An Experimental Tele-operated Robotic System

Patrick Lim
Automation Systems Team
Industrial Research
24 Balfour Road, Auckland,
New Zealand

Surangi Sharma and Werner Friedrich
Automation Systems Team
Industrial Research
24 Balfour Road, Auckland,
New Zealand

Abstract

Automation has been introduced in various industries primarily to improve efficiency, productivity and worker safety. In applications where fully autonomous systems are not feasible, semi autonomous systems can be applied instead to achieve these goals. An experimental tele-operated system has been developed consisting of a manipulator with a gripper attachment. This paper describes the integration of key system components and a control architecture that has the flexibility to adapt to various applications. A key component is the human machine interface from which the human operator controls the manipulator. Focus of this research is to improve the quality of control. This is achieved by increasing the feedback channels to the user in the form of tactual stimulus in addition to vision. Control strategies were developed for this stimulus to present critical operational and task information that can be exploited for control. Preliminary experiments indicate that this concept was successful in the completion of a simple pick and place task. The research outcomes will provide solutions for both tele-operated and tele-robotic systems.

1 Introduction

Semi-autonomous systems are widely used in applications that usually demand some human input. This is evident in complex tasks that cannot rely solely on machine sensors for full automation. These systems have enabled humans to accomplish tasks that are often beyond their physical abilities. In addition, they can be controlled remotely thus removing humans from hazardous environments.

In general, a semi-autonomous system can be classified as a *teleoperated* or *telerobotic* system. A human operator controls the system via a human machine interface (HMI) unit. By definition, a teleoperated system is one that is manually controlled. A telerobotic system incorporates a human operator in the execution of a task either by shared or traded control.

Research in the area of teleoperation has been extensively carried out. Numerous examples can be found in the literature. Among them are applications in the area of computer assisted surgery [Troccaz et al, 1996], fuel reprocessing [Draper, 1994], virtual control [Zhai & Milgram, 1992] and space teleoperation [Tilley et al, 1991].

One important issue concerning teleoperated systems is the reliability of human input. Studies have shown that whilst humans are capable of very complex operations, they are limited in their abilities for space orientation and interpretation of geometrical data [Lumelsky, 1992]. Apart from physiological limitations, other factors such as fatigue, loss of concentration and repetitive strain will also affect the quality of control.

A number of schemes have been proposed to address these limitations. Schryver [Schryver & Draper, 1996] proposed a supervisory control where the user is responsible only for strategic inputs leaving low-level control responsibilities to the robot. Draper [Draper, 1994] proposed the use of force reflection in the joystick handle to assist operators. Sundstrom [Sundstrom et al., 1995] also reported on the preference of users for force reflecting position control. Results have been encouraging with lower error rates, lower peak forces and more consistent application of forces.

In this paper, we propose implementing force feedback in the forms of force reflection and force resistance. The aim is to use this tactual stimulus to generate information that can be exploited for improved control.

2 Overview

The human operator within a teleoperated system is an integral part of the control loop and essentially closes the loop by performing three functions. Firstly, the operator perceives the machine and task status information through various perception channels such as sight, tactile and hearing.

Secondly, the brain will process relevant information and determines necessary actions to achieve a certain goal. And, thirdly, is the articulation of specific body members to perform those actions.

An automated system can perform very similar functions to humans. A sensor based system provides vital machine status to the main controller. The controller processes the information and determines the necessary course of action or actions. These are then relayed to the machine outputs or actuators.

In a teleoperated system, however, an operator has exclusive control of a robot. The system generally consists of a HMI unit, a system controller and a programmable machine. The system controller supervises all operations within the system and serves as a link between the HMI unit and manipulator. Information between these sub-systems is bi-directional. The program receives control information from the HMI unit and actuates the manipulator accordingly. It also receives information from sensors and delivers feedback information to the HMI unit. User interaction is through this HMI unit.

