Simulation Tools for Collaborative Exploration of Hexapod Machine Capabilities and Applications

Joseph A. Falco
Intelligent Systems Division, Manufacturing Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland

Biography

Joe Falco is a mechanical engineer in the Machine Systems Group within the Intelligent Systems Division at the National Institute of Standards and Technology (NIST). He received his bachelor of science degree in mechanical engineering from the University of Lowell in 1987. He has spent the last 8 years at NIST involved in the design and development of robotic and machine tool systems for automated, intelligent, and virtual manufacturing in the areas of composites, welding and material removal.

Abstract

The Manufacturing Engineering Laboratory (MEL) of the National Institute of Standards and Technology (NIST) has recently initiated the National Advanced Manufacturing Testbed (NAMT). This is a testbed to demonstrate how machines, software, and people can be efficiently and effectively networked together to improve productivity and foster innovation at all levels of a manufacturing enterprise. "Characterization, Remote Access, and Simulation of Hexapod Machines," a technical project within the NAMT, involves the investigation of a new class of parallel-actuated machine tools based on the Stewart Platform. This paper describes how the characterization and simulation efforts of this project are being integrated with remote access capabilities. This process will allow external collaborators to perform real time experiments and to interactively use simulation and modeling tools for this experimental machine tool from geographically distributed locations. Special emphasis is placed on simulation tools developed within this project, as well as the remote access capabilities being used with them.

Introduction

Hexapod machine tools offer potential benefits of high stiffness, speed, and acceleration due to low moving mass and reduced need for special foundations. However, these machines' non-intuitive kinematics, work volume, and error characteristics create obstacles to industry's acceptance. To address these difficulties, this project is developing modeling and simulation tools to assist with application development. Remote access capabilities are also being developed to enhance collaborative research between geographically distributed government agencies, industry, and university partners who are involved in research and development activities on these new machines. A suite of modeling and simulation tools is being incorporated into the project. This includes machine animations, custom workspace analysis, part placement software, and novel machine error modeling and visualization capabilities. Internet access of these tools is being explored to provide potential machine users with an opportunity to understand Hexapod motion capabilities. Virtual manufacturing simulation tools will assist in developing applications for Hexapod machines. They will also help to improve NIST's understanding of the effects of individual error sources on machine motion. The NIST Hexapod is also outfitted with a wide variety of measurement instrumentation to characterize machine performance. An important aspect of this project is to provide Internet access to such sensor data in (near) real-time to allow remote participation in Hexapod machining experiments. These remote capabilities, as well as live audio and video of the machine, are expected to be useful tools for both Hexapod machine tool research collaborators and potential end users who will determine the feasibility of using Hexapod machine tools for their manufacturing applications.

Hexapod Machine Tools

Recently, several machine tool builders introduced prototypes of a new class of machines based on the Stewart platform[1] [2]. These new machines derive their stiffness from the geometric arrangement of the structural components. Current prototype Hexapod machine tools (Fig. 1) include the Giddings & Lewis Variax, the Hexel Tornado 2000, the Geodetic Hexapod, and the Ingersoll Octahedral Hexapod. These machines tend to be very stiff and have relatively low moving mass, which leads to potentially higher accelerations and velocities. Also, the self-contained structure reduces the need for a special foundation, increasing the portability for factory rearrangement. Approximately two years ago, NIST purchased and installed a prototype Ingersoll Octahedral Hexapod[1] to investigate this new class of machine tools.

