High-Precision Five-Axis Machine for High-Speed Material Processing Using Linear Motors and Parallel-Serial Kinematics

Sameh Refaat*, Jacques M. Hervé**, Saeid Nahavandi* and Hieu Trinh*

* Intelligent Systems Research Lab., Deakin University, Geelong, Vic 3217, Australia, nahavand@deakin.edu.au
**Ecole Centrale Paris, Recherches Mécaniques,92295 Châtenay-Malabry, France, jherve@ecp.fr

Key words

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Abstract

The paper describes some details of the mechanical and kinematics design of a five-axis mechanism. The design has been utilized to physically realize an industrial-scale five-axis milling machine that can carry a three KW spindle. However, the mechanism could be utilized in other material processing and factory automation applications. The mechanism has five rectilinear joints/axes. Two of these axes are arranged traditionally, i.e. in series, and the other three axes utilize the concept of parallel kinematics. This combination results in a design that allows three translational and two rotational two-mode Degrees Of Freedom (DOFs). The design provides speed, accuracy and cost advantages over traditional five-axis machines. All axes are actuated using linear motors.

1. Introduction

Five-axis machines have numerous applications in material processing and factory automation applications. Five-axis milling machines represent one prominent application. These machines utilize a spinning cutter that initially has vertical or horizontal axis. The machine then allows three rectilinear motions (X-Y and Z) of the cutter with respect to the material to be processed. Further, the cutter axis can be made to rotate about two of these rectilinear axes, which allows reaching five faces of the material to be processed (assuming cubic/parallelepiped-shaped material). This is called five-face machining if the tilting range of each of the rotational DOFs is 90 degrees or higher. In many cases the tilting range is less than 90 degrees. There are several designs of the three Cartesian/Translational axes. The selection of the configuration of these axes depends on the desired travel, rigidity and other secondary criteria [Slocum, 1992]. These axes do not represent any design problem and it is usually straightforward to optimize their design using Finite Element Analysis (FEA) methods. The current work is not concerned with the design of these three translational motions.

The configuration of the rotational axes, on the other hand, can represent a design problem. If one of the rotational DOFs is provided to the material to be processed, then there is a need for a powerful motor that is capable of accelerating large masses. That can lead to unnecessarily large mechanical design if large work-pieces are to be processed and/or high speed machining is sought. Although gearing can be used to amplify the motor force/torque needed to accelerate the work-piece mass, this is against the current trend in high-precision applications where direct drives are usually preferred. Also, the deflection error becomes more difficult to control when a heavy work-piece is rotated. Bearing stiffness in this case will be a main issue. The situation can even be worse if the two rotational DOFs are to be provided for the work-piece. The error of the two rotational axes will be accumulated as the two axes are connected in series. See Figure 1 for examples.

The situation can be improved if the two rotational DOFs are to be provided to the cutter. See Figure 2 for examples. The cutter spindle is usually much lighter than the work-piece and consequently this will allow the high acceleration needed in high-speed machining. However, the issue of accumulated error is still there as two DOFs are still connected in series.

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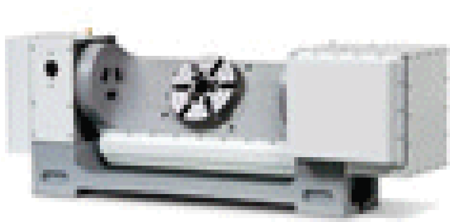
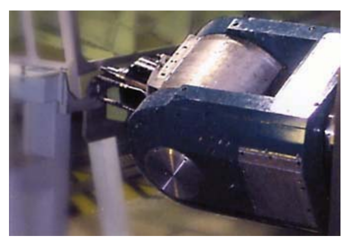


Rotary Table from Vertex

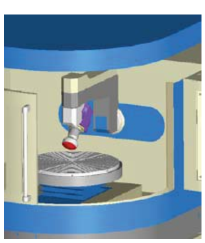
DMU 50 eVolution from Deckel-Maho

Figure 1 - Two Rotational DOFs for the Work-Piece

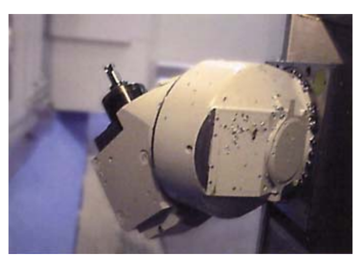
Two DOFs Head from PDS



FOGS D40 from DS Technologies



IRP-200 from ZEEKO



Swivel-Head From DS Technologies

Figure 2 - Two Rotational DOFs for the Cutter

The other problem in this configuration is the fact that the radius to be covered and the swivel-length influence the desired joint speed exponentially. One can see, with the help of Figure 3, that covering small radii would represent a problem. If the motion/contour speed is required to be maintained at certain value the joints speed and acceleration needs to go to very high values at the corners particularly when the path curvature radius decreases. The situation gets even worse when the swivel length increases, as demanded by some applications. Moreover the mechanical design is incapable in the first place of high accelerations because of the stiffness problems.

