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Parallel Kinematic Machine Research at NIST: Past, Present, and Future

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Abstract

Unchained from the confines of controller limitations, the industrial application of parallel kinematic machines in manufacturing is beginning to emerge. The launch of commercially available hexapod machine tools at the 1994 International Manufacturing Technology Show in Chicago represented the first radical departure in machine tool design since the introduction of numerical controls. The parallel actuator technology promises to offer manufacturers a number of advantages relative to conventional machine tools, such as a higher stiffness-to-mass ratio, higher speeds, higher accuracy, reduced installation requirements, and mechanical simplicity. Several machine tool makers in the U.S. and around the world are pursuing parallel actuator technology, while their prospective customers—manufacturers—are beginning to contemplate what the novel multi-axis machining technology might mean for their operations.

As part of the Manufacturing Engineering Laboratory's National Advanced Manufacturing Testbed (NAMT), NIST researchers and collaborators from industry and universities are studying the new tools' unique capabilities. The work includes extensive tests on an octahedral hexapod machine tool that was installed at NIST in May 1995. Research areas include machine metrology, performance characterization test methods and standards, performance enhancement methods, simulation and remote experimentation tools, and open architecture controller interfaces. This paper will give an overview of history and current status of research in parallel kinematic machines at NIST. The merits and key challenges of parallel kinematic machine tools will also be addressed, and directions for future research will be identified.

1. Introduction

Improving product quality, reducing product cost, and shortening the product development cycle have always been critical for companies to stay competitive. These competitive drivers result in a continuing need to achieve improvements in accuracy, speed, and versatility in machining operations. These pressing needs pose challenges to the machine tool research community, and have driven several machine tool companies to revisit some of their basic assumptions about machine tool design. As a result, prototypes of a new class of machine tools based on parallel kinematic structures, known as parallel kinematic machines (PKMs), have been introduced.

The six degree-of-freedom Stewart platform [1] is one PKM configuration that has been used recently in a number of new machine tool designs. A Stewart platform machine tool typically consists of a moveable spindle platform connected to a rigid base through six identically jointed and extensible struts. The Stewart platform mechanism is characterized by high force capacity, high structural rigidity, and low moving mass [2]. For machining applications, disadvantages of the Stewart platform include a complex work volume, limited orientation range of motion, and a requirement of six actuators for a five degree-of-freedom task (milling, drilling, and similar operations). Several prototypes of Stewart-platform-based machine tools, commonly called hexapods, have been produced in the U.S. by companies such as Giddings & Lewis[1], Hexel Corporation, and the Ingersoll Milling Machine Company.

These machine tools promise some key advantages over conventional machine tools, but they raise important questions as well. How should the performance of these machines be characterized? What is the best way to describe the work volume? What degree of accuracy is achievable? What are the best control algorithms to employ? Can they be cost-competitive? What types of machining applications are best suited to these machines? How can part programs be optimized for them? What configurations provide the most versatility for the least cost? These are just a few of the important issues raised by hexapod machine tools. Since the early 1990's, NIST has conducted research in a number of these areas. This paper summarizes the past, current, and future work at NIST in parallel kinematic machines, and examines some of the remaining challenges. In this paper, the discussion is focused on the six degree-of-freedom Stewart platform mechanism, reflecting the configuration of the prototype machine at NIST. However, there are certainly other parallel kinematic arrangements that may be well suited for use as machine tools (perhaps even more so than the Stewart platform).

2. History of PKM Research at the NIST Manufacturing Engineering Laboratory

Interest within the NIST Manufacturing Engineering Laboratory (MEL) in innovative applications of Stewart platform mechanisms dates back to the mid 1980's, when James Albus and his colleagues in the Robot Systems (now Intelligent Systems) Division developed a concept for a robot crane (Figure 1). The machine, now called the RoboCrane [3,4], is a Stewart platform configuration where six winch-actuated cables are used to suspend and control the platform. The RoboCrane was developed originally under a Defense Advanced Research Project Agency (DARPA) contract to stabilize loads on conventional cranes. Many different RoboCrane configurations have been developed for applications ranging from large-scale manufacturing and construction, to stabilized cargo handling, helicopter rescue, and hazardous waste remediation. The principal advantage of the RoboCrane over conventional crane systems is improved control of the position and orientation of the load.

