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The Neurovisualization Lab at the University of Virginia is currently developing the Integrated Remote Neurosurgical System (IRNS) to allow remote neurosurgical procedures for access to underserved localities. The system allows a remote neurosurgeon to control a robotic microscope through the use of 3-D input devices, communicate through live audio and video over an ATM switch, and view presurgical imagery. The surgical team in the operating room will also have access to the same images and communication facilities. The system will also serve as a training tool through the use of a complete robotic simulation we have developed. We have also instituted safety precautions in the form of restriction of robot motion, monitoring of robot joints, and protocol of system use. We have developed a registration system to assist in the implementation of these guidelines. A task analysis has led to development of a prototype user interface, and the preliminary integration of available components has been completed. We report on the current state of the system and ongoing development with respect to the user interface and integration

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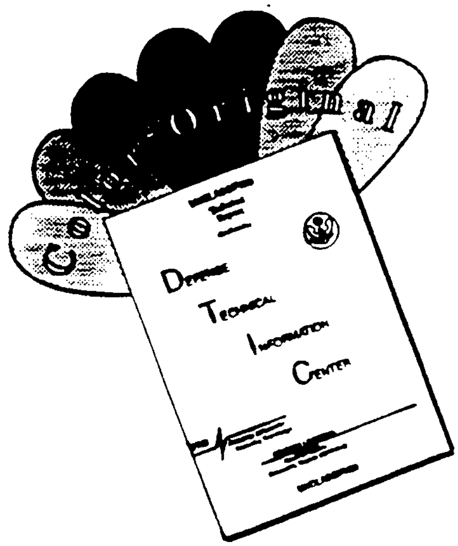

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Contents

1 Introduction

New computer and communications technologies, coupled with advances in microscope and manipulator design, have made it possible to extend the capabilities of neurosurgeons into previously inaccessible locations, such as under-served rural and inner city environments or battlefield situations. We are constructing the Integrated Remote Neurosurgical System (IRNS), a remotely-operated neurosurgical microscope with high-speed communications and a surgeon-accessible user interface. The IRNS will allow high quality bidirectional mentoring in the neurosurgical suite. Our research goals are twofold: First, to provide an integrated training environment, and second, to develop a clinical system allowing a remote neurosurgeon to lend expertise to the OR-based neurosurgical team.

The IRNS uses a generic microscope/transport model, allowing a wide range of operating room equipment to be controlled. In our case, the equipment is the Carl Zeiss [1] MKM surgical microscope/transport. Translation from generic commands to hardware-specific transport commands is performed by SuMIT (the Surgical Manipulator Interface Translator). A SuMIT interface has been developed for the MKM.

To the remote surgeon, the most important aspect of the IRNS is the Remote Planning and Navigation Workstation. The workstation incorporates surgical planning capabilities and can view real-time video from both the microscope and an overhead video camera. It also incorporates the ability to remotely position the microscope head and to its focus depth. The remote workstation includes a 3-D input device which uses tracking technology to allow the remote surgeon to intuitively position the microscope. Bidirectional audio and image archiving are also implemented.

The training goals of our research are also embodied in the remote workstation. Real-time simulation of the microscope transport is provided by the commercially available Telegrip simulation package from Deneb Robotics [2]. Telegrip is used to produce a realistic view of what the remote surgeon would see on the planning workstation. The simulation permits pre-surgical simulation, post-surgical critique, and training for surgeons without access to an actual microscope transport system.

The components of the IRNS are integrated using ATM [3] switching to provide low latency data transfer. Guidelines have been devised to ensure safe system operation both during normal operation (i.e. transport control handoff, collision avoidance) and under error conditions (i.e. loss of communication, transport failure, OR emergencies). A registration system has been developed to ensure precise monitoring of the patient and microscope.

The IRNS provides an opportunity to assess the benefits of remote surgical mentoring. By integrating high performance workstations and microscope carriers, the system demonstrates the usefulness of communications and computing resources in improving access to specialized surgical facilities. This research, along with the more sophisticated systems that will follow, will serve as a foundation and testing platform for extending the surgeon's skills without regard to time zone or geographic boundaries.