2.1 HMI unit

The HMI unit is an essential part of the machine that is accessible to the operator. Functionally, it can be divided into the *input* and *feedback* sections as shown in figure 1. The input section interprets operator's control commands

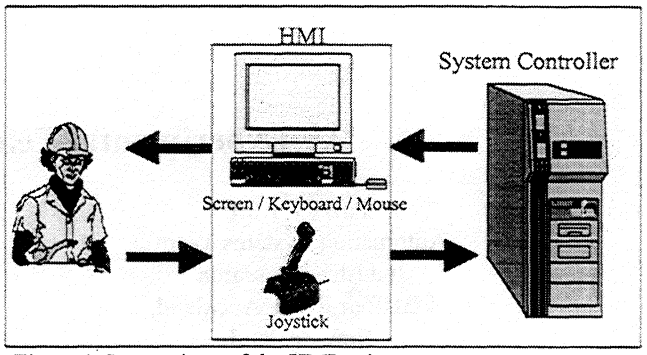

Figure 1: Interactions of the HMI unit.

and delivers instructions to the machine.

Commonly, most HMI units will require some form of physical contact by humans to input devices such as keyboards, touch screens, computer mice and joysticks. Other more sophisticated units use sensors to interpret eye movements, speech or hand gestures. In the feedback section, machine sensor information relayed to the operator in the form of visual display or force feedback on the joystick. Obviously, only certain HMI types are capable of operating with force feedback.

The HMI unit is physically divided into two major parts; control console and status display. The function of the control console is to facilitate operator control of

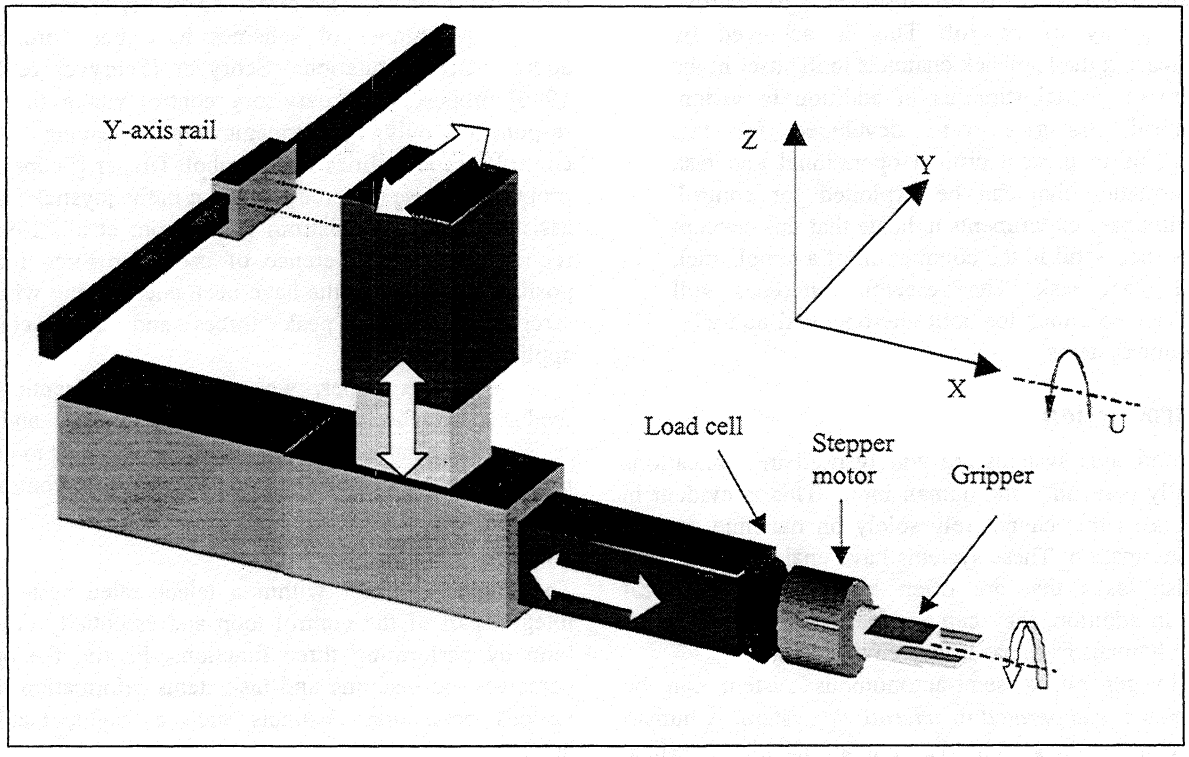

Figure 2: Diagram of a four axes manipulator with a gripper attachment.

manipulator and end effector while the status display provides useful operational and machine status information.