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[1] Certain commercial equipment, instruments, and/or software are identified in this paper to describe the subject matter and to specify the experimental procedure adequately. 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 equipment, instruments, or software identified are necessarily the best available for the purpose.

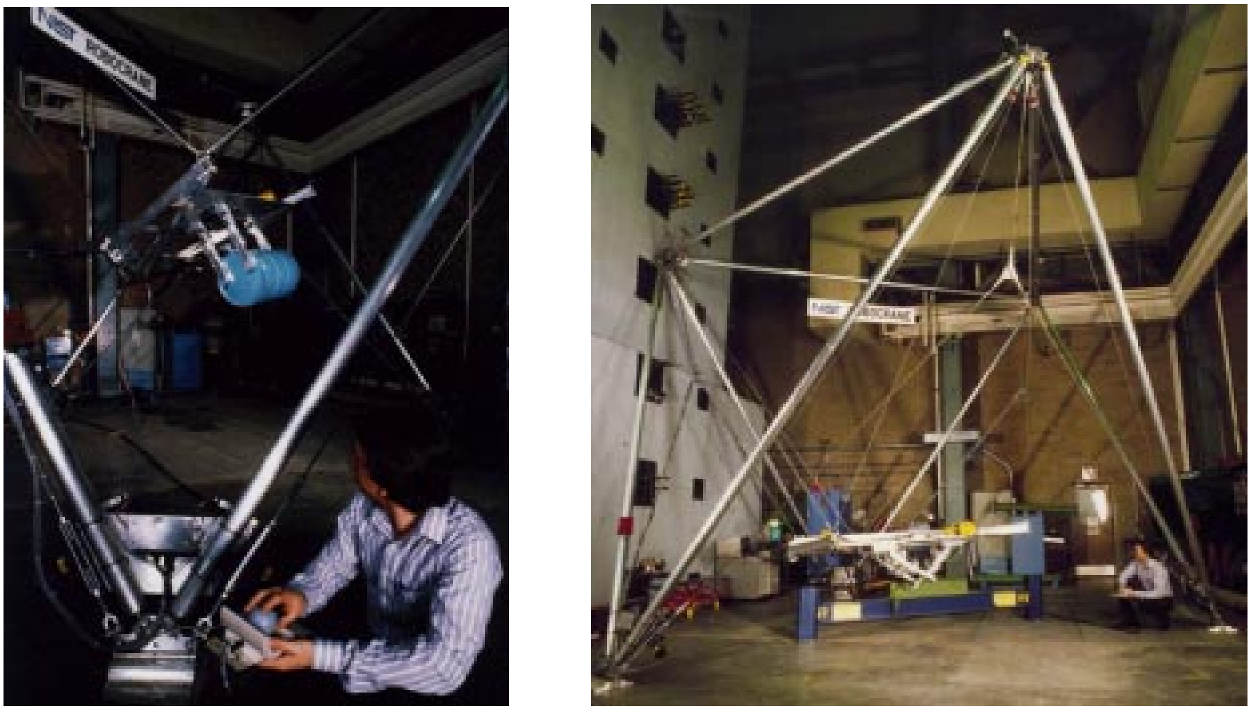

Figure 1. NIST RoboCrane.

NIST research into Stewart platforms also produced an innovative structure from which to suspend the RoboCrane work platform. An octahedral structure containing the three upper support points necessary to suspend the work platform provides exceptional structural stiffness in a lightweight frame. This combination of a Stewart platform and an octahedral space frame was also recognized by NIST researchers James Albus and Clayton Teague to have potential advantages for machine tool applications. In 1991 they proposed a “New Class of Machine Tools” based on this concept, and built the model shown in Figure 2. The model configuration shown actually can be considered to be three Stewart platforms in series (lower motion platform, “virtual” Stewart platform for laser metrology, and upper fixed platform) nested within a fourth fixed Stewart platform that forms the structural frame. The benefits expected to result from this configuration included greatly improved stiffness and accuracy characteristics compared with conventional designs.