This document will describe the IRNS in its current state, including the system architecture, communications architecture, safety guidelines, user interface, and hardware. We will then discuss the future research and development goals for the IRNS.

2 IRNS System Architecture

2.1 Overview

The IRNS consists of two worksites, the operating room and the remote workstation. They are connected via an ATM network (see figure 1). Each worksite hosts several architectural elements, such as workstations and cameras. Locally, these elements are interconnected by ATM, Ethernet, or RS-232 connections, and are ultimately linked by a site workstation. The ATM link is responsible for carrying all video, audio, and control data. The system is currently simulating the MKM and optical registration system in Telegrip until the hardware is acquired. The models will still be retained for the simulation and training goals of the project. The ATM network, room camera software, audio communications, and user interface are all present.

2.2 Communications Design

Asynchronous Transfer Mode (ATM) networking is an emerging communications technology in which fixed-length "cells" of data are transferred at speeds of over 2.3 Gbits/sec [4]. The primary advantage of ATM is that it was specifically designed for simultaneous data, voice and video transmission - precisely the characteristics required for telemedicine.

We have implemented a four-node ATM switch network that incorporates both WAN and LAN elements. High performance workstations are linked together using 100 Mbit/sec LATM connections through a Newbridge Networks' Model 36150 8x8 ATM switch for file transfer and distributed computing tasks. Another LATM connection links our lab with the principal Operating Rooms in the University of Virginia Health Science Center. This connection is used to transmit image data, JPEG video and audio information between the lab and the O/R.

For transmission of image data and control/feedback information, both locally and remotely, we use TelRIP [5], a general purpose data exchange system. TelRIP uses a data-centered approach to modularity, meaning that programs communicate with one another by specifying the types of data they wish to send or receive. An advantage is that our processes can continue to run without knowing the state of other processes on the network. This approach also allows us to standardize the interfaces to devices and controls without predetermining the exact implementation of each interface.

2.3 O/R Worksite

The O/R worksite consists of the following components:

- A surgical stereomicroscope mounted on a robotic transport,
- One or more 'bird's eye' view cameras on pan/tilt heads,
- An optical registration system, and
- A workstation to display and annotate pre-surgical and inter-operative medical imagery.

Live video from both the stereomicroscope and the O/R view camera(s) is routed through JPEG compression hardware before transmission across the ATM link and is subsequently decompressed, again in hardware, at the remote location. The O/R "bird's eye" view cameras were included to give the

