Virtual Manufacturing Tools for Collaborative Exploration of Hexapod Machine Capabilities and Applications

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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 a remote virtual environment. This environment 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.

Introduction

Hexapod machine tools offer potential benefits of high stiffness, high speed, and acceleration due to low moving mass and reduced need for special foundations. However, non-intuitive kinematics, work volume, and error characteristics of these machines 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. These 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 the availability of such sensor data over the Internet 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. This paper provides an overview of the NAMT Hexapod Project[5] and describes a remote virtual environment being explored for remote collaboration.

The NAMT Hexapod Project

Recently, several machine tool builders introduced prototypes of a new class of machines based on the Stewart platform[1][2][8]. 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

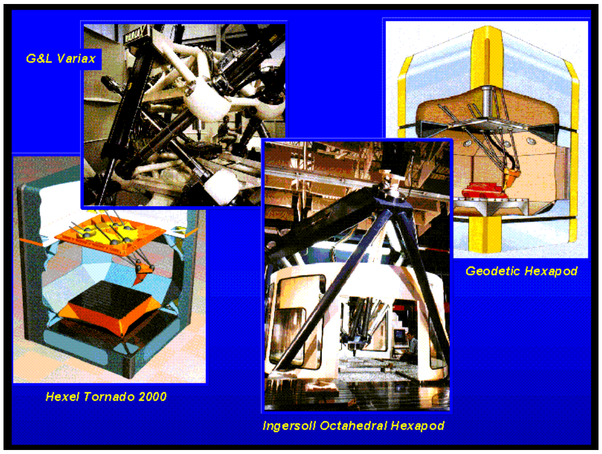

Figure 1 -Prototype Hexapod Machine Tools.

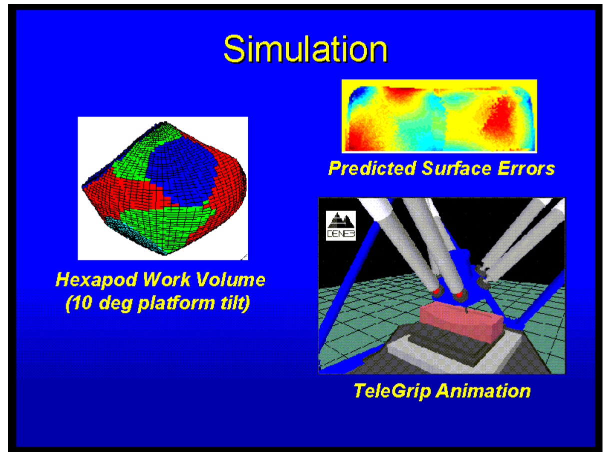

Figure 2 - Modeling and Simulation Tools.

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.

NIST has established a project plan through industry interactions, workshops, and participation in a national Hexapod users group. This plan includes a study of the characteristics of these new machines and collaboration 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 machines, as well as to characterize and develop these applications. 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 to help maximize machine tool performance.

1 Certain commercial equipment, instruments, or materials in this paper are identified to adequately specify the experimental procedure. Such identification is not intended to imply recommendation of 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.

NIST is using the NAMT communications infrastructure[4] to enable remote participation in Hexapod research efforts. This NAMT infrastructure supports real-time access to hardware and software, where user bandwidth 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. The NAMT infrastructure 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 bandwidths. The Hexapod integration into this infrastructure (Fig. 3) will provide real-time audio/video feedback, remote camera control, and remote interfaces to simulation and modeling tools.

The Ingersoll Octahedral Hexapod (Fig 4) 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 end, 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 intersect approximately at the vertices of an equilateral triangle. The lower ball joints are equally spaced on the spindle platform. Figure 5 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

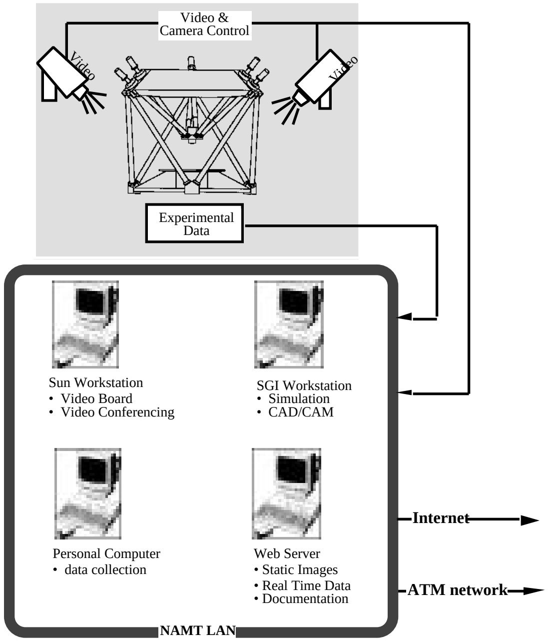

Figure 3 Hexapod/NAMT interconnections.