The control console consists of a four axes joystick, control switches, mouse and computer keyboard. The main function of the joystick is to provide dynamic control of manipulator. Its secondary function is to deliver feedback to the user in the form of force feedback. Control switches that are strategically placed on the handle and computer keyboard enable selection of features and actuation of end effectors.

The status display provides vital real time data of machine status, operation mode and parameter settings. With the use of a keyboard, the user is able to change parameter settings and select control options.

Joystick displacement is measured by rotary potentiometers. Potentiometer analogue signals are in the range of 0-5V. The system controller through the analog input port monitors these signals. A force feedback mechanism consisting of DC motors is installed to provide force feedback to the control handle. Linear amplifiers drive DC motors to supply feedback forces proportional to the analogue signals generated by the system controller.

2.2 Manipulator

A four DOF manipulator was developed as shown in Figure 2. It consists of three linear axes, one rotary axis, a four component load cell and a gripper unit.

An assembly of two rectangular telescopic robotic arms mounted on a horizontal track provides linear motions in the x, y and z-axes. The robotic arms are actuated pneumatically. The fourth axis is rotation about the x-axis actuated by a stepper motor. The joystick is used to control the direction and speed of each axis.

A load cell is installed to measure impact forces in the x, y and z-axes. These forces are reproduced in proportion as force feedback on the joystick from which the operator is aware of contact with objects. The load cell is a 4-component piezo electric model that measures three linear forces and one moment. It uses a specialised driver to drive the piezo crystals and a signal amplifier that produces output signals in the range of ±10V.

The end effector is a simple on-off type pneumatic gripper. It has a pair of jaws that are fixed with foam gripping plates for better grip. In the open state, the jaws have a separation of 60 mm. The gripper is designed to grasp a rectangular object with surface dimensions of 150 mm by 40 mm.

3 System controller

Implementation of the tele-operated system requires the interaction of sub-systems on both hardware and software levels. The hardware level concerns physical integration of devices such as sensors, controllers, drivers and actuators. The software level comprises of modules that control,

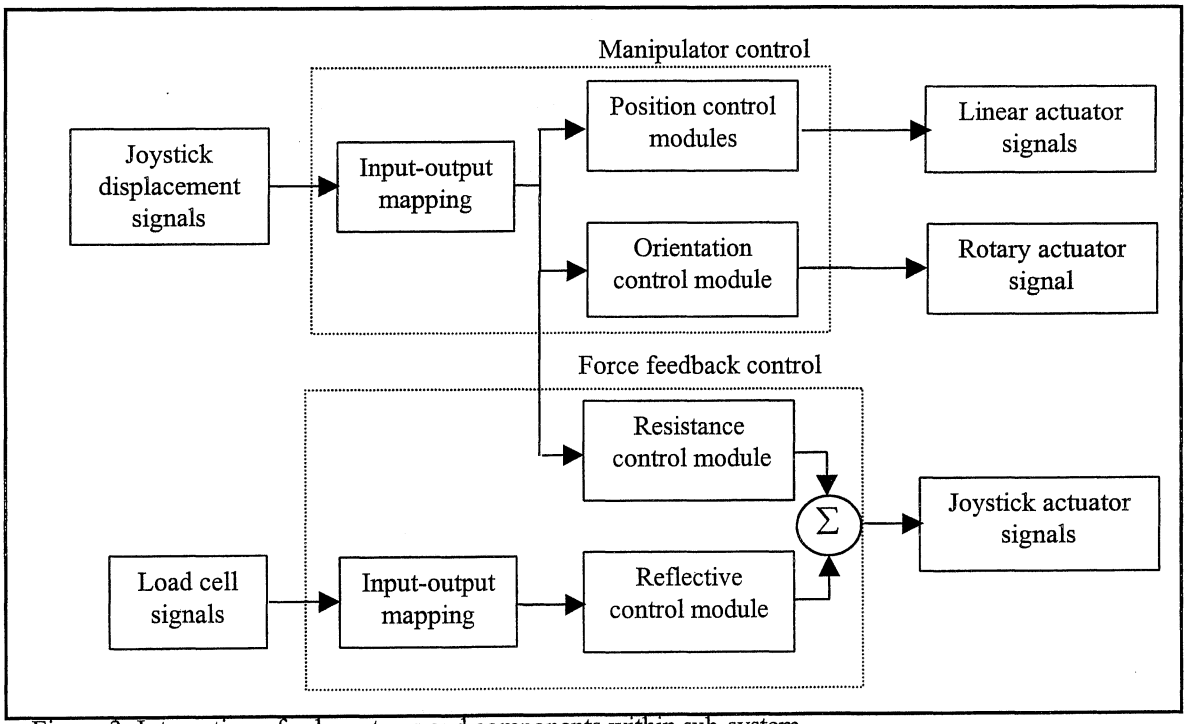

Figure 3. Integration of sub-systems and components within sub-system

interface and synchronise these devices.

