operator is an undesirable mode of operation from the standpoint of a single operator maintaining control of several robots simultaneously, it must still be accepted as a necessary evil in isolated (hopefully) circumstances.

Consequently, it is incumbent on the OCU designer to consider if there is some way to take advantage of this more natural means of teleoperating a robot without impairing the operator's ability to **immediately** have both hands free as the situation requires. We propose here that there are, in fact, methods for achieving this. The key elements of this approach to using direct-contact devices in TMR applications include:

- Availability of small, low-profile devices,
- Body ("sewn-on") mounting of the device in an unobtrusive, yet accessible, location,
- Incorporation of a dead-man switch on the device to provide immediate context switching to autonomous operation when the operator must interrupt teleoperation, and
- Behavioral software support for the dead-man switch.

The last two elements (related to the dead-man switch) are actually desirable for any means of teleoperating a TMR robot, not just the proposed direct-contact approach. For example, even if it were possible to teleoperate a robot by brain waves only, there must still be some consideration given to detecting when the operator is unable to continue this mode of operation because of distracting influences.

A widely used device in virtual reality research and CAD is the Spaceball, currently produced by Labtec, which in fact claims that it is the "most widely used 3D motion controller in the automotive, aeronautic, and consumer design industries worldwide." It allows intuitive interaction with small forces and limited motion of a ball suspended over a base platorm, as shown in Figure 10. Although this particular implementation is larger than desired for TMR usage, there are no significant difficulties in producing a smaller version. It supposedly is driftless, which eliminates the need for periodic calibration to zero out biases that may be interpreted as robot commands.

Figure 10: SpaceBall 3003 FLX from Labtec.

Logitech manufactures a line of similar devices, including the SpaceMouse XT (Figure 11a) and CyberPuck (Figure 11b). These devices (http://www.logicad3d.com/products/products.html) provide motion control in up to six degrees of freedom simultaneously using a disc-shaped device, with a lower profile than that of the SpaceBall. The sensitivity is adjustable, with up to 600 levels. The CyberPuck lacks the user-programmable buttons of the SpaceMouse, which could be useful as part of a minimalist user interface, but may be difficult to package in a wearable configuration. No calibration is necessary for these devices, and they support either RS-232 or USB connections. They also require no separate power input, drawing power instead from the data connection.

Figure 11: a) Magellan/SPACE MOUSE "Plus XT" (188 x 120 x 44 mm and 720 grams) and b) Cyberpuck (140 x 140 x 45 mm and 510 grams).

A significantly different approach is taken by Digital Image Design, Inc. with their Cricket (http://www.didi.com/www/areas/products/cricket/). The Cricket (Figure 12) is a 3D input device, specifically tuned to work in non-immersive desktop Virtual Reality environments. It provides 6DOF spatial input along with two conveniently located buttons for user-defined functions. The buttons are pressure sensitive, and the thumb button (on the upper surface of the handle) acts as a "flat joystick," sensing motion in three dimensions. Perhaps most interesting is the incorporation of vibration output as a means of providing tactile feedback through changes in amplitude, frequency, and waveform. Problems with the Cricket include availability (Digital Image Design appears to only recently have begun considering production of the concept), and tracking technology (it was designed to work in a virtual environment laboratory with external support). Nevertheless, it is interesting conceptually and provides a bridge to the next section, which considers tracking systems.

Figure 12: Cricket.

#### 2.2.1.4 External observation/tracking systems

At first glance, it would seem impractical to consider the field deployment of systems that have been developed for the recognition of body position and gestures in controlled environments by observing the user with external cameras or other sensors. But it may be reasonable to mount support equipment in the rear opening of a HMMWV or other vehicle. Such devices have been shown to be useful for gesture recognition in remote environments [Chien 98].

The Polhemus FASTRAK system (http://www.polhemus.com/ftrakds.htm) is based on the creation of magnetic fields by a stationary transmitter, which are in turn sensed by a receiver mounted on the user, with both the receiver and transmitter connected to a control unit by cable. At distances as large as 30 feet, it accurately computes the position and orientation the receiver as it moves through space in real time with only 4 msec latency. It can be used with multiple receivers, sacrificing only the position report rate. The computer interface is high-speed RS-232 interface (up to

115.2K baud) or an optional IEEE-488 interface at up to 100K bytes/sec. It is not necessary to maintain line of sight.

Figure 13: Polhemus FASTRAK system.

The Flock of Birds system from Ascension (http://www.ascension-tech.com/products/flockofbirds/flockofbirds.htm) is similar (Figure 14), and was originally developed for military applications. Each Flock receiver makes up to 144 position measurements each second, with latency of approximately 15 msec. The DC field technology is supposedly more robust in harsh environments. A single transmitter/controller can work with up to four units, as in the case of four robot operators each equipped with tracker mounted on their head or hand, all operating in the vicinity (approximately 10 ft.) of a single support vehicle. The host computer interface is RS-232, with selectable baud rates up to 115 kBaud. Static position accuracy is given as 0.07" (1.8mm) RMS, and static orientation accuracy is given as 0.5° RMS. The receiver is less than 1 cubic inch.

Figure 14: Ascension Technology Flock of Birds system.

Systems such as these would likely be used best to convey gestures. The use of gestures for mobile robot operation has been investigated with visually-detected gestures, which is a more difficult recognition problem, but conceptually similar. Fong et al. found that such gestures could be used to teleoperate a mobile robot (Figure 15), but it was not as easy as would be expected based upon human experience with following such gestures [Fong 00]. They concluded that it would probably be necessary to add other inputs to disambiguate visual gestures.

Figure 15: The virtual joystick mode of the *GestureDriver*, showing right, left, forward reverse, and stop commands [Fong 00].

### *2.2.2 Keyboards*

Any keyboard device is a severe compromise to the hands-free requirement of TMR. During operation of the OCU with robots, input of textual and numeric data must be avoided, and this should be a key concept behind the development of the software that implements the user interface. During breaks from active robotic control, it would be advantageous to have the capability of annotating logged data within the OCU, and perhaps performing other functions that would be much easier with a full keyboard.

One possibility would simply to support the connection of a standard PC keyboard when the user is at a command post or some other location where equipment is available. If possible, it would be preferable to have built-in capability for those instances where the operator cannot return to such a facility between periods of robot operation. A novel approach is a flexible keyboard within the operator's uniform, such as the embroidered approach shown in [Pentland00] (Figure 16). COTS possibilities include "chord keyboards" like the Twiddler (Figure 17), handheld touch-typing keyboards like the AlphaGrip (Figure 18), and small "normal" keyboards like those from Electrone (Figure 19).

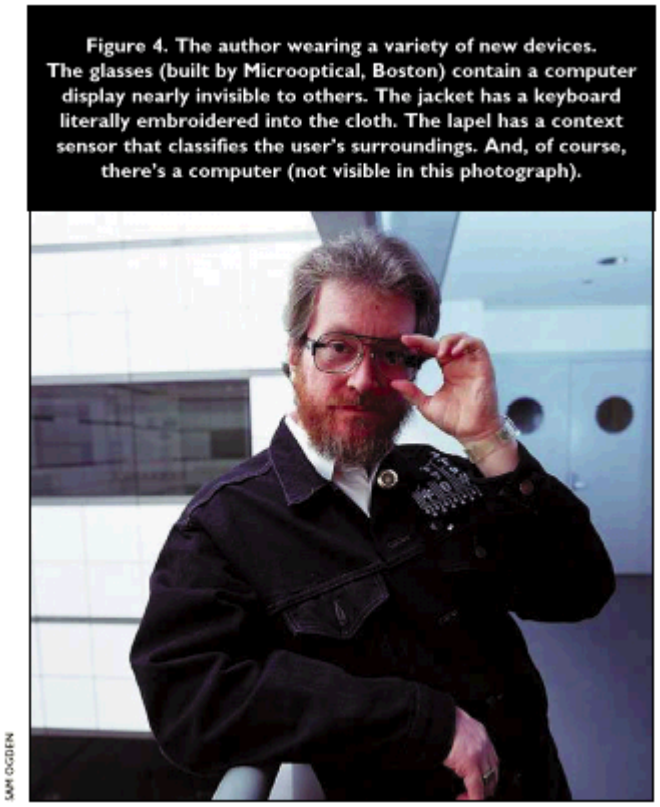


Figure 16: Embroidered keyboard concept (and Microoptical display), from [Pent-


Figure 17: The Twiddler one-hand keyboard.

Figure 18: AlphaGrip

Figure 19: Electrone Model 9001 (10.25 inches wide, about 60% of a standard keyboard).

### *2.2.3 Speech Recognition*

Speech recognition input is undesirable in a TMR OCU because of background noise, changes in voice characteristics under stress, and the general problems associated with recognition technology. One such problem is that there is a tradeoff between recognition reliability and the degree of speaker independence. And without speaker independence, there is the problem of training the voice recognition software in the field for a specific user. This is unfortunate, because there is evidence that voice control is superior to manual control of devices such as pan/tilt camera platforms [Draper 87], but speech recognition is still not a hurdle that is worthwhile for TMR to take on.

Motorola has added a voice control system as a technology upgrade to a variant of the Land Warrior system, the Force XXI Land Warrior (http://www.mot.com/GSS/SSTG/ISD/ws/vcs.html). In this concept, voice is used for hands-free control of radios and the display. Although targeted at high-noise background environments, there is still valid concern this sort of technology is not yet suitable for a TMR OCU. A "wait-and-see" stance is probably the most appropriate course to take – by using some Land Warrior components (computer and radios), TMR could leverage develop-

ment in those areas and have the optional use of the voice control system, if it proves to be reliable, without becoming dependent on the technology.

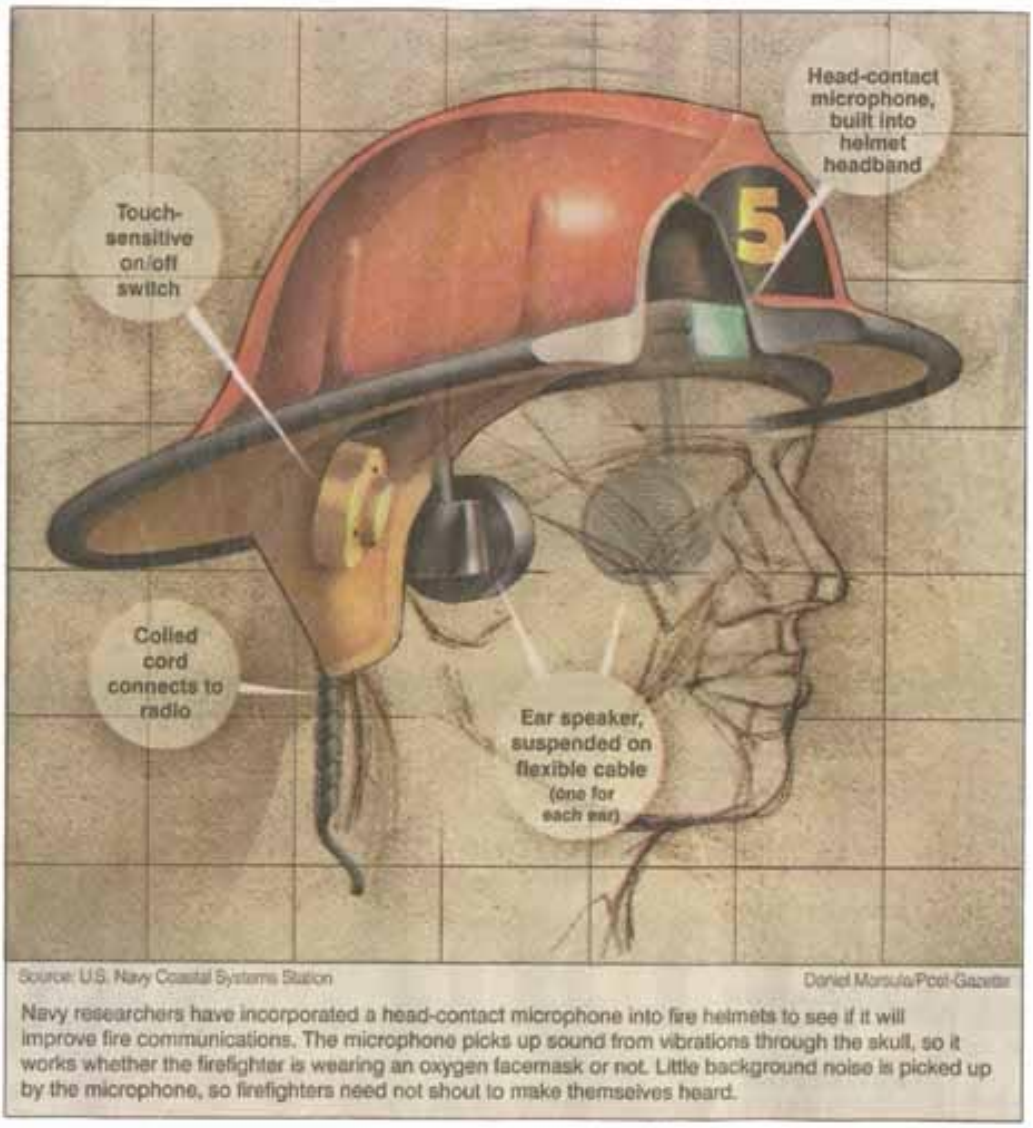


Figure 20: Head-contact microphone modified for firefighter helmet use.

Independently of whether or not speech is used for direct operator input, it may be advantageous for the OCU to include a complete audio system that can be used either with the computer or with wireless communications equipment, multiplexing the two channels and providing the best possible performance in a noisy environment. The output speakers of such a system will be addressed later. A candidate input technology (http://www.mtac.pitt.edu/WWW/html/pg_article.html, http://www.stac.ufl.edu/flc/Head%20Microphone.html, developed originally for Navy SEALS at the Coastal Systems Station of the Naval Surface Warfare Center, utilizes direct conduction of sound from the operator to the microphone through the skull, thus eliminating the need for holding a microphone in a particular place and simultaneously reducing background noise considerably. This technology is being commercialized by Sensory Devices, Inc. for use in firefighter helmets (Figure 20).

### *2.2.4 Eye Trackers*

Discussions at Oak Ridge National Laboratory have identified the importance of assessing the operator's attention state. Eye trackers are one possible means of achieving this, and they also provide the additional capability of acting as pointing devices for the user. But the physical size of devices such as the EyeGaze (LC Technologies, Inc.) and the helmet mounted iView (SensoMotoric Instruments) makes them impractical at this time, given the limited benefit of having them as part of the TMR OCU, as shown in Figure 21. Experimental platforms like the visor used at the University of Pennsylvania's Head-Mounted Eyetracking Lab (http://www.cis.upenn.edu/~ircs/Trueswellabs/HeadmountedET.html) do not address the portability factor, either.

Figure 21: The portable version of the EyeGaze system (left) and the iView helmet mounted system (right) are not suitable for a mobile warfighter.

### *2.2.5 Other*

Ultimately, an effective means of controlling a robot may be the use of brainwaves, muscular electric signals (myography) or small, subtle movements of muscles such as those in the face. Efforts in this area include those of MindTel and Sandia Laboratories.

At MindTel, under the direction of David Warner, a series of TNG transducers (Figure 22) have been developed to flexibly interface a variety of devices to computers, with a primary emphasis on aids for the disabled. TNG-1 was the first of these, and was targeted at direct input of EMG (electromyographic) signals from facial or other muscles (http://www.pulsar.org/2k/technology/coretech.html). Perhaps because of limited success with EMG sensing, subsequent TNGs have relied on more standard sensors (e.g., resistive) that are mounted in some fashion where the user can manipulate them, even with only limited muscular control.

The Sandia research [Amai 00] has attempted to actually control a small mobile robot (a Mini-RATLER™) using a commercially-available device, the CyberLink™ MindMouse. While the Sandia team was able to construct a reasonable mapping of detectable signals to robot control functions, there are clear obstacles to using this approach in the foreseeable future. Brain waves, in particular, are extremely difficult to control under stress or even in the face of minor distrac-

tions. Facial muscular movements and the resulting signals are easier to control, but difficult to distinguish enough for any fine level of control. Without improved technology in this area, robot control is likely to consist primarily of overt (almost discrete) commands generated by general muscular motion within a fairly large region of the face (e.g., movement almost anywhere in the jaw/neck region could be interpreted as a single discrete command). This corresponds in many respects with commanding a robot with cursor keys, and as noted earlier, discrete "cursor-key" approaches to robot control are not particularly promising.

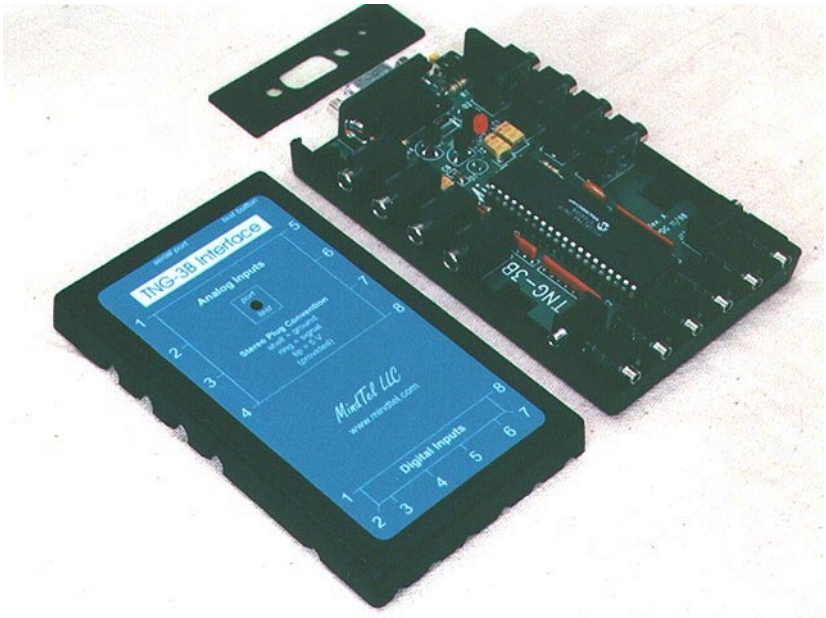


Figure 22: TNG-3B, the most recent sensor interface from MindTel.

[Robinson 98] also describes some of the limitations of electromyography as a means of robotic teleoperation. Although a potential site on the lower arm is identified as to provide a range of specified control signals, they also recognize practical difficulties with EMG control.

Given that a TMR OCU may want to input from various muscles and would probably take the more reliable course of detecting movement directly rather than by means of EMG, it may be useful to consider resistive touch sensors such as those from Infusion Systems (http://www.Infusionsystems.com/). These devices are targeted at musicians for the control of instruments, lighting, and effects during performance. The basic Touch Sensor is a 1.7"x1.7" touch pad, with a 1-2 msec response time and capable of sensing pressure over a range of 100 grams to 10 kg. With identical specifications, mini- and micro- versions are available as 0.5" and 0.2" diameter circles, respectively. A 24" x 0.5" strip, trimmable to user requirements, is also available.