On the other hand, Parallel-Kinematics Mechanisms (PKMs) is a concept that has been gaining on-off interest during the last 50-60 years. In Parallel kinematics the platform/spindle is moved using a number of links/legs that influence that platform from a number of points. See Figure 7 below. These PKMs have many advantages and some drawbacks [Tsai, 1999; Merlet, 2000]. Six-DOFs PKMs might be sought of as PKMs in the extreme where the drawbacks of such PKMs are extremely pronounced. These drawbacks are mainly limited work-space and poor manipulability usually because of the badly posed system singularities. To utilize the benefits of the concept of parallel kinematics while avoiding its drawbacks there is a trend of relying on PKMs with less than six DOFs. Three-DOFs PKMs attract decent amount of interest for this reason. A large number of these three-DOFs PKMs have been proposed. See [Tsai, 1999; Merlet, 2000] for an early survey and See [Refaat el, 2005] for a more recent review.

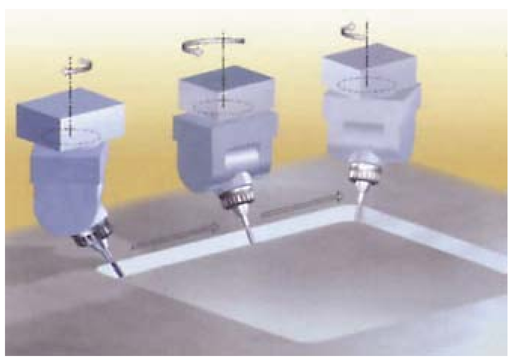
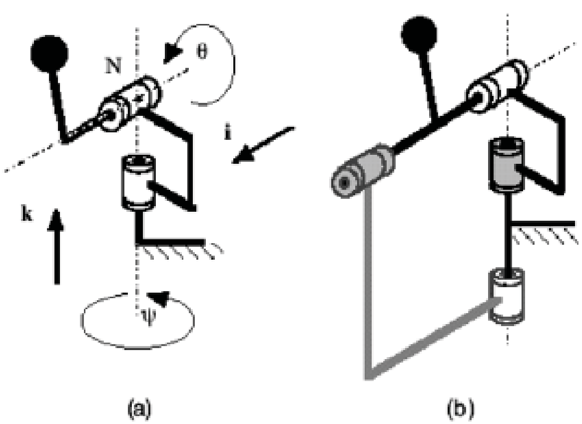
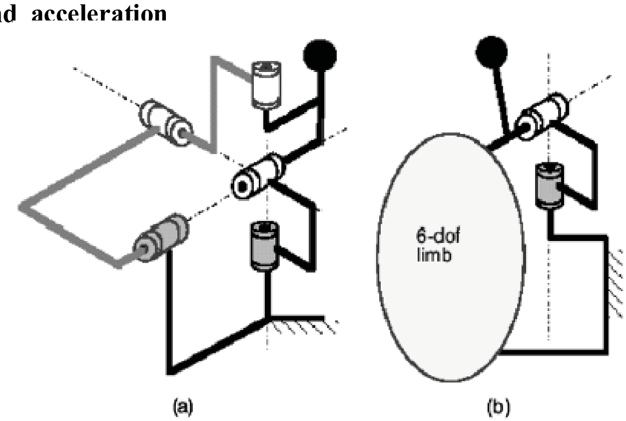


Figure 3 - Machine Geometry/Kinematics demands high joints speed and acceleration



(a) Serial pan-tilt wrist. (b) Parallel pan-tilt wrist.

Figure 4 - Simple Conceptual PKM for two rotational DOFs



(a) Spherical pan-tilt wrist. (b) Nonoverconstrained 2-DOF wrist.