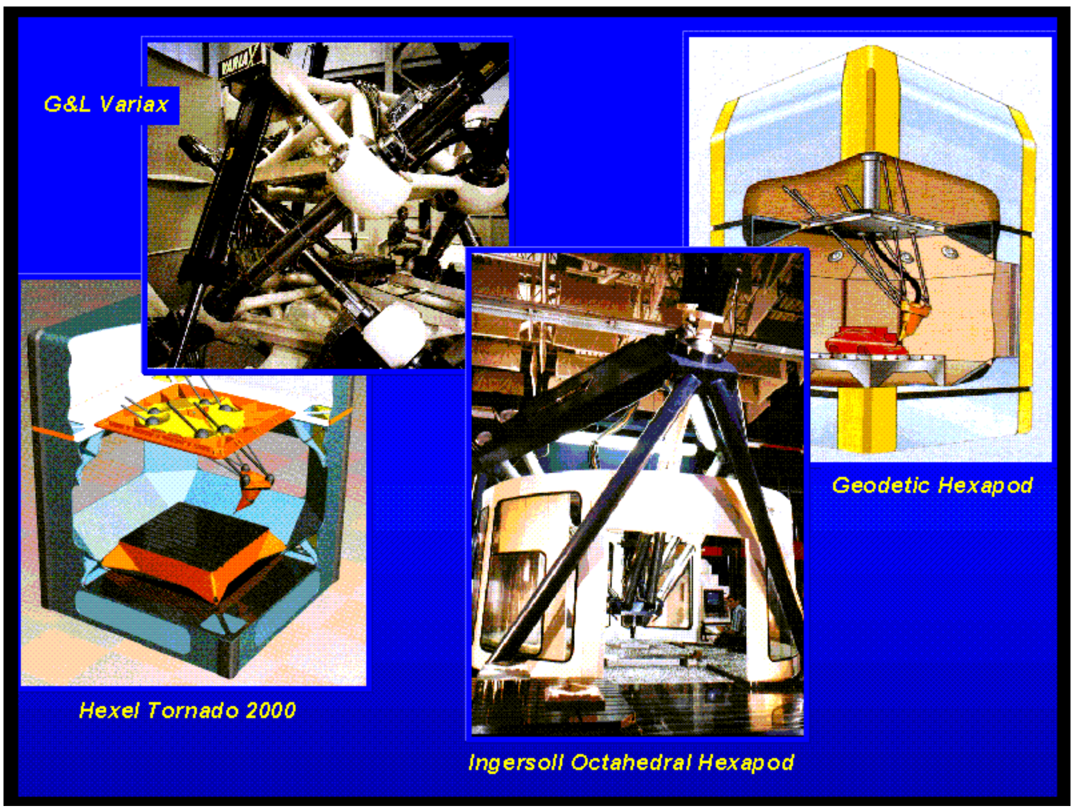

Figure 1 -Prototype Hexapod Machine Tools.

1 Certain commercial equipment, instruments, or materials in this paper to adequately specify the experimental procedure are identified. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Through industry interactions via workshops and participation in a national Hexapod users group, NIST has established a project plan. This plan includes studying the characteristics of these new machines and working with other Hexapod researchers to generate standard test methods and measurement procedures for them. A reservoir of application experience is being assembled to help machine tool users see what Hexapod machines can do and how these machines might best be applied to user operations. Modeling and simulation tools (Fig. 2) are being used to speed development of applications for these nonintuitive machines, as well as to aid in characterization and development efforts. Due to the scarcity of these prototype machine tools, capabilities to make it easier for industry to interact and participate in Hexapod research are also being developed. Controller and calibration experiments are being performed toward maximizing machine tool performance.