3.1 Hardware interface

The system controller runs on a Pentium 333MHz under Windows NT operating system. It interfaces with devices through multipurpose I/O cards that are connected to the PC bus. They enable all input and output signals to be monitored and generated respectively by the system program. All analog input signals are bipolar and differential. They are wired to I/O cards with shielded twisted pair cables to minimise noise transmission.

3.2 Control architecture

The system program is written in a graphical programming language, LabVIEW™ and is designed to operate in real time. Within each program loop, it must perform data acquisition, information processing and signal generation with minimal time delay otherwise poor control results. The architecture is designed to be flexible such that the system functionality can be expanded by addition of function modules.

The control architecture is shown in Figure 3. It consists of two main sections. One section is responsible for manipulator control for both position and orientation of the tool. The other section determines the measure of force feedback to be exerted on the joystick.

3.2.1 Input-output mapping

The initial stage is the mapping of input components to the respective output components. For example, the joystick produces four displacement signals, which are used to control the four axes of the manipulator. Each displacement signal is pre-assigned to a manipulator axis. Similarly, four load cell signals are also mapped to the four joystick actuators. When a different mapping is required, the operator can simply re-configure it off-line and assume control with the new mapping.

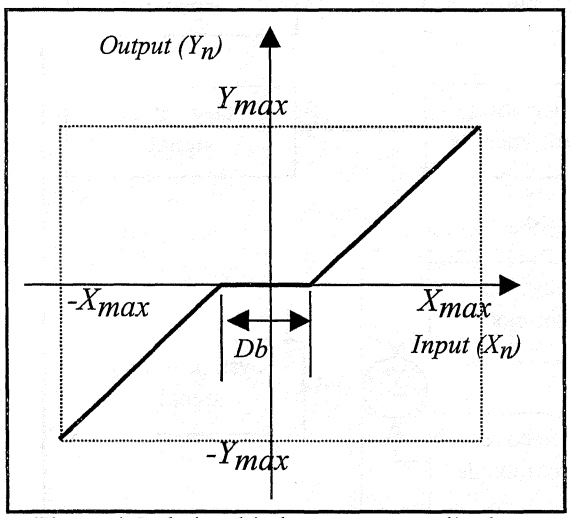

Figure 4. Relationship between normalised input and normalised output signals.

3.2.2 Normalisation / de-normalisation

Each control module performs a number of functions. Firstly, all input signals are normalised to –100% and 100% value based on the respective variable dynamic range (Eqn. 1). Processing of data is then done in the normalised state. After data is processed, all output signals are then de-normalised (Eqn. 2).

Normalising is used because all input and output components have dissimilar dynamic ranges. Using this concept enables any normalised input variables to be interchanged without reprogramming.

$$X_n = \frac{200(x - x_{min})}{(x_{max} - x_{min})} - 100 \qquad (1)$$

$$y = \frac{(Y_n + 100)(y_{max} - y_{min})}{200} + y_{min} \qquad (2)$$

3.2.3 Control module

Input variables are coupled to respective output variables by control modules. They process normalised input data and determine suitable output data to be generated. Each mapping is governed by control parameters. Control parameters are user preset values that determines the output value based on the input value. The parameters are dead band (Db) and gain. The relationship between the input and output is shown in Figure 4.

The region between $[-X_{max}, X_{max}]$ is the full dynamic range and remains unchanged. However, the region between $[-Y_{max}, Y_{max}]$ is governed by the gain setting and changes accordingly. Y_n is the normalised output and dependent on the value of X_n (Eqn. 3). Sensitivity of the system is evaluated by the ratio of the output dynamic range over the input range. It increases with the ratio. Zero is the lowest sensitivity.

$$Y_n = \begin{cases} 0; & -\frac{Db}{2} \le X_n \le \frac{Db}{2} \\ \left(X_n - \frac{Db}{2}\right) \times Gain; & X_n > \frac{Db}{2} \\ \left(X_n + \frac{Db}{2}\right) \times Gain; & X_n < \frac{Db}{2} \end{cases} \qquad (3)$$

3.3 Control strategy

The strategy is to employ force feedback to provide useful information to the operator while controlling the joystick by way of force reflection and force resistance. These forces are superimposed on the joystick handle but are

distinguishable by functionality and measure. Force reflection is a measure of the force in proportion to the force impacting the tool head.

