DESIGN AND TESTING OF A HIGH SPEED, 5-DOF, COORDINATE MEASURING MACHINE WITH PARALLEL KINEMATIC STRUCTURE

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1.0 Introduction

During the past several years, a great deal of attention has been paid to parallel kinematic machines as an alternative structure for machine tools and other robotic equipment. Numerous claims have been made about the inherent advantages of this type of architecture, including superior stiffness and positioning accuracy. Despite these claims, and substantial effort by many research groups and industrial concerns, at this time few if any PKM machine tools are in use in daily manufacturing activities.

The goal of the work reported here was to examine the parallel kinematic architecture as applied to coordinate measuring machines, and to explore the accuracy attainable with this type of structure. In the following sections, we will describe a novel 5-DOF parallel structure with self-calibration capabilities which we are developing for use as a CMM. We will describe the basic design features, the kinematic relations which govern its motion, the metrology system, and the self-calibration algorithms. Finally, we will report on the results of accuracy tests of the assembled machine.

2.0 Design Concept

The basic structure of the hexapod coordinate measuring machine (HCMM) is shown in Figure 1. Kinematically, HCMM can be thought of as two tetrahedrons with a common base[1]. The apexes of the tetrahedrons are joined by a rigid center rod, which carries the CMM probe. At the three base joints, pairs of struts meet in double Hooke joints with a common center. At the apexes, three struts are joined to the center rod by spherical 4-bar linkages with common centers. Since the six struts all connect to the center rod at two points, the center rod cannot be rotated about its own axis by the extension of the struts. Therefore, the machine has only 5-DOF, and requires only 5 actuators. The sixth strut is passive (non-actuated) and serves only to carry a redundant measurement system, which is used for self-calibration. HCMM is designed to be able to measure objects within a cylindrical workspace 400 mm in diameter and 400 mm tall.

Figure 1. Hexapod Coordinate Measuring Machine

3.0 Base Design

The base structure of HCMM is assembled from structural steel components and consisting of three vertical stands with appropriate connections to support the work table and maintain their position. Atop the stands, an equilateral triangular weldment is kinematically supported by a ball and v-groove system. The 3 base joints are attached to this triangle, which has a side length of approximately 2175 mm. .

3.0 Strut Design

The 5 actuated struts of HCMM are designed to provide rapid movement of the center rod and attached probe by extended and retracting rotating nut

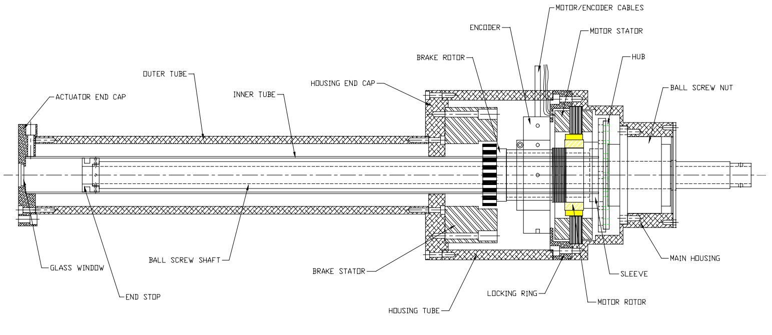

Figure 2. Schematic of HCMM actuated strut.

ballscrews under servo control. The rotating nuts are actuated by frameless DC servomotors with the rotor directly attached to the nut and the stator attached to the strut body. The body of the strut also houses a brake and a rotary encoder. The ballscrews have a 15mm hole through their length to permit co-axial strut displacement metrology using laser interferometry. The screw has friction seals and travels within an outer tube which enables the laser path to be evacuated. The struts can extend from a minimum length of approximately 900 mm to a maximum length of 1425mm. Tests of a single strut show it to be capable of extensional accelerations of 30 m/s^2 (3 g), and extensional speeds of up to 3 m/s at maximum motor rpm. A schematic of the actuated strut is shown in Figure 2. The response to a commanded motion with 3g acceleration is shown in Figure 3. The passive strut is similar in construction except that it has no motor and utilizes a recirculating ball spline instead of a ballscrew.