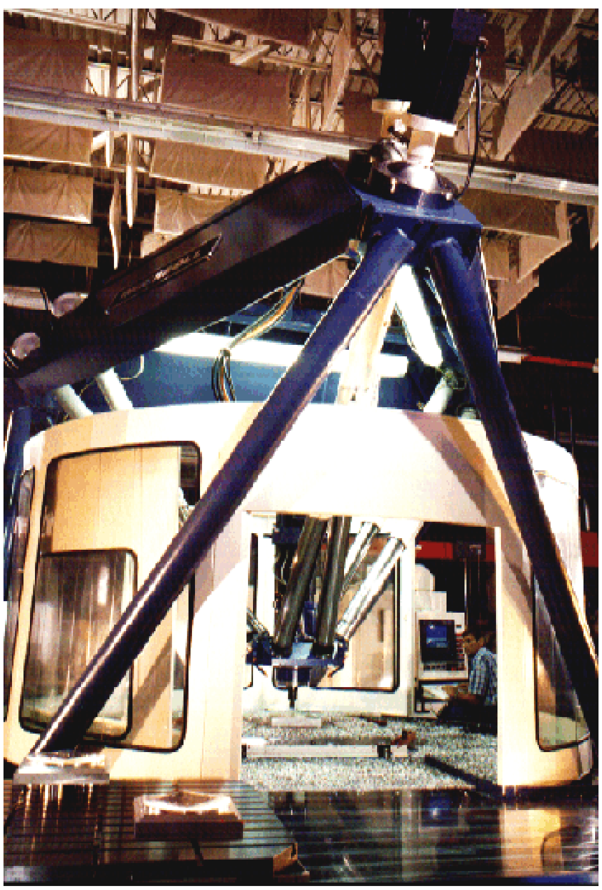

Figure 4 - Ingersoll Octahedral Hexapod.

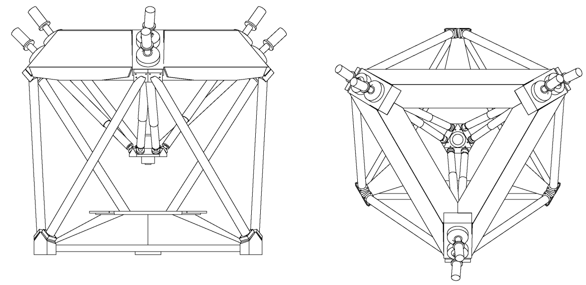

Figure 5 - Top & Side View of Ingersoll Octahedral Hexapod.

about the vertical axis, constrained by software to prevent collisions between struts.

A simulation model of the Ingersoll Hexapod was constructed in Interactive Graphics Robot Instruction Program (IGRIP)[3] from imported Pro/ENGINEER[6] 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. Limit checking is performed for all 12 ball joints and the 6 strut extensions and indicates violations graphically and logs them to a file. A socket-based interface enables remote interfacing with IGRIP. Several tools have been developed on top of the Hexapod simulation. These include the following:

- A manual control tool to position the simulated Hexapod using absolute position values.
- A verification tool to test Numerical Control (NC) programs.
- An error visualization tool to depict errors as predicted by the Hexapod error models.
- A visualization tool to show controller output data during controller development work.

The NC verification tool (Fig. 6) indicates limit violations while testing a composite lay-up mold test part for the Space Station escape pod designed according to geometry from NASA Johnson Space Flight Center.

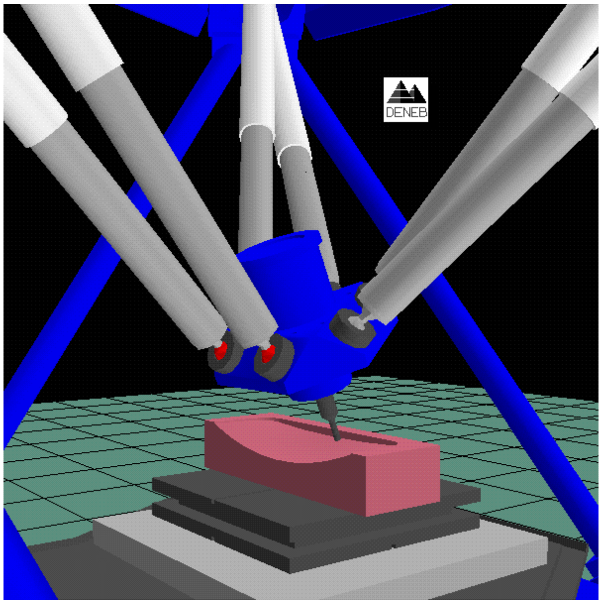

Figure 6 - Verification of NASA Test Part.

