Positioning accuracy of non-conventional production machines – an introduction

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Abstract:

The paper deals with machines employing parallel-kinematics structures (PKS). They represent a relatively new generation of machine tools. Typical for all PKMs are the two “platforms”, where one of the platforms is fixed, that are connected by struts. Depending on the number of struts, the machines are referred to as hexapod or tripod machines. Such machines offer several advantages comparing to the conventional machine tools with serial kinematics, such as high flexibility, high stiffness, and high accuracy. It is very suitable for High-Speed-Machining (HSM), light machining and has received a wide interesting in manufacture industry. To achieve a desired positioning accuracy and stability, the static and dynamic properties of the machine must be searched and mathematically described. The calculation of the estimate of positioning deviation, including respective uncertainty and covariances, is much more complicated task comparing to the serial kinematics. The research will be mainly focused on Tricept, the parallel kinematic structure with three telescopic rods.

Keywords: Parallel kinematic structures, production machines, positioning accuracy, uncertainty

1. Introduction

Since 1993, the biggest manufacturers of production machines from Japan, Germany, USA, Italy, Switzerland, record still growing demand for advanced production machines, always faster and more accurate. The growing amount of production means a sharp competitiveness among manufacturers, pushing down the prices and increasing demands on their performance and ecological parameters. This is a main consideration that forces individual manufacturers to bring innovative and non-conventional designs of production machines into industrial practice [7].

Adaptation of production machines to always growing demands requires still more expensive and more sophisticated approaches. Application of the so called parallel kinematic structures (PKS) is one of possibilities.

The advantage of PKS comparing to conventional machines is given by their higher stiffness, higher accuracy, significantly better ration load/own weight; they can reach higher accelerations of effector (technological head).

2. Parallel kinematics structures

Kinematic chain is a set of kinematic pairs that are pairs of bodies mutually connected by a coupling (joint). Such coupling represents a common restriction of movement of a pair of bodies [8].

Serial kinematic structures are characterized by the fact that the output movement is created from individual movements of consequential parts of a kinematic chain.

Fig. 1 Several types of kinematic structires: hexaglaid, hexapod, nonapod and tricept [1]

To move an effector of such a chain, the position change in a single joint is enough, i.e. change in between the two parts of a kinematic chain. The rest of kinematic pairs can stay in standstill.

Parallel kinematic structures (PKS) are represented by a more complex kinematic structures. The resulting movement of an effector (technological head) is created in cooperation of all kinematic elements. The movement of any element affects position of all other parts.

The main part of PKS is represented by parallel positioned kinetic elements (telescopic rods, arms). One end of rods is connected to a fixed frame, the other end of rods is connected to a movable platform. Due to this, PKS are also called mechanisms with closed kinematic chains with one or more loops.

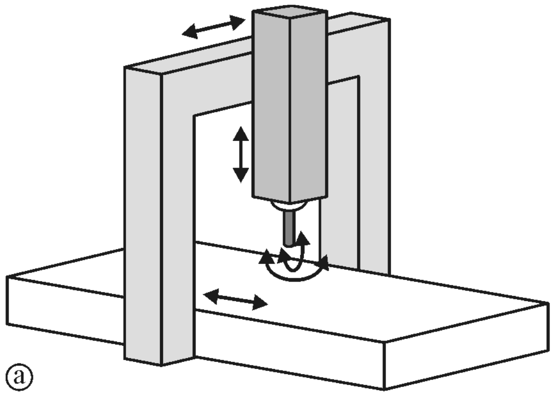
The synthesis of PKS is not created by a simple summing of individual partial displacements but through a very complex calculation as the kinetic elements are parallel located.

When classifying different classes of PKS, number of telescopic rods is an important point of view. Following types of PKS are known: hexaglaid, hexapod, nonapod, triept, etc. (see Fig. 1). The common condition is that for correct control of movement of the body in a space, one must remove 6 degrees of freedom (DOF). When considering so, several designs are over-determined.

3. Tricept

When combined with CNC machines, tricept belongs to the group of modern production machines, introducing the so called High-Speed Cutting (HSC) technology. They enable to reach a high velocity of movement, and the acceleration can be as high as 2 g.