4.0 Joint Design

The kinematic model used to control HCMM assumes that the joints at the ends of each strut provide perfect spherical motion. Furthermore, it assumes that each pair of base joints and each set of three center rod joints is perfectly concentric. This is analgous to the assumption of axis straightness and orthogonality in serial cartesian machines. As a practical matter, it is very difficult to construct such joints with satisfactory accuracy. Therefore, HCMM employs the parallel kinematic machine equivalent of a "metrology frame", by incorporating a precision reference sphere at the center of each joint. (Figure 3). These spheres are mounted to the base and center rod in a manner which places them outside of the structural load path of the machine. The strut metrology system uses these sphere surfaces as kinematic references, thus allowing the requirement for accuracy of joint motions to be relaxed.

5.0 Strut Metrology System

Each strut carries a laser and the associated optics necessary to measure the change in strut length interferometrically. (Figure 4) The metrology system is mounted to the strut body via a 4-DOF kinematic adjustment system which allows the measurement beam to be directed down the strut axis. The interferometer itself is carried on a flexure mounted stage with

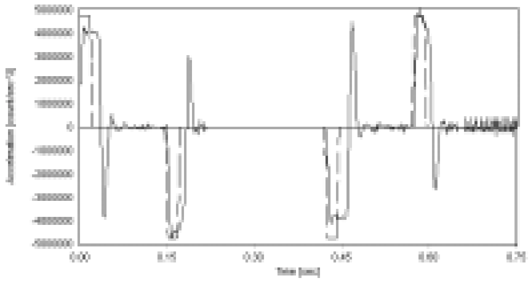

Figure 3. Response of HCMM strut to a commanded 3g acceleration. (Dashed line is commanded, and solid line is actual response)

Figure 4. HCMM center joint design, showing reference sphere.

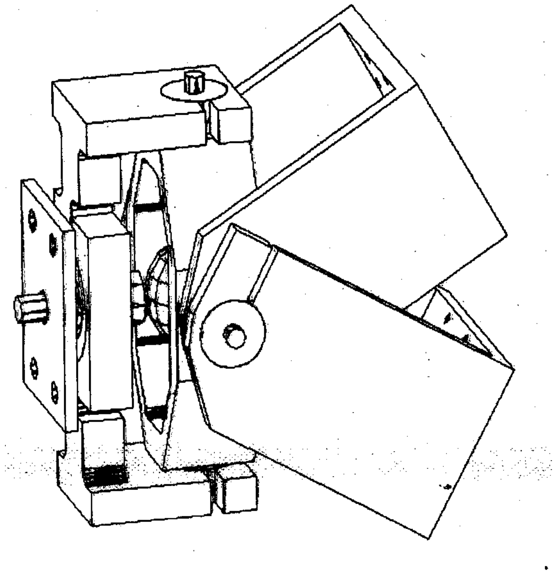

Figure 5. Schematic of HCMM base joint design.

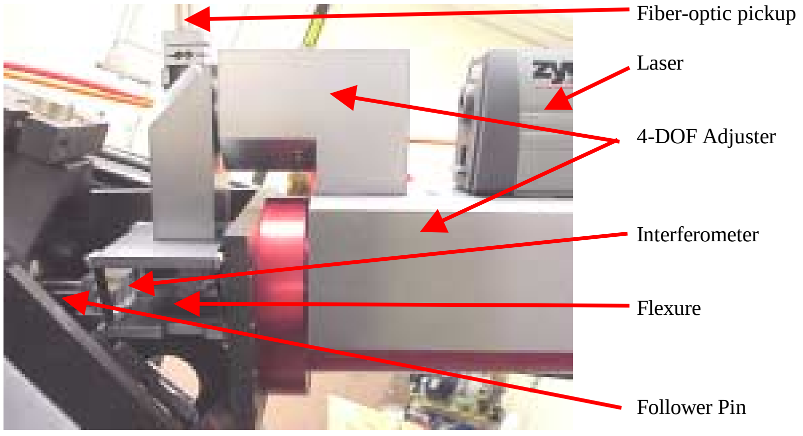

Figure 6. Closeup of HCMM strut metrology system

a flat faced follower which rides against the reference sphere on the base joint. The target retroreflector is also spring mounted to ride against the reference sphere on the center rod. The laser beam is brought to the interferometer via a system of mirrors and another 4-DOF adjustment system which allows the laser beam to be properly aligned to the interferometer optics. After leaving the interferometer, the laser beam enters the evacuated strut through a window. The use of an evacuated beam path for the laser measurement beam obviates the need for correction of wavelength variations due to atmospheric conditions.