Figure 5 - Base Actuation for PKM with two rotational DOFs

One can see that using PKM is potentially capable of solving the problems of the two rotational (pan-tilt) DOFs described above. This is because two or more kinematics chains (limbs) are used to share the load. The simplest conceptual parallel kinematics solution is to use one of the configurations of Figure 2 and simply add another limb that acts in parallel to the existing one and maintains the same DOFs of the platform. See Figure 4 [regenerated from Hervé, 2006]. The problem of the mechanism of Figure 4.b is that one of the two actuating motors will be moving. Practically this is usually not acceptable. This actuation issue can be overcome if the 2nd limb is to have more than two DOFs. See Figure 5. Now even more rotational joints are sharing the load. Many other configurations of that second limb can be found in the literature [Hervé, 2006; Carricato and Parenti-Castelli, 2004]. However, the mechanism is becoming more complicated and the costs of manufacturing and assembly are becoming considerably higher.

2. Machine Kinematics

Here we propose to solve the problem of the two rotational DOFs using a three DOFs PKM. This PKM is to provide the two rotational DOFs as well as one translational DOF. This translational DOF is needed anyway. The mechanism that can realize these three DOFs can only be asymmetrical [Refaat el al, 2005]. This means that the limbs of the mechanism are not identical. In this work a symmetric mechanism that can realize two-mode operation is proposed. The first mode is one rotation and one translation and the 2nd mode is another rotation and the same translation. In other words, only one rotation at a time can be realized. This single translation is chosen to be vertical (Z axis). These three DOFs are to be combined with two other traditional serially connected prismatic joints/axes leading to the proposed five-axis machine. The additional prismatic joints act in X and Y directions. See Figure 6.

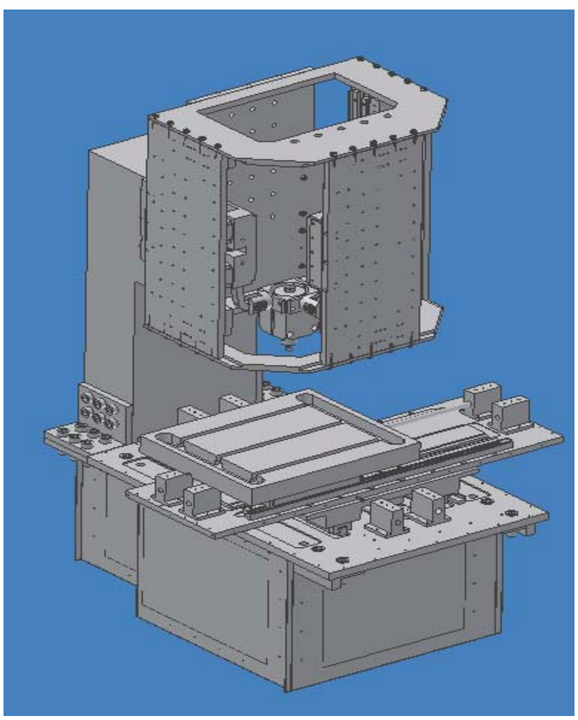


Figure 6 - The proposed Industrial-Scale Five-Axis Machine

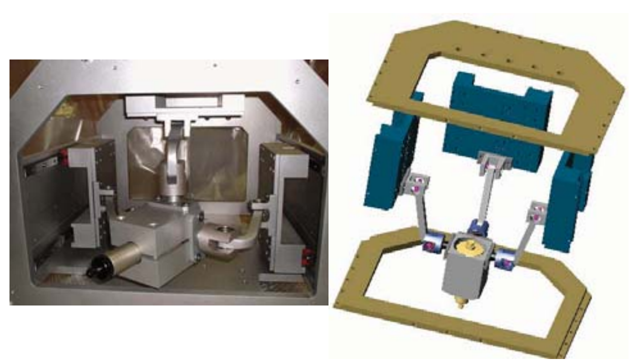


Figure 7 - Industrial-Scale Three DOFs Head

Figure 8 - The P-R-R-R Limb of the PKM

Figure 7 shows the parallel-kinematics part of the machine. One can see that this mechanism consists of three identical limbs. Figure 8 shows one of these limbs. Each limb is a PRRR (Prismatic-Revolute-Revolute-Revolute) chain.

The proposed mechanism has many advantages. It is modular. Three limbs are now sharing the load. Fast linear actuators are used. Position measurement is very close to the end point leading to overall higher accuracy of the mechanism. Simple links that are easy to be made rigid are used. The mechanism cost is relatively low. The two rotational DOFs are realized at virtually no mechanical cost. The actuator that would be used for the Z axis under normal circumstances has been divided into three small actuators.

The detailed kinematics equations of the mechanism are beyond the scope of this work. The PKM proposed here is actually a member of a PKMs family whose kinematics has readily been analyzed in details [Refaat el al, 2006a].