By contrast, force resistance is an applied force to certain regions within the joystick dynamic range. These regions are known as *control boundaries*. It is introduced to provide the operator with strategic spatial information. With this information, the operator is able to find key joystick positions rapidly that produce known results such as moving the manipulator at a certain speed. By this, the operator can control a machine with greater confidence and reliability.

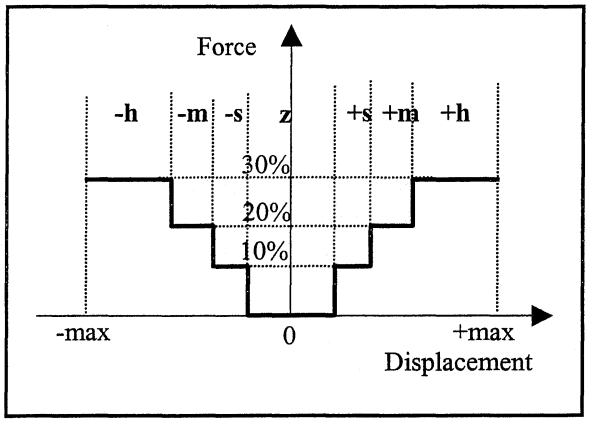

Figure 5. Resistance force applied at control boundaries on each joystick axis.

Figure 5 shows a measure of force applied at these regions. Since the joystick is related to the manipulator velocity, these regions are formed to distinguish between zero (z), slow (s), medium (m) and high (h) speeds.

The inner boundary is a dead band region. There is no manipulator movement in this region. Once past this region, speed increases linearly with displacement. The control boundaries become tactile indicators that inform the user where these positions are and subsequently the various speeds. The user sets the demarcation of the range into a number of specific categories.

4 Experiment

A simple pick and place experiment was set up to test all the functionality and operational features of the system. The overall aim is to assess the control strategy that was implemented to improve quality of control. This experiment involves the control of all axes to accomplish the task. Force reflection and force resistance have been activated to support joystick control.

An experimental test bed consisting of a whiteboard and a magnetic duster is shown in Figure 6. The experiment involved executing tasks such as gripping,

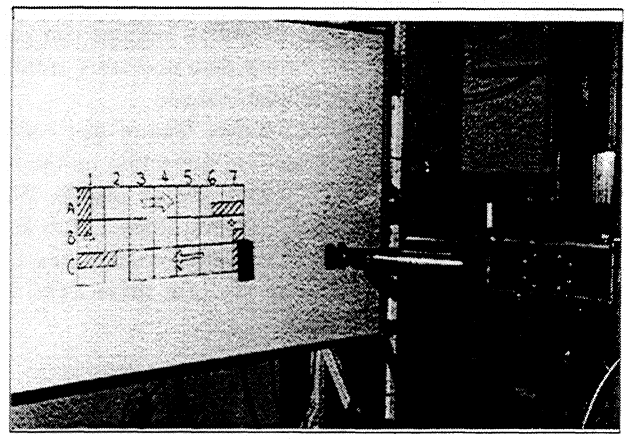

Figure 6. A whiteboard and magnetic duster were used for pick and place testing.

transporting and releasing the object. Four pre-selected locations with different orientations were marked on the whiteboard. The duster is placed on the first location. Subjects were asked to perform the task as accurately and as quickly as possible.

The first task is to position the gripper in the right orientation to grip the object. When the object is picked up, it is moved to the next position. The subject can move one or more axis at a time depending on the level of confidence. When the object is at the second position, it is released. The robot arm is then retracted and subject rests for a few seconds before commencing to the next position and so on.

The joystick is placed behind the robot but over on the right hand side so that the subject's vision of the robot's work space is not obscured. It is mounted on a platform that is height adjustable.