During the course of pursuing a start-up project to build a prototype of this new machine tool design, NIST researchers became aware that a commercial machine tool builder was in the process of building a prototype machine with a very similar configuration. NIST decided that a commercial prototype would provide a good starting point for investigations, and procured an experimental prototype Octahedral Hexapod machine tool from the Ingersoll Milling Machine Company (Figure 3). This Octahedral Hexapod, the second made by the company, was installed at NIST in May 1995. The machine stands about 5 m tall and is equipped with an 11 kW, 0 rpm to 6000 rpm spindle. An identical seventh strut mounted on a separate test stand was also supplied with the machine.

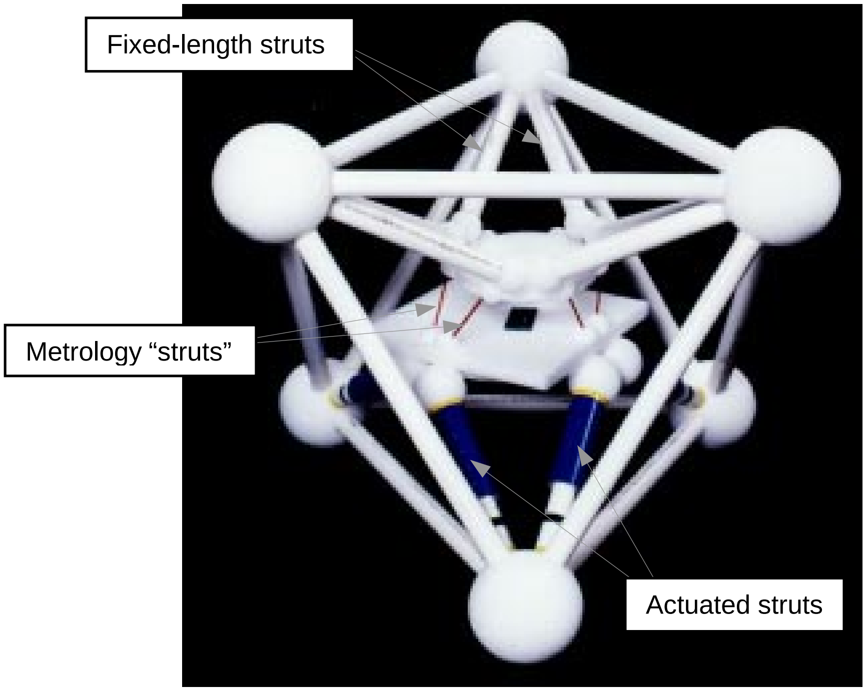

Figure 2. Concept for new class of machine tools.