Six of these touch sensors are included in the Infusion Systems TouchGlove, designed as a controller for drum machines. One sensor is mounted in each fingertip, and one is mounted in the palm. Since the TMR operators hands are already in demand, it may be more appropriate to consider the use touch/pressure sensors elsewhere, such as in the shoes where they can be activated by toe movements.

Finally, we note that relative to operator attention and perhaps to operator stress level, it may be useful to assess certain physiological conditions, such as heart rate, breathing rate, and gal-

vanic skin response. This is a lower priority with respect to initial deployment and will not be considered in detail at this time. Emerging technologies such as the "Smart Shirt" (http://vishwa.tfe.gatech.edu/gtwm/gtwm.html) provide possibilities for nonobtrusive monitoring of vital signs, utilizing optical and conductive fibers woven inside the garment.

### *2.3 Output Device Technologies*

There is tendency to rely primarily upon visual output to convey information to any remote operator of autonomous or teleoperated systems, mainly because of the high information bandwidth of visual displays. The importance of non-visual feedback is stated in the context of UAVs in AFRL research [Draper 00], in which it is noted that detecting turbulence visually is probably too slow or too unreliable for effective and safe control. This is not to say that non-visual feedback cannot be conveyed by visual means, and the AFRL recommendations in fact include the display of other data (e.g., orientation and attitude) by HUD techniques. The following sections first consider the available technologies for non-distracting visual displays and then other means of providing operator feedback.

#### *2.3.1 Displays*

Prior efforts have shown that real-time video is the single mechanism most relied upon for feedback when it is necessary to take control of a robot, either one designed for dedicated teleoperation [Draper 95, Hainsworth 00, Wettergreen 97, Ballou 00, Laird 00, Power 00] or for teleautonomous (telereflexive) operation [Bares 97, Fong 00, Gilbreath 00]. For this application alone, if nothing else, it is necessary to survey and evaluate displays that may be feasible for field operation in TMR scenarios. Based on this, and in conjunction with other TMR requirements, we can formulate three principles that can guide the survey of video display technology:

1. It is necessary, at least in isolated instances, to display full video frames (camera views, maps, etc.),
2. It is desirable, MOST of the time, to display augmented reality data in the least obtrusive manner possible (still allowing the operator to "see through" the data), and
3. At some intermediate level of frequency, it MAY be necessary to display GUI interfaces, such as menus and dialog boxes.

The need to satisfy these constraints with a heads-up display, minimizing the inconvenience of managing two separate visual inputs at once, has been noted by various researchers, including [Starner 95].

One example of an impractical and distracting display is the early Land Warrior prototype shown in Figure 23. Although it can be swung out of the way (which may be suitable for intermittent use by soldiers in general), this is not desirable for a soldier interacting almost constantly with a group of robots while still maintaining awareness of his surroundings. And while one could argue that such a display is transparent in the sense that one eye still can see beyond it, experience indicates that this is difficult in practice.

Figure 23: Early Land Warrior helmet mounted display that clearly exhibits some of the features to be avoided.

Newer developments in wearable display technology are less cumbersome and provide some degree of transparency (and admittedly are less ruggedized). But even casual observers can see the problem. At a gathering of wearable computer enthusiasts and vendors, CNN reporter Ann Kellan observes "One eye on the monitor, one eye on the real world, may be natural for these techies, but it takes getting used to," noting that it takes a conscious effort to pay attention to reality.

#### 2.3.1.1 Head Mounted Displays

Head mounted displays have been used in military applications for many years already, but suffer from criticisms of awkwardness, visual discomfort, fragility, and vision obstruction. As long ago as 1995, however, Starner et al. [Starner 95] argued that such displays are victims of several misconceptions. First, they note that focus depth is not a problem, since many units have adjustable focus depth, and this can be set to provide a level of comfort exceeding typical fixed display monitors. There is an implicit assumption here, arguably not valid for TMR, that the user will have a somewhat constant focus depth in the real world. Supposedly this assumption holds true for many everyday situations, such as walking down the street, sitting in a meeting, etc.

Second, Starner et al. note that these displays do not act as an "eye patch," with the display image possibly overriding the real world, and instead allow most users to easily merge the images from both eyes. They do acknowledge, however, that the greater the degree of difference between display content and real-world content, the more difficult this may be. And finally, they argue that there is no significant adaptation period when taking these displays on and off.

Improvements in head mounted displays (HMDs) have resulted in those such as the Land Warrior HMD, developed by Kaiser Electronics, as shown in Figure 24. Devices such as this are rugged enough for military use, and they attempt to avoid the distraction issue by allowing them

to be moved aside completely or at least out of the direct line of sight, as in Figure 24(b). Comprised of an 800 x 600 pixel resolution LCD, the unit provides a 40-degree FOV.

Initial experiences with these displays in warfighting experiments are encouraging. Also, the use of an HMD in the MPRS (Man Portable Robotic System) seemed to cause no difficulties during exercises in which robots were teleoperated in tunnels, aside from the reported desire of secondary operators to also see the video and some difficulties in bright sunlight [Laird 00, Bruch 00].

Figure 24: Land Warrior HMD developed by Kaiser Electronics. (a) side profile (b) in use while aiming a weapon.

Alternatives to the rugged Land Warrior HMD exist providing other attractive characteristics. TekGear (www.tekgear.ca) is producing the M2, a high end portable viewing device targeted at mission critical display. The integral LCD provides 800 x 600 resolution in full color. The base model shown in Figure 25 is intended to be a universal form factor and can be modified to OEM configurations (e.g., helmet-mounted).

Figure 25: TekGear M2. a) complete headset version, and b) details of LCD display.

| TekGear M2 Specifications | |
|---|---|
| Field of View | 22° Horizontal, 16.6° Vertical |
| Optics | High Efficiency, See Through |
| Video Resolution | 480,000 pixels (800 x 600) |
| Pixel Pitch | 12 Microns |
| Input Signal | 24 bit Digital RGB GVIF interface |
| Video Refresh Rate | 60Hz |
| Contrast | 50:1 |
| Operating Temperature | 0 to 50 degC |
| Storage Temperature | -10 to +80 degC |
| Shock and Vibration | Industrial Environment |
| Total Weight | 210g |
| Controls | Brightness, Image Flip |
| Power Consumption | Under 2.0W |
| Input Voltage | 5V DC |

MicroOptical Corporation (http://www.microopticalcorp.com/) has developed an "Invisible Monitor" technology that can be clipped on as in Figure 26(a) or integrated into eyeglasses as in Figure 26(b). The C-1 clip-on field test kit contains one Invisible Monitor Clip-on information display with "see-around" display optics, articulating mounting arm, and VGA and NTSC conversion electronics. The housing of the conversion electronics is separated from the display by a 4-foot cable. The Integrated EyeGlasses contain simlar optics, cabling, and conversion electronics.


Figure 26: MicroOptical C-1 Clip-On display (a) and integrated eyeglasses (b).

Figure 27: Thad Starner from Georgia Tech wearing the MicroOptical glasses.

| MicroOptical Specifications | |
|---|---|
| Display Format | 320 x 240, 16-Bit Color<br>(640x480 under development) |
| Refresh Rate | 60 Hz |
| Field of View | Approximately 11 degrees horizontal |
| Optics | Left eye version is available now, right eye versions by special order |
| Focus Range | Pre-set to 1 meter (other distances available upon request) |
| Eyeglass Frame Size | Clip-on fits most wire frame glasses. Plano glasses supplied |
| Video Input | Standard VGA, female DB-15 connector and standard NTSC, RCA plug |
| Power Requirements | 9 V, 100 mW (display and backlight).<br>9 V, 2.9 W (VGA interface).<br>9 V, 1.9 W (NTSC interface)<br>4.5 V, 300mW (RS170). |
| Operating Temperature | 32 degrees to 104 degrees F (0 degrees to 40 degrees C) |
| Storage Temperature | -4 degrees to 104 degrees F (-20 degrees to 40 degrees C) |
| Head-Supported Weight | Clip-on: 33 grams<br>Integrated EyeGlasses: 62 grams |

#### 2.3.1.2 Retinal Displays

Even the best HMD implementations have several problems, including limited field of view (without sacrificing real field of view), size, weight, resolution, brightness, lack of true transparency, and power consumption. A promising approach to solving these problems of traditional HMDs is the virtual retinal display (VRD). Invented at the HIT lab of the University of Washington (http://www.hitl.washington.edu/research/vrd/) in 1991, VRDs do not require the size and energy associated with actually forming an image on a screen, instead directly scanning the image onto the retina in the most efficient way possible. The technology is being commercialized by Microvision

(http://www.mvis.com/) as the Retinal Scanning Display (RSD). In keeping with the intent herein of providing an interface more akin to augmented reality, the RSD is targeted at applications in which it is necessary to display an image that is overlaid and does not block a user's view. Initially, this is monochrome, but with technology improvements it will be possible to provide full-color displays. According to a recent trade publication article, "adding green and blue is only a matter of time, especially since funding from the commercial and military industries is ample, and the Army, Navy and Air Force are all investigating the RSD for use in next-generation AR HMD systems" [Ciufo 00].

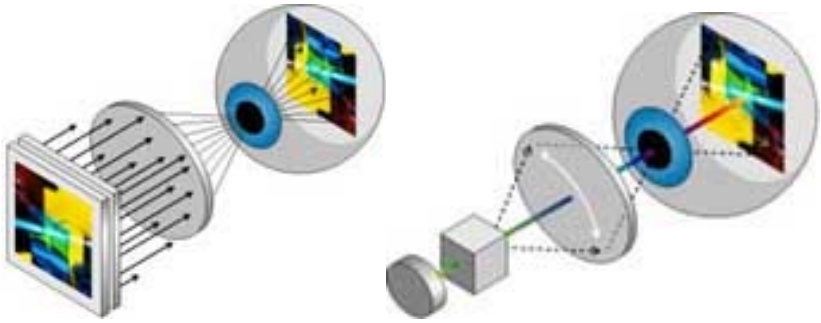

Figure 28: Viewing a planar image (a) vs. the Retinal Scanning Display approach (b).

RSD relies upon low-intensity lasers and microelectromechanical (MEM) devices to scan an image directly onto the retina of the eye, as shown in Figure 28. This completely eliminates the need for an image display such as an LCD, as well as the optics required to allow the user to focus on the close device. Since the image characteristics can be controlled directly by a host computer, it is possible to vary the size or apparent distance as needed. Although initial versions, like that shown in Figure 29, rival other HMDs in physical size, it should be possible to immediately reap the benefits of a sharp, clear, transparent display.

Figure 29: Nomad prototype RSD headgear from Microvision.

| Retinal Scanning Display Specifications | |
|---|---|
| Resolution | VGA (640 X 400 pixels)<br>SVGA (800 X 600 pixels*) |
| Luminance | 1-480 FL at the eye (500+ FL*) |
| Grayscale | 32 user discernable gray shades |
| Dimming Ratio | 1000:1 |
| Field of View: | 30 degrees horizontal, 22 degrees vertical, approximately equivalent to a 19" Monitor |
| Display Color: | Monochrome red (635 nm) |
| Refresh rate | 60 Hertz |
| Interface | SVGA*, VGA, NTSC*, PAL* |
| HMD weight | < 1.5 lb. (657g) |
| Power | 12 VDC |
| | * in development, available mid 2001 |

For all of its promise, RSD technology is not without its risks. In addition to the fact that commercial deliveries have not begun, and some of the specifications pertain to upcoming improvements, other possible problems include difficulty in maintaining proper alignment of the exit pupil with the eye, cost reduction, and ruggedization.

#### 2.3.1.3 Omnidirectional camera imagery

TMR has accepted the value of omnidirectional (actually, *panospheric* is probably a better description) camera imagery for typical missions. Development of the OmniCam at Columbia University (http://www.cs.columbia.edu/CAVE/omnicam/) resulted in the licensing of the technology to RemoteReality (http://www.remotereality.com), formerly CycloVision Technologies. Although other omnidirectional approaches had been implemented, this was the first to provide a *single effective viewpoint* [Baker98]. Such a viewpoint preserves perspective in all directions, and thus makes it possible to choose a direction to look at any time and see it from exactly the same point in space. In robotic applications, prior work with NASA's Nomad [Wettergreen 97] and the Ames Marsokhod Rover [Christian 97] had established the usefulness of this data for a variety of applications including teleoperation, exploration, reconnaissance, or searching.

From the standpoint of OCU design, the important issue is the presentation and use of omnidirectional imagery. Ongoing research at the University of Pennsylvania has addressed this within the context of TMR and similar applications (http://www.cis.upenn.edu/~kostas/omnigrasp.html). Some of the most relevant work on utilization of omnidirectional images for teleoperation has been done at Lehigh University (http://www.eecs.lehigh.edu/~tboult/remote-reality.html). Vehicles, including the one shown in Figure 30, have been teleoperated by presenting users with interfaces combining multiple unwarped images [Power 00]. Usability studies have indicated some disorientation problems, and not surprisingly the forward view is most suitable for normal driving [Boult 00].


Figure 30: A vehicle built at Lehigh for teleoperation with omnidirectional imagery.

### *2.3.2 Audio*

The operator must remain in voice contact with other military personnel, and it is straightforward to allow any OCU audio outputs to reach the operator through a shared output device. Intuitively, it illogical to use an earphone or headphone, since this would mask local sounds that may be important cues of impending danger to the operator. Consequently, direct auditory conduction through facial bones appears to be a more appealing prospect. But although studies have shown that bone-conduction speech recognition thresholds are similar to normal air-channel thresholds [Edgerton 77], and even though noise-masking characteristics are also similar in the two mechanisms [Robinson 82], there are few COTS products that directly use conduction, aside from hearing aids. According to the Military Audiology Association, research continues in this area (http://www.militaryaudiology.org/newsletter02/aac.html), but little published data is available.

### *2.3.3 Tactile and Haptic devices*

One of the most widely adopted technologies for tactile/force feedback is the TouchSense technology available from Immersion (http://www.immersion.com). This has been incorporated into a variety of entertainment products (mostly joysticks, steering wheels, or variants thereof) and several medical products. Medical applications include training, such as the simulation of the sensation of insertion of a needle, catheter, endoscope, or other medical device into a human subject (HT Medical). Analogous sensations for a robot operator could include the "skin resistance" as the robot attempts to penetrate a door or other opening, the "pierce-and-relax" sensation as the

robot succeeds, and the “steady drag” as the robot moves down a hall or other close-quarters situation.

SPAWAR researchers have uses a vibrating pager-like device inside a pendant controller to directly provide velocity feedback [Gilbreath 00]. Hong, et al. demonstrated force feedback to teleoperate a mobile robot with a joystick over both level ground and stairs [Hong1999]. The reflected force corresponded to the potential field of nearby obstacles in the level ground case and to the impulse force of climbing when on stairs.

Fong et al. [Fong 00] have used the Delta Haptic Device (Figure 31),device developed at the Ecole Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology) to provide feedback during teleoperation of a small Koala Robot (Figure 32). The robot is equipped with short-range proximity sensors, and the *HapticDriver* interface transmits to the operator a force proportional to the closeness of detected obstacles. Trials with test subjects (complete novices at a trade show) showed that the force feedback often made the difference in being able to drive through a maze without collisions. It was determined to be an “effective interface for navigating cluttered environments and for performing docking maneuvers.” Unfortunately, the Delta Haptic Device is impractical for field deployment, and it is not obvious how a portable device could be constructed to convey that degree of force information.

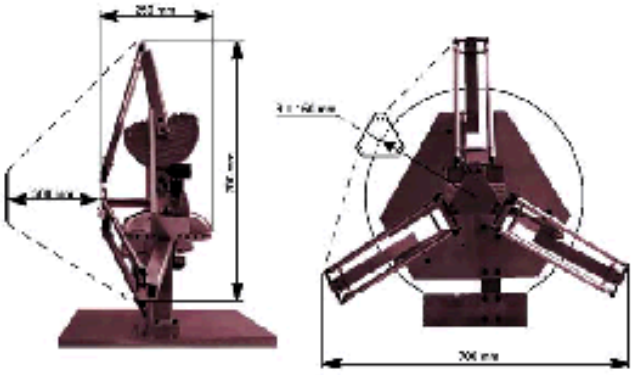

Figure 31: The Delta Haptic Device.

The *HapticDriver* currently uses only 2D force information, but the developers are considering the possibility of mapping wheel torques, 3D orientation, or accelerations into 3D forces, perhaps allowing operator perception of driving across uneven terrain or through minor obstructions, humps, etc.

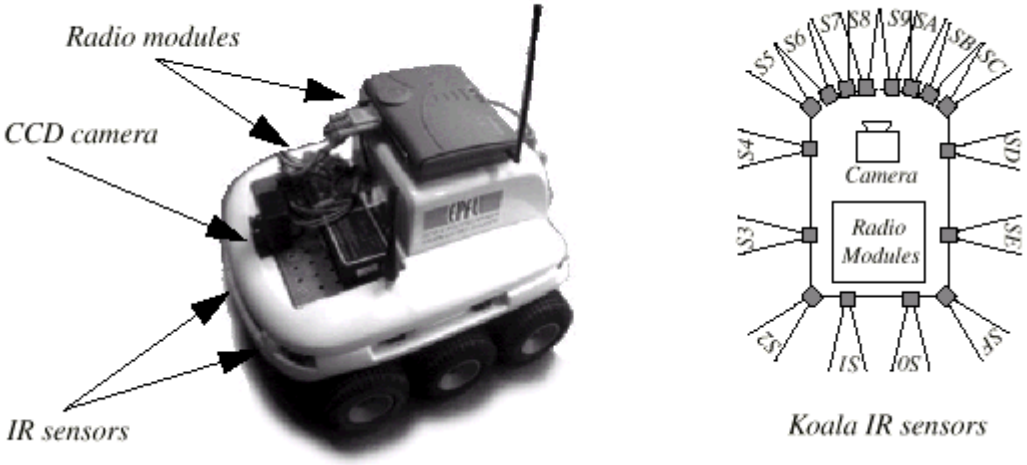


Figure 32: Koala robot used for teleoperation with haptic interface.

#### 2.3.3.1 Gloves for Haptic and Tactile Feedback

True haptic feedback is not an option for a man-portable configuration at this time. Devices like the Delta Haptic Device described above are far too cumbersome. The least objectionable implementation is the CyberGrasp, from Virtual Technologies, the maker of the CyberGlove described earlier (http://www.virtex.com). Designed to be used in conjunction with the 22-sensor version of the CyberGlove, the CyberGrasp is a massive cable driven mechanism, clearly not practical for a TMR OCU. Furthermore, it requires a 6DOF sensor like the Flock of Birds or Polhemus systems discussed earlier.

Of greater interest, and also manufactured by Virtual Technologies, is the CyberTouch option for the CyberGlove. This introduces small vibrotactile stimulators into each finger and on the palm of the glove. The stimulators are individually addressable and support both pulsed and sustained vibration. According to Virtual Technologies, it is possible to achieve the perception of touching a solid object, which could of course be useful if using a glove to teleoperate a robot. Even aside from such a capability, the vibrotactile stimulators provide a means of signaling the operator without requiring visual attention. This could be useful both during continuous control of a robot (to convey remote sensory information or robot status) or simply to get the operator's attention as an "interrupt." Specifications of the CyberGlove include a vibrational frequency range of 0-125 Hz, a vibrational amplitude of 1 N peak-to-peak @125 Hz, and a weight of 5 oz.