5 Discussion and future work

A total of six subjects participated in this experiment. Although it is a relatively small number of subjects, the results were sufficient to confirm preliminary success of the concept. All six subjects were able to perform the above tasks successfully when force feedback was activated but all failed when force feedback was deactivated.

There were a number of deficiencies in the system, which prevented further trials to be done without substantial modifications to the system.

5.1 Handling of joystick

All subjects agreed that the resistance on the joystick assists them to execute proper control although it requires less effort to use without it. With resistance, they are aware of certain strategic control areas within the dynamic range. The dead band boundary enables the user to move one axis

without causing involuntary movements on the other axes. However, effort to overcome boundary regions can cause the joystick to be displaced further than necessary resulting in unwanted increases in manipulator speed.

Force reflection was another feature that enabled the operator to "feel" forces that are impacting on the tool. This is helpful during pick up and release phases. While moving the joystick, the sensing of tool impact with either the whiteboard or duster confirms that contact has been made. It enables the subjects to perform these tasks with greater reliability and confidence.

5.2 Tele-operated system

One major factor in teleoperation control is the time delay between the control and response of the system (C/R). The controller response and pneumatic drives contribute to this C/R delay. Since the operator is an integral part of the system, a variable reaction time is also added to the delay. An appreciable delay may result in poor control. C/R delay must be reduced to a minimum.

Another factor is the consistency of speed. The system is currently using direct proportional drives without position feedback. Consistency in speed cannot be guaranteed.

5.3 Future work

The next phase is to extend the functionality of the current system to a tele-robotic system. This includes installing specific hardware, extending system capabilities and redevelopment of the manipulator. These tasks include:

- install motion control system to enable coordinated motions of the linear axes.
- modify HMI unit to incorporate new features.
- extend system capabilities by developing new program modules.
- redevelopment of manipulator to incorporate new hardware.

6 Conclusion

An experimental tele-operated system has been developed. The system was successfully trialed by operators executing *pick and place* routines via a force feedback joystick. Force feedback was used as an additional perception channel to provide tactile information for better control of the manipulator. On this channel, both force resistance and force reflection were implemented concurrently. Force resistance was used as tactile indicators to provide strategic spatial information while force reflection enabled the operator to *feel* forces that were impacting the tool head. Both were successfully trialled.

References

[Draper, 1994] J.V. Draper, *Hand acceleration impulse bandwidth during target acquisition: Implications for teleoperator bandwidth requirements*, IEEE Transactions on Systems, Man and Cybernetics, 24(6), pp 931-936, 1994.

[Lee & Lee, 1992] S. Lee & H.S. Lee, *Advanced teleoperator control system design with human in control loop*, Winter Annual Meeting of the American Society of Mechanical Engineering, 1992.

[Lee & Lee, 1992] S. Lee & H.S. Lee, *An advanced teleoperator control system: Design and evaluation*, Proceedings 1992 IEEE International Conference on Robotics and Automation, 1992

[Lumelsky, 1992] V. Lumelsky, *On human performance in telerobotics*, IEEE Transactions on Systems, Man and Cybernetics, 21(5), pp 971-982, 1991.

[Schryver & Draper, 1996] J.C. Schryver & J.V. Draper, *Network simulation analysis of level of control for the single-shell tank waste retrieval manipulator system*, (ORNL/TM-12752). Oak Ridge, TN: Oak Ridge National Laboratory, 1996.

[Sundstrom et al., 1995] E. Sundstrom, J.V. Draper, A. Fausz & H. Woods, *Test bed control centre design concept for tank waste retrieval manipulator systems*, Proceedings of the ANS Sixth Topical Meeting on Robotics and Remote Systems, pp. 187-193. Monterey, CA: The American Nuclear Society, 1995.

[Tilley et al, 1991] S.W Tilley, M.G. Hollars, C.M. Francis & A.H. Tadros, *Space telerobotic research and applications at Space Systems/Loral*, Proceedings of the 14th Annual Rocky Mountain Guidance and Control Conference, 1991.

[Troccaz et al, 1996] J. Troccaz & Y. Delnondedieu, *Semi-active guiding systems in surgery*, A two-dof prototype of the passive arm with dynamic constraints (PADyc), Mechatronics Vol. 6, No.4, pp 399-421, 1996.

[Zhai & Milgram, 1992] S. Zhai & P. Milgram, *Telerobotic virtual control system*, Cooperative Intelligent Robotics in Space II, 1992.