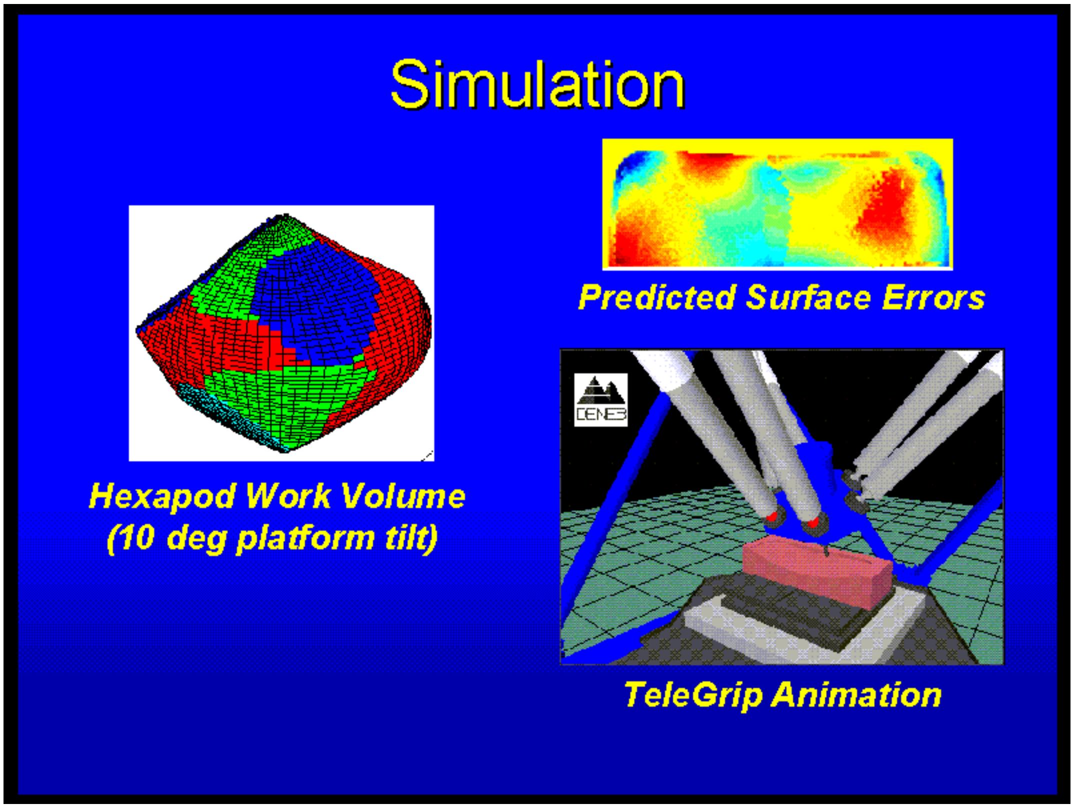

Figure 2 - Modeling and Simulation Tools.

IGRIP Based Simulation Tools

The Ingersoll Octahedral Hexapod (Fig 3) consists of six ball screw driven linear actuators (struts) attached, via ball and socket joints, at one end to a self-contained octahedral structure, and at the other to a moving platform, which houses a spindle motor and cutting tool. Based on the concept of the Stewart Platform, the upper ball joints that are attached to the octahedral structure are arranged so that the forces through strut pairs approximately intersect at the vertices of an equilateral triangle. The lower ball joints are equally spaced on the spindle platform. Figure 4 shows a top and side view of the Ingersoll Octahedral Hexapod to depict this Stewart Platform concept. Computer controlled actuation of the struts produces five degrees-of freedom (DOF) motion of the platform with the sixth degree of freedom, rotation about the vertical axis, constrained by software to prevent collisions between struts.