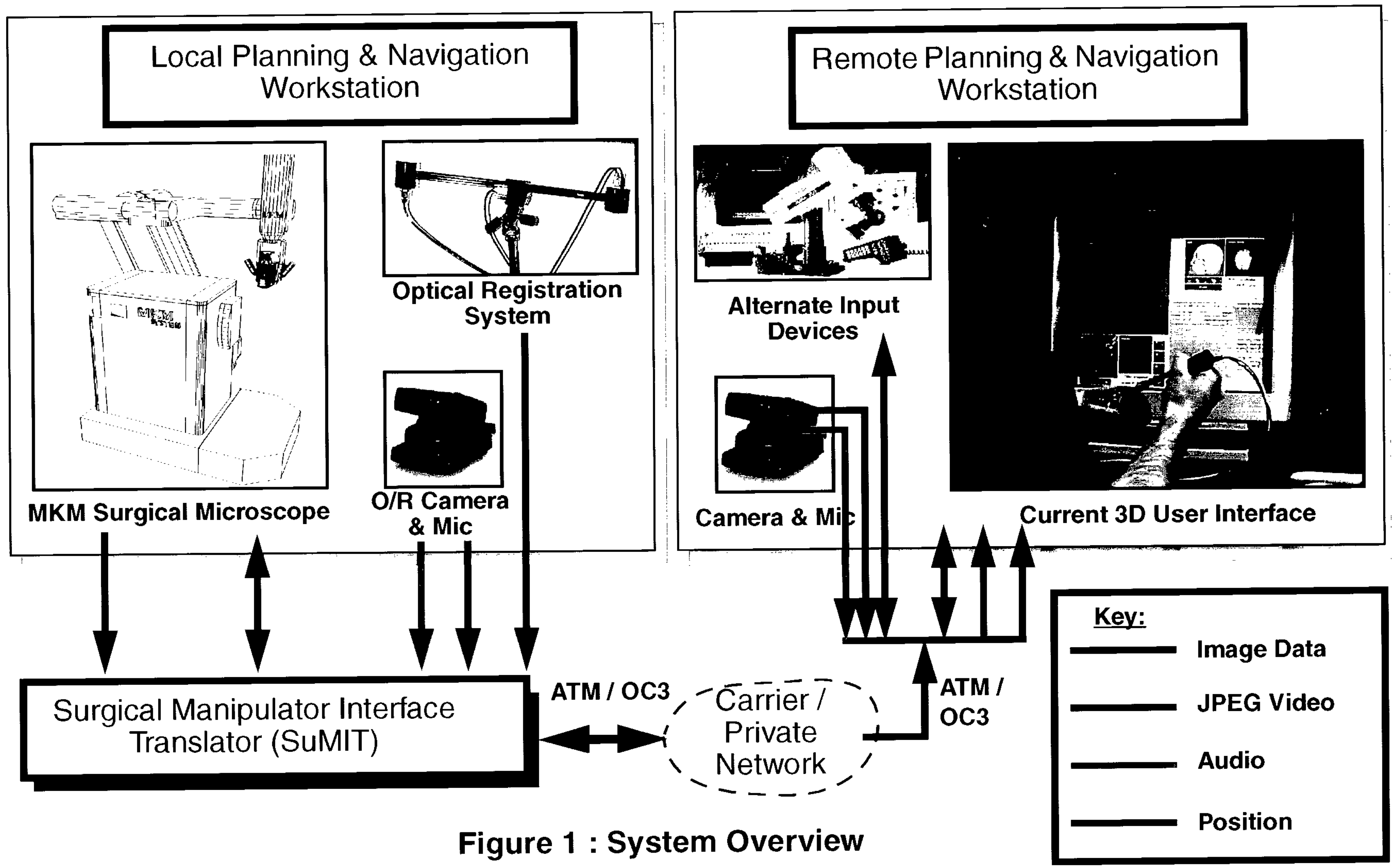

Figure 1 : System Overview

remote surgeon feedback on the situation in the O/R. This type of feedback is known to improve the interactivity of collaborative systems [6] by giving the remote user a sense of presence at the local site (in this case, the O/R).

The optical registration system, a simulation of Image Guided Technologies' Flashpoint 5000 [7], is also interfaced to the overall system via the central workstation. This component is used to calculate the relative positions of the robot base and patient by sensing targets which are placed on them. Locations of these objects are represented internally as a series of coordinate systems. Using these locations, as well as other information gathered by the system, we can monitor the location of the patient relative to the microscope.

The workstation can display views from the stereomicroscope, pre-surgical MR and CT images, and 3D surgical planning images. Users in the O/R can interactively slice through patient data, zoom in on images, and view a rendered volume of the brain. In addition, verbal communication between the O/R and the remote site is provided through microphones and ATM-linked audio.

2.4 Remote Worksite

The remote worksite consists of a graphics workstation providing:

- Microscope control,
- Robotic transport control,
- Video from the microscope and O/R view cameras, and
- Surgical planning facilities.

Microscope controls which are extended to the remote workstation include manual focus and zoom adjustments as well as the automatic focusing control. These controls can be activated by using verbal commands to the system's speech recognition software, Speech Systems Phonetic Engine 500 [8].

Microscope transport positioning control can be performed in three ways:

- Graphically - The surgeon can manipulate the graphical user interface (GUI) to translate the microscope.
- Verbally - The surgeon can issue commands to the microscope by speaking.
- Analogically - The surgeon can use magnetically tracked spatial input devices to effect the same orientation on the microscope.

Facilities on the layout of the GUI allow the surgeon to pan the microscope and zoom using arrow buttons and a thumbwheel-style widget. These buttons can be activated either by using the mouse or by pressing the touchscreen. In addition, speech recognition software allows the remote surgeon to control panning and zooming of the microscope simply by speaking "pan left", "zoom in", etc.

