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A telerobotic virtual control system

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ABSTRACT

A project to develop a telerobotic "virtual control" capability, currently underway at the University of Toronto, is described. The project centres on a new mode of interactive telerobotic control based on the technology of combining computer generated stereographic images with remotely transmitted stereoscopic video images. A virtual measurement technique, in conjunction with a basic level of digital image processing, comprising zooming, parallax adjustment, edge enhancement and edge detection have been developed to assist the human operator in visualisation of the remote environment and in spatial reasoning. The aim is to maintain target recognition, tactical planning and high level control functions in the hands of the human operator, with the computer performing low level computation and control. Control commands initiated by the operator are implemented through manipulation of a *virtual image* of the robot system, merged with a live video image of the remote scene. This paper discusses the philosophy and objectives of the project, with emphasis on the underlying human factors considerations in the design, and reports the progress made to date in this effort.

1. BACKGROUND AND PROBLEM DOMAIN

Advancing technology is increasingly providing more powerful tools for transferring human perceptual and cognitive capabilities to remote or hazardous environments. With the objective of combining machine computational power with human intelligence in teleoperation, the Teleoperation and Control Laboratory at the University of Toronto is currently undertaking a project to develop a telerobotic “virtual control” capability.

To clarify our concept of virtual control, as well as how this project differs from other related efforts reported in the literature, it is helpful to establish a taxonomy of telerobotic operating scenarios, together with a summary of the various levels of human operator control which are either currently possible or foreseen. In this section we describe our task objectives, in terms of our classification of teleoperation systems.

A number of classification schemes for describing teleoperation have been proposed by other authors. One of these, set forth by Sheridan and his colleagues, categorises teleoperation systems according to degree of control automation [Sheridan, 1984]. On a spectrum ranging from minimal to maximal autonomy, teleoperation can be accomplished by means of :
(1) manual control without computer aiding;
(2) manual control with significant computer transforming or aiding;
(3) supervisory control with a major portion of control performed by the human operator;
(4) supervisory control with a major portion of control performed by computer;
(5) fully automatic control, where human operators primarily observe the process without influencing it.
The goal of our project is to elevate human mediated teleoperation from level 1, at which telemanipulation typically takes place at present, to level 2 or 3, depending on the situation.

Teleoperation tasks can be categorised also according to the type of environment in which they take place. In our taxonomy, we classify tasks according to the degree of uncertainty about the task environment, the objects being manipulated, and the operations that need to be performed.

Case 1: Remote World Fully Modelled

In this category, the objects being manipulated, the operating environment and the operational procedures (the actions) are either repetitive or varying but predictable. In the former case, which corresponds to most current scenarios in industrial robotics, a programmed robot can handle the task with little human intervention. In the latter case, the human operator is able to operate the remote robot by selecting predetermined routines or by combining known operational elements, which can be considered as part of a given vocabulary within a command language (e.g. “Move to Point A”) [Sheridan, 1988].

Case 2: Remote World Partially Modelled

This category includes operations in man-made environments, such as nuclear power plants and space platforms, where all the potential operational procedures of the task can not necessarily be anticipated in sufficient detail to enable predetermined routines to be created. In such environments, however, some geometrical knowledge of the environment and the objects within it can be modelled a priori, even though the spatial relationships between the objects and their environment are not known exactly. In other words, the remote world is *partially known*, or *unstructured*. Many graphical simulation or virtual reality techniques have been proposed to aid teleoperation in this case [e.g. Ince et al, 1991; Rocheleau et al, 1991; Browse et al, 1991; Spofford et al, 1991; Bejczy et al, 1990]. These techniques essentially assume the availability of geometrical knowledge of portions of the environment and of some of the objects within it, which otherwise could not be simulated. In such cases, support to the human operators can be achieved by constructing a database of geometrical models of known portions of the task environment and providing the operator with a completely graphical simulation of the remote worksite. Alternatively, wire-frame images of relevant objects in the environment can be introduced into a video image of the real worksite. With state of the art graphics technology, it is relatively straightforward to create such virtual images, but the difficulty of continuously coordinating virtual images with objects in the real task space remains. A variety of means for measuring and updating estimates of the real world, such as laser scanners, laser pointers, sonar scanners, video imaging, etc., can be used for this purpose [e.g. Takase, 1991; Christensen et al, 1991].