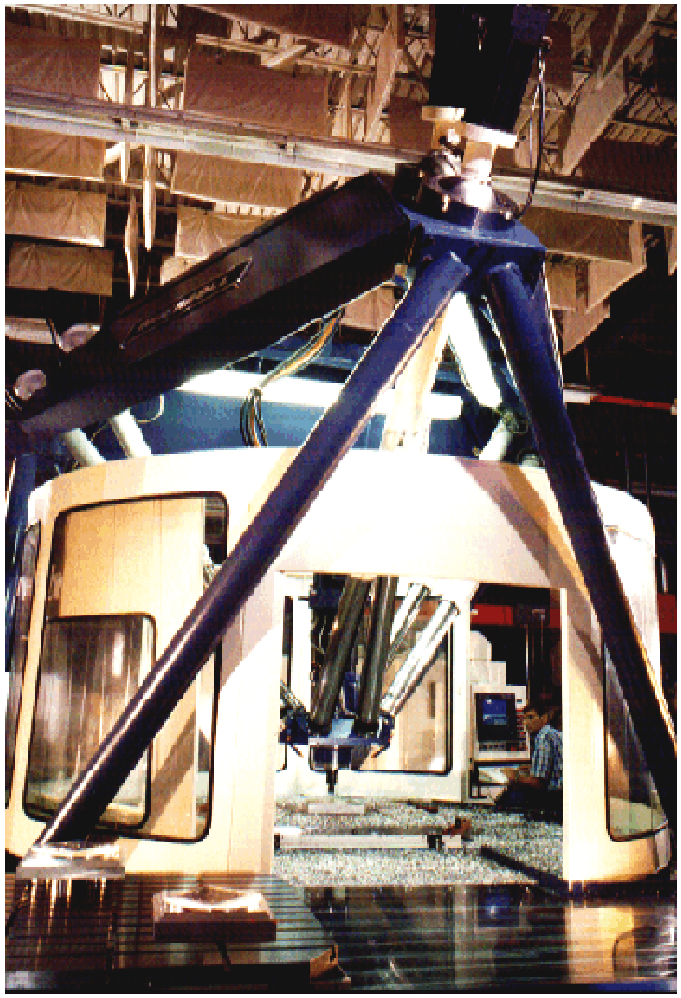

Figure 3 - Ingersoll Octahedral Hexapod.

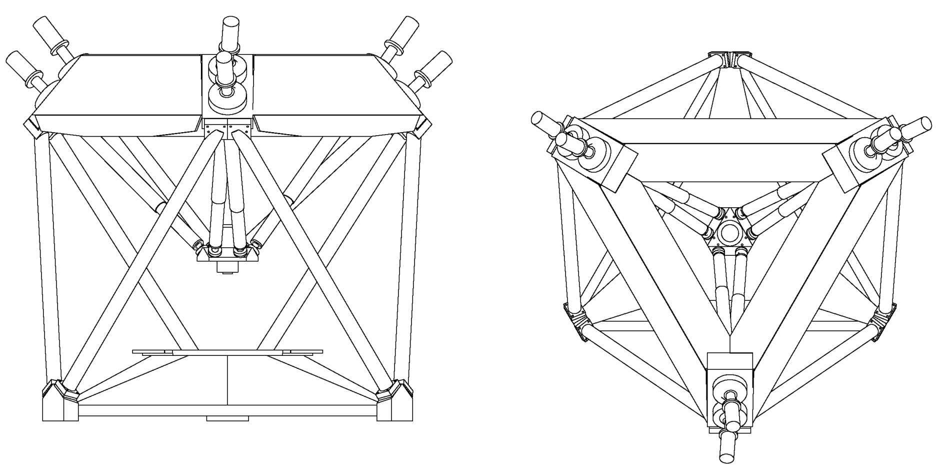

Figure 4 - Side & Top View of Ingersoll Octahedral Hexapod.

The simulation model of the Ingersoll Hexapod was constructed in Interactive Graphics Robot Instruction Program (IGRIP)[3] from imported Pro/ENGINEER[4] solid models of the machine tool's components. Emphasis was placed on constructing a model that closely depicted the Ingersoll Hexapod so that remote users could easily associate the simulated machine with the actual machine. Because IGRIP kinematics libraries do not directly support parallel actuated devices, Hexapod motions are simulated using the IGRIP Multi-T-jog mode. Here, the platform is modeled as a 5 DOF simple device and each of the struts are modeled as 5 DOF serial devices . Each strut has a ball joint which is mounted to the Hexapod octahedral structure, a linear joint (ball screw actuation) and a second ball joint at the platform. All struts are configured to Multi-T-jog to a respective tag point that is attached to the platform at each of the 6 socket centers. Limit checking is performed for all 12 ball joints and the 6 strut extensions using a NIST-developed Graphic Simulation Language (GSL) procedure. Alternative solutions to simulate Hexapod machine tools in IGRIP are being investigated[5].