The current version of the system uses "props" [9], which are real-world objects with magnetic trackers embedded within them. There are two props: one which represents the microscope (a stylus) and one which represents the patient's head (a brain model). By monitoring the orientation of these trackers, the system can give the actual microscope the same orientation with respect to the patient. This interface technique has been in use at our lab for some time (on a prototype surgical planning tool), and has received enthusiastic support from both surgeons and residents for its ease of use.

Feedback from the OR is provided in video and audio forms. The remote surgeon is presented with live (30fps) video from the microscope and the O/R camera views. A graphical simulation of the microscope transport's current position is also shown, to give the surgeon a better feel for the spatial configuration of the patient, microscope, and transport. Snapshots of the view through the microscope can be taken and saved along with the positioning information necessary to return the transport to the snapshot view. To return the microscope to the position from which snapshots were taken, commands may be issued via the graphical user interface or by verbal command.

The surgical planning and audio facilities are identical to those on the O/R workstation.

3 Safety Precautions

The responsibility of overall system safety is divided between four different methods:

- Restriction of Robot Motion - The robot's motion is limited to a specified safety envelope.
- Registration of Critical Objects - The precise locations of the patient and microscope must be known at all times.
- Implementation of an Operation Protocol - Users must follow a rigid set of procedures during the system's use.
- Installation of Safety Hardware - A set of safety processors ensure that the robot is functioning normally.

To avoid collisions, the robot's motion is restricted first to a working volume, the set of all points which can be physically reached by the robot. The Telegrip package can graphically display this work volume. On a second, smaller level, the working volume is constrained by the patient and the operating area. Generally speaking, motion will be constrained within a spherical safety envelope above the operating area. Presently, more detailed specifications on the MKM are being acquired to accurately calculate this envelope. Registration becomes necessary in order to calculate the safety envelope and monitor the locations of the patient and robot. This registration system has been implemented in our simulation.

The registration system consists of two components: the optical registration system in the O/R and the user interface at the remote site. While the optical system measures both the locations of the patient and robot base, the user interface provides the surgeon's intended location of the microscope relative to the patient. These coordinate systems are then combined to provide a measurement of the location of the robot with respect to the patient. Motion commands from the user interface will be checked at the O/R for safety limitations based on this registration to ensure that the robot does not move outside of its safety envelope. SuMIT then performs the low-level translations necessary to convert positions in these internal coordinate systems into robot-specific motions.

Another important problem in maintaining the safety of the robot's motion is the avoidance of singularities. These are configurations of the robot arm where certain directions of motion may be unattainable. They often correspond to points on the boundary of the robot's workspace, out of its maximum reach.

The key to avoiding singularities is to keep the working volume of the robot within its dextrous workspace, which is the set of all points that the robot can reach with an arbitrary orientation of the tool. Singularities are determined by the structure and parameters of a particular robot. They can be calculated and shown on a package such as Telegrip. The IRNS software is designed to recognize singularities and provide feedback to the surgeon should the robot approach one. This feedback is currently given by color-coding the affected joints in Telegrip, but will be provided later through force feedback in the remote surgeon's input device.

Both the O/R and remote sites can control the robot, although not at the same time. Handoff of control between the two sites will be negotiated between the remote surgeon and the team in the O/R site. A single "dead man's switch" interface ensures that only one party has control of the microscope at any given time. The robot is in a stopped state upon startup and shutdown of the system. Should communication between the remote and local parties be severed, aborted commands are retried until some timeout. The local team in the O/R always has the option to switch to controlling the robot themselves. In short, the local team is able to continue the procedure should communication with the remote surgeon be lost.

The MKM system is also equipped with a number of safety processors which monitor the robotic arm for failures such as excessive velocity and range limits. Procedures for recovery from failures related to these safety processors will be followed in accordance with the MKM manuals [10].