Case 3. Remote World Unknown

This category differs from the preceding one in that little or no geometrical knowledge about the remote environment and the objects within it is assumed to be available beforehand. The operational domains which most readily come to mind as examples of this case include underwater robotics, mining, nuclear waste cleanup and military robotics [e.g. Grodski et al, 1991]. From the literature it is evident that, beyond Sheridan's original display aiding concepts [Sheridan, 1984], relatively little effort to provide the human operator with more advanced assists has been targeted to this category. Although interactive modelling has been suggested for adding unknown objects on-line into the geometric database [e.g. Oxenberg et al, 1988; Burtnyk et al, 1990], the feasibility of letting the human operator manually teach the database during actual teleoperation, when time constraints and environmental complexity can be an important factor, is questionable.

Work underway in our laboratory is aimed primarily at assisting operators in dealing with remote manipulation tasks in the unknown environments (case 3), by providing a toolbox of means, based primarily on stereoscopic video displays, superimposed stereoscopic computer graphics and machine vision, for interactively probing a remote unknown world, making quantitative measurements of relevant landmarks, object locations and required teleoperator trajectories, and communicating these to the computer for further, higher level machine control.

2. OBJECTIVES OF THE PROJECT

As a well established principle in human factors engineering, a well-designed human machine system should combine what *humans* are good at with what *machines* are good at. As technology advances, the areas at which machines are good are expanding, forcing designers of human machine systems to take these trends into account. In the context of telemanipulation, technology is bringing improvements to both low level perception (machine vision) and dexterous motion / sensor based robotics [Burtnyk et al, 1990]. Machines (computers) are nevertheless still very poor at high level perception and cognition, that is, object recognition, situation understanding, decision making and strategic task planning. Clearly therefore, future teleoperation systems should exploit accurate and reliable low-level machine capabilities and leave human operators to concentrate on higher level functioning. In other words, we aim to exploit machine power to off-load the human operator and thereby elevate her from continuous, purely manual control to higher level cognitive and perceptual functions, such as pattern recognition and decision making. Figure 1 illustrates schematically this concept of partitioning human and machine functions.

In transiting from traditional teleoperation interfaces (Fig. 1a) to interfaces for advanced teleoperation (Fig. 1b), the attempt to move the human-machine interface leftwards necessitates a concentrated research and development effort. The most challenging work lies in the area of bilateral human machine communication. Referring to the feedback pathway (the block labelled Sensing + Perception), work is necessary in transforming what the machine “sees” and presenting this in an appropriate form to the human operator, to facilitate visualisation of the remote worksite. Referring to the forward pathway (the block labelled Instruction + Control), the human operator’s understanding of the situation, the objects she recognises, and her plans for carrying out the task all have to be transformed into actions that the robot can perform, by means of flexible interactive control concepts.

The ultimate goal of our project is to develop a “virtual control” mode, which involves effort along both of the pathways illustrated in Fig. 1b. In this new mode, a video/graphics interface serves as *both* perceptual aiding device and control mediator. In the Sensing + Perception channel, tools for aiding the human operator to visualise and measure the remote scene, as described in next section, are being developed. In the Instruction + Control channel, a *graphic pointer* and/or a *virtual robot* are being employed for control mediation. That is, instead of steering the real telerobot directly, the human operator will be able to express her instructions and controls either by manipulating the robot end effector via the graphic pointer, by means of resolved control in three dimensions, or by manipulating an entire virtual robot and allowing the real robot to follow afterwards. In addition to its control function the virtual robot superimposed upon the real scene is therefore also a graphical tool for enhancing the human operator’s perception of the real robot within the constraints of the real environment, for which an explicit model is not necessary (case 3). To reflect environmental constraints, the virtual robot should be geometrically identical to the real robot. For the purpose of reflecting the human operator’s commands / instructions, on the other hand, the virtual robot does not necessarily have to replicate the real robot kinematics and dynamics.