## *2.4 Support Technologies*

### *2.4.1 Cabling and Communication*

The larger issues of reliable communication between robots, warfighters, and command posts will not be addressed here, and in fact are the subject of other programs with much wider scope than robotics. For the purposes of near-term demonstrations, the working assumption must be that wireless communication between agents (robotic or human) will be much as it has been in the 2000 TMR demonstration, a mixture of wireless point-to-point modems and standard WLAN (wireless local area network) technology with add-on equipment to improve performance. To address early deployment of robotic units and the need for improved LPI/LPD performance, this will have to be replaced with emerging military radio technology, possibly from the Land Warrior program or a new "lightweight warrior" ATD (advanced technology demonstration) that could begin in 2000-2001 [Erwin 00].

Of greater interest for the design of a near-term OCU is the interconnection of the devices that are proposed for an individual warfighter. Most of the devices can be interconnected with cables that pass through sewn loops on the uniform, minimizing the possibility of snagging. Wireless Bluetooth technology for peripherals, where available, is certainly a possibility to minimize the use of cables. Because of its short range, it is less of a risk for a deployed system, but should still be used only with caution and after prior testing. Infrared peripherals, using protocols such as IRDA, are generally not desirable because of their requirement that line of sight be strictly maintained.

But since it is necessary to provide cables to supply power to wireless peripherals, it is arguable whether any significant advantage is gained by not using the same cable route to convey signal information. This is especially true of some of the RS-232 serial devices which can be self-powered off of the wired data interface.

### *2.4.2 CPUs*

As noted earlier, wearable computing technology is the logical source to ultimately provide COTS components for the heart of the OCU. In the short term, for the sake of ruggedness, there are distinct advantages in considering the Computer/Radio Subsystem (C/RS) of the Land Warrior program, developed by Motorola (http://www.mot.com/GSS/SSTG/ISD/ws/warriorcrs.html). Although more bulky than the sleekest units currently available from vendors like Xybernaut and VIA, the C/RS is still only 3.2 pounds (with radio, frame grabber, and GPS) and provides a variety of interfaces, including

- VGA or RS-170 for Helmet or Hand Held Display with Touch Screen
- Thermal Weapons Sight or Video Camera video input
- Radio Interfaces, 2 internal, 1 external
- 4 Channel Laser Detector
- PCI and ISA Bus for future expansion
- Keyboard/mouse
- 2 ea. RS-232

- Ethernet
- USB

Physical size is 10.6 x 7.0 x 1.7 in. for the computer and 4.5 x 3.0 x 1.5 in for the radio, and is designed to be carried within a backpack frame.

### *2.5 Operator Interface Design and Integrated Augmented Reality*

The importance of an augmented reality (AR) model to describe the conveyance of remote information in a TMR OCU has already been discussed. In this section, we elaborate on some notional concepts for the actual implementation of the operator interface and the incorporation of AR techniques. This is necessary to develop a complete concept of a recommended hardware implementation in the next section.

The nature of the robot status information being displayed in prior efforts to develop OCUs tends to depend on the criticality of the robot (its intrinsic value, relative to the risk in which it is placed) in conjunction with the "cost" of displaying such information. In cases where robots are sent into dangerous situations, such as advance exploration of mines [Hainsworth 00] or space applications [Lane 00a, Wettergreen 97, Christian 97, Nguyen 00] and where multiple large format displays are available, informational displays become very extensive. Since such situations normally fit the "Mission Control Station" model of an OCU, often with multiple operators available to monitor mission status, it is quite understandable to build displays that provide all information that may possibly be useful.

NASA Ames has developed the Virtual Environment Vehicle Interface (http://img.arc.nasa.gov/VEVI/index.html) for the purpose of remotely teleoperating robotic vehicles such as Nomad [Wettergreen 97] and the Ames Marsokhod Rover [Christian 97]. This approach, however, takes the extreme position of immersing the operator in a complex representation of the robot's environment in order to maximize the probability of successful operation, since the robot is extremely valuable, latency is high, and the environment is typically not well known. But given the available bandwidth for display of data, visual or otherwise, sacrifices must inevitably be made in the status information provided by a TMR OCU. It cannot be "designed by committee" to accommodate the wishes of all designers and potential users, as difficult as the decisions may be to defend later with the benefit of hindsight.

Even if the adverse effects (primarily distraction) of a teleimmersive environment could be tolerated, it is interesting to note that some research suggests that it may not even be that effective of an approach for many tasks. In applications involving remote driving and operation of heavy equipment, researchers at the Helsinki University of Technology [Halme 00] discovered that the use of a head tracker with a pointable camera was sometimes helpful in choosing direction in unfamiliar terrain, but not as useful when moving in a specific direction, as when being constrained by walls or tunnels. The use of a HMD in any of these applications was found to be stressful and could cause nausea.

In the context of the MPRS program, SPAWAR researchers also note the taxing nature of teleoperation through onboard video, often accentuated by problems with contrast and lighting [Laird 00]. The results of MPRS tests with military users at Fort Leonard Wood are somewhat

limited in their applicability to the primarily autonomous nature of TMR, since most users were uncomfortable with any degree of autonomy in the MPRS systems.

After experiments with Dante II [Bares 97], the following guidelines emerged with respect to the interface design:

> *"Consistent appearance and interaction:* Similar or identical design throughout the interface allows operators to focus on robot actions rather than the mechanics of using the interface.
>
> *"Functional organization:* It is appropriate to embed the functional layout within the interface to avoid operator confusion. The use of operational control contexts pro-vides a unifying and simplifying perspective on human-machine interaction. This approach enabled us to concisely organize the interface so that commands appropriate for a particular type of function are grouped together.
>
> *"Uncluttered layout:* Clean graphical design with qualitative or simple quantitative representations of sensor and state information allows quick assessment of current conditions. Numeric data provides precision and should support graphical features unobtrusively.
>
> *"Simple command generation:* Clear, easy-to-use controls allow efficient, rapid command sequences. Easily modified values and reusable commands are important for reducing operator workload during teleoperation.
>
> *"Visual indication of safeguards:* Different command safeguards are appropriate depending upon the situation and the types of commands being applied. Indicators that clearly reflect active safeguards reduce operator misconceptions and error." [Bares 97]

Mobile robot operator interfaces, whether for teleoperation or supervisory control, and regardless of the operational domain (air, ground, underwater, space) historically have several major modes. While there are differences in nomenclature and in implementation, it is only a minor oversimplification to say that most prior work advocates the use of at least four primary modes:

- Sensor/status mode,
- Command mode,
- Robot perspective mode, and
- Map mode.

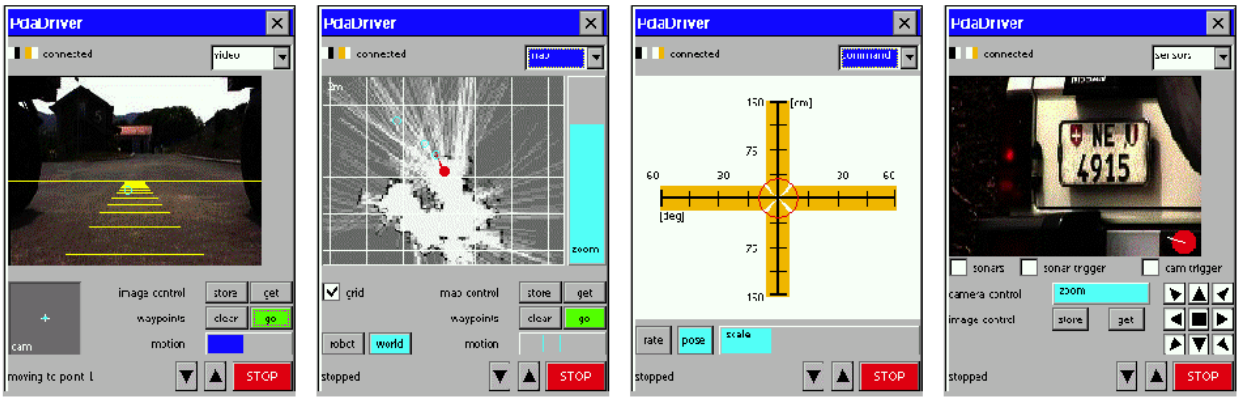


Figure 33: Multimodal display of the PdaDriver, showing their "video," "map," "command," and "sensor" modes [Fong 00].

Archetypal examples of multimodal interfaces for teleoperation of mobile robots include the Virtual Dashboard of the NASA Nomad [Wettergreen 97], the PdaDriver [Fong 00], and TMR concepts [Bay 00]. Depending on display constraints, some were implemented as multiple panels on a large display, and some were implemented as alternate user displays. Also, lessons learned from the Dante II mission to an Alaskan volcano [Bares 97] included the importance of graphical displays of telemetry in a multi-page format. There is also demonstrated value in the use of attitude and heading reference displays similar to those used in heads-up displays of aircraft [Hainsworth 00]. Definitions of the four modes for the purposes of this discussion follow:

***Sensor/status mode*** provides all critical information about the robot's internal state and its external sensors. It may also be called *telemetry* mode, especially in the case of machines with little or no autonomous capability. It is the mode typically used to assess the operational state of the robot and its ability to proceed.

***Command mode*** provides an interface tailored to issue commands to the robot, perhaps allowing the user to drive it with a virtual joystick or with cursor keys, to actuate mission-specific devices, to change default speeds, gains, and sensitivities, etc.

***Robot perspective mode*** is usually dominated by one or more camera views from the robot's current position, but may include any environmental perceptions that enhance the general impression of telepresence. Remote driving is often conducted from this display, since it is intuitively the most comfortable for typical operators.

***Map mode*** provides a top-down perspective of the robot's local environment, placing it in context with known (or hypothesized) environmental features, geographical coordinates, other robots, etc. Often, multiple levels of zooming are provided. This mode is often required for global navigation.

In the best implementations, there is modal overlap, and it is therefore possible to make use of some of the same functionality in different modes, but the rationale for the different modes usually includes a) there is insufficient space in the display to provide all interfaces at once and b) even if there were enough space, it would be overwhelming to the operator.

In a TMR OCU, it is especially desirable not to present too much information, so the multimodal model is appropriate, and the typical modal interface will generally be even less informa-

tion-rich than full-fledged GUI interfaces. With creative use of some of the alternate input devices (other than visual displays), it becomes possible to convey some additional data, including that of modes other than the active mode. And if the primary visual display is effectively transparent, some of the modal information can be displayed as non-distractive AR data.

Several opportunities exist for the effective use of AR displays. During manual teleoperation, for example, the effect of autonomous behaviors (e.g., obstacle avoidance) can be masked from the actual motor control, but displayed as arrows on the "driving mode" display (e.g., as arrows away from obstacles). Similarly attractive forces can be shown as well, as in the pheromone robotics displays of Payton [Payton 00]. Also, research at the University of Maryland has shown that there is great value in showing the predicted effect of operator commands, especially when there is high latency in communication [Lane 00b].

With respect to the design of the OCU interface, much can be learned from the efforts at Carnegie Mellon in the area of *collaborative control*, their description of joint human-robot operation, in which the robot may function autonomously and make requests of the human operator [Fong 99]. The Georgia Tech *MissionLab* system supports the notion of *teleautonomous control*, in which human control can be superimposed upon robotic behaviors, and several interface concepts have been developed to support this modality.

### *2.6 OCU System Design*

From the standpoint of hypothesizing an integrated system design that would be appropriate for TMR applications, it is proposed that a multimodal interface (as discussed in the previous section) be implemented on a hardware suite consisting of the following major items:

- Wearable computer,
- See-through heads-up display,
- Gesture-sensitive glove on dominant hand,
- Fingertip contact-sensitive glove on secondary hand,
- Direct-contact "joystick-type" device sewn into uniform at mid-thigh,
- Helmet-integrated microphone and audio feedback.

Key points to this approach include:

- Microphone is used for person-to-person communication only, not voice recognition,
- Attention-getting "operator interrupts" provided simultaneously by audio alarms and flashing visual indicators,
- Navigation of multimodal visual screens, video feeds, etc., strictly by fingertip commands of secondary hand,
- Use of dominant hand only as required for critical positioning and gesturing, including glove commands or joystick control (by dropping hand to thigh, either sitting or standing).

Much of the rationale for this approach has been provided earlier in the discussions of the various devices and previous user interfaces. Central to the design philosophy is the fact that the operator of the proposed system can perform a variety of control operations without requiring use of his dominant hand or losing sight of the immediate surroundings.

Specifically, a reasonable approach would be to allow the operator to select between four different operational modes by "double-tapping" his thumb against one of the four fingers on the same (non-dominant) hand. The operational modes correspond to those described earlier, and many variations are possible, but for example:

- Index finger – command mode
- Middle finger – sensor display mode
- Ring finger – map mode
- Little finger – immersive robot view mode

This particular choice of displays might be designed to be increasingly immersive, where the command mode and sensor display mode simply superimpose a few gauges and indicators over the operator's normal visual field, while allowing minimal screen navigation and user input with "single-taps" of the thumb against the four fingers.

The dominant hand could be dropped to the thigh-mounted "joystick" for finer control of user input in these screens, but this feature would primarily be used for driving in the map mode (which takes up a bit more of the visual field), and the immersive "robot's-eye" view mode (which ideally is seldom used). Similarly, the gesture recognition glove on the dominant hand could be used for additional input functions in these modes, under the same assumption that the operator would not have entered these modes unless he temporarily had use of both hands for robot operation.

Figure 34: Key devices for the implementation of the proposed approach, including the contact sensitive PinchGlove, the gesture sensing DataGlove, the low-profile CyberPuck for mounting on the thigh as a joystick, and the virtual retinal display.

The actual hardware used to implement (Figure 34) this could consist of

- any of a variety of wearable computers, including a subset of the Land Warrior system,
- a PinchGlove for the non-dominant hand,
- a DataGlove for the dominant hand,
- a CyberPuck for attachment to the uniform at the front of the thigh, and
- the Virtual Retinal display.

Backups to all of these devices are commercially available, but the largest risk is probably in the display. Both the MicroOptical and TekGear displays are viable alternative to virtual retina technology. All of these devices require ruggedization, but all are suitable for experimentation in their current form. As noted earlier, comms gear being developed for Land Warrior and other programs should be integrated where possible.

## 3. HUMAN FACTORS AND TMR

### *3.1 Human Factors Introduction*

In designing a TMR system capable military use, we first revisit the principles of teleoperation and study how this has evolved into telepresence. We can learn from the history of this area about human factors issues that affect design, operator selection and training.

[Draper 95] defines a teleoperator as a "general-purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments." He cites several human factors challenges in teleoperation which are likely germane to TMR:

- Human role: what level of control is chosen (supervisory, shared, traded, etc.)
- Design of feedback systems (viewing, force)
- Pace of control (user, machine, or non-real-time);
- Role of feedforward
- Measuring performance.

An interesting quote appears in [Draper 93]:

> *In teleoperation, the [human-machine] interaction ... is more than merely an exchange of information - energetic interactions are as least as important.*

One of this things this report focuses on is how to achieve more than just information exchange and to be able to tap into the user's perceptual, cognitive, and motor channels more effectively than with mere information presentation.

#### *3.1.1 Organization of Control*

Sheridan's work is considered central to telerobotics research. Figure 35 denotes the many different aspects of control feasible, ranging from manual to supervisory to fully automatic (autonomous) control.

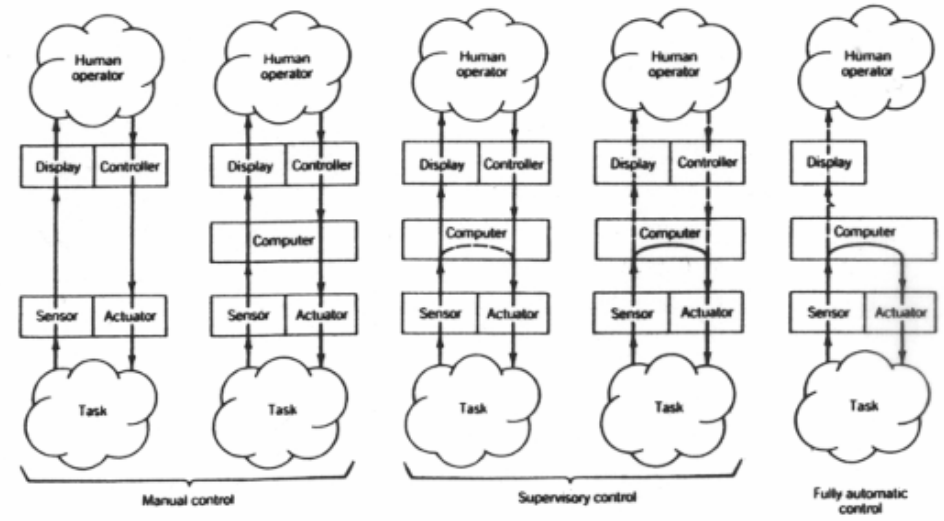


Figure 35: Levels of Control for Teleoperation through Autonomy (from [Sheridan92])

### *3.1.2 Telepresence and Cognition*

[Draper et al 1998] cite studies that show that the shape of the robot controller is not important during teleoperation but spatial correspondence is. The artifact must be easy to use and predictable. Other studies have shown that displaying force information via audio can produce better results than with haptic displays. They use the definition of telepresence as "a mental state in which a user feels physically present within the computer mediated environment.". Sheridan refers to telepresence as the loss of awareness of the actual user's surroundings. Table 1 shows the many different definitions and performance factors associated with telepresence, while Table 2 lists several psychological models developed for telepresence.

| *Approach* | *Nature of Telepresence* | *Causes* | *Relationship to Performance* |
|---|---|---|---|
| Akin et al. (1983) | A feeling of actual presence at the work site | 1. Manipulator dexterity<br>2. Feedback scope and fidelity | Telepresence improves performance |
| Sheridan (1992 a, b; 1996) | User feels physically present at the remote site; compelling illusion; subjective sensation | 1. Sensory fidelity<br>2. Sensory control<br>3. Manipulability | Telepresence improves performance |
| Steuer (1992) | The sense of being in an environment; the experience of presence in an environment by means of a communication medium | 1. Vividness<br>2. Interactivity | Telepresence improves performance |
| Zeltzer (1992) | Sense of being in and of the world | 1. Autonomy<br>2. Interaction<br>3. Presence | Telepresence may improve performance, but may make tasks more difficult and fatiguing |
| Slater and Usoh (1993, 1994) | The (suspension of dis-) belief that they are in a world other than where their real bodies are located | 1. External factors<br>2. Internal factors | Telepresence improves performance |
| Witmer and Singer (1994) | subjective experience of being in one place when physically in another; subjective sensation, much like 'mental workload'; a mental manifestation | 1. Control factors<br>2. sensory factors<br>3. distraction factors<br>4. realism factors | No clear relationship |
| Schloerb (1995) | The person perceives that he or she is physically present in a computer-mediated environment | 1. Information flow<br>2. Ability to manipulate computer-mediated environment | Performance must reach some minimum level before telepresence can occur; relationship not established beyond that |
| Mühlbach, Böcker, and Prussog (1995) | Sense of sharing space with distant interlocutors | 1. Spatial presence<br>2. Communicative presence | Performance improves telepresence |

**Table 1: Performance factors in telepresence (from [Draper et al 98])**

| *Approach* | *Nature of Telepresence* | *Causes* | *Impact on Performance* |
|---|---|---|---|
| Behavioral Cybernetics | Relationship between feedback and feed-forward (not experiential) | Degraded by temporal, spatial, and filtering perturbations | Performance improves with cybernetic telepresence |
| Flow | Concentration on an activity to exclusion of distracting stimuli | Focus on task; match between task requirements and user abilities | None |
| Distal Attribution | a compelling impression of being at the location occupied by the slave device | Relationship between sensory inputs and nervous system commands necessary to respond; moderated by quality of afference-efference linkages | Performance improves with telepresence |
| Situation Awareness | Maximization of SA in the computer-mediated environment accompanied by the loss of SA for the local environment | Focusing attention on the computer-mediated environment | Depends on importance of local SA |

**Table 2: Psychological Approaches to Telepresence (from [Draper et al 98])**

Tele-existence appears to be synonymous with telepresence and is defined by [Halme and Suomela 2000] as "the situation where the main senses of operator, like sight and hearing, are transferred to the remote place by telecommunication means so that he/she have the 'feeling' of presence". They conducted experiments using an ATV with an operator in a stereo-head mounted display, with head tracking audio capabilities. Five scenarios were tested: driving in a corridor, in unknown terrain, for loading, maneuvering, and fast driving. A small subject pool (5 men) was used. Principal results included the facts that training improved performance, and that loading was the most difficult task. System differences in display made little difference after training on a repeatable task. In a different experiment it was noted that servo cameras controlled by head movements were rejected as very bad by all drivers, both subjectively and objectively. This may have been due to the position of the cameras that were located where a driver normally sits, instead of along the centerline of the vehicle. Camera placement appears to be a very important factor for telepresence systems. Stereovision did help in the loading task. The head mounted display was also uncomfortable and induced nausea in the drivers. The conclusion was that a monitor was better than the technology they introduced.