6.0 Kinematics

The kinematic structure of HCMM was chosen to reduce the number of parameters in the kinematic model to a minimum. In general for parallel kinematic machines (PKMs) it is straightforward to compute strut lengths corresponding to a given position and orientation of the moving body (inverse positional solution). However, for most machines of this architecture, the computation of the platform pose corresponding to a given set of strut lengths is more difficult (forward positional solution). In general, multiple forward solutions are possible and iterative techniques are needed to find them. When a PKM is used as a CMM, the computation of the probe tip coordinates from the strut displacements requires the forward positional solution. Since this computation needs to be performed hundreds of times in the measurement of a typical part, it is critical for a CMM with parallel kinematic structure to have a forward positional solution which is computationally efficient, and preferably in closed form..

One of the reasons for choosing the kinematic architecture of HCMM was that its forward and inverse positional solutions are both easily obtained in closed form. Since HCMM is essentially composed of two tetrahedra with a common base, the simple algebraic equations for the solution of a tetrahedron given in Ziegert and Mize [2] can be used to solve for the coordinates of the upper and lower reference spheres on the center rod. For each of these tetrahedra, the only information needed to compute the coordinates of the apex relative to a coordinate system defined by the base triangle is the absolute length of each of the six edges. These lengths consist of the three base lengths, which are assumed to be constant, and the lengths of the three struts. Since the laser interferometers used for strut metrology can only measure changes in the strut lengths, the total length of each strut is obtained by adding the initial length to the change in length measured by the interferometer. Therefore, for each tetrahedron, six kinematic parameters (3 base lengths and 3 initial strut lengths) are needed to compute the coordinates of the apex. Since the two tetrahedral share a common base, there are only 9 independent kinematic parameters. However, the center rod length remains constant during motions of HCMM. This fact is used to allow self-calibration as described in the next section. Therefore, the center rod length becomes a 10th kinematic parameter which is determined in the self-calibration procedure. Once the numeric value of these ten parameters is determined, the probe tip coordinates are obtained by projecting a line through the apexes of the two tetrahedra to the probe tip. During operation, each time the probe tip coordinates are computed, the length of the center rod is also computed. If this value deviates excessively from the calibrated value, it is a sign that the data are suspect, and it may be time to perform a new self-calibration.

The equations used to compute the apex coordinates of the two tetrahedral and project a line through them to the probe tip, constitute the kinematic model of HCMM. This model and its inverse may be used to transform from strut coordinates to cartesian world coordinates and vice-versa. The 10 kinematic parameters used in the model are all nominally constant, and must be determined via calibration of the fully assembled machine. The accuracy of these parameter values strongly affects the positioning accuracy of the machine.

7.0 Self-calibration

As explained above, HCMM has 5-DOF of motion, and therefore has 5 actuated struts. The sixth strut is passive and is simply a telescoping tube arrangement which extends and retracts as the HCMM is moved throughout its workspace, and which carries a laser interferometer system to measure its length changes. This redundant measurement information is used to by the self-calibration procedure in the following manner:

1. The machine is moved to its home position, and each of the strut laser interferometers is electronically zeroed. Note that at this position, the 3 base lengths, the lengths of the 6 struts, and the center rod length are known only approximately.
2. The machine is moved to a pre-selected set of poses in the workspace. At each pose, the change in length of each strut from its initial length is recorded.
3. Using an initial guess of the kinematic parameters, and the recorded strut displacements, the coordinates of each tetrahedron apex is computed. The length of the center rod is then computed as the distance between these points. If the kinematic parameters used to compute these coordinates and lengths are correct, the center rod length should be constant for every pose of the machine.
4. A search is performed for the set of kinematic parameters which minimizes the sum of squares of differences in the predicted center rod length over the pose set.

An extensive simulation [3] of the self-calibration procedure has been performed to determine the optimal pose set, and the effect of measurement noise on the quality of the calibration results. The results of this simulation showed that satisfactory calibration can be obtained using as few as 30 separate poses in the calibration set if they are properly selected.

Since the time required to collect the self-calibration data is very short (approximately 2 minutes), semi-automatic compensation for thermal deformations of the machine structure may be achieved by simply performing the self-calibration at intervals determined by the fluctuations in the thermal environment and the thermal time constant of the machine structure. Another indication which may be used to determine the need for recalibration is the computed center rod length. Each time a coordinate is measured, the coordinates of the upper and lower tetrahedron apexes is computed prior to computing the probe tip coordinates. The center rod length is computed as the distance between these points. Excessive variation in the computed center rod length is an indication that recalibration is needed.

8.0 Machine accuracy

Accuracy testing of HCMM is currently underway. Results of these tests will be reported in future publications.

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