Concepts similar to our virtual control concept have been reported by other authors [e.g. Browse & Little, 1991; Bejczy et al, 1990; Conway et al, 1988]. All of those virtual robot concepts are intended basically as a tool for the human operator to explore feasible plans and express these to the robot control system. One potential application of such a control means, for instance, is for implemention of predictor displays, for overcoming time delays in manual control loops. The principal characteristic of our virtual control concept which distinguishes it from the others, however, is that our virtual robot is constrained to the real environment even though the computer does not possess an explicit world model of that environment. If the operator’s plan is unfeasible and would result, for example, in a potential collision, the adverse consequences of the plan would be identified not just by human perception but by means of a very basic software collision detection capability, which will operate *interactively*, in cooperation with the human operator.

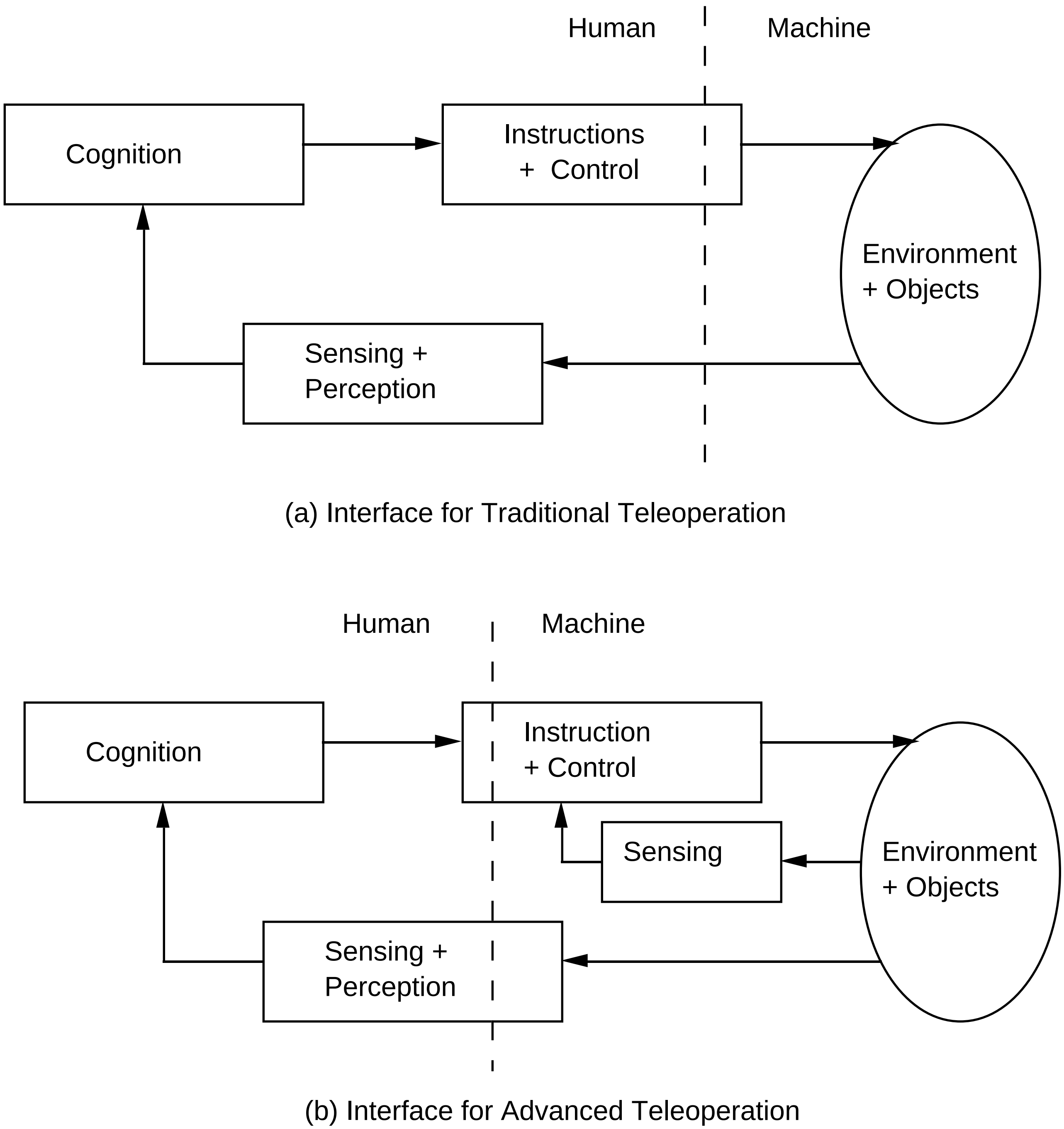

Fig. 1. Human-Machine Task Partitioning for Advanced Teleoperation

In order to accomplish this, it is essential that the virtual control system have the capability of *merging* the computer generated virtual robot with the remotely sensed "reality". Technically, a basic stereoscopic machine vision system, based on interactive signal processing software, is being developed, to enable the computer to “see” the locations of objects to be manipulated, as well as obstacles in the environment, *as indicated to the system by the human operator*. This is especially important for the case of previously undetermined telerobotic procedures.

It is anticipated that our virtual control concept will offer a number of potential advantages for a variety of near- to mid-term teleoperation tasks, which might otherwise be carried out on a strictly manual control basis. These advantages include:

- Overcoming human operator visualisation limitations, by providing a stereoscopic view of the remote worksite, together with a variety of on-screen stereographic display enhancements.
- Off-loading the human operator by releasing her from the direct control loop. This will be especially useful for the very slow processes which characterise space teleoperation.
- Allowing the human operator interactively to plan, and thus optimise, robot trajectories to avoid obstacles and potential collisions.
- Overcoming memory limitations, by allowing the human operator to test the feasibility of certain trajectories and procedures off-line.