Another study in telepresence [Ballou 2000] looked at remotely operated submersible vehicles. Again a very small data set was used that is inadequate to draw conclusions. Observations suggest however that here as well, operators performed better with a panel display than a head mounted one, although the reasons for this are unclear. It was also noted that novice users tend to lock their head in position when active coupling of head position to the camera is present.

[Simsarian 2000] studied user interfaces for teleautonomous control in the context of virtual reality, i.e., where a well-defined model exists for the environment in which the robot operates. While this is an interesting premise, unfortunately it holds little utility in battlefield scenarios as a priori models of the world are generally not available at the level of detail required nor do they necessarily correlate with the realities of the moment.

It is worth observing that some recognize the importance of trying to quantity the notion of presence in systems such as these. [Prothero et al] describes *vection* which refers to a "sense of self-motion induced by visual cues". They provide insights into how metrics for certain classes of vection can be measured. Presence is less well defined here, but they advocate a measure referred to as *simulation fidelity* in terms of "the ability of a virtual environment to induce a change in perception of gravity-referenced eye level. The latest references refer to the beginning of experiments to determine the usefulness of metrics such as these.

## *3.2 Sensory Feedback*

This section surveys the impact various sensor modalities have in teleoperation from a human factors perspective; i.e., what works and what doesn't, especially as related to TMR issues.

### *3.2.1 Sensory Characteristics of Humans*

[Corliss and Johnsen 1968] present in Tables 3-5 a summary of the sensory channels, and their limits, by which a human operator can be engaged with a teleoperator. No doubt gaps in these tables can be closed and refinements made due to human studies since their compilation, but they do provide useful information that can be applied to interface design.

| Sense | Intensity Range | | Intensity Discrimination | |
|---|---|---|---|---|
| | Smallest Detectable | Highest Practical | Relative | Absolute |
| Vision | 2.2 to 5.7 x $10^{-10}$ | Roughly, the brightness of snow in the midday sun, or about $10^{9}$ times the threshold intensity | With white light, there are about 570 discriminable intensity differences in a practical range. | With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 millilamberts. |
| Audition | 1 x $10^{-9}$ ergs/cm$^2$ | Roughly, the intensity of the sound produced by a jet plane with afterburner or about $10^{14}$ times the threshold intensity | At a frequency of 2,000 cps, there are approximately 325 discriminable intensity differences. | With pure tones about 3 to 5 identifiable steps. |
| Mechanical vibration | For a small stimulator on the fingertip, average amplitudes of 0.00025 mm can be detected. | Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold | In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.5 mm provides 15 discriminable amplitudes | 3 to 5 steps |
| Touch pressure | Varies considerably with body areas stimulated and the type of stimulator. Some representative values:<br>Ball of thumb—0.026 ergs<br>Fingertips 0.037 to 1.090 ergs<br>Arm—0.032 to 0.113 ergs | Pain threshold | Varies enormously for area measured, duration of stimulus contact and interval between presentation of standard and comparison stimuli | Unknown |
| Kinesthesis | Joint movements of 0.2 degree to 0.7 degree at a rate of 10 deg/min can be detected. Generally, the larger joints are the most sensitive | Unknown | No data available | No data available |
| Angular acceleration | Dependent on the type of indicator used<br>1. Skin and muscle senses 1 deg/sec$^2$<br>2. Nystagmic eye movements 1 deg/sec$^2$<br>3. Oculogyral illusion 0.12 deg/sec$^2$ | Unconsciousness or "blackout" occurs for positive "g" forces of 50 to 8 g lasting 1 second or more<br>Negative forces of 3 to 4.5 g cause mental confusion, "red-vision" and extreme headaches lasting sometimes for hours following stimulation | No data available | No data available |
| Linear acceleration | In aircraft—0.02 g for accelerative forces and 0.08 g for decelerative forces | For forces acting in the direction of the long axis of the body, the same limitations as for angular acceleration apply. | No data available | No data available |

*Adapted from Ref. 55.

**Table 3. Human Sensory channels (from [Corliss et al 68])**

| Sense | Wavelength or Frequency Range | | Wavelength or Frequency Discrimination | |
|---|---|---|---|---|
| | Lowest | Highest | Relative | Absolute |
| Vision (hue) | 300 mμ | 1,500 mμ | At medium intensities there are about 128 discriminable hues in the spectrum | 12 to 13 hues |
| Interrupted white light | Unlimited | At moderate intensities and with a duty cycle of 0.5, white light fuses at about 50 interruptions per second | At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 375 separate rates of interruption in the range of 1 to 45 interruptions per second | No greater than 5 or 6 interruption rates can be positively identified on an absolute basis. |
| Audition (pure tones) | 20 cps | 20,000 cps | Between 20 cps and 20,000 cps at 60 db loudness, there are approximately 1,800 discriminable steps | 4 to 5 tones |
| Interrupted white noise | Unlimited | At moderate intensities and with a duty cycle of 0.5, interrupted white noise fuses at about 2,000 interruptions per second. | At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 460 separate interruption rates in the range of 1 to 45 interruptions per second. | Unknown |
| Mechanical vibration | Unlimited | Unknown, but reported to be as high as 10,000 cps with high intensity stimulation. | Between 1 and 320 cps, there are 180 discriminable frequency steps. | Unknown |

**Table 4: Discriminatory capabilities of Human Senses (from [Corliss et al 68])**

| Parameter | Vision | Audition | Touch | Vestibular |
|---|---|---|---|---|
| Sufficient stimulus | Light-radiated electromagnetic energy in the wavelengths from 400 to 700 mμ (violet to red) | Sound-vibratory energy, usually airborne 20 cps to 20,000 cps | Tissue displacement by physical means >0 to <400 pulses per second $\frac{\Delta pps}{pps} \simeq 0.10$ | Accelerative forces Linear and rotational accelerations |
| Spectral range | 120 to 160 steps in wavelength (hue) varying from 1 to 20 mμ. | ~3 cps (20 to 1000 cps) 0.3 percent (above 1000 cps) | | |
| Dynamic range | ~90 db (useful range) for rods = 0.00001 mL to 0.004 mL; cones = 0.004 mL to 10,000 mL | 140 db (0 db = 0.0002 dyne/cm$^2$) | ~30 db, 0.01 mm to 10 mm | Absolute threshold ≃0.2°/sec/sec |
| Amplitude resolution $\left[\frac{\Delta I}{I}\right]$ | contrast = $\frac{\Delta I}{I}$ = 0.015 | 0.5 db (1000 cps at 20 db or above) | 0.15 | ~0.10 change in acceleration |
| Acuity | 10 arcminutes | Temporal acuity (clicks) ≃0.001 sec | Two-point acuity = 0.1 mm (tongue) to 50 mm (back) | |
| Response for rate for successive stimuli | ~0.1 sec | ~0.01 sec (tone bursts) | Touches sensed as discrete to 20/sec | ~1 to 2 sec nystagmus may persist to 2 min after rapid changes in rotation |
| Reaction time for simple muscular movement | ~0.22 sec | ~0.19 sec | ~0.15 sec (for finger motion, if finger is the one stimulated) | |
| Best operating range | 500 to 600 μ (green-yellow) 10 to 200 foot-candles | 300 to 6000 cps 40 to 80 db | | 1 g acceleration directed head to foot |
| Indications for use | 1. Spatial orientation required.<br>2. Spatial scanning or search required.<br>3. Simultaneous comparisons required.<br>4. Multidimensional material presented.<br>5. High ambient noise levels. | 1. Warning or emergency signals.<br>2. Interruption of attention required.<br>3. Small temporal relations important.<br>4. Poor ambient lighting.<br>5. High vibration or g forces present. | 1. Conditions unfavorable for both vision and audition.<br>2. Visual and auditory senses. | 1. Gross sensing of acceleration information. |

*Adapted from Ref. 55.

**Table 5: Human sensory characteristics (from [Corliss et al 68])**

### *3.2.2 Vibratory Feedback*

Kontarinis and Howe at Harvard University investigated how effectively vibration can convey information in teleoperation environments. They categorize relevant tasks in three categories:

1) Where detection of vibrations is the fundamental goal (i.e., detecting a vibration on a door)
2) Where performance can be enhanced by indicating the mechanical state of the hand-object system (e.g., indicating when contact has occurred as in grasping a doorknob).
3) Tasks where vibration information regarding the environment in not important, but vibration increases the subjective feel of the environment to the user.

They used a teleoperated hand system to conduct experiments for ball bearing inspection, puncturing, and a peg-in-slot task. Results indicated:

- Force and vibration are complementary modalities, and vibration in conjunction with force is most useful.
- The importance of high-frequency feedback is task related.
- Display design is low cost, using a simple loudspeaker. More expensive tactile feedback units can be provided with pins to operator's fingertips.

[Desombre et al 95] physically shook operators using a vibratory platform and evaluated the consequences on their ability to perform simple decision-making tasks. The relevance of this study to TMR is for operators who may be doing mission specification or run-time control while on the move in a vehicle. This is a form of stress testing. Bar graphs seemed better perceived than polygonal visualizations under these conditions in certain cases. Overestimation of graphic shapes tended to occur which was not found in bar graphs when vibration was present. Oddly subjects time to perceive bar graphs when shaken decreased over stable states.

### *3.2.3 Haptic/Tactile Feedback*

Hoffman at the University of Washington observed that most VR systems do not provide force or tactile feedback. He used a mixed reality feedback system, with both VR and actual physical components, which indicated that the subjects performed more effectively in this environment than in pure VR without tactile feedback. This is not surprising but does document these results. This same group expanded this work further, showing that tasting virtual objects enhanced the realism of these virtual experiences as well. Again not a surprise, but it does formally document this aspect. The experiment involved touching and tasting a candy bar when the same object was seen within a virtual environment. It is unclear how this could be practically implemented, but it is of note that it would be of value in enriching the overall immersive experience to the subject.

[Burdea 96] studied haptic (force and touch) feedback for VR applications. In his book, he provides data on spatiotemporal resolution of various body regions (Table 6). He also discusses the various classes of skin mechanoreceptors (Merkel disks, Ruffini Corpuscles, Meissner corpuscles, and Pacinian corpuscles) as well as thermoreceptors and nocireceptors (pain). This was

translated into a figure depicting human finger sensing and control bandwidth suitable for hand feedback (Figure 36). This all translates into a set of interface requirements shown in Figure 37.

**TABLE 2.1 Average Pressure JND as a Function of Contact Area**

| Body site | Contact Area ($cm^2$) | | |
|---|---|---|---|
| | 1.27 | 5.06 | 20.27 |
| | Pressure JND | | |
| Elbow (Volar) | 0.167 | 0.062 | 0.040 |
| Elbow (Dorsal) | 0.113 | 0.052 | 0.033 |
| Wrist (Dorsal) | 0.188 | 0.044 | — |
| Overall Average JND | 0.156 | 0.053 | 0.037 |

Adapted from Tan et al. [1994]

**Table 6: Spatiotemporal resolution of various body locations (from [Burdea 96])**

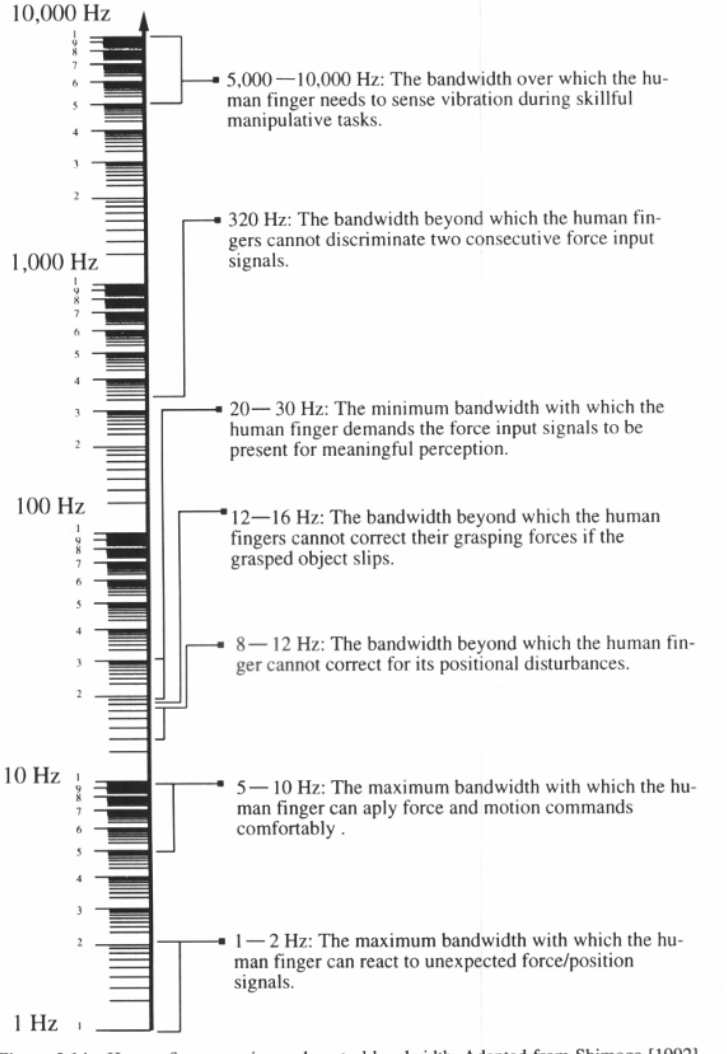


**Figure 2.14** Human finger sensing and control bandwidth. Adapted from Shimoga [1992]. © Éditions Hermès. Reprinted by permission.

Figure 36: Human finger sensing response (from [Burdea 96])

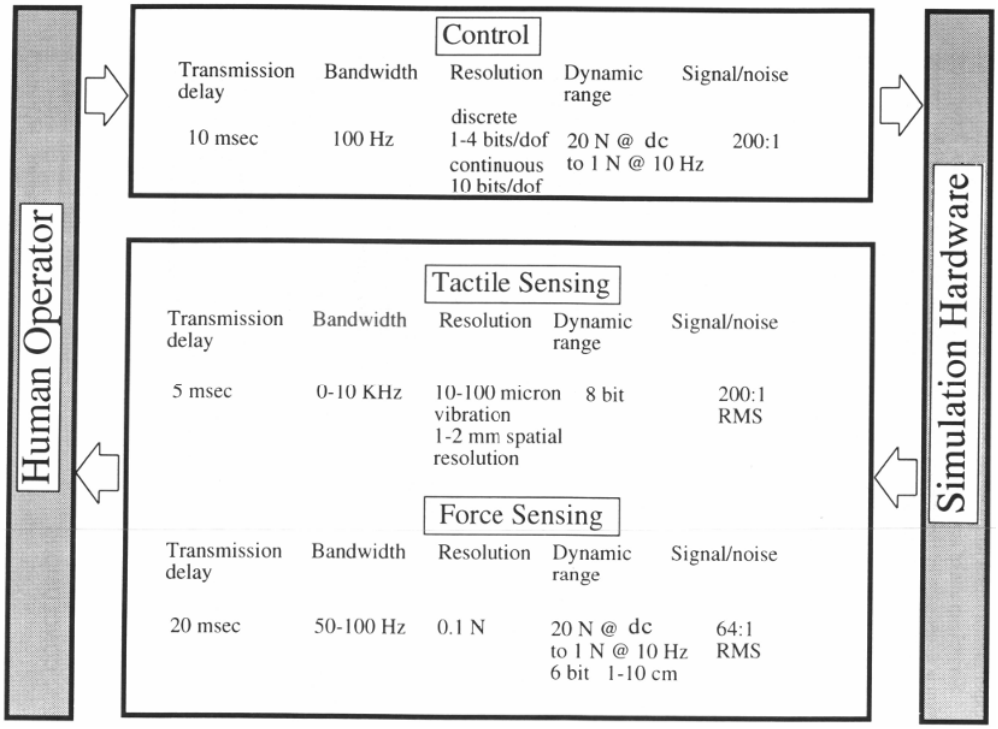


Figure 37: Tactile Interface Requirements (From [Burdea 96])

### *3.2.4 Auditory feedback*

The [National Research council Report 1998] provides guidelines when to use auditory presentation over visual presentation for soldiers (Table 7). Table 8 further shows the advantages and disadvantages of variants of auditory displays of information to the soldier.

| Use auditory presentation if: | Use visual presentation if: |
|---|---|
| 1. The message is simple. | 1. The message is complex. |
| 2. The message is short. | 2. The message is long. |
| 3. The message will not be referred to later. | 3. The message will be referred to later. |
| 4. The message deals with events in time. | 4. The message deals with location in space. |
| 5. The message calls for immediate action. | 5. The message does not call for immediate action. |
| 6. The visual system of the person is overburdened. | 6. The auditory system of the person is overburdened. |
| 7. The receiving location is too bright or dark adaptation integrity is necessary. | 7. The receiving location is too noisy. |
| 8. The person's job requires him or her to move about continually. | 8. The person's job allows him or her to remain in one position. |

Source: Deatherage (1972: Table 4-1).