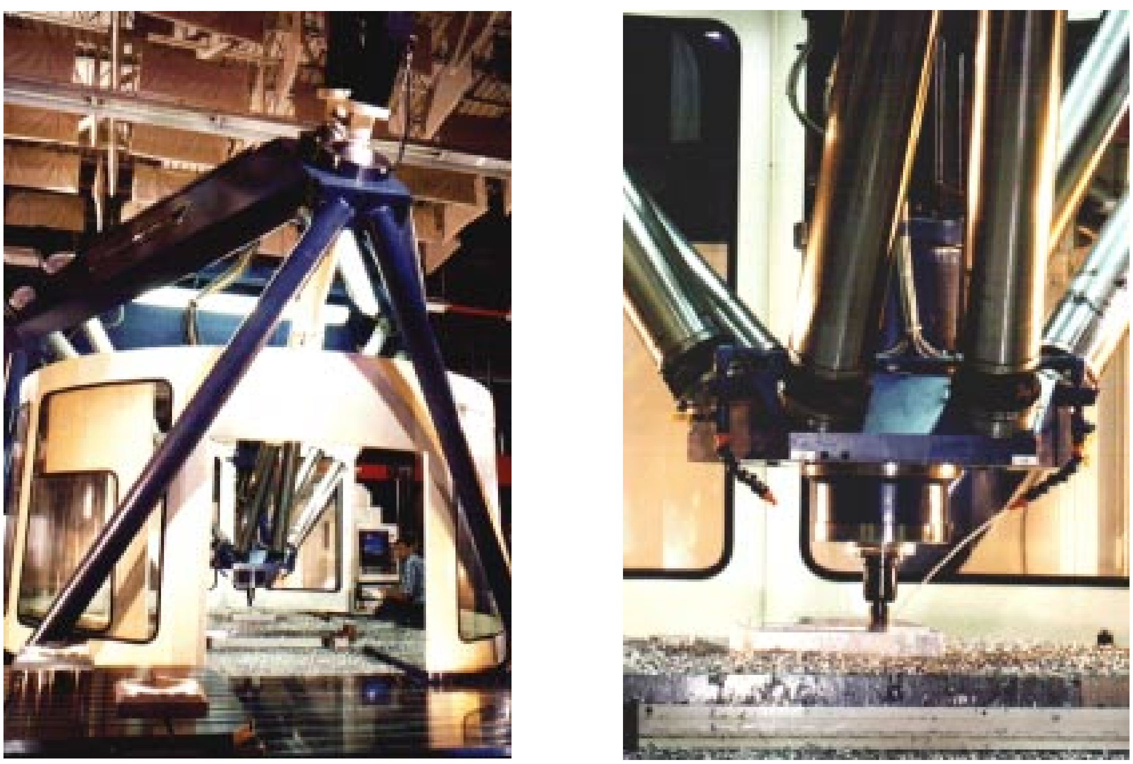

Figure 3. Experimental prototype PKM at NIST.

3. U.S.A. Hexapod User Group

With the rising interest in the U.S. in PKMs, Sandia National Laboratories, the Massachusetts Institute of Technology (MIT), NIST, and other organizations formed a hexapod user group (HUG). This group consists of machine tool builders, users, and research institutions that have an interest in PKM development. Representatives of approximately 34 industry, university, and government organizations have participated in meetings of the HUG. The first meeting was held at MIT in August 1996. Subsequent meetings have been held at NIST in March 1997, the American Society of Mechanical Engineers (ASME) International Mechanical Engineering Conference and Exhibition (IMECE) in November 1997, Sandia National Laboratories in June 1998, and the Ingersoll Milling Machine Tool Company in September 1998. These informal meetings provide valuable opportunities to share PKM experiences, results, ideas, and plans for future investigations, as well as to identify industry needs and concerns. Of course, hexapod machine tool development also draws on work in parallel kinematic mechanisms (largely for robotics applications) performed at a number of universities and other organizations long before the HUG was formed.

4. Current PKM Research Areas at NIST

Industry workshops held in planning NIST's PKM program highlighted the following needs:

- An in-depth understanding of the characteristics of PKMs
- Standard test methods and measurement procedures to evaluate their performance
- A reservoir of application experience to draw from
- Modeling and simulation tools for developing applications and test methods
- Remote access capabilities to make it easier for external collaborators to interact and participate in the work being done
- Examination of controller and integration issues

As a result, a PKM research and development program was designed to achieve the following goal: *To measure, extend, and demonstrate the capabilities of hexapod machines through the collaborative development and use of metrology, remote access, and simulation tools*. The program is an interdisciplinary effort involving all of the divisions of MEL and several government, industry, and university partners. The NIST PKM program is being conducted within the National Advanced Manufacturing Testbed (NAMT) [5] of the Manufacturing Engineering Laboratory. The following sections provide an overview of the PKM work in progress at NIST.

4.1. Metrology and Performance Characterization

One of the key areas of interest for NIST is performance characterization of PKMs. NIST's institutional focus on measurement and long history of involvement in machine tool performance characterization and related standards make this a natural area of inquiry for MEL. Conventional metrology systems such as laser interferometers, ballbars, electronic levels, capacitance gages, and load cells can be applied to PKMs to provide a great deal of information. However, the interpretation of the data obtained when testing a PKM is often quite different than when the same equipment is applied to conventional machines. Also, special set-ups and machine motions must frequently be used to obtain the desired result. As an example, a special set-up for a laser measurement of the relative position error of a strut is shown in Figure 4. NIST metrologists and machinists have performed a wide variety of measurements and cutting tests on the experimental PKM at NIST. Some of the NIST work in this area is discussed in [6,7]. Newer metrology devices, such as the laser ball bar [8] have also been found to be very useful in performing PKM measurements. In addition, NIST is investigating novel metrology devices that allow six degree-of-freedom errors to be measured simultaneously. Such a metrology instrument would be extremely valuable for characterization and calibration of hexapod machines.

