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Multi-sensor measurement system for robotic drilling

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ABSTRACT

In this paper we present a multi-sensor measurement system for robotic drilling. The system enables a robot to measure its 6D pose with respect to the work piece and to establish a reference coordinate system for drilling. The robot approaches the drill point and performs an orthogonal alignment with the work piece. Although the measurement systems are readily capable of achieving high position accuracy and low deviation to perpendicularity, experiments show that inaccuracies in the test scenario and slippage on the work piece when exerting clamping force considerably impact the results. With the current robotic drilling system an average position deviation of 0.334 mm and an average deviation to perpendicularity of 0.29° are achieved.

1. Introduction

Drilling and riveting is a key operation in the assembly of airplane structures. An aircraft fuselage or wing consists of multiple large-scale skin sheets mounted on supporting structures (stringers, frames) for stability reasons. The connection between external shell and internal supporting structure is achieved through riveting. Between 5000 and 15000 rivets are typically secured in place for each skin panel. The process of drilling and riveting covers the following steps: First the components to be joined are clamped. Clamp-up is necessary to avoid vibrations and build-up of dust and chips in-between layers of multi-layer, multi-material stacks during drilling as well as to facilitate jam-free insertion of bolts during riveting. Then a hole with countersink is drilled. In order to establish a keyed and friction-locked connection, a sealing compound is applied; a rivet is inserted and fastened. For safety reasons, the qualities of materials and of assembly processes pose tremendous requirements on aircraft manufacturing and necessitate constant quality assessment and control. The material range includes aluminum, steel and titanium alloys, composites such as carbon fiber reinforced plastics or glass laminate aluminum reinforced epoxy.

Drilling and riveting are accomplished in one of the following three ways: manually, by specialized riveting machine, or by robot. In manual operation, an operator uses a hand drill to drill a hole and a fasting tool to secure the rivet. Though being highly flexible, manual assembly suffers in terms of quality, repeatability and speed. In addition, processing dust can pose health risks to operators. Specialized riveting machines offer fully automated drilling and riveting capability and achieve high accuracy, repeatability, and efficiency [1]. In addition, automated machining facilitates documentation of process parameters and monitoring of quality. Gantry equipment with specialized machining tools used to move work piece and riveting head, however, require significant investments in terms of equipment and support infrastructure. This makes such machines considerably less flexible. Industrial robots equipped with drilling and riveting end effectors offer a certain compromise between, on the one hand, flexibility of operation and, on the other hand, quality, efficiency and speed [2,3]. However, robotic machining still is a challenging task due to the various kinds of errors influencing pose accuracy as well as lack of mechanical stiffness of robotic joints and the end effector [4]. Even today, industrial robots are mainly deployed in manufacturing tasks that are highly repetitive such as handling and welding. For this purpose, robots are optimized to achieve consistent results for repeating tasks (repeatability). In contrast, robot accuracy describes the error between the requested task and the actual task reached by the robot. For example, a standard KUKA KR210 specifies a repeatability of ± 0.06 mm, but experiments imply an absolute accuracy of only ± 3.0 mm. Consequently in order to achieve high accuracy drill holes, the robot accuracy needs to be kept in mind. There are different sources of errors influencing a robots' accuracy; for a detailed error analysis see e.g. [5]. Compensation of such errors is either accomplished through models (e.g. kinematic calibration) or using an external measurement system; e.g. through additional encoders on each robot joint [6] or optical systems [7].

Due to the size of work pieces in airplane assembly, referencing of

Abbreviations: CMM, Coordinate measuring machine; TCP, Tool center point

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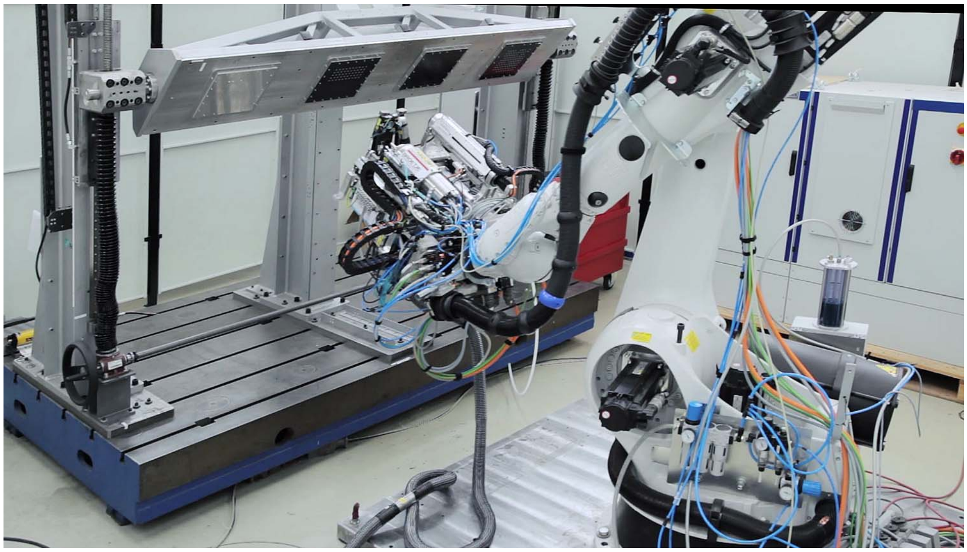

Fig. 1. Robotic drilling and riveting cell; test setup.

the robot to the work piece, i.e. the determination of the relative transformation from either robot base or robot end effector, respectively, to work piece coordinate systems to specified precision, poses a challenge. There are three approaches to implement this: global, semi-local, or local referencing.