A verification tool has been developed to test Numerical Control (NC) programs on the simulated Hexapod machine tool using a GSL program to interpret Ingersoll Hexapod NC dialect and convert the data to IGRIP motion commands to drive the animation. Using the NIST's limit checking procedure, limits can be checked at every NC block or at simulation update cycles. Limit violations are graphically displayed on the animation and are also logged into a file with their respective NC program blocks. Thresholds can also be set within the procedure to notify the user that the machine tool is in close proximity to limits. NIST has successfully used this tool to test NC programs and to determine work piece placement for application development work. A composite lay-up mold test part for the Space Station escape pod, designed according to geometry from NASA Johnson Space Flight Center, was machined in wax and forty-five mounting rails were machined for the NIST Center for Neutron Research Disk Chopper Time-of-Flight Spectrometer. NC verifications using this IGRIP tool (Fig 5, a&b) were performed prior to actual machining.

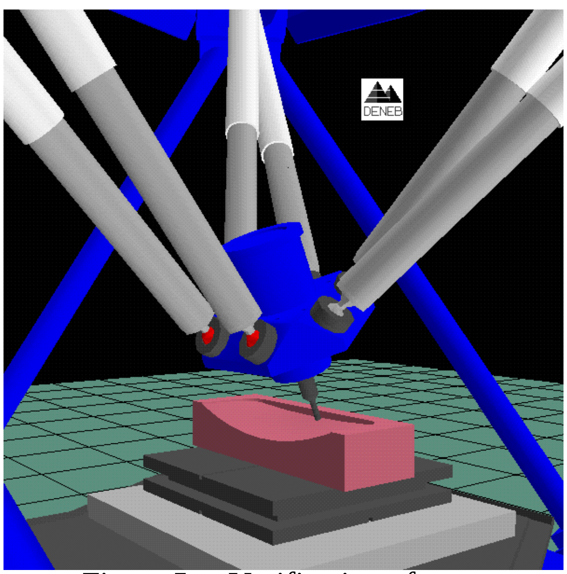

Figure 5a - Verification of NASA Test Part.

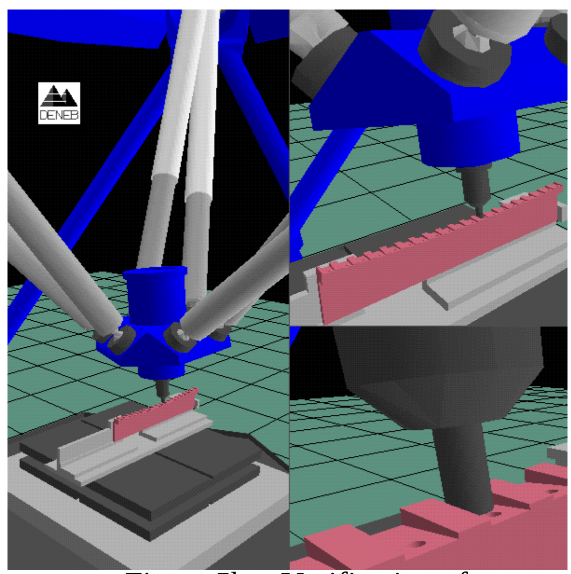

Figure 5b - Verification of Detector Mounting Rail.

An error visualization tool was developed to use with the NIST Hexapod simulation. This depicts the relative motions between desired machine tool trajectories and trajectories with errors as predicted by the Hexapod error models. The errors are displayed as scaled vectors of different colors during the animation of machining. Red error vectors indicate that the tool is cutting more material than desired, and green indicates the opposite. The animation feedback interface technique displays a transparent “ghost image” of the spindle platform at the desired positions and a real solid model for the actual positions (Fig. 6). The ghost device and the actual device are synchronized using IGRIP input/output (I/O) communications. Vectors using the IGRIP Command Line Interpreter (CLI) draw function are created.