**Table 7: Auditory versus visual presentation (From [NRC 98])**

| | Advantage | Disadvantage |
|---|---|---|
| Monaural | Inexpensive<br>Single earphone | Sounds can not be localized<br>Reduced signal detection<br>Reduced speech intelligibility |
| Biaural | Small increase in signal detection | Headphones required |
| Stereo | Increased signal detection<br>Increased speech intelligibility<br>Minimal increase in complexity | Headphone required |
| 3DAD | Improved signal detection<br>Improved speech intelligibility<br>Signals localizable<br>Multiple channels monitoring<br>Waypoint navigation | Increased complexity<br>Headphones required |

**Table 8: Relative Merits of Auditory Feedback Modalities (From [NRC 98])**

[Hollier et al 99] discuss a range of presentation methods and technologies using 3-D spatial sound to the end-user, but unfortunately they do not include any formal user analysis of its efficacy.

### *3.2.5 Visual imagery*

Work by [Prothero and Hoffman 95] at the University of Washington confirmed what appears to be the obvious, that a wider field of view does indeed increase the feeling of presence in a human subject in immersive environments. 38 subjects were used to confirm this hypothesis. Goggles were also shown to be better (foreground occlusion) than a background occlusion (projection onto paper).

[Sayers et al 95] at the University of Washington studied visual feedback for undersea remote teleoperation. A heavily constrained communications channel required the use of automatic windowing and subsampling of the image. This study, however, focused on the technical design of the system with seeming little regard for operator capabilities.

### *3.2.6 Improper Feedback: Motion Sickness*

Research at the University of Washington's Human Interface Technology Laboratory studied the effects of motion sickness in virtual environments. Clearly TMR does not want to induce this phenomenon in its users. This group has constructed a means and metrics by which motion sickness can be evaluated. It appears that it is primarily due to visual-inertial sensory conflict. A solution appears to be maintaining an independent visual background for the immersive environment that is consistent with the subject's inertial cues. Thus if a TMR operator is driving while operating, feedback from the driven vehicle should be coupled to the immersive environment for background projection.

Preliminary research has attested to the feasibility of this approach using a head-mounted display. Observations include:

1) That a simple stationary background grid in the sky portion is insufficient to reduce motion sickness.
2) The induced motion of the background grid did not appear in peripheral vision.
3) A simple foreground grid did assist in reducing motion sickness.

### *3.3 Operator Performance*

Sheridan states [Sheridan and Ferrell 1974] two relevant tenets: when working at capacity one can increase speed only at the expense of accuracy, and conversely; some parallel processing can be carried out, but to do several tasks will require switching among them.

In reference [Sheridan and Ferrell 1974] to an earlier study by Merkel, response times are increased when:

1. The stimulus is unexpected
2. There are many possible stimulus-response pairs
3. The stimulus or responses are unfamiliar
4. It is difficult to discriminate between stimuli or when searching or scanning is required for detection
5. The response is related to stimulus in complex manner
6. The response in difficult to perform.
7. Visual stimuli responses are longer than auditory which are longer than for tactile

These trends can serve as targets for TMR interface and training design.

#### *3.3.1 Metrics*

It is interesting to note that in the early work in teleoperation system design [Corliss and Johnsen, 1968, Johnsen and Corliss, 1967] virtually no effort was dedicated to human factors evaluation, as evidenced in statements such as "Assertions regarding the relative effectiveness of different teleoperators often imply that considerable experimental data exist, but no thorough studies have been made" [Johnsen and Corliss, 1967]. Unfortunately, the situation appears only slightly better today, with more lip service than actual experimental studies having been conducted. Most human factors studies have not focused on direct measurements of human control of robots, but rather involve other forms of control (e.g., air traffic controllers) from which we must extrapolate.

There are exceptions however. In discussions with John Draper at Oak Ridge National Laboratories, one of the main users of teleoperators over the past several decades, he alone is involved in human factors related work. In a sense it is better that there does exist at least one individual within DOE to design and conduct these studies, but it is a sad commentary still regarding how engineering typically regards human factors issues.

The most commonly used metric for quantifying performance of teleoperators is task completion time [Book and Love, 1999]. Other measures considered include are typically resolved into total task time, time effectiveness ratio (time relative to if the task was performed directly by the human), and unit task time (related to performance of subtasks of the overall task). Operator fatigue, success ration and subjective user satisfaction are also common measures, although often difficult to evaluate analytically. Task-specific metrics are also created on an ad hoc basis, and may in this context deal with detectability issues.

So-called information-based performance measures relate the rate of information that is transmitted through the system to or from the operator. While the definition of manual control is self-evident, supervisory control refers to a human operator(s) intermittently or continuously programming a robot that itself is operating autonomously. The operator also continuously receives information from the robot. In a fully autonomous system, the human operator is rather an observer than a controller.

### *3.3.2 Operator Characteristics in Supervisory Control*

Moray outlines the general characteristics from the human end of supervisory control:

1. Scheduling what to do
2. Sampling a display or other data source
3. Acquiring data through sensing
4. Combining information from past and present sources
5. Decision-making
6. Diagnosing the system state
7. Executing the appropriate action
8. Allocating control between human and computer

The advantages of this approach over pure teleoperation also become apparent:

1. Improved performance over operator alone
2. Once taught, more efficient performance
3. Enables tasks operator may not be able to do due to remoteness (e.g., signal delays)
4. Reduces operator workload
5. Improves operators task planning through predictive displays
6. Help operator to monitor, detect and diagnose system failures
7. Provides failure actions when operator responses would be too slow
8. Makes direct control easier by better display and control aids
9. Reduces costs, saves lives by removing operator from hazardous environment.

Figure 38 shows how control of navigational processes can be affected at multiple levels under supervisory control. Sheridan further indicates that human skills and reasoning proceed at multiple levels as well, referring to Rasmussen's paradigm (Figure 39). Of particular relevance for the robot unit concept is the control of multiple robots concurrently (Figure 40).

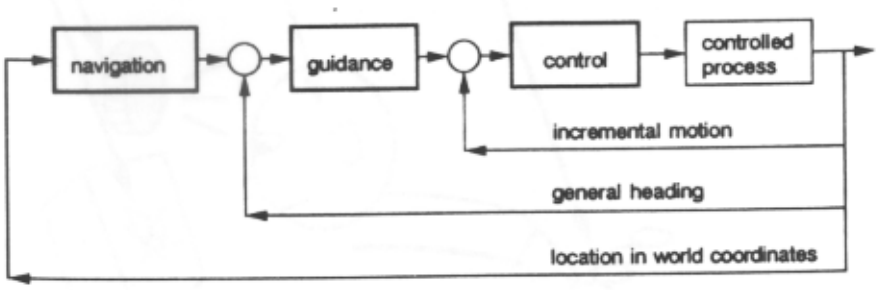


Figure 38: Supervisory Control (from [Sheridan 93])

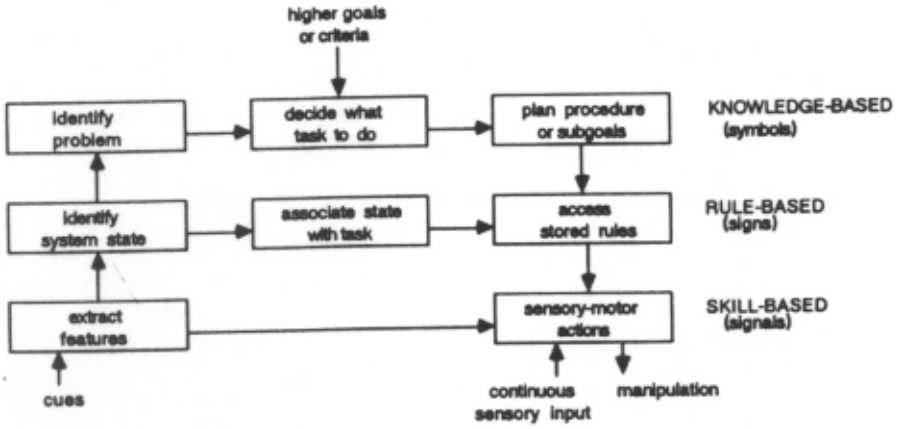


Figure 39: Multiple Levels of Human Reasoning (from [Sheridan 93])

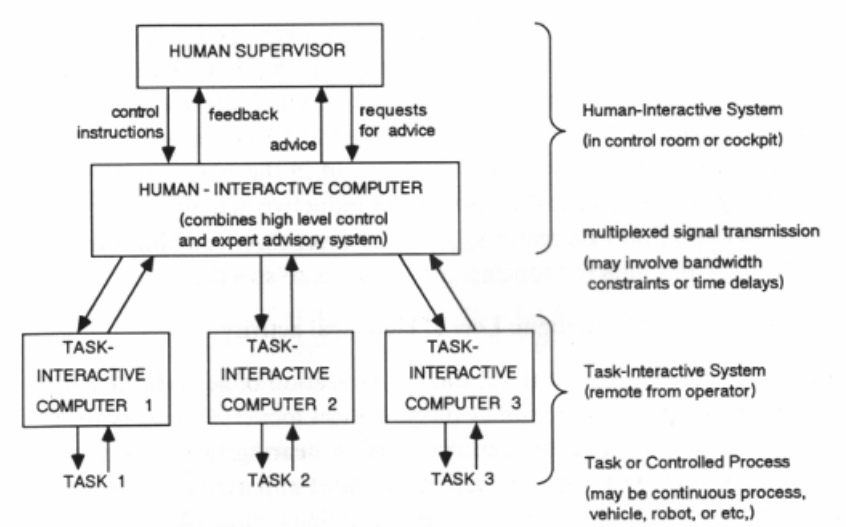


Figure 40: Control of multiple computers/robots concurrently (from [Sheridan 93])

Interestingly, Sheridan's experimental results indicate that human subjects "approached optimal behavior ... both when they had plenty of time to plan and when their workloads were reasonably heavy" in multitask environments [Sheridan 93]. There was an observed time, as workload increased when the subjects switched from planning ahead to putting out fires and shedding tasks. This clearly points to a need for effective workload management on a robot unit operator.

Figure 41 shows the different requirements placed on the operator in shared control: specifically including the abilities to plan, teach, or intervene, and monitor performance. We study human factors affecting performance of these duties throughout this report.

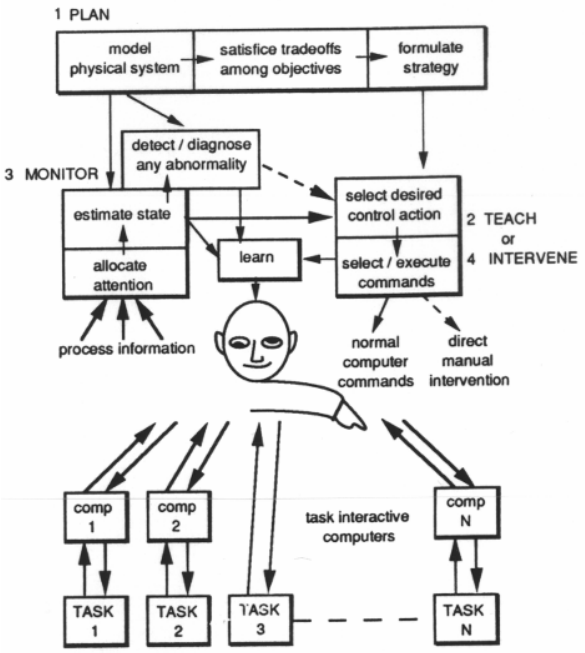


Figure 41: Requirements placed on Operator (from [Sheridan 93])

Sheridan also discusses the importance of human-attention allocation models as a component of supervisory control systems. Figure 42 shows the range of tasks when supervisory control is better than direct teleoperation relative to the time required to provide the capability to the robot.

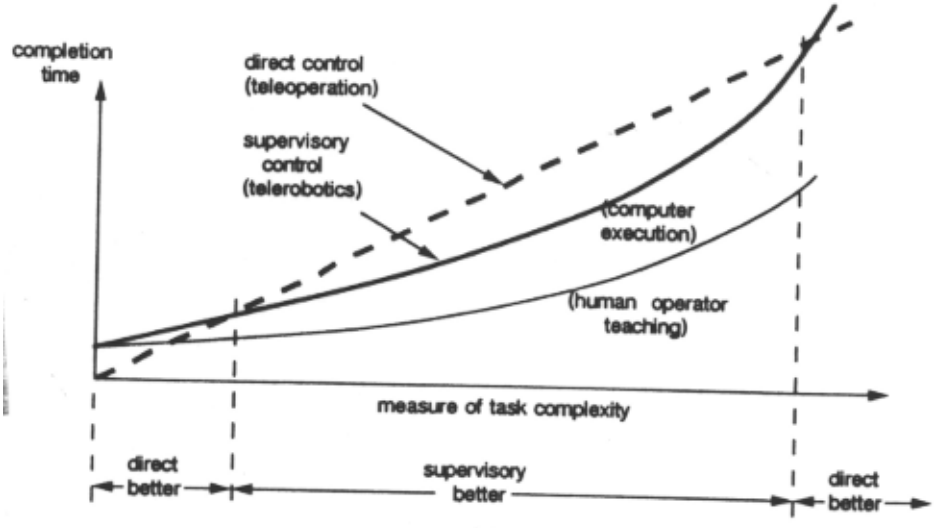


Figure 42: Teleoperation versus Supervised Control (from [Sheridan 93])

### *3.3.3 Monitoring Tasks*

[Thurman and Mitchell 95] discuss why monitoring is difficult via operator displays. First it is a boring and passive task, which when under supervisory control does not require active engagement of the operator. Monitoring is also an unstructured, ill-defined task for complex systems. Finally, in general the interfaces operators use are often not designed for monitoring. Sometimes artificial tasks are deliberately added to displays to ensure that the operator remains engaged. The authors advocate a specific design methodology for these displays based on task, operator and information-flow analysis which has been shown to provide better fault detection rates among other things, where this methodology for creating operator displays for highly automated supervisory control systems which is depicted notionally in Figure 43. It starts with the necessary operator functions and proceeds through an analysis to produce the necessary information at the right time in the display. Although it was tested on a NASA satellite ground control system, it has relevance for TMR-related display design and should be considered as a candidate methodology for the design of such a system.

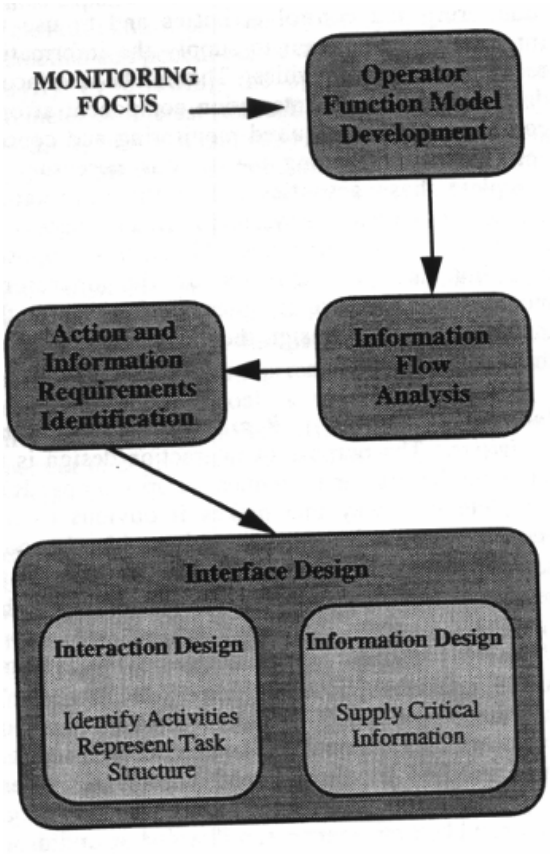


Figure 43: Design Methodology for monitoring/control interfaces
(from [Thurman and Mitchell 95])

### *3.3.4 Driving/Navigation Performance*

Specific human factor problem and issues related to driving that may have relevance in a TMR robot unit include:

- Distraction and confusion while driving
- Reading and interpreting maps, text, and symbolic displays
- Increased hand control complexity
- Ignored or too-complex warnings
- Excessive dependence
- False alarms
- Effective heads-up displays
- Situational awareness displays
- Automatic control of speed/braking or steering imposed on human control
- Transients in human to fully automated platoon control
- Variations in operators due to age, education, etc.

Work by [Levison and Baron 1997], studied the impact of task difficulty in driving a remote vehicle. It is possible that these results may potentially extrapolate to multi-vehicle remote driving as needed for TMR Robot unit applications. Table 9 summarizes their results.

| Perf | Performance Trends | |
|---|---|---|
| | Model | Experiment |
| Multitask vs single-task driving performance | Multitask worse | Multitask worse |
| Increasing difficulty of the driving task | More attention to driving task<br>Driving performance degraded | More attention to driving task<br>Driving performance degraded |
| Increasing relative importance of the auxiliary task | Less attention to driving task<br>Driving performance degraded | No significant influence on attention or driving performance |
| Driver-controlled attention | Better performance when not attending to road | Better performance when not attending to road |
| Periodic attention | Better performance when attending to road | |

**Table 9: Driving Performance (from Levison and Baron 97])**

An earlier experiment by Noy summarized in [Levison and Baron 1997] found that:

1. Driving errors were larger for dual-tasks than single task conditions
2. Making driving harder had only modest impact on driving performance, a larger impact on scan behavior, and little impact on secondary task performance
3. Making the difficulty of the auxiliary task harder did not affect the driving and scanning performance significantly, but had large impact on auxiliary task performance.
4. Oddly, driving performance was slightly better when subject when looking at auxiliary task display rather than road.

[Draper et al 99] cite a study for robotic rover navigation tasks conducted in simulation. It was interesting to note that the more immersive the environment was, the faster it took to conduct the navigational task. There was a correlation that showed immersive environments helped for this class of task (which was not always the case for others). It was believed that the ability to direct attention assisted here.

[Peterson et al] at the University of Washington studied the effects of two different interfaces for navigation. One was a joystick controller and the other a sophisticated virtual motion controller that senses the body of the user by having him stand on it (Figure 44). Maneuvering performance was better with a joystick when following a marked route. The ability to form a mental map (survey knowledge) and alternate route planning was better with the body controller and was dependent on how difficult the task environment was (i.e., the more difficult the better the body controller was). It was postulated that the additional kinesthetic and vestibular modalities might have aided sensory integration that people normally expect while wayfinding in unknown areas. Route learning (replicating the same route) was the same for both devices. The subjects used head mounted displays.

