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On-line calibration and uncertainties evaluation of spherical joint positions on large aircraft component for zero-clearance posture alignment

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ABSTRACT

With the improvement of performance requirements for modern aircraft, such as speed and leak tightness, the posture alignment of large components without clearance is now extremely required in the aircraft industry. Nevertheless, the inherent errors of both the components themselves and the posture alignment system lead to high risk of collision during the inserting stage, among which the positional errors of spherical joints that connecting the large component to the numerical controlled locators are identified as the primary error source by existing studies. In this paper, a novel method for on-line correction and uncertainties evaluation of the positions of spherical joint centers (SJCs) is presented. Firstly, the rough positions of SJCs are identified based on the nominal model, and the finite element analysis (FEA) method is applied to preliminarily compensate the self-weight deformation of the component. Secondly, the on-line correction model of SJCs is further established, majorly on the basis of the displacements of locators and the relative postures between the initial posture and the new posture after each motion. Thirdly, to improve the correction accuracy, a new relative posture evaluation model considering the anisotropic measurement uncertainties of key points is suggested and solved by particle swarm optimization, and the correction uncertainties are then analyzed using Monte Carlo simulation. According to the numerical experiments, the proposed relative posture evaluation method has demonstrated more robustness evaluation results than the conventional approaches, and also leads to lower correction uncertainties of SJCs. Moreover, since the relative posture evaluation is a common problem in robot calibration, it also provides a promising alternative or supplement for the conventional optimal posture selection method to improve calibration accuracy. The practical application for a wing to fuselage assembly has verified the effectiveness of the correction method, in which the largest positional error of SJCs has decreased from about 14.2 mm to less than 0.4 mm after correction, and the displacement calculation error has been accordingly reduced from 0.1 mm to smaller than 0.01 mm. Therefore, the security of posture adjustment in confined clearance has been largely enhanced.

1. Introduction

Posture alignment is one of the essential tasks for the assembly of large components, as the components must be accurately positioned and oriented before they are joined. Traditionally, posture alignment is achieved by manual work, which is time-consuming and labor intensive to satisfy the high accuracy for assembly [1]. Taking the typical wing to fuselage assembly as an example, since the integrated wing box after connection is not only the primary load-carrying structure but also act as a fuel tank, thus both high strength and leak tightness are required. For this reason, the inserting structures of the wing are generally designed to coordinate with the corresponding features of the fuselage in very confined clearance, which is usually smaller than 0.005″ [2]. This kind of assembly with strict mating requirements is generally called zero-clearance assembly, to distinguish from other assembly cases that permit large process compensation [3]. On the other hand, to ensure the structure security during the posture alignment for zero-clearance assembly, much more elaborate posture adjustment is desired since it is very easy for the components to collide with each other.

In the past decades, automatic posture alignment system has been introduced into the aircraft manufacturing enterprise. In these systems, the numerical controlled locators (NCLs) are used to support and adjust the posture of components [4], and the large-volume measuring systems such as laser tracker, laser radar and indoor global positioning system are applied to verify posture accuracy by measuring the key points (KPs) on the components [5]. Generally, these systems can be

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slickly applied to the posture alignment applications that without inserting process or inserting with relatively large clearance. Nevertheless, according to the assembly practice of the authors, the posture alignment with confined clearance is still an intractable task. For the purpose of improving the alignment accuracy, many researchers have made their contributions, majorly from the aspects of kinematic calibration of posture alignment system [6], and the posture evaluation or optimization of the large components [7].

In a typical automatic posture alignment system, the component is supported by three or more NCLs, and each locator is composed of three prismatic pairs which orthogonal to each other. The large component is connected to the locators via spherical joints, and these together constitute a well-known *n*-prismatic-prismatic-prismatic-sphere (*n*-PPPS) parallel mechanism [8]. From the aspect of geometric parameter identification or kinematic calibration of parallel platform, Oiwa discussed the joint errors and link deformations caused by external forces and heat [9]. Zhuang introduced a general framework for the self-calibration of parallel manipulators, in which the concept of creating forward and inverse measurement residuals by exploring conflicting information provided with redundant sensing was proposed [10]. Joubair presented a simple low-cost calibration procedure that improved the planar positioning accuracy of a double-arm SCARA robot [11]. Ecorchard proposed an efficient elasto-geometrical and calibration method that allowed the identification of both the geometrical and stiffness parameters of redundantly actuated parallel mechanisms with slender links [12]. In general, these methods have achieved satisfactory results respectively, but the calibration of the *n*-PPPS mechanism has its own difficulty to be tackled.