- Providing state related warnings on-screen, thereby reducing the risk of damaging the manipulator and/or objects in the operational environment, as well as decreasing the attention sharing workload of the human operator.
- Decreasing the costs of training and practising.

In addition to applications in remote manipulation, we anticipate that virtual control can be employed for intelligent manufacturing systems in industrial robotics as well [e.g. Takase, 1991]. For such applications, virtual control may enhance efficiency, as well as ensure operator safety, by using a superimposed simulated (virtual) robot on a workstation to "teach" the intended task, rather than directly controlling a real robot at the worksite using a teach pendant, as is currently the usual practice.

3. SYSTEM CONFIGURATION

Figure 2 shows the configuration of our current system. A pair of video cameras are used to provide two images of the worksite from slightly disparate viewpoints. In order to input the two video images into the computer through one frame grabber, an electronic mixing circuit is used to combine the two video channels into a single channel of interlaced NTSC frames, where one field is devoted to the left view and the other to the right. This approach enables us to view the stereo video image directly on a NTSC monitor, as well as record it on a standard VCR [Milgram et al, 1990].

A Silicon Graphics Iris 4D/310GTX 3D colour graphics workstation is used as our display and control computer. The frame grabber is a SGI LVD (Live Video Digitiser), which can grab and digitise 30 video frames per second. Each combined digital image is separated in the frame buffer of the Iris into separate left and right images. The left and right view are presented alternately at 120 Hz on the Iris monitor, producing a flicker-free field sequential combined colour stereo image. The viewer’s liquid crystal spectacles are synchronised with the Iris monitor by means of a low cost electronic sync separation circuit.

Using our current approach, the update frequency of the on-line image processing system is only 7.5 Hz, causing somewhat jerky motions of images on the workstation monitor. Although it is possible to improve the update rate with either a faster graphics workstation or a dual frame buffer to avoid separation of the left and right views, we are not intending to do so with our current proof-of-concept system. Instead, we retain an analogue real time option for viewing faster operations. The totally analogue option presents left and right images in real time (30 frames per second), with the graphics workstation synchronised with the source video signal through a genlock circuit.