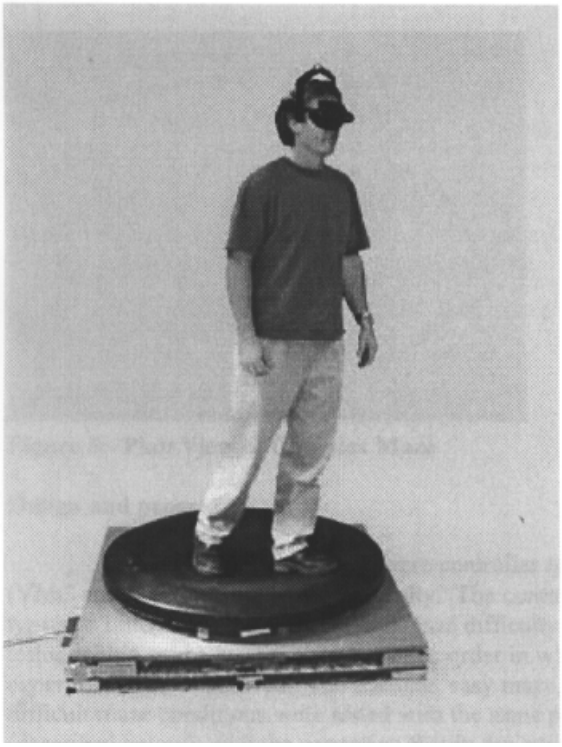

Figure 44: Experimental Setup (From [Peterson et al])

### *3.4 Human Factors and Displays*

Problems with displays, in general, include information overload, display inter-correlation and redundancy; and the keyhole problem (if information is not on the screen, how to get it?). This section focuses both on general issues as well as problems and trends associated with specific display types.

#### *3.4.1 Helmet Mounted Displays*

[Schrage 94] evaluated the state of the art in helmet-mounted displays (HMDs) in terms of human factors for aviation. A vendor inventory assessment was conducted. The human factors study was related to the anthropomorphic physical properties of the display system, than user perceptions, were they were ranked for adjustability, range of head movement and comfort. Additional psychophysical tests were performed on a pool of 4 subjects, for data such as image sharpness, color quality, acuity, and image quality. These were not evaluated, however, in terms of task performance unfortunately. Therefore we cannot draw conclusions from this study as to how well HMDs will or will not work in a TMR-related task environment.

#### *3.4.2 Heads-up Displays*

Other studies have pointed out difficulties with Heads-up displays (HUDs). In one case [Foyle et al, McCann et al], pilots took 2.5 seconds longer in responding to runway incursions with HUDs than without the technology. It is believed this is a consequence of attentional tunneling leading to inefficient processing of the regular out-of-the-window scene. Thus the use of superimposed symbology in HUDs is not always a blessing. Use of scene-linked symbology, i.e., enhancements of existing features, apparently assists in alleviating this psychological phenomenon. So careful choices should be made on what and how data are represented in heads-up displays. The authors recommend removing the HUD cues that distinguish its information from the natural world, in particular: color (typically saturated green), lack of perspective (planar instead), and differential motion (it does not move with the world).

The National Research Councils Report on Tactical Displays for Soldiers [1998] recommends that if the display occludes the soldiers' view, then hand-held or wrist mounted displays should be considered as an alternative to helmet mounted displays. The loss of local situational awareness may be unacceptable.

#### *3.4.3 Other Display considerations*

Studies involving displays for air traffic controllers were also considered as relevant, as they are used to improve their situational awareness [Johnston et al], a crucial TMR task. These SADs (situational awareness displays) currently rely heavily on alphanumeric information requiring multiple eye fixations and complex mental transformations to generate the 3D representation of the world. One notion is the use of perspective displays (as advocated for HUDs above). Color was also shown to be better than achromatic displays and was demonstrated to work well for managing attention. Using various spot sizes to represent planes that correlated to altitude also provided useful information regarding altitude versus uniform size spots.

Another potentially related study for teleoperation involved studies in support for pilots on taxiways in conditions of low visibility. We have just seen in the Singapore airlines disaster that such failure can lead to catastrophes. In certain aircraft, heads-up displays provide symbology to the pilot. A recent addition is the electronic moving-map display that, using GPS technology, depicts the aircraft's location in real-time. In some case, route guidance is provided on the display as well, showing where the plane should go as cleared by the tower. Pilots are able to move at greater speeds and make fewer navigation errors when these displays are available, especially when route guidance is provided [McCann et al]. The main problem seems to lie in the coordinate system, which is world-centered instead of egocentric, requiring the pilots to make several cognitive transformations that are "effortful and time-consuming". Work is ongoing in trying to align 3D perspective displays to eliminate these problems. The 3D displays did result in slower taxi speeds despite the pilots' preference for them, evidently due to fewer look ahead cues being available. Variable zoom levels were also presented and the pilots generally preferred the highest zoom. [Foyle et al 96] describe a system engineered to assist pilots based on human factors considerations for this very task, including scene-linked HUD symbology, a perspective moving map display, and 3D audio ground collision and warning system. The audio system actually provided stereo feedback as to the direction of the impending collision.

### *3.5 Mental Workload*

Mental workload, according to [Sheridan 93] consists of objective factors such as number of tasks, urgency, and cost of non-completion of task on time or correctly, as well as a range of subjective factors and environmental variables (workstation display geometry, ambient temperature, lighting, etc.) (Figure 45).

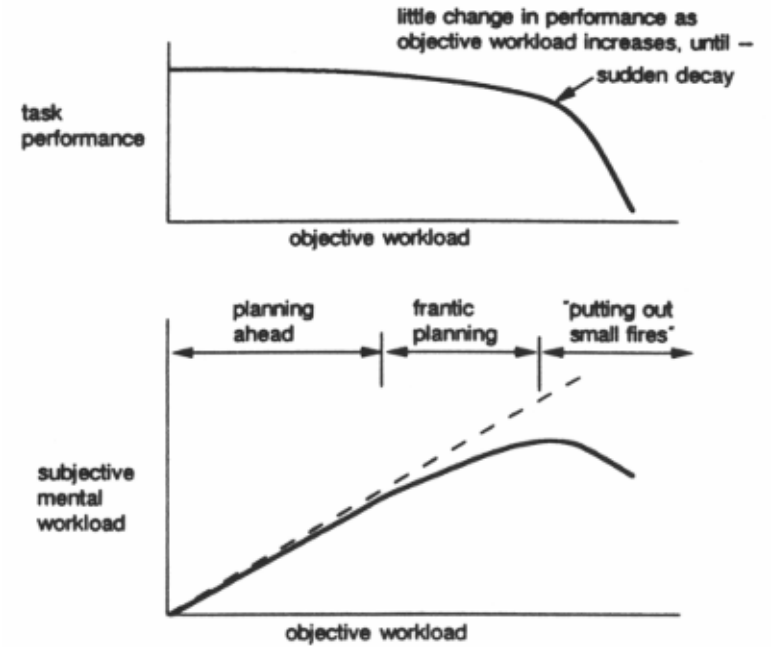


Figure 45: Mental Workload Factors (from [Sheridan 93])

Performance tends to decrease steeply when workload becomes too high, while through the normal range little change is noticed. It is worth noting that if the operator has too little to do, that performance declines as well due to inattention and lack of vigilance for monitoring. This is illustrated in Figure 46. Sheridan provides a rating system for workload measurement (Figure 47) and a decision model associated with it.

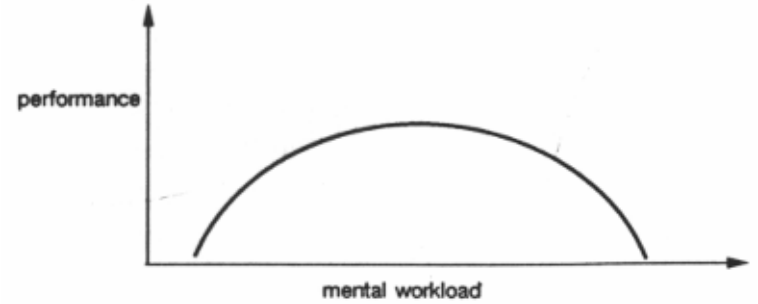


Figure 46: Relation of Performance to Workload (from [Sheridan 93])

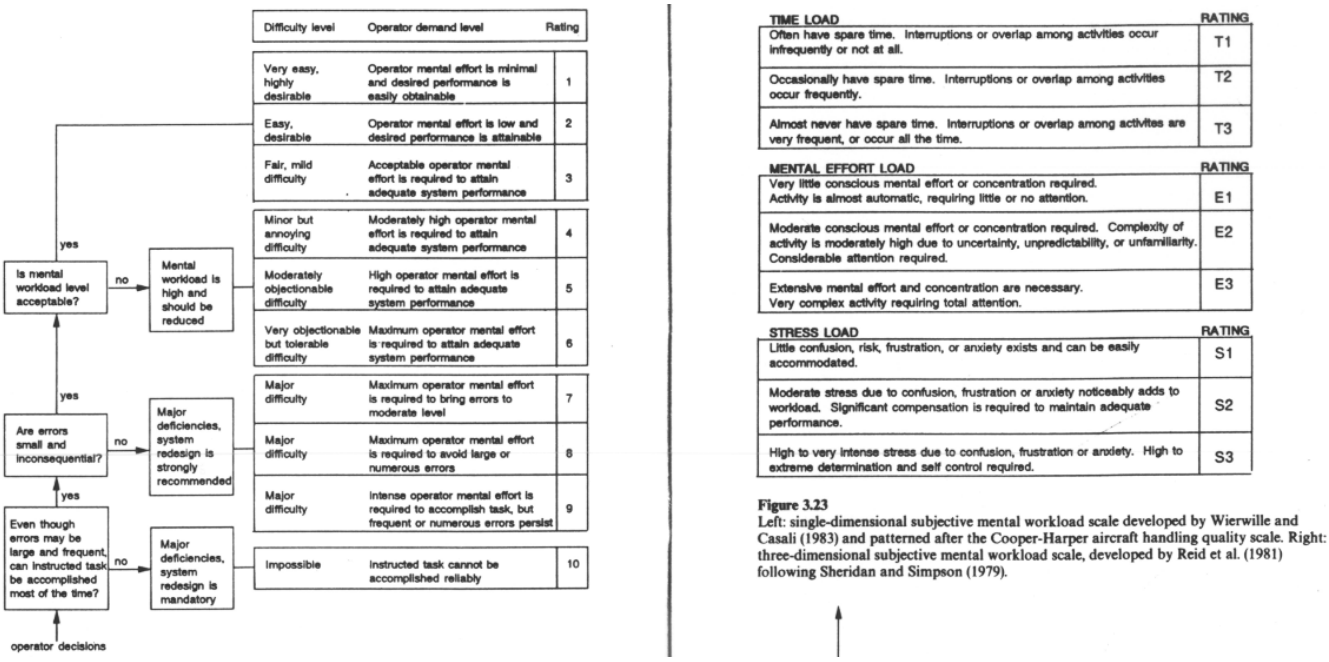


Figure 47: Workload Measurement Rating System (from [Sheridan 93])

Subsequent research by [Draper and Blair 96] studied the role of workload and flow in a similar context. In this study highly trained operators were used. They employed the NASA TLX workload index as a basis for quantifying their measurements (Table 10). The dimensions shown in Table 11 measured flow. Similar metrics could potentially be applied to TMR-related tasks. This led to their development of a cognitive model for teleoperation, which addresses the role of attention (Figure 48). It would be interesting to see how this model stood up to TMR type tasks.

| Scale Name | Scale Definition |
|---|---|
| Mental | How much mental and perceptual activity was required? |
| Physical | How much physical activity was required? |
| Temporal | How much time pressure did you feel? |
| Performance | How successful do you think you were? |
| Effort | How hard did you have to work (mentally and physically)? |
| Frustration | How discouraged versus gratified, annoyed versus content did you feel during the task? |

**Table 10: NASA Study Dimensions (from [Draper and Blair 96])**

| Flow Dimension | Flow Definition |
|---|---|
| Goals | Clarity of task-related goals |
| Attention | Strength of commitment of attentional resources to task performance |
| Challenge | Degree to which the task was a challenge for the operator |
| Control | Degree to which the operator felt in control of the situation during task performance |
| Others | Degree to which operator was concerned about other persons' opinions of his performance. |

**Table 11: Study Dimensions of Flow (from [Draper and Blair 96])**

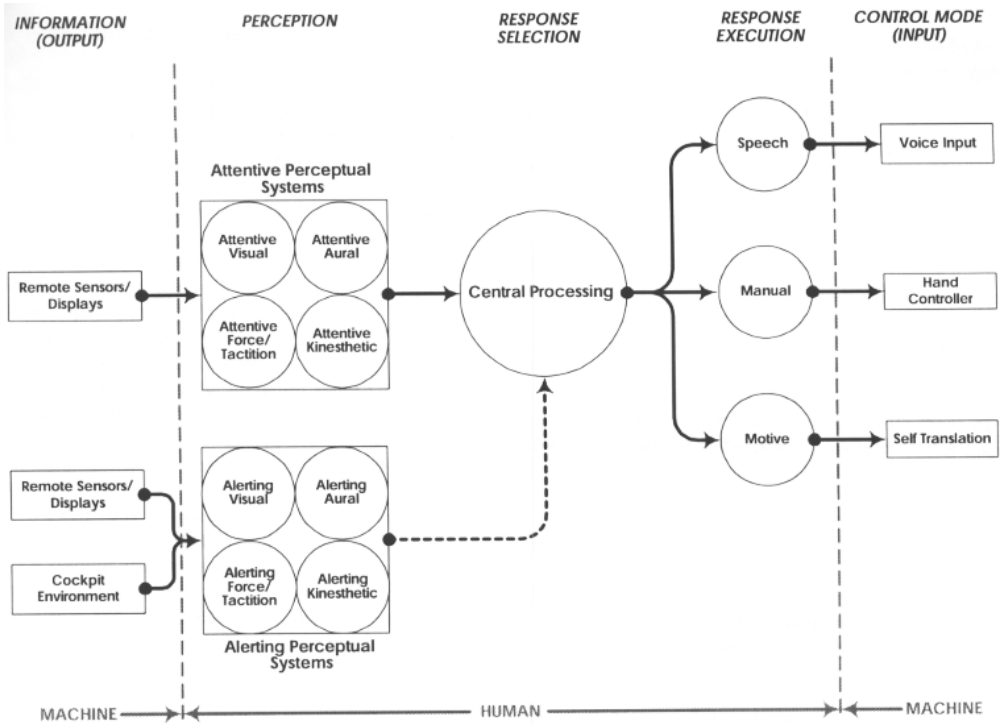

Figure 48: Attention Model for Teleoperation (from [Draper and Blair 96])

[Wei et al 1995] conducted user studies in operator supervision of a system and its relationship to workload. The came to several interesting conclusions:

1. It does not always follow that with more automation that operator performance will improve.
2. Optimal balance between mental load and system performance depends on both task number and task characteristics.

The overall conclusion is that the functions that should be automated in a system depend on both what enhances system performance and reduces operator workload (improves operator performance).

### *3.6 Human error*

A major question is when should the operator intervene within autonomous systems. Human errors seem to be most apparent during intervention [Sheridan 93]. Human error is an action that fails to meet some implicit or explicit standard of the actor or of an observer [Sheridan 93]. There exist several taxonomies for this sort of error, most notably the Senders-Moray taxonomy. Errors occur in the:

1. Environmental context: omission, substitution, unnecessary repetition, etc.
2. Cognitive/behavioral: attention, perception, memory, or control
3. Bias: anchoring, overconfidence, confirmation, cognitive lockup, tunnel vision
4. Behavioral complexity: simple sensing, detecting, identifying classifying errors; sequencing from memory; estimation errors in responses; reasoning errors
5. Exogenous (caused by actor) or endogenous (caused by actor's environment)

The main sources of error [Sheridan 93] include:

- Lack of feedback
- Capture (inappropriate conditioned responses)
- Invalid internal models
- Hypothesis verification on the basis of inadequate data
- Stress and perceptual narrowing
- Risk homeostasis (constant level of risk maintained even with safety aids)
- Individual error proneness
- CNS factors (sleep, drugs, emotionality, etc.)

Error factors can be reduced through solid design practices, training incorporating the ability to think about potential errors, and suitable environmental conditions.

Another class of errors that operators are prone to when dealing with complex system are associated with systems that function in various modes. This leads to mode error and ambiguity [Dezani et al 98]. Mode errors occur when a situation is incorrectly recognized, and although the correct action is taken for the perceived situation, it results in an error due to the misperception. Mode ambiguity is a bit different. This occurs when the operator has a different expectation regarding the outcome of the undertaken action in response to the situation. Obviously, neither of

theses situations is desirable, and effort must be made to reduce or eliminate the possibility in a TMR-style system. While the authors discuss methods to model these events, unfortunately no general proactive actions are prescribed.

Dual-task interference is another type of error. [Van Selst] notes that this problem occurs even in the absence of the need for a response. It is a consequence of the psychological refractory period effect, which provides a fundamental limit on human parallel task performance. There appears to be a central bottleneck in human information processing associated with the so-called cognitive slack associated with the problem. His study points to the root cause being related to stimulus classification and not action formulation. There is extensive literature on this phenomenon, and in TMR we must be concerned how to eliminate parallel situations to ensure rapid and correct responses.

Another source of human error is when the operator's mental model of the system is not in agreement with the system. [Palmer] studied flight operations for MD-88 and DC-9s and noticed that so-called automation surprise occurred when using the autopilot and autothrottle resulted in altitude deviations. In the case study, the automation worked correctly, but it did not respond as expected by the pilots. The lesson is to develop designs that either eliminate unusual automation modes or provide better displays of normal but unusual modes. Basically a "what you see is what you get display" is needed.

### *3.6.1 Fatigue*

Managing fatigue is another important area, especially for combat systems. [Rosekind et al] have studied this problem for NASA. Fatigue is unavoidable as there are circadian rhythms that force us into certain patterns of sleep. Sleepiness has been shown to affect waking performance, vigilance and mood even to the point where an individual is unable to perform at all. There are countermeasures that can be undertaken: minimizing sleep loss, having good sleep habits, providing a comfortable sleep environment, minimize the effects of food, alcohol and exercise, as well as manage circadian clock (chronobiotics). Social interaction, caffeine, bright light and melatonin all can be used to ensure alertness. There is little information on the design of systems to manage this affect, but operator fatigue management should play a role to ensure reliable performance in TMR systems.

### *3.6.2 Trust*

[Wickens et al 98] discuss the importance of trust by the operator in the automation they are using. This is clearly essential for acceptance of TMR-related technology as well. They cite 7 main attributes of trust:

1. Reliability
2. Robustness
3. Familiarity
4. Understandability
5. Explication of intention
6. Usefulness
7. Dependence of trusting person upon automation.

If any of these criteria are neglected in the design of a TMR system, it will adversely affect the acceptance by the end-user.

There is a danger as well in overtrust and complacency as well as mistrust when operators rely on complex automation more than they should. A calibration process for trust in the operator is required through the construction of accurate mental models by training and through the participation in automation design by potential operators.