Tricept belongs to the category of positioning mechanisms with closed (parallel) structure (see Fig. 2b). It consists of a fixed (upper) platform and a lower movable platform, the so called carrier. Both platforms are interconnected by three telescopic rods (actuators) and a center rod. The fixed platform and the telescopic rods are connected by primary joints of the 4th grade (removing 4 DOF – universal joints).



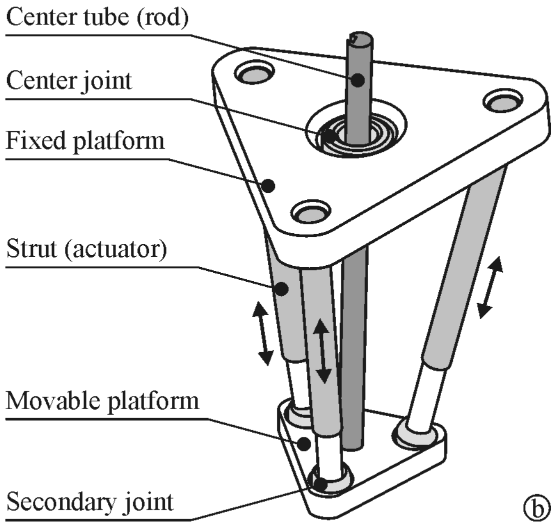


Fig. 1 Basic kinematic structures
a) serial, b) parallel
Figure adapted from [1]

Each rod consists of an extension part and a fixed part, both connected by the joint of the 5th grade (enables just axial movement). The movable platform is connected to the telescopic rods by joints of the 3rd grade (removing 3 DOF). The center rod is connected with the fixed platform through a center joint; the movable platform is connected tightly. The

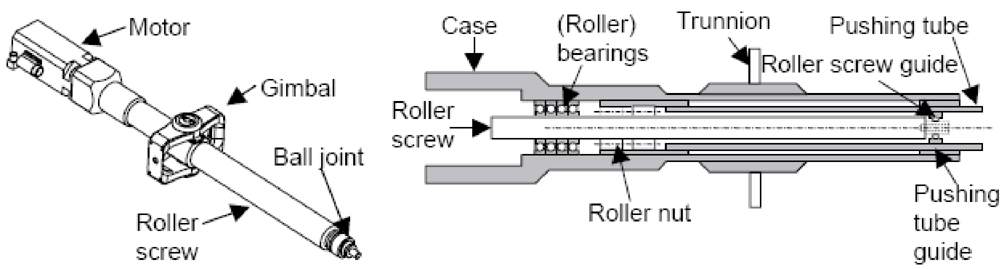


Fig. 3 Tricept 805 actuator (left) and roller screw subassembly (right) [8]

axis of the center rod always crosses the center point. The technological head is connected to a movable platform (a carrier). The whole assembly of a tricept is located vertically at the suspension frame of a production machine.

The definite position of the carrier is determined by length of individual telescopic rods - actuators. Therefore the accuracy of telescopic rods is of an utmost importance and determines the overall positioning accuracy of the technological head.

In general, any linear drive can be used as an actuator. The designs with the roller screws are employed very often (see Fig. 3). In that design an actuator consists of a roller screw that transforms rotational movement of the servomotor to axial movement of the pushing tube (see figure 3). In the upper fixed platform the actuators connected through gimbals, and in the lower mowing platform with ball joints. To eliminate backlash, actuators and joints are pre-stressed. Frictional losses increase with pre-stressing [8].

Besides that, hydraulic drives can be used as well; recently also electric linear drives are also available.

Among the PKM for machine tools, Tricept by SMT Tricept AB, Sweden (former Neos Robotics AB), is considered as one of the most successful PKM applications in manufacture industry [5] – see Fig. 4. The machine offers:

- high dynamic for high machining productivity,
- full 5-axis (even 6-axis) machining capability for high flexibility,
- large workspace (mm): $X = 2400$, $Y = 2400$, $Z = 800$,
- good static stiffness and high dynamic stiffness,
- very good price/performance ratio,
- scalability.

4 Influences to the positioning accuracy

The positioning accuracy of any production machine is represented by the closeness with which its actual pose matches the pose predicted by its controller. When comparing conventional serial kinematics with the parallel one, several significant differences occur. Therefore the determination of the positioning accuracy of the parallel kinematics represents a more complex and complicated task as for the serial one.

Manufacturing tolerances, *installation errors* and *link offsets* cause deviations with respect to the nominal kinematic parameters of the system. As a result, if the nominal values of these parameters are used (incorrectly) within the system control software, the resulting pose of the system will be inaccurate.