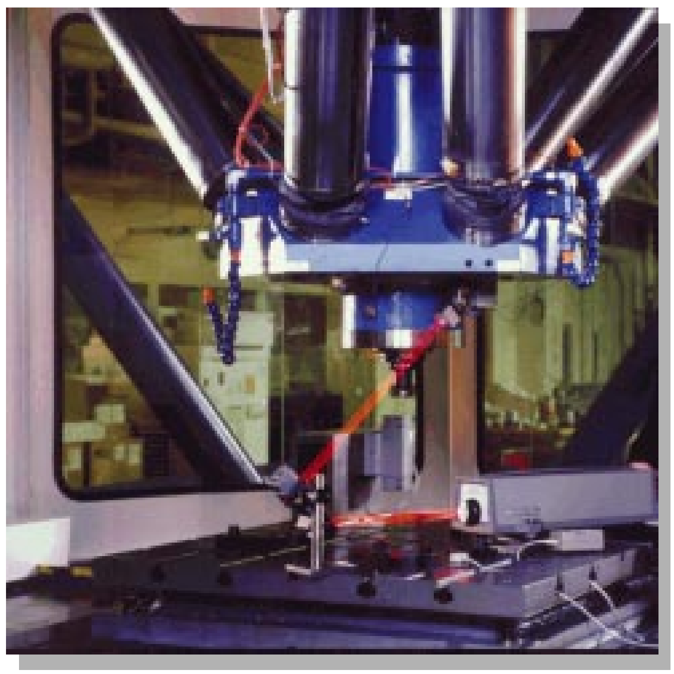

Figure 4. Special set-up to measure the relative strut length error.

Because the experimental PKM at NIST uses resolvers on the strut motors to infer the length of the struts, thermal expansion of the ballscrews is currently the most significant source of positioning errors. Next in significance are inaccuracies in the "constant" geometry parameters, including the position of the base and platform joints, and the average length of the struts. Joint friction causes noticeable errors as well. Of lesser significance are strut reversal errors, spindle thermal errors, relative strut length errors, gravity errors, and errors in the spherical joints.

Two areas that hold the key to accurate positioning capability for PKMs are accurate identification of geometrical (kinematic) parameters and thermally insensitive strut length measurement. NIST has been working in both of these areas to gain a better understanding of the performance characteristics of PKMs and to improve the performance of the experimental machine at NIST. These efforts are discussed briefly in the following two sections.

4.2. Calibration

There are several different approaches that can be used to estimate the kinematic parameters of PKMs. The first is to measure the geometry of machine components directly. This is not always practical to do, particularly for large frame components (e.g., the upper sphere joint locations for the machine shown in Figure 3). A second approach is to measure errors in the relative motion of machine components (e.g., strut angles). Third, measurement of all errors in the platform pose can be obtained for a number of different locations and orientations throughout the work volume. Finally, arbitrary performance evaluation tests (e.g., conventional ballbar tests) can be used to estimate kinematic parameters using a best-fit linear combination of parametric error shapes. The NIST error modeling and calibration work (using the third and fourth approaches above) is described in [6,7]. Simulation results indicate that the errors (other than thermal) of the PKM machine at NIST can be reduced by 70% or more by applying such a calibration technique. Machining tests to verify these results will be performed shortly.

4.3. Strut Metrology

The other area that has the greatest impact on the overall accuracy of many PKMs is strut length metrology. To achieve the highest accuracy, the goal is to obtain a thermally invariant measurement of as much of the total strut length as possible (sphere center to sphere center). Implementing a direct strut length metrology system on the PKM at NIST should greatly reduce strut length thermal errors (currently as large as 250 μm), increase effective strut stiffness, and improve geometric accuracy. The resulting increased stiffness should also help alleviate some of the errors caused by spherical joint friction and gravity loading.

A number of different strut length metrology system possibilities have been explored. These are illustrated in Figure 5. Figure 5a depicts the current strut length measurement system, based on a resolver mounted on the motor. One appealing possibility would be to measure along the axis of the strut using a laser down the center of the ballscrew (Figure 5b,c). This approach minimizes the Abbe error [9] and provides inherent protection of the beam from chips and cutting fluid. However, enclosing the laser beam within the strut complicates alignment procedures. Also, the beam travels through an atmospheric environment that has very significant thermal gradients (as a result of ballscrew heating and, in the case of Figure 5b, motor shaft heating) that are extremely difficult to measure. Beam directional stability problems are also encountered when the laser is mounted behind the motor as in Figure 5b (due to slight bending of the motor mount). The configuration shown in Figure 5c, where the beam is directed from the small sphere to the large sphere, poses substantial packaging challenges.