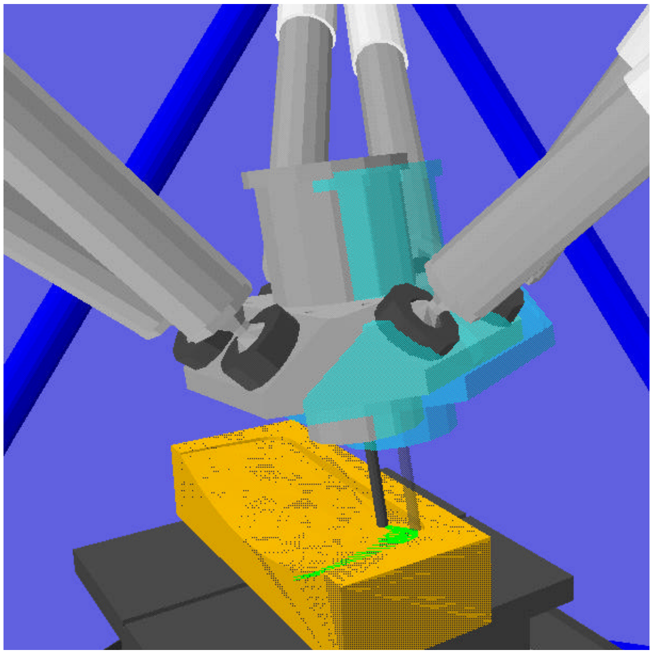

Figure 6 - Error Visualization of the NASA Test Part.

A tool to visualize controller output data during controller development work has also been created. One of NIST’s Hexapod project tasks is to develop an implementation of NIST’s open architecture controller, the Enhanced Machine Tool Controller (EMC)[6], for the NIST Ingersoll Hexapod. Retrofitting the Hexapod with this controller will enable NIST to more easily integrate performance enhancements, such as compensation for thermal and backlash errors. This tool interfaces to the NIST EMC controller using the IGRIP Low Level Telerobotic Interface (LLTI), which passes absolute platform poses and discrete I/O such as coolant on/off to the IGRIP simulation. This enables the NIST controller researchers to test controller designs by directing the controller output to the IGRIP animation through the LLTI interface before running on the actual machine tool.

The last tool that was developed allows a user to interact with the Hexapod animation by controlling each of its 5 degrees of freedom manually. A GSL program that polls mouse movement and converts relative mouse movement into machine animation motion has been written. The operator, using a combination of mouse buttons, can select which degree of freedom to move. The limit checking procedure can also be enabled while using this tool. This has been a very useful tool for people who are unfamiliar with the Hexapod and its motion capabilities. NIST plans to implement this tool using a space ball for more intuitive control of the animation.

Virtual Collaborative Efforts

NIST is using the NAMT[7] communications infrastructure to enable remote participation in Hexapod research efforts. This NAMT infrastructure[8] supports real-time access to hardware and software which depends on the capability of the users connection. The infrastructure integrates voice, video, and data on the same network using Asynchronous Transfer Mode (ATM) communications technology. It is connected to an experimental ATM network in the Washington, DC area. The infrastructure also supports standard Internet-based communications. This enables research efforts to be performed both at high-end and low-end network bandwiths. Hexapod remote capabilities will provide real-time audio/video feedback, as well as remote camera control and remote interfaces to simulation tools.

Remote interaction with IGRIP is possible using Deneb's Virtual Collaborative Environment (VCE) software interface and also through a socket based interface developed using Deneb's GSL at NIST. In order to use VCE, all sites need to have a locally owned IGRIP software license with VCE capability and identical copies of the simulation Workcell being shared. The VCE software uses a socket communications protocol where the IGRIP users are clients communicating with each other via a VCE server. The server relays IGRIP functions that are executed by the current master client to the remaining clients for execution. The Hexapod NC verification tool has been used interactively within this environment (Fig. 7) between NIST in Maryland, United Technology Research Center (UTRC) in Connecticut, and Sandia National Laboratories in New Mexico.