### *3.6.3 Vigilance Decrement*

Human performance degrades over time when monitoring systems with low event rates - this is called the vigilance decrement. Providing alerts and cues when significant events occur help reduce this phenomenon. Presenting a video image at that time may be best rather than continuous output. The operator is then challenged to identify what and where the event is. Mobile sensor platforms complicate the job for the operator, as the images are not static when compared to fixed cameras. Redundant reports from multiple overlapping sensors also must be correlated. Work at NOSC [Murray 1995] conducted studies on this problem with focus on multiple moving robotic systems but in indoor simulation only. Of note is the comment:

> *Results of this study provide some guidelines for predicting human-machine performance for systems involving multiple, autonomous sensors. The rapid increase in response time for even the modest levels of manipulations used here is cause for concern especially when newer systems are planned with large numbers of sensors and are designed for operations in cluttered environment.*

Human performance may be rate limiting in deploying multiple TMRs. [Murray 95] contends that traditional supervisory control (a la Sheridan) does not hold here. He advocates information extraction by the individual sensors ("keyholes") into a coordinated picture that could then possibly make the task more tractable. Also adding visual cues to the imagery (overlays) and methods to reduce redundancy from sensor overlap might also help.

### *3.6.4 Stress*

The National Research Council Report cites numerous sources of stress for the soldier that can have impact on interpretation of display performance. These include

- Physical Sources
  - Heat and Cold
  - Noise
  - Vibration (see Section 2.1)
  - Extended operations/Time of Day
- Operational Sources
  - Task
  - Information overload or underload
  - Information versus disinformation (trust)
  - Physical work

These factors can result in fatigue or performance failure.

Several specific design guidelines for soldier displays are forwarded.

1. Rely on absolute judgment. Don't make calls on variables such as intensity or color with more than 5-7 levels.
2. Don't violate expectations based on previous experience.
3. Present the same information in multiple formats (voice and visual) - it increases understanding.
4. Make displays represent things realistically.
5. Moving displays should match mental model of users expectations.
6. Ecological design should encourage display to maintain correspondence with the environment it represents.
7. Information gathering cost should be minimized. Reduce eye movements from one location to another.
8. Use multiple sensory resources (sound and sight).
9. Provide predictive aids.
10. Place required information in environment such as checklists.
11. Be consistent across displays and with user habits.
12. Provide graphic displays whenever possible as opposed to textual.
13. Simplify graphics as much as possible reduces workload in high-stress environments.
14. Present salient info in center of display; peripheral information is neglected in high-stress situations.
15. Use redundant audio and visual warnings for threat location.
16. Reduce data entry requirements and menus to bare minimum during engagements
17. Use a small and understandable icon set.

## *3.7 Human Factors in Design*

Now we examine how human factors considerations can and should influence the design of complex systems such as a TMR robot unit operator control unit.

### *3.7.1 Design Methodologies*

In this early work, [Corliss et al 68], they partition the design task into the following allocations:

- Human assignments: Pattern recognition, target identification, new exploration, long-term memory, trouble shooting and emergency operation, planning, interpreting complex data, inductive thinking, settings goals and priorities while evaluating results
- Machine assignments: Monitoring multichannel inputs, boring repetitious tasks, precise motions and force applications, high speed motions, short-term memory, optimization, deductive analysis, computing, and monitoring

They arrived at this division using an algorithmic systems approach to partitioning the work between man and machine. The following design activities are prescribed in sequence and could be applied to a TMR robot unit as well.

1. Hypothesize the potential basic role of man
2. Hypothesize potential complementary and support role of man
3. Review manned system solution feasibility
4. Develop a preliminary operator concept
5. Analyze personnel support requirements
6. Review potential operator role for acceptance and reliability
7. Synthesize optimal operator role
8. Establish feasibility of man-rated allocation
9. Develop potential man-rated allocations
10. Review allocation potential against psychophysical capacities
11. Review allocation potential against system or function constraints
12. Review allocation potential against human reliability
13. Synthesize man-rated allocations

A related design approach appears in [Johannsen 1997] and is shown in Figure 49:

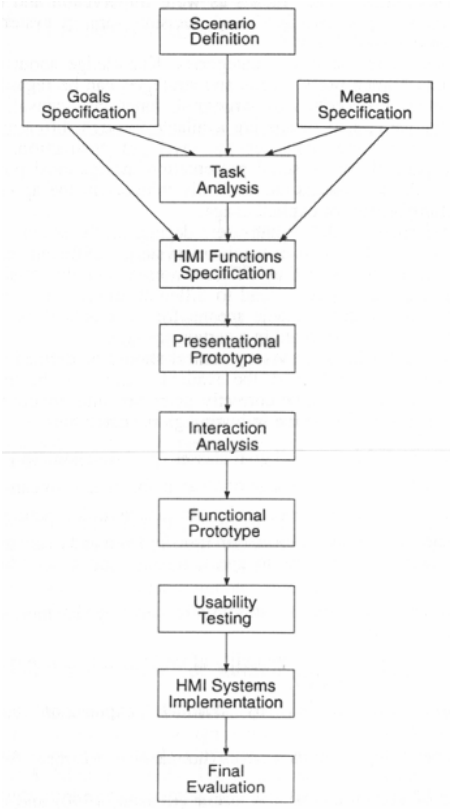


Figure 49. Johannsen's Design Methodology (from [Johannsen 97])

In another study, [Draper 93] cites three different ways to design telemanipulator systems:

1) Minimalist (TV and joystick)
2) More-is better- approach (full spectrum of sensory feedback)
3) Mission-oriented approach: acknowledges design tradeoffs in capability and cost seeking efficient solutions.

He recommends (as do we) the last of these approaches as the basis for design.
[Draper et al 99] further compares user-centered versus telepresence design approaches (Table 12). This helps to separate the hype surrounding immersive environments from the realities.

TABLE 1. COMPARISON AND CONTRAST OF DESIGN APPROACHES

| | *User-centered* | *Immersive/telepresence* |
|---|---|---|
| Information | Efficient displays promoting situation awareness; information may be summarized or pre-processed before presentation | Displays that reproduce the sensory milieu at the remote or simulated site and eliminate stimulation from the user's physical environment (all information presented may not be relevant to developing situation awareness for task performance) |
| Responses | Ergonomical controls accepting inputs from modalities appropriate to stimulus-response paired with displays and tasks | Devices that digitize human actions (e.g., walking) or the results of human actions (e.g., sound, as in speech) in a natural way |
| Attention | Controls and displays are designed to focus attention on critical parts of a task | Controls and displays are designed to re-create the environment, usually with no attempt to shape attentional processes |
| Fatigue/ease of use/ workload | Interfaces designed to be minimally fatiguing and for ease of use; workload is an important concern and the task may be modified to maintain acceptable levels throughout the mission | Interfaces designed to be no more fatiguing than if the user was physically present in the SE: ease of use is assumed to be optimal because of naturalness and transparency; workload is not raised as an issue |
| Training | Some training is usually assumed to be necessary to efficiently operate interfaces | Interfaces are assumed to be so natural as to make training unnecessary; naturalness is also assumed to promote skill transfer from SE to real world if SE is being used as training tool |

**Table 12: Comparison of Different Design Methods for telepresence (from [Draper et al 99])**

Sheridan [Sheridan 92], from an engineering perspective, describes 4 different classes of HMI interface systems (at the left) and their displays (right) as shown in Figure 50.

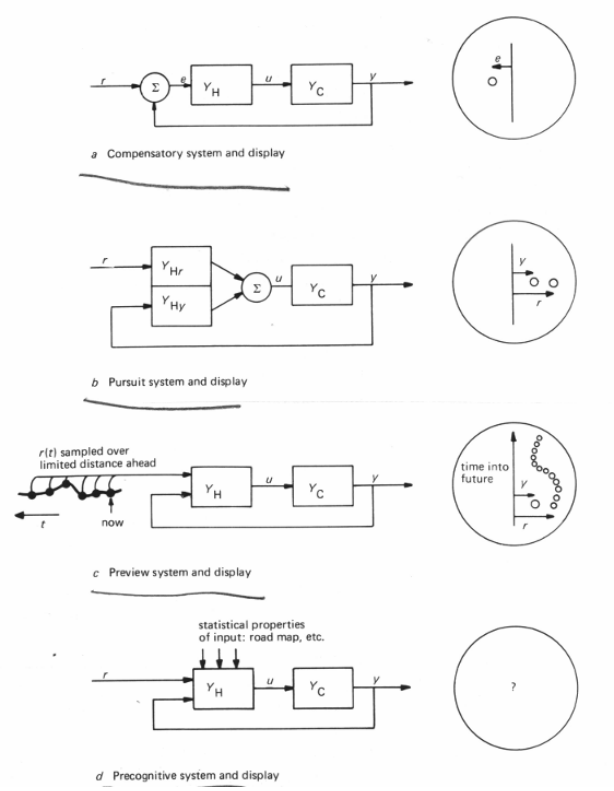

Figure 50: Sheridan's 4 classes of HMI designs (from [Sheridan 92])

### *3.7.2 Display Design Considerations*

The National Research Council study on Tactical Displays for Soldiers [97] provides guidelines for display system design of potential use in TMR.

1. Design should minimize itself as a physical barrier to acquiring environmental information such as sight and sound.
2. It should enhance sensory input only when required.
3. It should not distract attention.
4. It should minimize cognitive load on operator by:
   - Providing fused information from multiple sources.
   - Allow for easy input of information.
   - Minimize memory needs.
   - Reduce irrelevant information.
   - Simplify information presentation.
   - Reduce tasks.
   - Present information in properly ordered sequence for task.
   - Provide information in correct format (e.g., maps).
   - Provide suitable cueing and attention directing mechanisms
5. Design should minimize complexity and avoid complex automation.
6. Should provide new capabilities to soldier.

7. Should allow for the easy sharing of information.

[Draper et al 1991] conducted a series of experiments to determine when and if to use stereoscopic television displays for teleoperation. There results showed that is was heavily task dependent in terms of performance improvement. They contend that "it is necessary to use an ecological perspective when considering teleoperator viewing systems", hence it is crucial to understand the task-environment in which the robot(s) resides. So whether or not stereo display systems are suitable for TMR type tasks will require specific task-sensitive studies to be performed.

### *3.7.3 Task Analysis Models for Design*

[Draper et al 99] show the use of a task analysis model for the development of a DOD application for the navy (flight deck aircraft servicing). This formal approach assists in the design of an effective system, based on what is needed for what tasks. Summarizing the approach:

1. Identification of tasks and task elements.
2. Initial screening of tasks in terms of their impact on workload, and perceptual, cognitive, and movement requirements.
3. Development of task network models, establishing relationships between tasks.
4. Identification of task requirements for each task.
5. Identification of constraints on operation (physical and operational) to allow for development of alternatives.
6. Identification of subtasks (task decomposition).
7. Identification of replacement and alternatives (where robotics can best fit).
8. Evaluation of gains.

This process is iterative. The study cited above can serve as a potential exemplar for the development of a similar TMR-related study. One of the key outcomes would be a sound justification for the use of robotics technology in certain TMR-related task areas.

### *3.7.4 Alarm Design*

[Riera et al 95] discuss the role of alarms in supervisory processes when operators are in a removed supervisory room. This may only extend in some ways to the work in TMR. Two categories of alarms are cited: not-programmed alarms that arise from external events (sensors for intrusion, overheating, etc.) and programmed alarms defined at time of design (threshold exceptions, etc.). These programmed alarms are of 2 types: breakdown (failure of physical components) and process (abnormal condition or behavior). They provide an inductive method from dependability science as a basis for alarm design, which involves a functional analysis of the system.

[Kuchar and Hansman 95] describe methods for evaluating the performance of these alerting systems. Figure 51 shows how alerting systems relate to both the operator and environment. This approach incorporates a human response model in its design.

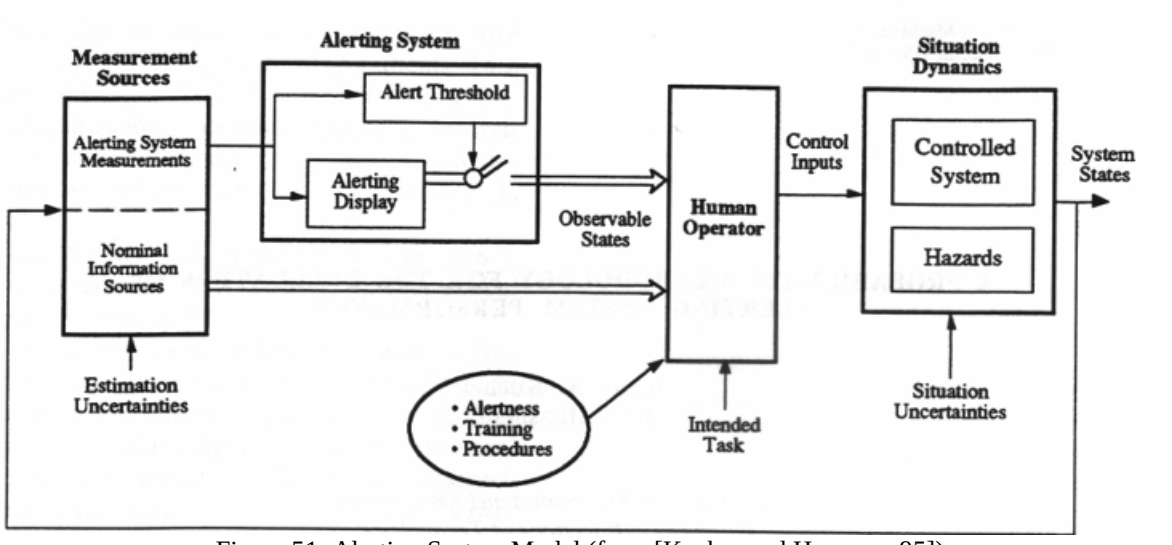

Figure 51: Alerting System Model (from [Kuchar and Hansman 95])

### *3.7.5 Teleoperator interface design*

Research at SPAWAR [Gilbreath et al 2000] used several techniques to reduce cognitive load on the user of a teleoperated Mobile Robot (Robart II). Human-centered mapping is one such strategy where a human guides map building and exploration. The operator guides the robot into an area, using natural commands (e.g., follow the wall on the left"). This disambiguates sensor data, as the robot can use the human input for labeling purposes. This is also one of the very few systems that document weapon control (non-lethal) for a mobile robot. Unfortunately no user studies were conducted to validate the hypothesis that these techniques are of direct benefit to the end-users.

Additional SPAWAR work studied teleoperation in sewers and tunnels [Laird et al 2000], which clearly are TMR relevant tasks. In this instance, user studies were conducted on a reflexive teleoperated interface. It was said that the interface provided more sophistication than required by the soldier, the soldiers preferring a purely teleoperated strategy, interestingly. More automation is clearly not always better. A heads-up display was useful within the tunnels but not outside due to glare. Another complaint was the inability to view the video by more than one soldier at a time. Lack of a zoom feature on the camera was also a complaint. A second generation OCU was created but has not yet been field-tested. In any case, the soldiers preferred slow and steady exploration rather than faster semi-autonomous operation for this task.

[Murphy and Rogers 96] describe TeleSFX/TeleVIA, a system that provides a method for semi-autonomous control of robots that incorporates user modeling. They introduce the notion of tele-assistance where the operator only provides support for the robot, not control. Here an intervening computational agent between the human and the operator facilitates the communication and control between them. The system uses focus of attention and hypotheses panels to help direct the operator's attention and goals. The examples presented are more for error detection and diagnosis rather than for navigation, helping the operator to determine what to do in the light of sensory malfunction. Having the intervening agent, between robot and operator, digest and process the information prior to requiring operator intervention minimizes communication. The ex-

tension of this work to a broader class of failure diagnosis is clear and could make a useful support agent for this single aspect of TMR mission conduct (sensor management).

## *3.8 Operator Selection*

Regarding operator selection, [Johnsen and Corliss 1967] state that "The operators [for telerobotics] should be selected with the same care as for jet pilots." In traditional teleoperation domains, they refer to the following essential capabilities (p. 65):

- Excellent depth perception
- Superior eye-hand coordination
- Display stability and resourcefulness in hostile environments
- Good physical condition

This assessment culminates in the statement that "Good manipulator operators are hard to find". Clearly TMR then should pay attention to the types of personnel dedicated to these tasks.

### *3.8.1 Individual Differences*

Ackerman (currently at Georgia Tech) has addressed the question of identifying individual differences between operators for air-traffic control and other complex skill acquisition tasks. This can aid in determining who may qualify as the best TMR operators. In one study, he addresses ability testing methods for general, reasoning, spatial, perceptual speed, and perceptual/psychomotor abilities for assessing terminal radar approach tasks. He has developed a theory of ability determinants (Figure 52) that relates skill acquisition to different people. It is broken into three phases: cognitive, psychomotor, and autonomous. While beyond the scope of this report to discuss the underlying theoretical implications, it is of note that this theory can be used to design tests that can be applied to tasks to differentiate who might be the best operators for multi-robot control tasks. Some generic conclusions on the air traffic controller test that were gender based, include that men perform better on spatial ability tasks, while women outperform men on perceptual speed tasks [Ackerman 92]. The key for TMR is understanding what tasks are involved. The analysis, if desired could be extended to other subject dimensions as well: education, age, etc.

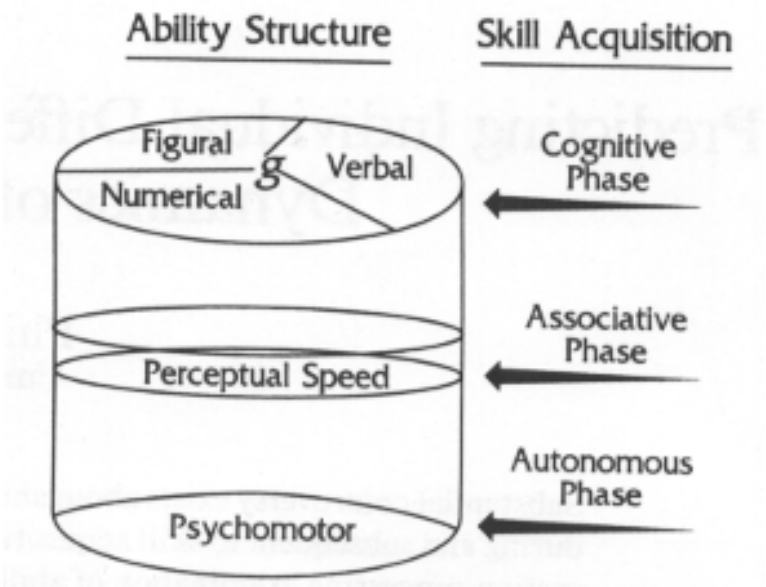


Figure 52: Ackerman's theory of Ability Determinants (from [Ackerman 92])

Ackerman's initial work led to a battery of tests that are used to evaluate potential air traffic controllers [Ackerman and Kanfer 93]. A wide range of tests (12), including things as seemingly simple as paper folding, letter/number substitution, dial reading, and necessary facts, to other tests involving spatial memory, problem solving and verbal tests were used to develop a composite of a potential controller. It is entirely possible that a similar set of attributes might also apply to TMR-type tasks, but a formal task analysis would need to be applied. This same battery of tests however may be useful, in differentiating just who might be the best controller given an accurate mapping of task criteria onto operator performance. Even more recently, he [Ackerman 99] has extended this to touch-panel testing, which potentially can provide an even more realistic interface assessment in conjunction with an operator's potential for performing in a TMR environment.