These problems can be avoided if the laser is mounted on the outside of the strut, as in Figure 5d. However, for this configuration, there will be substantial Abbe error as a result of cocking, or bending, between the inner and outer telescoping strut tubes. One solution to the Abbe error problem is to loop the beam around the other side using special optics, so that the

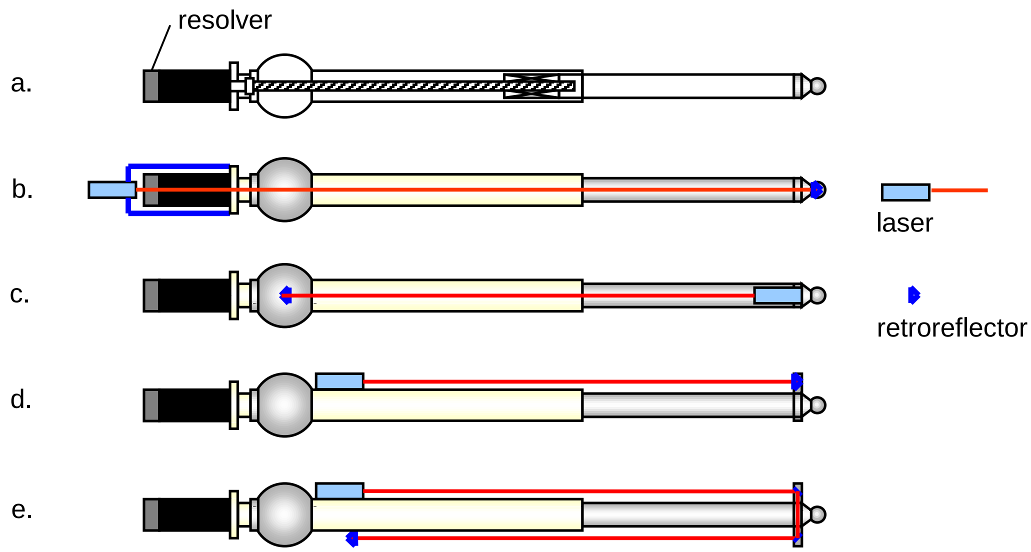

Figure 5. Strut length metrology system possibilities.

Abbe errors on either side of the strut effectively cancel one another (Figure 5e). This is the approach that has been taken in a prototype strut length metrology system that has been built and installed on the extra strut mounted on a test stand. Preliminary results indicate that a bi-directional accuracy of about 6 µm can be achieved for the strut using this technique [10]. A variation of this approach that is also being considered is to use a pair of diametrically opposed scales to perform the strut length measurement.

4.4. Stiffness Modeling and Testing

Understanding the static and dynamic stiffness characteristics of PKMs is another key area of interest at NIST, since these are key determinants of machine tool cutting performance. An early step in this effort was to perform static structural analysis of two-dimensional parallel kinematic structures [11]. Following this, University of Maryland (UMD) researchers worked with NIST and industry participants to develop static stiffness models and perform experimental stiffness testing (according to the ASME B5.54 standard [12]) of the prototype PKM at NIST. In addition to being an important aspect of machine performance, stiffness characteristics can also be used as criteria for optimizing the placement of parts in the workspace of a PKM. Stiffness modeling details and some early test results may be found in [13]. Additional work is underway to refine the model and identify the individual stiffnesses of key components. Full structural dynamic testing of the machine will also be performed in the near future.

4.5. Modeling and Simulation Tools

Because Stewart platform PKM motions are non-intuitive and the work volume is complex (and changes as a function of spindle platform orientation), it is imperative to have good modeling and simulation capabilities to efficiently develop and visualize machining applications. Working jointly with UMD, NIST has implemented several modeling and simulation tools.

