ARTICLE IN PRESS

Journal of Manufacturing Systems xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Quick health assessment for industrial robot health degradation and the supporting advanced sensing development

Guixiu Qiao*, Brian A. Weiss

National Institute of Standards and Technology 100 Bureau Drive, MS 8230, Gaithersburg, MD 20899, USA

A R T I C L E I N F O

Keywords:
Robot health assessment
Industry robot
Robot accuracy degradation
Advanced sensing
PHM

A B S T R A C T

Robotic technologies are becoming more integrated with complex manufacturing environments. The addition of greater complexity leads to more sources of faults and failures that impact a robot system's reliability. Industrial robot health degradation needs to be assessed and monitored to minimize unexpected shutdowns, improve maintenance techniques, and optimize control strategies. A quick health assessment methodology is developed at the U.S. National Institute of Standards and Technology (NIST) to quickly assess a robot's tool center position and orientation accuracy degradation. An advanced sensing development approach to support the quick health assessment methodology is also presented in this paper. The advanced sensing development approach includes a seven-dimensional (7-D) measurement instrument (time, X, Y, Z, roll, pitch, and yaw) and a smart target to facilitate the quick measurement of a robot's tool center accuracy.

1. Introduction

Advanced technologies are emerging in manufacturing, especially in the domain of cutting-edge information and communication technology, to improve manufacturing competitiveness and efficiency. Smart Manufacturing, which is the fourth revolution in the manufacturing industry, presents a fully-integrated and collaborative manufacturing system that responds in real time to meet the changing demands and conditions within factories and supply networks [1,2]. The successful implementation of smart manufacturing will bridge and connect hardware, software, and data to increase operational efficiency, asset availability, and improve quality while decreasing unscheduled downtime and scrap [3–6]. As smart manufacturing evolves, industrial robots are filling the need for advanced solutions in many manufacturing environments including automotive [7–9], electronics [10,11], consumer packaged goods [12], and aerospace manufacturing [13–15]. Smart Manufacturing is having a positive impact on factory floor-level robotic operations. More diverse systems, sub-systems, and components are being connected to increase the robot work cell capabilities. However, more complexity can lead to more sources of faults and failures. A robot system's health degradation, including robot tool center position (TCP) accuracy degradation, can compromise the efficiency, quality, and productivity of a manufacturing system. It is important that the robot system's health degradations are understood so that maintenance and control strategies can be adjusted to compensate for these degradations.

An industrial robot system is defined to include a robot, end-effector (s), and any equipment, devices, or sensors required for the robot to perform its tasks [16]. Many possible faults and failures could occur within the robot system given this system complexity. Faults and failures can be divided into three principal categories [17–19]: *faults, soft failures, and hard failures.* A *fault* is defined as a defect that is an inherent weakness of the design or implementation. For example, a fault could be an incorrect signal value or an incorrect decision within the system. A fault may result in a system's degradation [20]. A *soft failure* is defined as a condition when the system performance starts to degrade, where 'wear and tear' and/or external changes have occurred that have compromised the baseline health of the system. Under a *soft failure*, the manufacturing process is not capable of meeting its performance specifications [21]. If the performance degradation worsens, quality can decrease below specifications indicating a defect or unacceptable result. A *hard failure* is defined as a condition when a component or a piece of equipment breaks, or a system or component is unable to function as required [20]. In the hard failure condition, the manufacturing process is typically either frozen or shut down.