4 Graphical User Interface Design

4.1 Task Analysis

Feedback from surgeons and residents has been sought throughout the project's development. Observations of surgeons using robotic microscopes have been conducted at the University of Virginia hospital, and have also been reviewed on video logs. These observations are critical in determining the current deficiencies in the usability of the surgical microscope as well as the interaction style to which the surgeons have become accustomed. Our system can correct some of the observed problems (operating table movement, jerky motion of the microscope) because of the increased flexibility afforded by its remote interface and registration system. Interviews were also conducted to determine what major functions are desired by surgeons. Features which came out of this process include speech recognition capabilities, a simulated view of the microscope (through Telegrip), and the snapshot facility.

In addition to the design criteria specified by the task, current research concepts from the areas of robotic control paradigms and human-computer interaction were included in the design. The selection of input devices and the graphical user interface layout and interaction style were influenced in part by previous research [11] [12].

4.2 Interface Design

A layout for the remote console has been designed to conform to the needs of the surgeon. It represents the result of feedback received from surgeons and lay users as well as from our ongoing task analysis. The GUI currently includes:

- A large window which provides the view from the microscope. Built on top of this window is a "virtual trackball" [13] which allows the surgeon to rotate, pan, and zoom the virtual microscope relative to any point in space. This controller serves as a backup to the tracked 3-D input devices.
- A second, smaller window provides live video from a bird's eye view of the operating room. Controls on the window allow the surgeon to pan the camera in 4 directions as well as zoom.