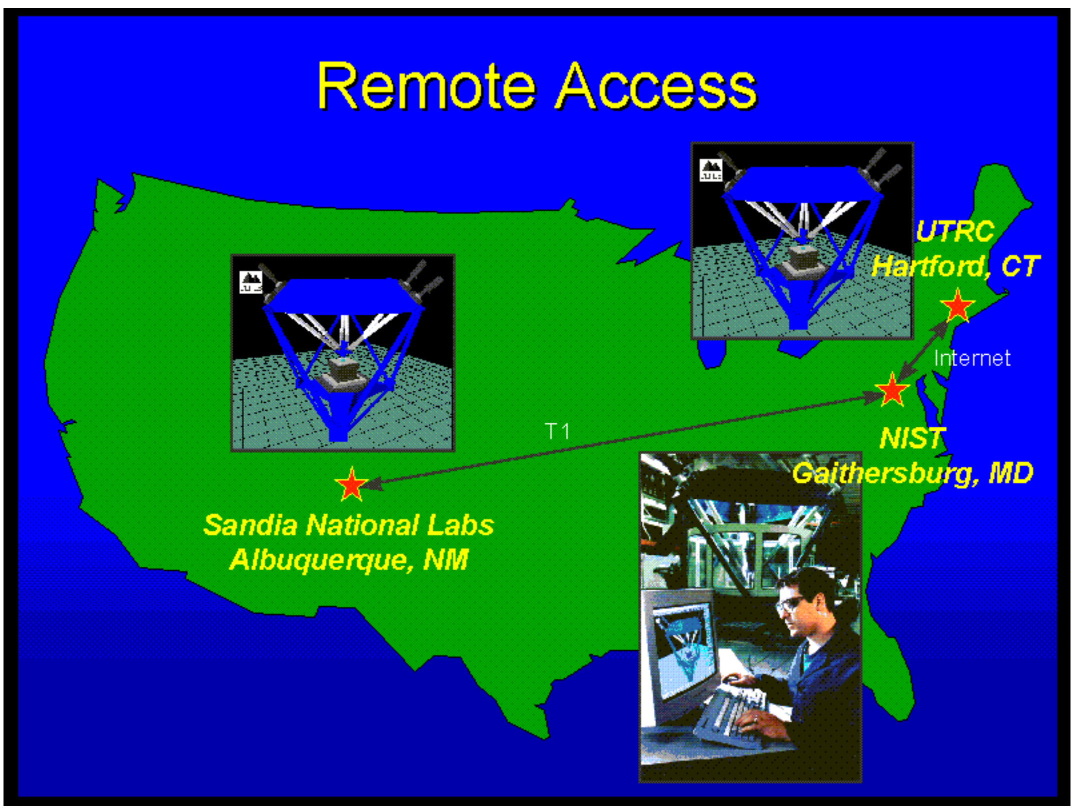

Figure 7 - Layout of a VCE Session.

The socket-based interface uses IGRIP's built-in socket functions to connect to an experimental "virtual environment" operator interface running on Netscape. This operator interface (Fig. 8) can be made accessible from anywhere on the Internet using a web browser. It will give the remote user the ability to interact with the Hexapod simulation. It will also provide other capabilities such as viewing real-time video, controlling camera positions, and accessing real-time data in addition to other modeling and simulation tools. Current functionality allows a remote operator to initiate IGRIP world manipulation functions such as zooming in and out, as well as selecting preset views and motion functions to position the simulated machine tool at a desired set of coordinates. At the end of any of the above operations, a digital image file is automatically updated. This reflects back to the remote users' web browser with a status report of the current position, as well as limit violations. To enhance this interface, a GSL procedure to generate digital movies using internal CLI functions and system calls to Silicon Graphics utilities is currently being tested. This will replace the digital image with a short digital movie of the animation during machine motion operations if desired by the operator. Hexapod/IGRIP operator interface efforts will continue with the ultimate goal being to enable outside Hexapod collaborators to access and use the suite of IGRIP based simulation tools which is being developed for this project. This operator interface currently supports real-time video and camera control in addition to IGRIP simulation access.