In global referencing, the absolute poses of the robot as well as the work piece with respect to a common coordinate frame is either known or needs to be precisely measurable. The common coordinate frame provides the means to transform coordinates from robot to work piece and vice versa; even in case of robot repositioning on a 7th axis provided the common coordinate frame is maintained.

In semi-local referencing, only a rough estimate of the absolute pose of the work piece is required. In addition, the work piece is assumed to exhibit reference features in the robot's work space which, when measured by the robot, can be used to establish a reference coordinate frame of the work piece (relative to the robot). For this to work, on the one hand, the robot's absolute pose needs to be precisely measurable and, on the other hand, the robot needs to be equipped with an internal measurement system which can recognize and localize the reference features. The rough pose estimate of the work piece ensures that the robot is able to position the internal measurement system in view of the reference feature being measured. In case of a robot repositioning, the semi-local referencing needs to be repeated based on reference features measurable in the repositioned work space.

In local referencing, the work piece is assumed to exhibit reference features in the vicinity of each work point which, when measured by the robot with an internal measurement system simultaneously, can be used to establish a reference coordinate frame for each individual work point. Here, rough absolute pose estimates for the robot and the work piece suffice. Whereas local referencing can do without, semi-local and global referencing require precise absolute pose measurements.

In aircraft manufacturing, precision machining requirements are demanding [3,6,8,9]. Acceptable values for the position accuracy of drill holes are in the range of ± 0.5 mm [9]. In order to ensure the functional capability of rivet connections, the orthogonality of drill holes is required not to exceed 0.5° [10,11]. Different approaches for orthogonal alignment of robotic tools are presented in literature. Eguti et al. [10] describe a movable clamp nose whose deviation is measured by four inductive sensors. With this method a deviation to perpendicularity of ± 0.5° is achieved. A method for freeform surfaces is described by Lee [12]. Here five light laser spots are used to calculate the orthogonality. With this approach a mean angular deviation of 0.846° degrees is achieved.

In this paper a multi-sensor measurement system for semi-local referencing and orthogonal tool alignment for robotic drilling is presented. For a detailed description of two approaches examined and used to boost robot accuracy in the described test scenario, we refer to a paper by our colleagues [5]. Notwithstanding, the measurement systems are independent of the particular approach taken to boost robot accuracy and, due to robot pose error being the dominant source of error, are designed and set up in such a way as not to introduce significant additional errors. The paper is organized as follows: In Section 2 the system design and the sequence of operations are outlined. In Section 3 the hardware specifics of the multi-sensor measurement system on the end effector is described in detailed, while in Section 4 the usage of this hardware to solve the measurement tasks referencing and orthogonal alignment are explained. The description of the necessary system calibration is contained in Section 5. In Section 6 the experimental setup and the results achieved are presented. Finally the paper is summed up with a conclusion and outlook in Section 7.

2. System design and sequence of operation

The robotic drilling and riveting cell consists of an industrial robot KUKA KR210 with a maximum reach of 2901 mm and a maximum payload of 210 kg. The repeatability is specified as ± 0.06 mm, but experiments indicate an absolute accuracy of only ± 3.0 mm. The robot is equipped with a tool changer carrying an actuated end effector (see Fig. 1). The end effector and tool changer weigh a total of 170 kg.

The end effector carries all relevant tools for drilling and riveting; the setup for drilling is illustrated in Fig. 2. The spindle is equipped with a HSK tool holder. It is mounted on a linear actuator which drives the spindle along the working axis towards and away from the work piece (spindle z actuator). In addition, a linear actuator is used to move different tools such as drilling spindle, measurement systems and rivet gun across the end effector frame to align with the working axis (tool y actuator). Contact with the work piece is established through the clamp nose with a three-point bearing. The clamp nose is mounted on a linear actuator with 24 mm stroke (clamp nose z actuator). All linear actuators are equipped with linear displacement sensors which can precisely measure the traveling distances. The linear actuators of the drilling spindle along z and the clamp nose are, moreover, equipped with force sensors which can measure the pressure applied on the work piece (e.g. in order to avoid deformation of the work piece). Drilling lubricant is supplied through a dispenser placed at the robot base. Drilling chips and dust as well as excess lubricants are extracted via suction device attached to the clamp nose. Detailed descriptions of the other measurements systems are contained in Section 3.