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Calibration and accuracy analysis of robotic belt grinding system using the ruby probe and criteria sphere

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ABSTRACT

Calibration in the robotic belt grinding of complex blades is considered as one of the key bottlenecks of measurement accuracy. To enhance the accuracy of robotic calibration system, an improved method is proposed in this paper to calibrate the tool (grinding machine) frame and workpiece (aero-engine blade) frame by holding the ruby probe as the main calibration tool. Firstly, the sphere-to-sphere method replacing the traditional point-to-point method is put forward to calibrate the flexible and fixed probe frame. Secondly, the calibrated flexible and fixed probe frame is employed to precisely seek the origin point of tool frame and then to calibrate it accurately. Thirdly, both the rough calibration (manual calibration) and fine calibration (auto calibration) are adopted to calibrate the workpiece frame, the resulting translation and rotation errors are controlled at small values to improve the calibration accuracy. Finally, a typical case on robotic belt grinding of aero-engine blade is conducted to validate the calibration results of the robotic belt grinding system (RBGS).

1. Introduction

The blade, as the key structural part of energy conversion devices, plays a decisive role in the overall performance, and its geometrical accuracy and surface quality directly affect the efficiency of energy and power equipment. Generally, the blades need to experience complicated machining process after casting or forging and the final finishing operation almost relies on the abrasive belt grinding. Both the manual belt grinding and multi-axis NC belt grinding are deemed to be the dominated finishing modes. As a new type of finishing style, robotic abrasive belt grinding of blades receives wide concerns and has been widely developed in modern manufacturing industry [1,2]. This technology not only ensures the accuracy and consistency of the machined surface, but also significantly reduces the equipment costs [3]. To better achieve the robotic belt grinding of aero-engine blades, a series of work, including: calibration of tool and workpiece frame [4,5], off-line programming [6,7], robotic path planning [8,9], macroscopic removal rate control [10], and force control technology [11,12], need to be done.

Whereas, the calibration accuracy of tool and workpiece frame is of great significance to the subsequent operation procedures and it greatly affects the grinding surface quality. Currently, the traditional point-to-point calibration method is widely applied to obtain the coordinate frame of tool and workpiece in some occasions, such as the robot spray [13], robot assembly [14], robot handling [15], robot palletizing [16] and robot welding [17] etc., where the requirement of finishing accuracy is not high. Relatively, a large number of works, focusing on the calibration of robotic belt grinding system, have been carried out from different angles. Li et al. [18] proposed a hand-in-eye method to calibrate the relationship between robot and scanner using a sphere, the fitting accuracy of the sphere, however, is not fully discussed and the tool frame calibration is not mentioned. Li et al. [19] reported on a new hand-eye calibration method by fully considering the joint parameters error and position error of the calibration equation, the results showed that the diameter deviation of criterion sphere decreased from 0.1493 mm to 0.0466 mm. However, the tool frame calibration is also not mentioned and analyzed in the paper. Xu et al. [20] introduced a new method by virtue of the 3D laser scanner to calibrate the workpiece frame and obtain the real morphology features of workpiece, whereas, the calibration and analysis of the tool frame is not discussed. Wang et al. [21] put forward an experimental method to calibrate the robotic grinding tool dynamically and the eccentricity of contact wheel in the real

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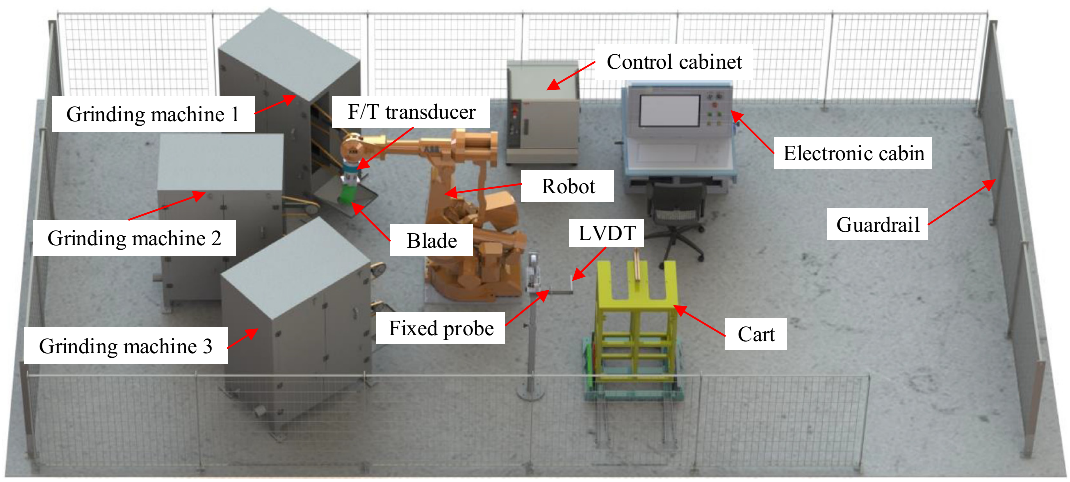