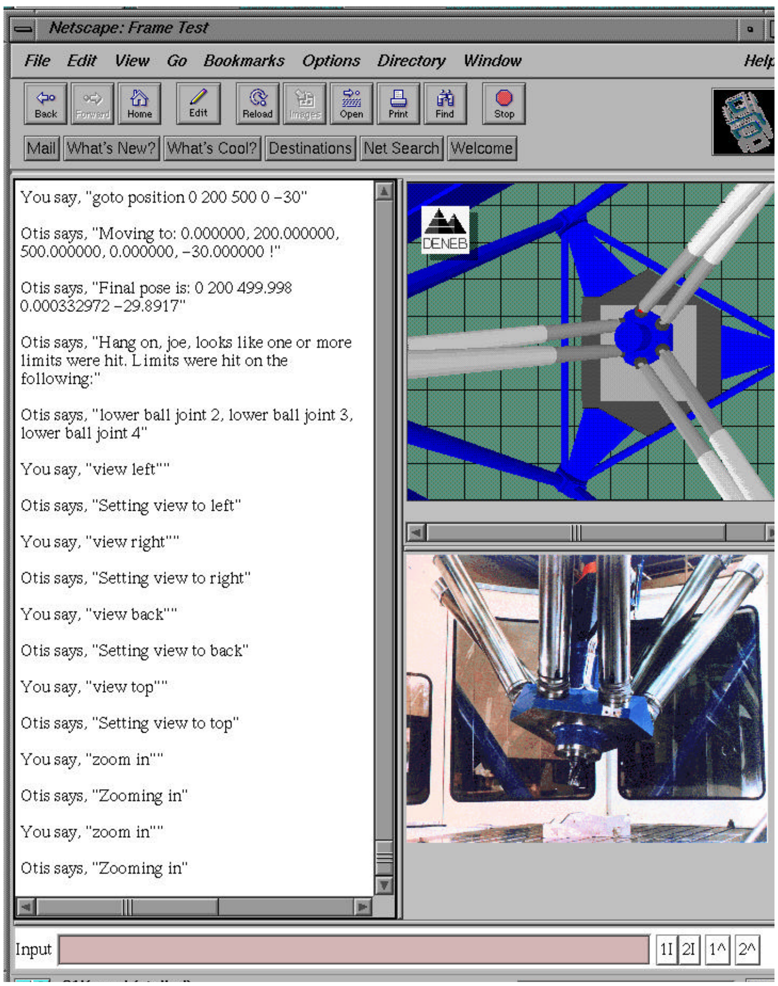

Figure 8 - Operator Interface during an IGRIP Session.

Summary

The NIST NAMT/Hexapod project involves the investigation of a new class of parallel-actuated machine tools that are based on the Stewart Platform. Characterization and simulation efforts of this project are being integrated with remote access capabilities. These will provide external collaborators with the ability to perform real time experiments. They will interactively use simulation and modeling tools for this experimental machine tool from geographically distributed locations. Within the project, the machine tool has been modeled using Deneb's IGRIP simulation software, and a host of IGRIP simulation tools have been developed. These include an NC verification tool, an error visualization tool, a controller verification tool, and a manual positioning tool. Remote access to these tools will be provided to collaborators across the U.S. using both Deneb's VCE software and a socket-based operator interface being developed at NIST. These remote simulation capabilities will prove to be useful tools for both Hexapod machine tool research collaborators and potential end users to determine the feasibility of using Hexapod machine tools for manufacturing applications.

Acknowledgments

The author acknowledges the significant contribution made to the development of these simulation tools by Nick Dagalakis, Elena Messina, Bob Russell, and Keith Stouffer within the Intelligent Systems Division at NIST.

References

[1] Huber, R. F., "This Man Wants to Change the Way You Machine Parts," Production, October, 1993

[2] Eastman, M., "Will Hexapods Go From Show Floor to Shop Floor?," Cutting Tool Engineering, June, 1995.

[3] IGRIP is a product of Deneb Robotics, Auburn Hills, MI

[4] Pro/ENGINEER is a product of Parametric Technology Inc., Waltham, MA

[5] Adam, S., Pacific Northwest Labs, "Simulation of Parallel Manipulators in IGRIP," Deneb User Group Meeting, Detroit, October 1995.

[6] Proctor, F., Michaloski, J., "The Enhanced Machine Overview," NIST Internal Report 5331, 1996.

[7] Program of the Manufacturing Engineering Laboratory, NIST Internal Report 5845, pp. 23-36, 1996.

[8] NAMT web site, http://www.mel.nist.gov/namt.