Simulation capabilities based on commercial simulation software have been implemented to visualize machine motions and verify part programs (Figure 6) [14]. The simulation checks for and indicates violations of constraints on joint angle limits, minimum and maximum strut length, and strut collisions. Special routines also allow two images—one solid and one semi-transparent—of the machine to be animated simultaneously. Combined with an error model of the machine, this enables the effects of different machine errors to be visualized by watching the ideal and (exaggerated) error-induced motions overlaid together. Although this "virtual machine tool" capability is also applicable to conventional machines, it is particularly useful for PKMs, where the effect of different types of errors on the spindle motion is considerably less intuitive. Additional "virtual manufacturing" and remote interaction capabilities are described in [14].

UMD researchers have worked with NIST to develop workspace analysis and part placement tools [15]. The workspace analysis capabilities allow plotting the work volume of the machine for arbitrary spindle platform orientations, using the same constraints as for the motion simulation. Web-based tools for workspace visualization also have been implemented (Figure 7), including the capability to generate Virtual Reality Modeling Language (VRML) [16] models of the work volume. A VRML model of the work volume makes it easy to view the work volume shape (and the limiting constraints for different regions) from any angle, using a VRML viewer. The UMD part placement software automatically generates the range of locations that a part blank can be positioned in order for all of the required machine motions to be reached without hitting limits. This results in considerable time savings over a trial-and-error approach to part location.

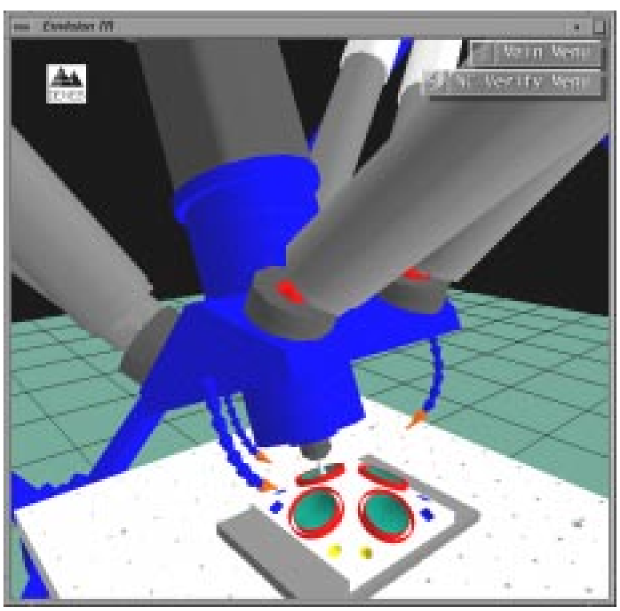

Figure 6. PKM motion simulation tool.

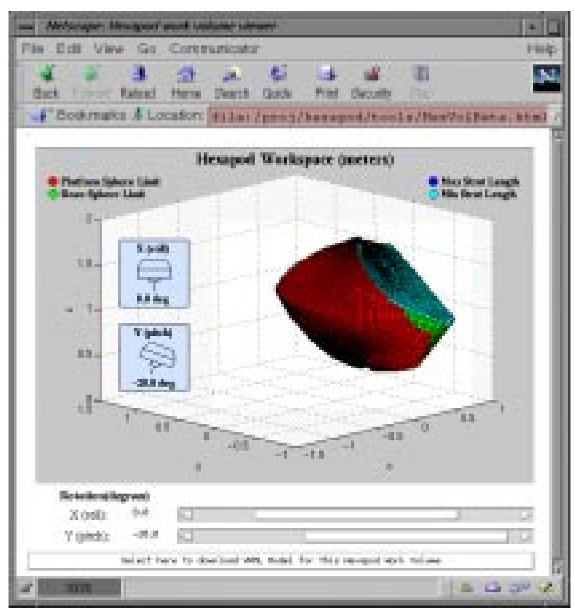

Figure 7. PKM workspace visualization tool.

4.6. Part Programming and Machining Applications

The procedure currently used to develop part program files for the PKM at NIST is very conventional. First, the cutter paths are defined using a Computer Aided Manufacturing (CAM) package that generates an Automatic Programmed Tool (APT) Cutter Location (CL) data file as an intermediate format. A postprocessor supplied by the machine vendor is then used to convert the APT CL data into a numerical control (NC) file consisting of G and M codes. Custom locally-developed file filters are used both before and after the postprocessor operation to provide enhanced functionality. Although the Stewart platform mechanism provides 6 degrees of freedom, the hexapod is programmed as if it were a 5-axis machine. The single degree of redundancy is resolved within the machine controller.