A program to determine workpiece placement on the Hexapod has been developed. Given the part program, machine kinematic parameters and limits, and tool offset, the program computes the envelope of fixture offsets, which is the subspace of part blank locations that result in all locations of the part program being reachable. The program was tested using the part program for the NASA test part and it promises considerable time savings over the manual trial-and-error approach to positioning the part blank. The program is being adapted to use a stiffness model of the Hexapod to determine part location. This will help achieve maximum machine tool stiffness during machining. NIST is developing an interface to this program to make it accessible by remote users.

NIST is developing error models for the Hexapod through experimentation. Programs to predict part geometry errors resulting from different types of machine errors are being developed in conjunction with these error models. The part geometry errors corresponding to different types of machine errors will be displayed using false-color plots of the part surface. NIST will also develop an interface to this program to make it accessible by remote users.

Remote access to real-time experimental data will soon be a capability within the NIST Hexapod project. Remote users will be able to access the Hexapod data acquisition system, which will include data from instrumentation (ie. thermocouples, strain gages, accelerometers) on NISTs Hexapod. Combining experimental data with audio and video data, including remote camera control, will allow remote collaborators to interact with NIST researchers in a "virtual environment" during Hexapod experiments. Remote users will be able to access databases of past experiments.

Hexapod Remote Virtual Environment

One of the approaches NIST is exploring for remote interaction is to construct remote "virtual environments," which are based on real-time text and near-real-time graphics. The aim of the virtual environment is to provide an electronic "place" where remotely-located people or groups can participate in experiments on the Hexapod. Remote users will use software tools, such as simulations, and interact with other remote participants and local NIST researchers in real-time, over the Internet, at low cost.

Within the virtual environment, each remote participant is represented by a virtual entity called an 'avatar.' The avatar can interact both with other avatars and with the environment in which all the avatars exist. The users see on their screen what the environment represents to their avatars, and the environment reacts to the actions of the users' avatars. Other participants also see the acts of the users' avatars reflected on their screens. The construction of these avatars is based on widely-available software used to create multi-user interactive games on the Internet.

The environment is filled with objects, including the avatars, which have properties that can be examined and used by the avatars. The environment manages consistency so that when one person's avatar makes some change to the environment, moves something around, or goes to another part of the environment, all other avatars experience the result in an appropriate manner, which is transparent to the users. The environment can be constructed in any manner. It can be filled with useful objects to facilitate free-form discussion among the users. This includes white boards, overhead projectors, note pads, filing cabinets, all of which actually perform as they do in a normal environment. Or, the environment can be constructed to represent any desired world and to enforce upon the avatars the rules by which that world operates. A unique feature of the NIST environment is that real-world device controllers may be represented by avatars in the environment. This allows bi-directional interaction between remote users and remote devices through their avatars.

This remote virtual environment is being applied to the NIST Hexapod Project. A set of virtual objects to represent different control systems for the Hexapod machine tool is being developed. These avatars will interact with the Hexapod environment's simulation and modeling tools, camera systems, and data acquisition systems. The current implementation of the Hexapod virtual environment enables remote users to interact with a Hexapod simulation and a camera system. It also gives the users the ability to communicate by means of text based discussions and slide presentations.

One of the avatars, represented as a virtual person, can answer questions and accept commands concerning the machine tool. It is an intelligent agent that is operated by a remote piece of software. This software, which runs the avatar of the agent, has expert-system knowledge of the operation of the Hexapod simulation tool and can notice things such as joint limits exceeded and point them out to the remote users. The intelligent agent can answer questions by deriving answers from raw data, and it can shield the user from having to know any detail about the operation of the device. The agent can accept general commands, validate them, and then operate the device on behalf of the user. It has a limited degree of natural language flexibility in its interface. The interconnections between the software entities that comprise the virtual environment are shown in Figure 7.