Fig. 1. The schematic diagram of the RBGS.

grinding process is considered in the paper, the robotic grinding style and its different effect, however, is not analyzed. Sun et al. [22] presented a static relative calibration method by holding the trigger to calibrate the TCP and workpiece and the zero reference in the paper is extremely vital to the calibration results, whereas, it is difficult to define and seek the zero reference in the real robotic grinding process and the specific calibration and analysis workpiece frame is not mentioned and discussed.

It is well observed that, the existing calibration methods are generally lack of detailed analysis of the overall calibration including the workpiece and tool frame calibration in the robotic belt grinding system (RBGS), thereby resulting in certain limitations and drawbacks in the robotic calibration system. Therefore, the improved calibration methods of RBGS, including tool (grinding machine) frame and workpiece (aero-engine blade) frame based on the calibrated flexible and fixed probe frame, are introduced to calibrate the RBGS precisely. Specifically, the sphere-to-sphere calibration method replacing the traditional point-to-point method is firstly proposed to obtain the flexible and fixed probe frame accurately. Then, the method to precisely seek the origin point of tool frame is put forward to finish the calibration of the tool frame. Next, both the rough calibration method (manual calibration) and fine calibration method (auto calibration) are introduced to obtain the workpiece frame accurately. Finally, experiments relating to robotic belt grinding of aero-engine blades are conducted to test the validity and practicability of the proposed calibration methods.

2. Calibration of the RBGS

Fig. 1 shows the schematic diagram of the RBGS mainly consisting of machining system, calibration system and control system, in which the calibration system is of particular importance to the subsequent robotic belt grinding process and it contains the 6-Degree-of-Freedom (6-DOF) robot, flexible probe, fixed probe and criterion sphere.

The coordinate frame of RBGS, as shown in Fig. 2, is mainly divided into two parts: the known ({B} and {Tool0}) and the unknown ({W_b'} and {T}). For the latter part, the {W_b'} and {T} should be calibrated to complete the robotic belt grinding of workpiece by introducing the ruby probe and criteria sphere. Therefore, the calibration includes the flexible probe frame {C}, fixed probe frame {P}, grinding machine frame {T} and aero-engine blade frame {W_b'}. The frame {C} and {P}, treated as the auxiliary frame, should be calibrated firstly, and then they are used to calibrate the {T} and {W_b'}.

2.1. Calibration of auxiliary frame {C} and {P}

Fig. 3 illustrates the general principle of the traditional 4-points calibration algorithm [23], which is based on the CCD camera to calibrate its relationship with the robot, and could be used to calibrate the robotic system frame. Some strict requirements should be satisfied to finish the calibration in the process of robotic system calibration, for example: (1) The calibration process must be point-to-point (calibration bar to fixed bar) by man-made; (2) the position of calibration bar, installed on the robot end-effector, cannot be changed in the process of robot calibration by using the reorientation mode of ABB robot in order to realize the space sphere fitting; and (3) the change of robot orientation should be large enough to ensure the calibration accuracy. Hence, the above strict requirements also bring some disadvantages: The difficulty in realizing the strict point-to-point process, as well as the poor calibration and fitting accuracy. Most importantly, the position of calibration bar point, regarded as the center of fitted space sphere, is always changing when the robot moves, and this could bring certain errors to the subsequent calibration. Therefore, this paper introduces an improved calibration algorithm to obtain the auxiliary frame which is divided into flexible and fixed probe frame in the RBGS.