A Spaceball™ six degree of freedom input device is used as a three dimensional input device. A CRS Plus industrial robot is currently serving as the remote manipulator.

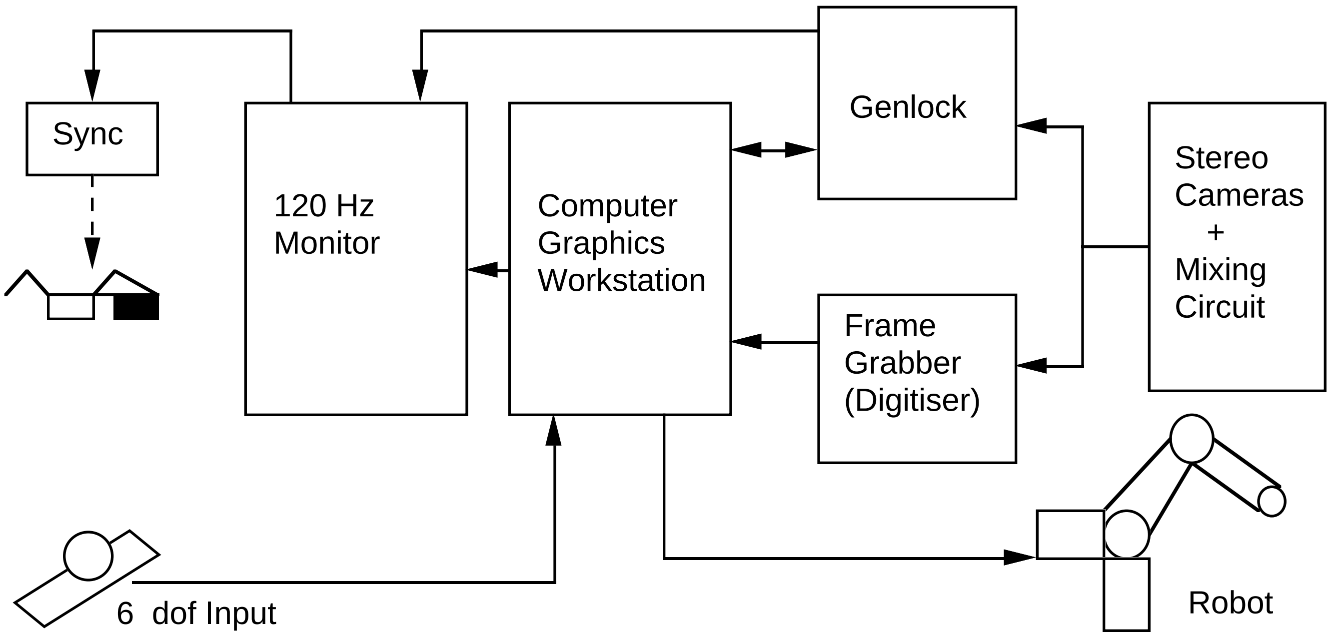

Fig. 2. Illustration of the System Configuration

4. CURRENT SYSTEM FUNCTIONS

4.1. Stereoscopic video + stereoscopic graphics display

Stereopsis has been shown to be one of the most effective depth cues which can be employed in teleoperation [e.g. Pepper et al, 1984; Drascic, 1991]. In our system not only the video images from the remote real scene but also the virtual objects generated by the computer graphics system are displayed stereoscopically. A great deal of experience has been accumulated in our lab using stereographics and stereovideo concurrently [Milgram et al, 1990; 1991]. In addition to serving as a viewing tool for the operator to perceive the remote world in depth, stereoscopic imaging is being applied here as a means for making initial estimates of three dimensional positions of points of interest, which are then verified by the hybrid machine vision system discussed in Section 5.1. Figure 3 shows an example of (stereo)graphics superimposed over (stereo)video. (For the purpose of this paper field sequential colour stereoscopic images must be presented as single (monoscopic) black and white stereo images.)