The current NIST virtual environment (Fig. 8) runs within a single Netscape web browser. The user is presented with three frames. The first is a text window that scrolls past; the second two contain graphics windows that change on command of the environment. In the text window, the user experiences what is happening in the environment in real-time. The text window presents descriptions of objects, events, and speech. When a person speaks through their avatar, the others in the same room immediately see what the person said; when someone does something that affects the environment, others immediately see a description of the event. The user controls what the avatar does, its speech, its actions, and its operations on the environment using natural language statements such as "go to the Hexapod room" or "look at the feed indicator." In some cases, such a textual description richly represents the events and places better than a picture. Some things are more easily said than displayed. The converse is also true - some things are much more easily conveyed in a

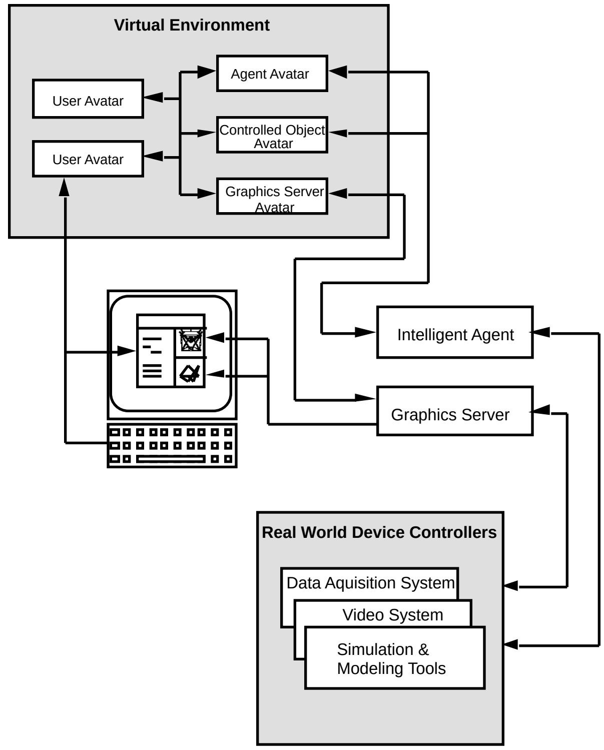

Figure 7 - Virtual Environment Structure and Interconnections

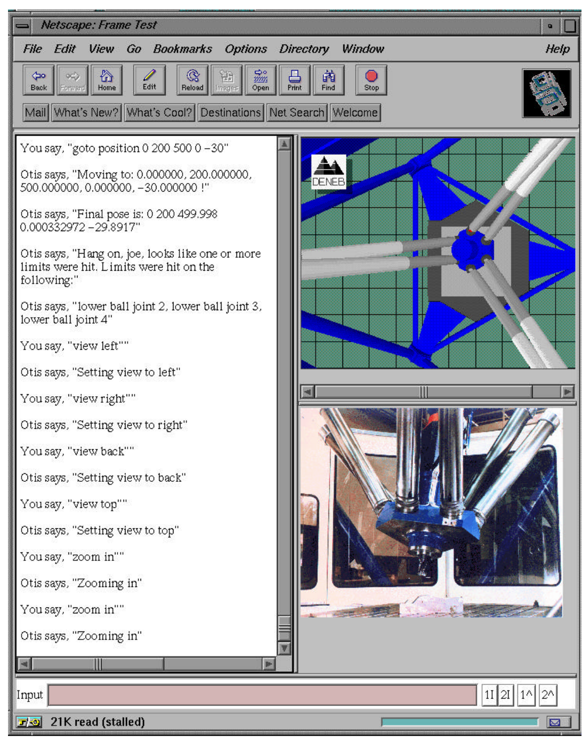

Figure 8 - Operator Interface during an IGRIP Session.

picture. For this reason the virtual environment also uses graphics windows.

The graphics window displays any picture such as a remote Uniform Resource Locator (URL) from the net or a locally-stored picture. In remote interactions with the Hexapod live camera, a picture captured using the video system shows the actual machine tool. Remote interaction with the IGRIP simulation produces a picture of the final position of the Hexapod for a commanded move. The download time for the graphics is limited to the time the user's connection permits. The content of the graphics can be controlled by an authorized user, or it can be automatically selected by the environment when specific events occur. Simple examples would be diagrams that accompany an explanation by a participant or operator. Other examples are pictures of objects, such as control screens, which automatically appear when an avatar looks at the object. More complex examples include output from simulation programs invoked via the environment by the user. Efforts are under way to implement control buttons for some common actions, such as turning or navigating through the environment, or for special-purposes such as running a demonstration. Other Hexapod project tools will be interfaced within this virtual environment as they become available Richer graphical representations such as digital movies and Virtual Reality Modeling Language (VRML) models[7] are also under investigation.

Conclusions

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 from geographically distributed locations using a virtual environment developed at NIST. This virtual environment richly interfaces distant people and events to the Hexapod in a structured way, using the universally-available and cost-effective Internet. Future implementations will add a level of interface to encompass multiple technical projects within the NAMT. This technology has many potential applications in manufacturing such as conferencing, training, remote observation, control of distributed manufacturing systems, and shared use of limited resources.

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