One difficulty that has been experienced in generating NC programs has been setting appropriate feedrates for motions that involve a change in orientation as well as translation. The programmed feedrate indicates the desired translational velocity of the tool tip without considering the rotation required to change orientation. All motions involving a change of orientation from the previous position use an inverse time feedrate—the feedrate indicates the amount of time to be taken to complete the motion block. The block execution time is computed automatically by the postprocessor based on the programmed (linear) feedrate and the translational distance. For blocks that involve a short translational distance but a significant rotation, the short block execution time that results can cause large strut velocities. One simple but effective solution to this problem is to limit the inverse time feedrate so that the rotational velocity does not exceed a constant fraction of the programmed linear feedrate (e.g. limit rotational feedrate in deg/min to be less than 30% of the linear feedrate in mm/min). Selecting the proper (fixed) fraction results in maximum strut velocities that are reasonably close to the programmed linear feedrate. This of course slows the translational velocity to below the programmed feedrate, but it results in much smoother overall machine motion.

The Octahedral Hexapod machine tool at NIST is used for both experimentation and machining jobs for internal customers of the NIST Shops. The aluminum and steel parts made for NIST customers to date range from simple mounting plates to a set of 45 detector mounting rails that were machined as part of the fabrication of a time-of-flight spectrometer. A number of test parts have also been machined in wax. For example, a large composite panel forming die test part was machined using part geometry obtained from a NASA Space Flight Center.

4.7. Controller Development

As supplied, the controller of the experimental PKM at NIST consists of an Ingersoll “Intelligent Front End” (IFE) computer and a conventional Computer Numerical Control (CNC) controller. The IFE interprets part program files (reads G and M codes), interpolates motion segments, performs inverse kinematics to compute the strut lengths required to achieve the desired tool position and orientation, and performs limit checks. The IFE also provides jogging and manual data input (MDI) capabilities, and handles administrative tasks such as part program file editing and management. The IFE sends strut position commands to the CNC, which performs low-level servo control and adds compensations for effects such as ballscrew lead errors and backlash.

One of the tasks of the NIST PKM project is to retrofit the machine with an open architecture controller. The motivations to do this are threefold: 1) to provide internal openness to allow the implementation and testing of experimental control algorithms, 2) to provide external openness to allow integration with higher level factory control systems, and 3) to provide an additional testbed for the validation of open architecture interface standards being developed for machine tools. External openness will also allow remote access of controller and sensor information for project partners who want to participate in remote experiments with the machine. The open architecture controller being implemented for the machine is based on work at NIST in this area [17].

NIST has also been working with researchers from the Ohio State University and the University of Florida on PKM control issues, such as the evaluation of model-based and cross-coupled control algorithms. Some of the work done by both of these groups is reported elsewhere in this volume [18,19].

5. Conclusions, Challenges, and Directions for Future Research

Progress in PKM development is being made on a number of fronts. At NIST and other organizations, a fundamental understanding of the nature of PKM errors—and how to measure and rectify them—is being acquired. Error and basic stiffness models are available. Calibration techniques have been developed and feedback metrology systems to improve machine accuracy are being implemented. Modeling and simulation tools to visualize PKM workspace and other characteristics, and to simplify the creation of PKM machining applications, have been built. Control algorithms to improve dynamic performance and other controller issues being investigated. And last, but certainly not least, successful machining applications have been carried out to make parts that are now in use.

NIST's PKM efforts to date, and interactions with industry and other researchers, indicate the following as significant challenges that remain and potential directions for future work:

- Work volume optimization (without losing stiffness)
- Alternative kinematic configurations
- Improved modularity/configurability
- Low friction, high stiffness joints
- Improved cost/performance ratio
- Improved machine dynamics
- Improved part programming
- Application/market development
- Improved control system capabilities
- Dynamic accuracy characterization
- Improved speed and convenience of calibration
- Standardized performance characterization procedures

Research and development efforts at organizations around the world are addressing these issues. NIST's work in PKMs will continue to focus primarily on performance characterization tests and standards, modeling and simulation tools, and open architecture controller implementation. Parallel kinematic machine tools continue to look promising, and yet some very interesting and difficult challenges remain. NIST looks forward to working with the rest of the PKM community to address these challenges.

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