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Kinematic calibration of a 3-DOF spindle head using a double ball bar

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ABSTRACT

This paper presents a simple and effective approach for kinematic calibration of a 3-DOF spindle head developed for high-speed machining. This approach is implemented in three steps, (i) error modeling that allows the geometric errors affecting the compensatable and uncompensatable pose accuracy to be classified; (ii) identification of the geometric errors using a set of distance measurements acquired by a double ball bar (DBB) with a single installation; (iii) design of a linearized error compensator for real-time error implementation. Experimental results on a prototype machine show that the compensatable pose accuracy can significantly be improved by the proposed approach.

1. Introduction

Machining large structural components with high metal removal rates is a challenging issue in the aircraft industry [1]. Conventionally, it requires a huge gantry 5-axis machine tool, weighing many tons and having a large footprint. A promising alternative is to use one or more machining stations moving along a long reference track that forms the base of a manufacturing system, where each station is a parallel kinematic machine (PKM) configured as a multiple-axis spindle head. This has been demonstrated by the very successful application of the Sprint Z3 head [2]. Motivated by this idea, a new spindle head, named the A3 head, has been designed and developed [3,4] (see Fig. 1); its topological structure is a 3-R$\underline{P}$S parallel mechanism having movement capabilities of one translation and two rotations (1T2R).

Geometric accuracy is one of the important performance specifications of the PKM based spindle heads as the high rigidity and high accuracy are the essential requirements [5]. It is well recognized that, provided that the manufacturing and assembly processes ensure sufficiently repeatability, a practical and economical way for enhancing pose accuracy is the kinematic calibration by software [5–7], a process by which the actual kinematic parameters can be estimated so as to modify the inverse kinematic model residing in the CNC controller. The critical step in such a calibration is to effectively and accurately estimate the measurement residuals, i.e., the discrepancies between the measured and the computed poses of the cutting tool.

In comparison with self or autonomous calibration in the joint space that minimizes the discrepancies between the measured and computed values of the active, passive and/or redundant sensors in the joint space, external calibration in the task space has been intensively investigated in the past decades. The approaches can be basically classified into two categories, i.e., the coordinate-based approach and the distance-based approach, heavily dependent upon the type of acquirable data. The coordinate-based approach deals with the identification problem by minimizing the discrepancies between the measured and

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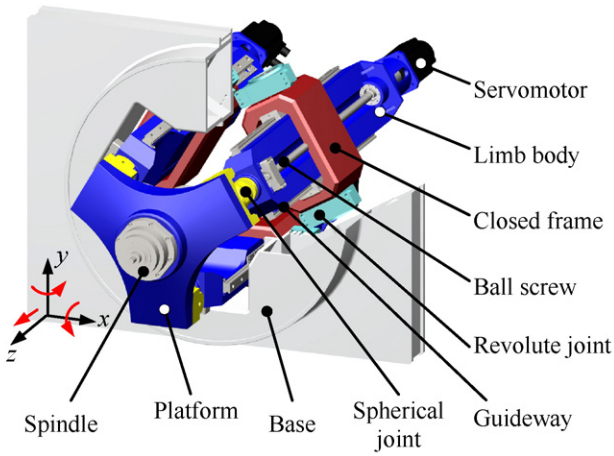

Fig. 1. 3D model of the A3 head.

computed values of the full/partial position and orientation of the end-effector directly, or the absolute coordinates of three or more reference points fixed on the end-effector. For example, Masory [8] and Zhuang [9] used a theodolite to measure the positions of three points on the platform of a Stewart platform and extracted the position and orientation information from these coordinate measurements. Vischer [10] measured the position errors of a Delta robot by attaching the end-effector to the probe of a 3D coordinate measuring machine, and the orientation errors by using three perpendicularly placed linear digital probes. Fan [11] investigated the calibration of a 3-R$\underline{\text{P}}$S parallel mechanism by measuring the orientation errors using an inclinometer and the positioning errors of a reference point using an X-Y table. Huang [12,13] studied the same problem by measuring the orientation errors of the end-effector using a specially designed fixed angle gauge and the positioning errors of a reference point using three perpendicularly placed dial indicators. The distance-based approach deals with the identification problem by minimizing the discrepancies between the measured and computed values of a set of distances between two or more points. This approach is more cost-effective than the coordinate based approach because it directly uses a contact 1-dimemsional measurement system such as a linear variable differential transducer or a DBB. Then, the partial pose information can be recorded when the end-effector moves along several prescribed paths within the workspace. The distance measurements can also be extracted indirectly from the absolute coordinates of one or more reference points on the end-effector at different configurations. For example, Ota [14] investigated the calibration problem of a 6-DOF parallel kinematic machine (PKM) known as HexaM using the data acquired by a DBB. Yukio [15] proposed an effective approach that employed a lower band FFT filter to improve the signal/noise ratio of circular measurements acquired by a DBB. Patel [16] presented a new calibration method that uses extra “legs”, e.g., a simple length measuring device or a string potentiometer, to identify the kinematic parameters of a hexapod-type PKM. Nubiola [17,18] proposed a novel measurement system comprising a single DBB and two custom-made fixtures. One fixture is attached to the base and the other to the end-effector, and each having three magnetic cups. It is possible to use the DBB to measure six distances between the magnetic cups on the tool fixture and the magnetic cups on the base fixture, and thus calculate the pose with high accuracy. However, the process of the measurements is manual and labor intensive, and only suitable for small industrial robots, particularly if a relatively small workspace is of interest. Many other researches also have been carried out using distance-based approach [19–22]. Compared with the coordinate-based approach, the advantages of the distance-based approach are that the obtained data is independent on the selection of reference frame and it is unnecessary to identify the errors describing the rigid body motion of robot frame relative to the world frame because robot localization can be carried out afterwards according to the environmental context.

Driven by the practical need to ensure machining accuracy, this paper presents a distance-based approach for kinematic calibration of the A3 head. It concentrates upon three key issues: 1) formulation of an error model that is able to distinguish the geometric errors affecting the compensatable pose accuracy from those affecting the uncompensatable pose accuracy; 2) identification of a full set of errors using distance measurements acquired by a DBB; and 3) development of a linear error compensator for real-time implementation. Experiments carried out on a prototype machine verify the effectiveness of this approach.

2. Error modelling

2.1. Inverse displacement analysis

Fig. 1 shows the 3D model of the A3 head, which consists of a moving platform, a base, and three identical R$\underline{\text{P}}$S limbs. Here, R, $\underline{\text{P}}$ and S represent revolute, actuated prismatic and spherical joints, respectively. Driven by three independent servomotor lead-screw assemblies, the platform achieves three degrees of freedom: one translation along the z axis and two rotations about the x and y axes. A spindle can be mounted on the platform to implement high-speed milling. For more information about mechanical design of the A3 head, please refer to [4].