The primary kinematic parameters of *n*-PPPS mechanism include the axis directions of NCLs and the positions of spherical joint centers (SJCs). Considering that these axis directions can be easily tracked and measured via high precision laser interferometer or laser tracker, so it is usually not a difficult task to precisely calibrate them. For the positional errors of SJCs, however, they are generally recognized as the main source of error that restricts the alignment accuracy [13–15]. Due to the inherent manufacturing and assembly errors, and the self-weight deformation as well, the spherical joints on the large component should unavoidably deviate from their nominal positions, which can sometimes reach tens of millimeters. As the SJCs are virtual points, they cannot be directly measured by instruments such as laser tracker. The sphere surface fitting is thereby an alternative [16]. Nevertheless, the fitting accuracy is restricted in this scenario due to that more than a half of the ball surface is inside the ball socket to ensure the safety of support [17]. To overcome this issue, Qiu developed a novel principle and device to obtain the positions of SJCs by installing three or four displacement sensors in the joint [18]. Although the positional deviations of SJCs can be well controlled, the device structure and revising algorithm are very complicated. As another alternative method, Li proposed an auxiliary measuring fixture to measure the SJCs indirectly [19]. Müller suggested a new reconfigurable handling system for large component alignment, in which the spherically mounted retro-reflector of the laser tracker has been extended by an apparatus allowing to track the ball heads placed on the components as well as the ball cups of the handling modules [20,21]. However, the manufacturing and maintenance costs of these precise fixtures or apparatuses are high, and the measuring process is also time-consuming.

To lighten the heavy burden of SJCs measurement for each vehicle assembly, it will be significant and meaningful to automatically calculate the positions of SJCs during the alignment process. Ma first introduced an automatic calculation method according to the locator displacements in the condition that the initial positions are given [22]. This method can eliminate the measuring process and thus improve the alignment efficiency. However, the errors of the initial positions are not corrected, which limits its application. Recently, Lei suggested an online calibration method to correct the positional errors of spherical joints, but the authors overlooked the singularity of their calibration model, and the displacements of all axes on each locator are required in their model [23]. According to the discussion above, it is observed that there are still some deficiencies in the existing measuring or correction method for SJCs that should be well addressed.

Posture evaluation is another crucial topic for large component alignment. In the mathematical sense, it is to determine the optimal Euclidean transformation between two sets of KPs that defined in the nominal model space and the current measuring space. Many researchers have carried out studies on this topic. The iterative strategy such as iterative closest point (ICP) method is widely used to register the cloud points on the free surface [24]. Both the singular value decomposition (SVD) method and the unit quaternions method provide a non-iterative solution for points matching [25,26]. The heuristic algorithms such as particle swarm optimization (PSO) have also been applied for registration [27,28]. By using a laser tracking system, a posture calculation method to determine the position and orientation of end effector was discussed [29]. Cheng proposed a posture evaluation approach based on temperature compensation and the tolerance of KPs [30]. Hou put forward a type of posture evaluation method for an aircraft wing component based on a special system that can achieve rapid measurement of the posture [31]. As can be seen, the existing studies for posture evaluation of large component majorly concentrated on the registration of measured coordinates and nominal coordinates of KPs, which means that only one set of points has suffered from positional errors or uncertainties. For the SJCs correction, however, as will be discussed in Section 3.3, the coordinates for relative posture evaluation between different postures are both measured values and thus suffer from non-ignorable uncertainties due to the large measuring distance. As a consequence, careful handling of these uncertainties is indispensable to derive more credible posture parameters. Recently, the linearization technique has been introduced to cope with the uncertainties on both sides of measured points in large-volume metrology [32–34]. Nevertheless, the linearization of rotation matrix and simplification of weighting matrixes in these methods will also introduce approximation errors, which will be numerically discussed in this paper.

On the other hand, the relative posture evaluation was also proved to have a large impact on the kinematic calibration accuracy of industrial robot or parallel mechanism [35]. For these calibrations, the large-volume measuring systems such as visual systems [36–38] and especially the laser trackers [39–44] are widely accepted as the posture measuring equipment. However, the measurement uncertainties are difficult to be contained in the calibration model [45]. To minimize the influence of measurement uncertainties on the relative posture evaluation and the final calibration accuracy, optimal posture selection has become a crucial topic in kinematic calibration [46–53]. As an example, Table 1 summarizes the typical measurement schemes for robot calibration using laser tracker in recent years, majorly covers the aspects of selection method of calibration postures, the number of reference points for relative posture evaluation and the handling of measurement uncertainties in calibration model. Among these studies, some researchers selected the optimal calibration postures based on quantitative indices such as the condition number and observability, or on the basis of qualitative analysis of accuracy characteristics of laser trackers. It is also observed that, most of these applications have measured three reference points on the end-effector or platform to evaluate the relative postures. In this paper, these evaluation methods based on three points are uniformly referred to as TRIAD method for consistency [39,41–43,50–52]. Moreover, although several studies have addressed the measurement uncertainties in their calibration models, the uncertainties are generally assumed to be i.i.d and thereby diagonally weighted [43,50,52]. Nevertheless, the distribution of measurement uncertainties of laser tracker is much more complicated than i.i.d, since they are varied for different points and changing in different calibration postures. As a consequence, the current handling strategies of measurement uncertainties in calibration can be further improved.