A variety of monocular depth cues can also be employed to enhance three dimensional perception. In remotely sensed video images, natural depth cues, such as interposition, size, gradients, shadows and perspective, already exist. In addition, synthetic depth cues may be added to the image to enhance sensation of depth. For example, introduction of a reference grid in perspective can enhance depth visualisation and has been shown to improve three dimensional tracking performance [Kim et al, 1987]. It is important to point out, however, that whereas such enhancements can easily be implemented in a *completely virtual* environment, it is very difficult to apply these concepts to enhance *real images* from a remote site. This difficulty is due to the fact that, in order to superimpose such depth cues onto a real video scene, they must be consistent with the spatial relationships among real objects in the real world image and should not for example *pass through* any real objects or surfaces in the real scene. In other words, in order to apply such virtual display aids to enhance the depth cues in the real image, a certain amount of spatial information about the real scene has to be *known* beforehand.

Fig. 3. "Virtual tape measure"

4.2. Virtual pointer and virtual tape measure

The initial stages of the project concentrated on superimposing a computer generated stereoscopic graphical pointer onto the analogue remote stereoscopic video scene, to be used by the human operator as a tool for exploring and making measurements within the real three dimensional video world [Milgram at al, 1990]. That work was motivated by the need of operators of remotely controlled systems to be able to perceive not only the *relative* locations of objects, but also their *absolute* locations in 3D space. Our stereoscopic pointer, illustrated in Figure 3, acts effectively as a *"virtual tape measure"*, which is superimposed onto the real-world stereo video image transmitted by the stereo cameras. The tape measure allows the operator to make absolute size, distance and location measurements within the real remote world. This absolute measurement is based on a relative three dimensional comparison of the pointer position with a designated target object location, as shown in Fig. 3. The principle behind this system, in other words, is to transform an otherwise *absolute judgement* task into a *relative judgement* task [van Cott & Warrick, 1972]. Initial experimental results indicate that subjects are indeed able to align virtual pointers with real targets essentially as well as they are able to align real pointer with real objects [Drascic & Milgram, 1991].

In addition to aiding the human operator probe and measure the remote scene, the virtual pointer can be used also as a tool for selecting and specifying points in the 3D scene for constructing and updating the computer world model. It is also used as the basic tool for realising the hybrid object location measurement system described in Section 5.1.

4.3. Zooming

To provide greater image detail, a zooming function has been developed. The close-up function enables stereo enlargement of any interactively selected volume in the scene. When portions of a stereo image are enlarged, many operations, such as aligning a stereographic pointer with a real object, can be achieved with less effort. Efforts are currently underway to incorporate an image interpolation capability into the system.

4.4. Parallax adjustment

Research has shown that incremental depth resolution is greatest at the plane at which the disparity between comparison stimuli is zero, that is, at the plane of convergence of the stereo cameras [Schor, 1991]. During most teleoperation tasks, however, areas relevant to the task at hand can not always be held in the vicinity of the camera convergence point, which appears on the monitor with zero parallax. Some points of interest might be so far from the camera convergence point in fact that the resulting parallax on the screen might exceed human limits of stereoscopic fusion. Excessively large crossed (in front of screen) or uncrossed (behind the screen) parallax can also occur when the operator uses the zooming function described above to have a close-up view of details of the image.

In response to these problems, a parallax adjustment capability has been added to our system, to enable operators as desired to compose the stereo image so that the point of interest is effectively at the fixation plane. This parallax shifting function is done quite easily with the digitised stereo video system. A similar technique, but implemented in hardware, has been reported in [Diner & von Sydow, 1988]. Parallax adjustment is essentially equivalent to controlling inter-camera separation (but not convergence angle). To do this in hardware by controlling the remotely located cameras, however, is both slower and a more costly technique. It has also been shown that points beyond the camera convergence point have greater depth distortion, while areas closer to the cameras than the convergence point have less distortion [Diner & von Sydow, 1988]. Since closer areas will appear on the screen with greater parallax, shifting the left or right fields by means of parallax adjustment may result in a comfortable stereo presentation to the viewer while keeping the depth distortion at a minimum.