To a large extent, technological head positioning inaccuracy is induced by the propagation of *geometric* errors, *compliance* errors and time-variant *thermal* errors. The geometric errors come from manufacturing imperfections, misalignments or joint wear. Compliance errors are due to the flexibility of machine joints and link deflection under self-gravity and external load. They also depend on the technological head's actual position. Thermal errors result from thermal distortion and expansions of robot components due to internal and external heat sources such as motors, bearings and ambient temperature change.

Link and *joint flexibility* has a significant impact on machine performance and stability. Link gravity and external payload cause the deflection of links and flexible joints thus affecting the machine performance. Link compliance effects are represented by six differential component changes: three translational and three rotational changes.

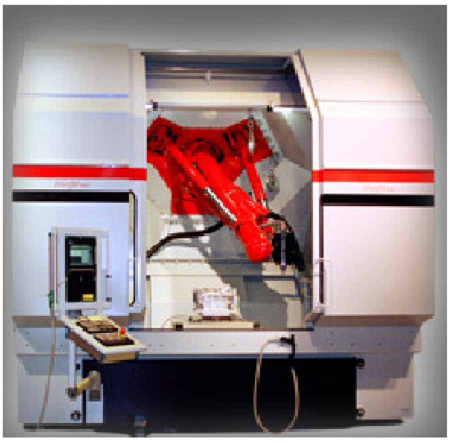


Fig. 4 PKM application in production machine [5]

5 Estimation of the positioning accuracy

When calculating estimate of the positioning accuracy, the main problem is to find a function describing positioning of the technological head in dependence on behavior of telescopic actuators. In apart from the serial kinematics, the positioning depends on trigonometric functions thus leading to nonlinear calculations. The practical consequence is that the positioning accuracy depends not only on the accuracy of telescopic actuators but also on the position within the workspace. Besides that any inaccuracy of the actuator reflects itself in the notable change of the position of technological head thus affecting its positioning accuracy. The inaccuracy of the actuator arises from its design but is affected also by thermal effects and deformation due to work load. The thermoelastic deformation of each component of the kinematic chain must be calculated individually and transformed to a global deviation in the position and orientation of the technological head. Compensation of the thermal deformations in parallel kinematics is thus a non-trivial task.

One must consider also the problem of direct and inverse kinematics. When using a serial kinematic structure, decomposing the desired path of the technological head to movement of each axis is not a big problem. The same problem for parallel kinematics leads to non-homogenous solutions. As a result, calculating the permissible positioning errors of individual actuators from the desired positioning accuracy of the technological head is not a trivial task as well.

The estimation theory enables to determine the estimate of positioning deviation of the technological head for any position of actuators, providing also the uncertainty of that estimate [3, 6]. This is a significant difference to the standard ISO 230-2:1997 calculating the positioning deviation only in several points along the axis travel [4]. Moreover the standard assumes the serial kinematics so that it cannot be used for parallel kinematic structures. The method based on estimation theory cannot give a response changed positioning deviation due to a variable work load of the whole structure. The estimation theory can give a response to positioning deviations arising from the actuators that are generated by a predicable way measurable by accordingly defined design of experiments.

To get reliable input data, several measurements must be performed. When the function between the positioning of each telescopic actuator and the resulting position of the technological head is known, one can calculate the estimate of positioning deviation and respective uncertainty. To do so, one must also determine all sources of uncertainty, namely those arising directly from actuators.

6 Conclusions

To satisfy still growing demands and requirements put on production machines, the biggest world producers try to offer new non-conventional technologies and approaches. The employment of parallel kinematic structures represents one possibility to reach higher operation velocity, acceleration and better overall performance.

Introducing of PKS brings several challenges to RTD activities. The computation of resulting path of technological head, solving the inverse kinematics of parallel telescopic rods, requires a deep theoretical research supported by a number of experiments. In line with this effort stand also computation of positioning accuracy of the technological head. Apart from the serial structure, the parallel kinematics does not offer a simple transformation function, enabling relatively easy calculation of estimate of the position deviation as well as calculation of the respective uncertainty. The introduction of estimation theory offers one of possible approach.

Acknowledgment

This paper was prepared under the support of VEGA grant agency, grant No. 1/0265/08.

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