3. Mechanical Design and Motion Control

The stress, strain and natural frequencies of the machine depicted above has been analyzed using ANSYS finite element software, and the dimensions of the various parts have been selected to ensure natural frequencies higher than 400 Hz of all parts, sub-assemblies and assemblies of the machine. That in turn allowed wide bandwidth position control loop free of resonances [Refaat et al, 2006b]. Static deflections at the end point have also been maintained at 5 the microns when a 3KW spindle is used.

Further, various control methods have been utilized to control motion of the five linear motors of the machine. These methods have shown promising results [Refaat et al, 2006b].

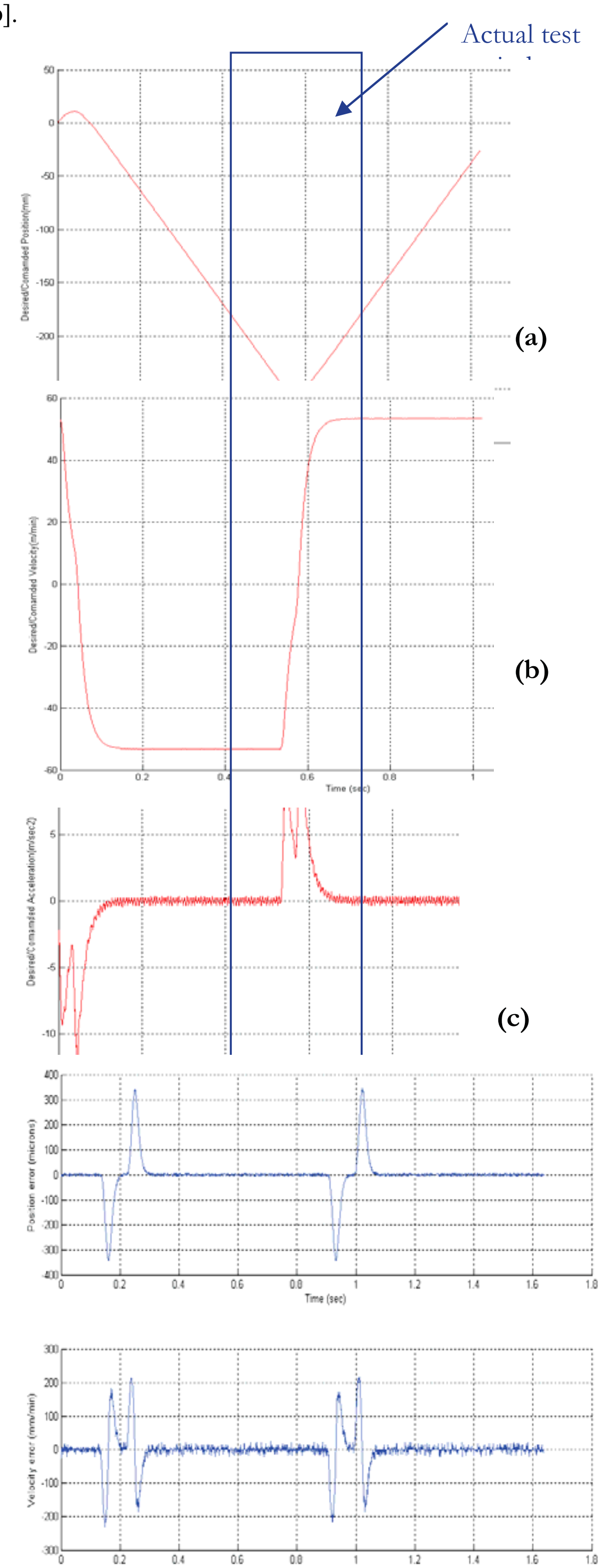


Figure 9 - State/Test Signals and Error Signals

The control method used was a hybridized version of polynomial and sliding mode control. Some selected parameters of the control were also adapted on-line using simple gradient algorithms. Figure 9 shows position and velocity errors for the given position command. These results have been re-generated from Refaat et al, 2006b. The specifications of the used linear motors were also explained in that work.

The machine can realize a speed of 2 m/sec and acceleration of 20 m/sec^2 while maintaining the servo error below 15 microns at all times.

4. Conclusions

An industrial-scale five-axis machine that utilizes the concept of parallel kinematics has been proposed. The presented machine is limited in power. Milling machine spindle power can reach tens of KW. The authors cannot contemplate a reason that would make it not possible to increase the power of the proposed design. In fact this a subject under study at this stage. The machine uses 5 linear motors for actuation. Some details of the kinematics and the mechanical designs of such a machine were discussed. The focus was on the use of that machine as a milling machine. The merits of the proposed machine compared over existing five-axis milling machines configurations have been highlighted. Many other uses of the proposed machine are possible.

6. Acknowledgements

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