4.5 Edge detection and enhancement

An important step towards merging virtuality with reality was to develop a stereoscopic edge detection system, which is essential for determining locations of and geometrical relationships among real-world objects. Edges are defined as the curves in an image where rapid changes occur in brightness, or in the spatial derivative of brightness [Horn, 1986; Canny, 1986; Nalwa & Binford, 1986]. For our purpose, such changes include those places where surface orientation changes discontinuously, where one object occludes another, or where the border of an object occurs. In analogy with human vision, where changes of colour also help to locate the borders of an object, colour differences have also been included in our edge detection program. Figure 4 shows an edge detected robot together with a wire-frame overlay.

In combination with a Gaussian filter, a Laplacian Operator has been used as the primary step in the edge detection routine. In order to detect the zero-crossings from the Laplacian output, interactive thresholding is used to cut off weaker components, relative to the peak magnitude of the Laplacian output. That is, if a threshold other than the standard default value is required, an optionally interactive function is provided to allow the human operator to manipulate this according to the particular image and personal preference.

Fig. 4. Edge detection and enhancement

5. CURRENT DEVELOPMENTS

5.1 Hybrid Object Location Measurement System

Although the *accuracy* of the virtual pointer has been shown experimentally to be quite good under laboratory conditions [Drascic & Milgram, 1991], the reliability of that completely human mediated concept was called to question. This is due to the fact that in such a scenario measurements are totally dependent upon human visual perception and the computer "knows" nothing about the image from the real scene. That is, the computer graphic images are superimposed onto the live video image, but the video scene is not "seen" by the computer.

Our present system enables us to apply machine vision technology to augment the human operator in aligning the pointer with designated object features. Based on edge detection and segmentation, a significant point, such as a corner, which is closest to the virtual pointer will be identified and its coordinates will be calculated and displayed on the screen by overlaying the computer's version of the designated object feature onto the corresponding portion of the actual object. In other words, the computer will "tell" the operator where the machine "thinks" that the intended point (e.g. corner) is. This will remove from the operator the workload of having carefully to align the stereo pointer to the point of interest, by requiring instead only fairly gross estimates. It will also increase system *reliability* by eliminating complete dependence on human stereo visual acuity and judgement. That is, whenever the operator does not agree with the machine's decision, the opportunity will always be available for iteratively double checking.

5.2. Creation of virtual robot

Figure 5 shows a preliminary version of the virtual robot, superimposed on a real scene. In the picture, the real robot to the right is displayed in digitised (stereo)video and the virtual robot to the left is generated in (stereo)graphics. The Spaceball™, the virtual robot and the CRS Plus industrial robot will all be integrated in the near future. A monoscopic version of this capability is described in [Browse et al, 1991].

Fig. 5. The virtual and real robots

As a tool for assisting the human operator to instruct and control the teleoperator, virtual control does not necessarily have to be conducted though the medium of a virtual robot, as illustrated in Fig. 5. Depending on the capabilities of the robot control system, virtual control may be realised through control of the virtual pointer alone, as described in Section 5.1, by accurately specifying relevant target locations to the control computer.

6. SUMMARY AND CONCLUSION

Developments in computer science and robotics provide improved opportunities for elevating the human operator from the direct control loop to higher level cognitive tasks in teleoperation. In this paper we propose an interactive, supervisory control concept – "virtual control" – for telemanipulation in both known and unknown environments. By exploiting the computational powers of the control computer and the perceptual and cognitive powers of the human operator, we started by applying low level machine vision algorithms to the digitised video image, making reliable measurements and merging virtual aids with the remote scene. Based on a digitised stereoscopic graphic and video imaging system, a battery of tools for aiding the human operator to observe, probe, measure and thereby visualise the remote environment have been developed.

The cornerstones of our approach, which have been maintained from the inception of the project, include: depth-rich spatial information presentation; integration of stereoscopic video and graphics display technologies (combining the virtual with the real); and combination of human cognitive and perceptual capabilities with machine computational power.

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