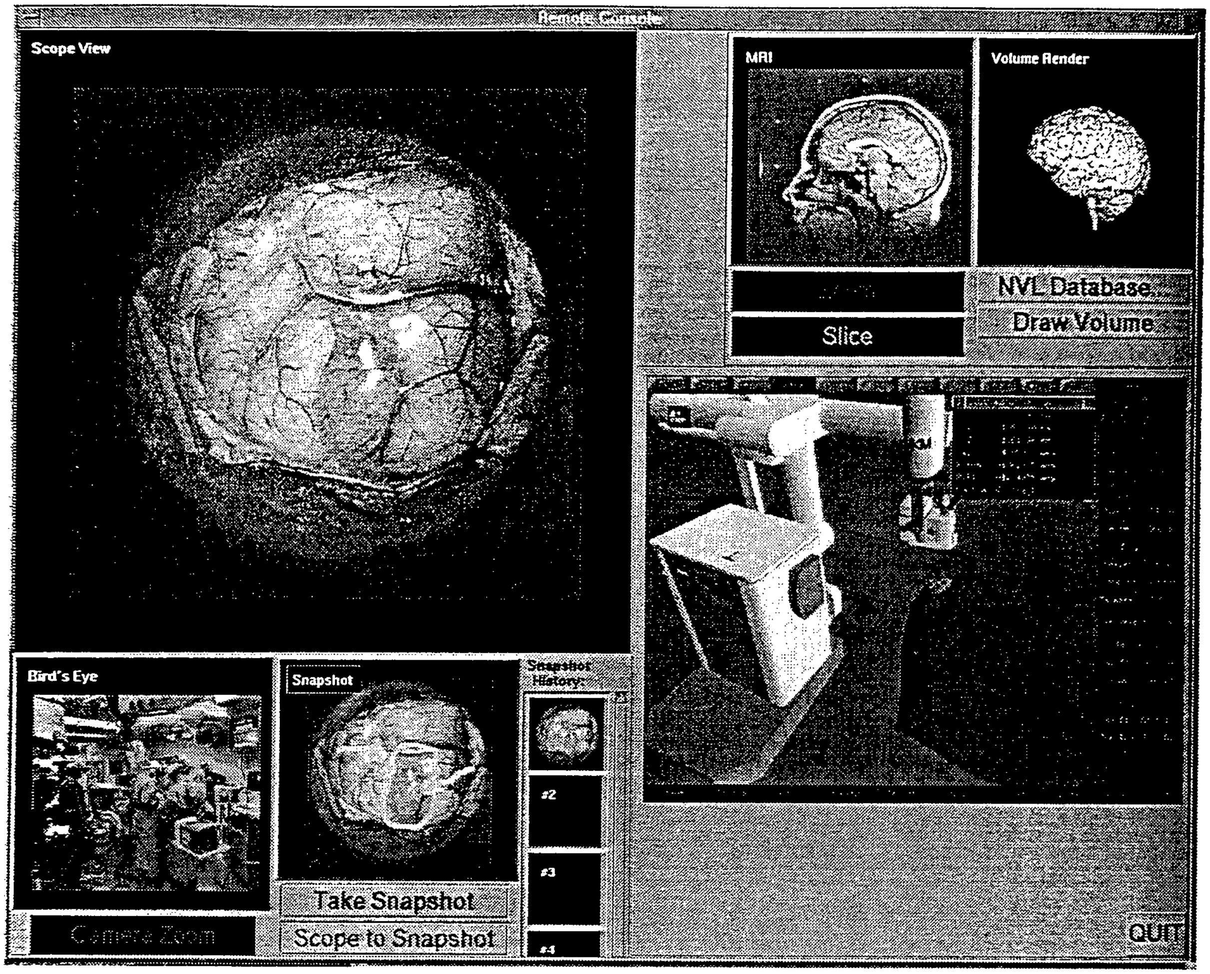

Figure 2: Layout of remote workstation interface

- Two more windows provide views of the patient's MRI data and a rendered image of a segmented volume of this data. The surgeon can easily zoom and slice through the data using thumbwheel-style widgets beneath the windows.
- A "snapshot" facility allows the surgeon to record still images from the microscope camera and store them. A separate window normally displays the most recent snapshot, but a history menu of thumbnail images lets the user select an older snapshot to display. Upon command, the microscope transport can return to the position from which any snapshot was taken.

A speech recognition system has been integrated into this prototype for use in issuing verbal commands. Most of the GUI functions now have verbal equivalents, such as panning the microscope and taking snapshots of the current microscope view. Response has been positive from our primary consulting surgeon and casual visitors to our lab, so this means of interaction is continually being enhanced to include more commands.

Currently, the user interface is connected to the Telegrip robot simulation package through the use of the TelRIP networking software mentioned above. The user is able to remotely control the simulated robot through the GUI. See figure 2.

4.3 Robot Simulation

A model of the robotic microscope transport was developed in Telegrip so that the actions of the robot could be simulated when it was not actually available. It is a complete simulation with closed-form inverse kinematics linked into Telegrip through a shared library. The closed-form solution is more rapid than the iterative one and, more importantly, is capable of determining the singular positions within the workspace of the microscope transport. This model can be manipulated locally through the Telegrip UI and remotely through any TCP/IP link. Various other components of the O/R have also be modeled in this simulation including the camera, optical tracker and patient.

5 Ongoing Work

Even though the props-based interface currently connected to the remote workstation is intuitive and easy to use, it contains a great deal of instability due to the tracking technology and is incapable of providing active force feedback. Therefore, we intend to replace it with a force-reflecting hand controller. This type of controller will give the surgeon an intuitive way to guide the microscope transport, simply by pushing or pulling on a handle mounted on a table-top robot. Force reflection will be used to indicate boundaries outside of which the remote surgeon may not move the microscope. The hand controller could then be combined with another tool to allow the two-handed interaction that the current props-based interface now provides.

The system will soon have the capability of whiteboarding. This will allow users at either the local or remote sites to "sketch" on images using a touchscreen or mouse. These annotations will be reproduced simultaneously on the other side of the ATM link, allowing the remote surgeon and the local O/R team to communicate visually as well as verbally. Whiteboarding software has been developed and will soon be integrated into the remote and local user interfaces.

In addition, the trackball-style interface used in the GUI of the remote console will probably be replaced with additional whiteboarding capabilities. This ability to overlay graphics onto our video streams would open the way for more complex enhancements such as overlaying of segmented images and augmented reality elements [14].

Because the IRNS is still under development, we have not conducted any formal experiments. When we have a complete prototype implementation (expected by December 1996), we plan to conduct trials with our consulting physician in order to take measurements on network loading, operational efficacy, learning time, and positional accuracy. We have a working simulation with some real components, and need only the MKM and optical registration system to move from simulation to prototype.

6 Acknowledgements

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