[Duncan et al 93] explored attention in the context of distraction. The test involved driving a car in an urban environment. This provides a measure for how easily distracted potential operators are, and can serve as measure of individual operator ability for TMR related tasks.

### *3.8.2 Skills needed*

Air traffic controllers (ATC), who are charged with spatial management tasks TMR have been singled out as having much potentially in common with TMR operators controlling multiple vehicles. [Wickens et al 98] describe 9 ability categories that an ATC needs:

1. Spatial reasoning ability
2. Verbal reasoning ability
3. Numerical reasoning ability
4. Perceptual speed factor for coding
5. Selective attention

6. Short-term memory
7. Long-term memory
8. Time-sharing
9. Manual dexterity.

Verbal reasoning perhaps is the only one that might be extraneous to TMR. Much could be learned at looking in detail at training procedures for ATCs and seeing how similar processes could be applied in this program. Tables 13-15 illustrate task sets for and attributes of Air traffic controllers. Similar tabular analysis could be applied to TMR robot unit tasks

| Task Set | Cognitive/Sensory Attributes | Number of Tasks |
|---|---|---|
| Entry | Coding | 134 |
| Receipt | Movement detection | 3 |
| | Spatial scanning | 34 |
| | Filtering | 43 |
| | Image/pattern recognition | 42 |
| | Decoding | 157 |
| Analysis | Visualization | 7 |
| | Short-term memory | 35 |
| | Long-term memory | 10 |
| | Deductive reasoning | 107 |
| | Inductive reasoning | 16 |
| | Probabilistic reasoning | 43 |
| | Prioritization | 23 |
| Communication | Verbal filtering | 132 |

**Table 13: Task set/Cognitive attributes for ATCs (from [Wickens et al 98]).**

| Attributes | Examples |
|---|---|
| Coding | Enter information into the maintenance log |
| Movement detection | Listen for alarm printouts |
| Spatial scanning | Observe status panels for status data |
| Filtering | Identify significant status data on status panel |
| Pattern recognition | Form mental picture of facility status |
| Decoding | Read a facility configuration display screen |
| Visualization | Determine operations impacts from weather picture |
| Short-term memory | Remember status information to record in log |
| Long-term memory | Remember procedures |
| Deductive reasoning | Determine that facility data are questionable |
| Inductive reasoning | Estimate impact from historical trend data |
| Probabilistic reasoning | Evaluate the nature of a degradation |
| Prioritization | Establish order for restoring equipment |
| Verbal filtering | Identify relevant verbal information |

**Table 14: Example ATC cognitive attributes (from [Wickens et al 98]).**

| Cognitive Functions (Higher To Lower) | Cognitive/Sensory Attributes | Number of Tasks |
|---|---|---|
| Plan/resolve | Prioritizing | 23 |
| Predict longer term | Inductive reasoning | 16 |
| Compare, predict shorter term | Deductive reasoning, pattern recognition, probabilistic reasoning, visualization | 199 |
| Transmit information | Coding, decoding, verbal filtering | 423 |
| Remember | Short-term memory, long-term memory | 45 |
| Identify | Filtering, movement detection, spatial scanning | 80 |

**Table 15: Hierarchy of attributes of ATCs (from [Wickens et al 98])**

### *3.8.3 Tunnel Vision as basis for selection*

Tunnel vision is defined by Boer [Boer 1995] as a narrowing of attention by concentrating on a part of system where the operator loses the overview. Narrowing of attention occurs as mental workload increases. At high levels of workload task-relevant stimuli are excluded. This occurs in situations for example when the operator is handling fault management. In certain cases, tunnel vision also occurs due to waiting for information. Boer suggests that it is possible to assess the proneness of operators through tests, and where necessary provide remedial training for "weak" operators. Of course if this is a criteria for selection, these "weak" operators who are prone to tunnel vision can be excluded from the population of potential TMR operators.

### *3.9 Training operators*

Perhaps the best results regarding guidelines for training teleoperators and operators of autonomous systems is contained in the Final Report of a Workshop sponsored by DOE entitled "Guidelines for the Development of Training Programs for the Operation and Maintenance of Robotic Equipment" [Byrd and Duke 98]. This report, provided by John Draper from ORNL, is highly relevant to TMR as it describes in details the duties, tasks and elements for teleoperators, advanced teleoperators, and autonomous systems. These are mapped onto the knowledge, skills, and abilities sets that individuals either need to possess or be trained to possess. Relevant portions of this report are reproduced in Appendix A. These can be easily mapped onto Soldier training publications (STP) and Training Support Packages (TSPs) as used by the DOD in general. New Military Occupational Specialties (MOS) can be created for telerobotic operators, as the skill sets in this DOE study are clearly enumerated and many of which would be highly relevant to TMR. This report can provide guidance in the formulation of DOD mission training plans as well. STPs, TSPs, and mission training plans for typical infantry tasks can be found at the home page for the Army's Training and Doctrine Digital Library (http://155.217.58.58/atdls.htm). A suitable follow-on task for TMR would be to attempt to develop a TSP and STP for specific TMR relevant MOSs, e.g., robotic operation and maintenance, based on the datapool provided in the DOE report.

[Chappell and Mitchell] point out that well trained novices does not result in expert performance. Expert operators anticipate patterns of normal operation and quickly recognize prototypical failure modes, while exhibiting confidence in their ability. Various techniques can be used to train novices including computer-based instruction, low-fidelity, high-fidelity and high-fidelity with motion based simulators, Often the compression of large volumes of materials results in stress in the trainees. The authors recommend the introduction of intelligent tutoring systems to bridge the gap from trained novice to expert. These systems are tailored to the individual student's needs.

Gopher [Gopher 93] studied issues regarding the role of attention control and how to train operators to perform better. In particular, he was concerned with strategic control of attention, i.e., do people know how well they invest attention and execute related attentional strategies. Successful examples include:

- Focusing attention (voluntary selection).
- Dividing attention (coping with concurrently presented tasks).
- Switching attention (voluntary movement of control from one task to another).
- Investing graded levels of effort (dividing attention over tasks of differing priorities).

Problems that occur in people in managing attention include:

- Failure to protect primary-task performance.
- Dissociation between subjective estimates and performance measures of workload.
- Lack of adequate feedback.
- Attention capture by automatic components (subjects needed to be trained to be able to relax and release attention).
- Ability to release resources voluntarily.

Gopher developed a series of tests [Gopher 93] that are geared to enhancing an operator's ability to manage attention more effectively, a crucial role for control of multirobot missions. In particular he used videogame scenarios to develop these skills, which might account for the intuition that those who are good at video games might also be good for TMR related tasks.

[Zachary et al 98] describe a training environment for tactical teams. It provides performance assessment, cognitive diagnosis, and instructor support in addition to simulation facilities. The task domain is for the Air Defense Team component of the Navy's AEGIS command and control system. The AETS training system embeds cognitive models of each of the trainees. The value of embedding models is predicting actions and diagnosing faults. Unfortunately no data was available regarding the efficacy of this method.

Other new approaches to training [Wickens et al 98] include the use of embedded training where the training resides within the actual operational system. These embedded trainers:

1. Require operators to perform tasks in response to simulated inputs
2. Present realistic scenarios including downgraded operational modes
3. Be interactive in assessing the operators ability
4. Record performance and provide feedback.

### *3.10 Cognitive Modeling*

[Kirlik et al 1993] studied human performance in a simulated task related to some potential TMR applications. In particular they looked at scout aircraft operating in dynamic and uncertain environments that could be controlled either manually via joysticks or through the designation of waypoints via a map interface. One and two person crews were studied. The scout craft in which the operator was notionally housed controlled 4 semiautonomous friendly craft with the goal of finding desirable target objects within the world. A large number of enemy craft were also present. While the task itself was somewhat contrived, it did give rise to an affordance-based model of cognition that was used to account for the human performance in the task. The outcome of the work in regards to user interfaces is that automated assistance could be designed based on the user model and that highly effective graphical representation could be created based on the affordance that the system needs to convey to the user, rather than on some arbitrary available representation. Similar modeling processes could be applied to TMR operators, that would result in analogous models to what is depicted in the Figure 53 that resulted for this particular task.

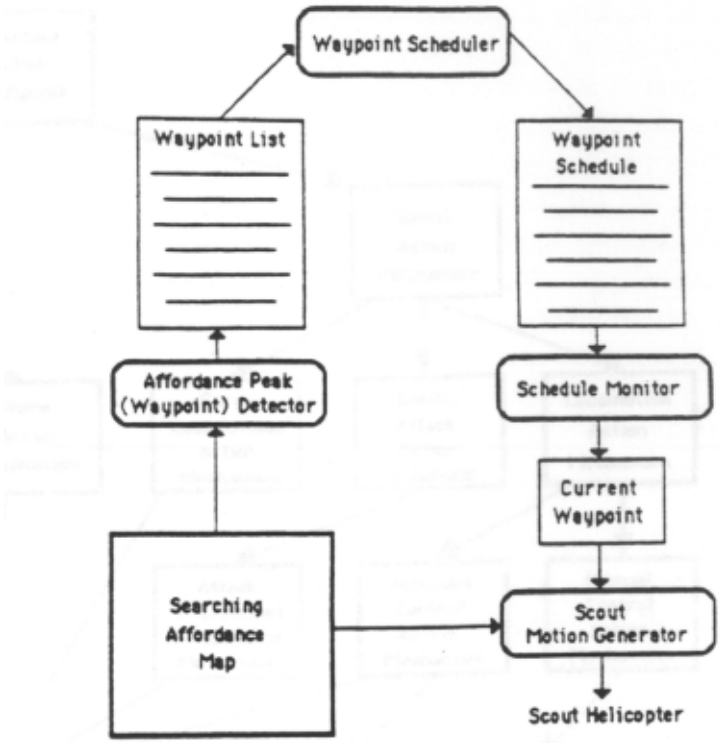

Figure 53: Kirlik's Model of Scout Search path planning (from [Kirlik et al 93])

[Callantine and Mitchell] have studied how operators select and use various automation modes to control complex dynamic systems. This methodology is potentially applicable to TMR-type tasks for tracking just how operators perform their tasks. The cognitive model on which it is based is called OFM-ACM: Operator Function Model for Systems with Automatic Control. While this system has been tested in flight cockpits for Boeing 757/767 simulators it may be extendible to other domains such as TMR as well. No explanations for actions are provided just tracking and organization of the user data itself.

### *3.11 Summary Recommendations – Human Factors*

The assumptions underlying the recommendations in this section are based upon discussions with LTC John Blitch, DARPA Program Manager for the Tactical Mobile Robotics Program. We are considering a system where a field operator may be capable of controlling up to 4 TMR units simultaneously. These may be coupled with multiple operators, each capable of managing similar units. At issue is what should the interface be like in terms of managing load, what types of skills are necessary for such an operator, how could training be most effectively conducted, and how could we evaluate performance. The following recommendations speak directly to these issues in that context.

It must also be stated as there are no studies that specifically address the human factors for this task domain, the basis for these recommendations is from extrapolation of studies that typically consider only one or a few of the related issues. As such these recommendations are speculative and must be confirmed through formal studies to truly be considered well founded. They do provide a basis for generating hypotheses for subsequent formal testing in TMR scenarios,

which is a strong recommendation for the TMR program. For many of the recommendations below, the reference study on which it is based is cited alongside the recommendation itself.

1. It is clear that straight teleoperation will be inadequate for such a complex task, due to the cognitive difficulties in managing multiple robotic units, with the additional complexity of conducting these operations in stressful environments. Low-level supervisory control is even questionable in terms of providing the necessary operator support. Thus specialized high-level supervisory control with the ability to treat the robots as a unit, or fully automatic (autonomous) control, with alert-based operator intervention, is likely the best course [Sheridan 93].
2. Telepresence is likely not a viable solution, due to the need for the military operator to maintain an awareness of his surroundings as a defensive posture. Thus situational awareness must be twofold: local to the operator as well as remote from the distributed robotic team.
3. Regarding specific sensory cues for inclusion in an OCU for TMR:
    a. Vibratory information can be useful to provide feedback on state achievement, or where it may increase the subjective feel of the operator to the robot's environment as in the presence of an enemy [Kontarinis and Howe].
    b. Mixed haptic/visual feedback has been demonstrated to provide enhanced control over purely visual feedback systems. Specific data is provided in Section 3.2.3 for guidance in the design of such a system based on the limitations of human spatiotemporal response.
    c. Auditory presentation (given a sufficiently quiet environment) is valuable for short simple messages that do not need to be remembered and that are involved with current events. They can be of particular value if the operator is on the move. Stereo and other forms of auditory presentation can provide 3D information regarding the source of an event (e.g., presence of target) [Burdea 96].
    d. Motion sickness in the operator is something that needs to be considered for any form of heads-up or helmet-mounted display when the operator is ambulating or driving. Coupling the visual feedback from the robot with the motion of the observer seems one of the better approaches to avoid this effect.
4. Regarding display characteristics:
    a. If the operator will be on the move and subject to vibratory stresses, bar graphs are recommended over polygonal representations as graphics, as these have been shown to be more accurately interpreted [Desombre et al 95] under these conditions.
    b. Operator stimuli should be presented in an easy to discriminate manner that reduces visual search or scanning time [Sheridan and Ferrell 74].

c. For monitoring tasks, where boredom or tedium may be a factor, means by which to keep the operator engaged with the TMR robots is important to avoid the so-called vigilance decrement. Artificial tasks can be added for this purpose [Thurman and Mitchell95]. As TMR is likely to have robots that possess a high level of autonomy, it is important that the operator not be lulled into a false sense of security.

d. Use of scene-linked symbology for heads-up displays, superimposed on returning video imagery is strongly recommended to attain real-time response for events that need such attention. The use of perspective (distance-dependent symbol size), differential motion, and natural coloration can also reduce attentional tunneling in the operator[Foyle et al, McCann et al].

e. A helmet-mounted display should not occlude the soldier's view in the field. Wrist-mounted or hand-held displays are recommended as an alternative if the HMD cannot be so designed [National Research Council].

f. Egocentric coordinate systems for displays are preferred over absolute geographic ones [McCann et al] to reduce the need for mental transformations in the operator's head. How this can be accomplished with groups consisting of multiple robots is harder to determine at this time, and warrants additional investigation.

g. The OCU must be designed recognizing that it will be used in a stressful environment, incorporating the specific stress reduction guidelines presented in Section 3.6.4 [National Research Council]. Also incorporate the other design guidelines from this NRC study in the OCU's display design (Section 3.7.2).

h. Employ a tested design methodology for OCU design, rather than an ad hoc approach. Candidates from Section 3.7.1 and 3.7.3 include [Corliss et al 68], [Johannsen 97] and [Draper et al 99]. A mission-oriented approach as advocated by [Draper 93] is recommended.

5. Regarding robot design characteristics:

   a. Camera mounting position on a TMR if used for visual feedback control can have significant impact on operator performance [Levison and Baron 97]. Human factors studies should be undertaken to evaluate just what the effects are of low-mounted ground hugging cameras on operator performance. No such study is in existence to the best of our knowledge.

6. Regarding Operator Performance:

   a. There are fundamental concerns as to whether humans are capable of managing complex distributed sensing and actuation environments at all [Murray 95]. Serious studies should be undertaken early in TMR, to evaluate if operators are potentially capable of managing as complex a task as envisioned for 4 robot units. To a degree, this will determine the requisite level of autonomy for the robots, if the task would otherwise require significant operator interaction (and not simply monitoring).

b. It does not always follow that more automation improves operator performance [Wei et al 95]. Judicious choice of automation techniques should be made in the design of TMR, avoiding the use of automation for automation's sake. This is further confirmed for TMR-like tasks for single robots operating within sewers [Laird et al 2000].

c. Human error occurs most frequently during intervention [Sheridan 93]. Special care should be engineered into the system to reduce this possibility.

d. Appropriate levels of trust must be developed between the operator and the robots, somewhere between mistrust and overtrust [Wickens et al 98]. Section 3.6.2 cites the relevant criteria which must be addressed in design and training.

e. Other human errors to which attention must be paid include:

   i. Mode error and ambiguity [Dezani et al 98]

   ii. Dual-task interference, a potentially very serious source of error for controlling groups of robots [Van Selst].

   iii. Misalignment of operator's mental model of the system with the actual system [Palmer]. This can be partially addressed through training.

7. Regarding operator selection:

   a. Different individuals have different abilities. Care should be taken in operator choice. It appears very unlikely that all soldiers will be properly suited for TMR tasks involving teams of robots, even with suitable training. Potentially, a good TMR operator may be far and few between.

   b. Test batteries exist that can be used to help determine which individuals are likely to be best suited for TMR operations. It is recommended that air-traffic controller tests be considered as a point of departure for such evaluations [Ackerman and Kanfer 93]. They appear easy to administer and likely will need to be supplemented with additional functionality. A first cut based on ATC operators regarding the skills needed for TMR is presented in Section 3.8.2 [Wickens et al 98].

   c. Specialized attentional testing to avoid including operators who are prone to attentional tunnel vision is also recommended [Boer 95].

8. Regarding operator training:

   a. In order to avoid adverse impact on response time, training should focus on familiarizing operators with relevant TMR stimuli and their presentation: to reduce their unexpectedness [Sheridan and Ferrell 74].

   b. Appendix A contains guidelines for the training for the operators for robotic equipment developed by the DOE. These guidelines should be seriously considered and expanded appropriately for TMR-related tasks [Byrd and Duke 98].

c. The use of intelligent tutoring systems integrated directly into the OCU appears to simplify in-situ training of operators [Chappell and Mitchell].

d. Tests to improve the ability of an operator to manage attention are available, which is crucial for a multirobot environment [Gopher 93]. These should be considered for applicability to TMR.

e. Training environments can also be of value (which is well-known) and perhaps TMR should consider investing in such an embedded simulation system [Wickens et al 98].

9. Evaluation:

a. Definition of metrics for task and operator performance must be defined clearly and early in the design process. Traditional metrics include task performance time and success ratio, but measurements of operator stress, fatigue, and workload management are certainly necessary as well for TMR.

b. The workload measurement rating system (Figure 45) or the NASA TLX workload index [Draper and Blair 96] appear to be suitable candidates for the basis of quantifying operator performance for TMR tasks.

c. Alarm-based operator performance can be assessed using methods similar to those developed by [Kuchar and Hansman 95] (Section 3.7.4).

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## ***Appendix A. Operator training***

This material is reproduced from Byrd, J., and Duke, E., (Eds.) "Final Report: Guidelines for the Development of Training Programs for the Operation and Maintenance of Robotic equipment", Morgantown, WV, U.S. Department of Energy, Federal Energy Technology Center.
pp. 15,19,23,e-3-47

## ***Appendix B. Human Factors Considerations and Display Systems***

This material is reproduced from National Research Council, Tactical Display for Soldiers: Human Factors Considerations, National Academy Press, Washington, D.C., 1997. pp. 70-87.