Faults and failures can impact a robot system in numerous ways, including influencing some key performance factors of a robot, e.g., accuracy, velocity, force, and torque. These factors are commonly identified as critical indicators of the system health. Robots are employed to move and manipulate end-effectors accurately (e.g., grippers, welding wands) to certain specifications. Tool center accuracy can be used to assess the health of an industrial robot. For example, accuracy is

* Corresponding author.
E-mail addresses: guixiu.qiao@nist.gov (G. Qiao), brian.weiss@nist.gov (B.A. Weiss).

https://doi.org/10.1016/j.jmsy.2018.04.004
Received 16 December 2017; Received in revised form 2 April 2018; Accepted 9 April 2018

Please cite this article as: Qiao, G., Journal of Manufacturing Systems (2018), https://doi.org/10.1016/j.jmsy.2018.04.004

a critical health factor for applications that demand both position and path accuracy (e.g., arc welding, robot machining, and robot composite material layout). If accuracy degrades, a robot will weld or drill at incorrect positions. The production quality will be compromised. Accuracy is also critical for applications that are using an external system to position parts relative to the robot arm, or using an external system to guide a robot's operation. For example, a vision system may be used to locate a part; this information would be passed to the robot controller that would then command the robot to pick it up [22]. The degradation of a robot's position and orientation accuracy will lead to a decrease in manufacturing quality and production efficiency. Given the high output rate of production lines, it is important to develop techniques to assess a robot system's health conditions that predict soft and hard failures. Robot health degradations are less observable compared to system freezes or shutdowns. In the robot health degradation condition, the robot is still running and appears to be making parts, but actually working at a decreased level of performance and/or quality.

As a subset of the NIST's Prognostics, Health Management, and Control (PHMC) project, PHMC for robotics research is ongoing. The research aims to develop the measurement science within industrial robotics domains to promote the advancement of monitoring, diagnostic, prognostic, and maintenance strategies [23,24]. One output of this research involves developing a quick health assessment methodology emphasizing the identification of the robot accuracy changes. This methodology will enable manufacturers to quickly assess the robot's tool center position and orientation accuracy degradation.

Section 2 in this paper will give an overall view of the quick health assessment methodology. Details of the modeling and algorithm for the methodology are presented in previous publications (refer to [25,26]). Section 3 will present the development of the vision-based 7-D measurement system. Section 4 will present the innovative design of the smart target. Section 5 wraps up the paper and highlights future work.

2. Workflow of the quick health assessment methodology

A quick health assessment is a methodology that aims to assess the robot tool center accuracy degradation throughout the robot work volume. The methodology includes: 1) advanced sensing to measure the robot tool center positions and orientations; 2) a test method to predefine the robot movements and model the robot errors to reflect the robot geometric and non-geometric errors; and 3) algorithms to process measured data to get the robot health assessment using limited measurements. The quick health assessment methodology addresses the following challenges:

1) Measuring the actual robot positions and orientations with the minimum interruption of production. The details of the challenges and solutions for the advanced sensing development will be presented in Section 3 and 4 of this paper.
2) Assessing the robot tool center errors from all directions. As shown in Fig. 1(a), a robot could have multiple inverse kinematic solutions to reach to a three-dimensional position in Cartesian space. As a result, the error magnitude and direction can change by choosing different inverse kinematic solutions. This makes the assessment of the tool center accuracy difficult since it's hard to measure the accuracy from all directions.
3) Assessing the accuracy of the whole robot work volume using limited measurements. A robot may work on different tasks within its work volume using different poses. As shown in Fig. 1(b), the spherical space is the work volume calculated for this robot. The inner layer represents the work volume calculated for the robot tool center. The outer layer of the spherical space represents the work volume calculated for the current tool. The quick health assessment methodology should assess the robot's accuracy degradation over the whole work volume with all possibilities of different poses of the arm. It's impossible to take unlimited measurements since the interruption of production is expensive. An efficient test method is needed to assess the robot's overall health using limited measurements.
4) Decoupling the measurement instruments' uncertainty from the actual robot errors: The uncertainties coming from measurement instruments are usually treated as joint errors [27]. In this case, the assessment results may be biased. The modeling and algorithm development are needed to solve these challenges.

The goal of the methodology is to enable manufacturers to assess a robot's tool center accuracy degradation quickly. The quick health assessment can quickly detect problems if the of environmental conditions change, reconfigurations occur in the work cell, or manufacturers need to make sure the robot has not experienced a degradation when an important part is put in the work cell. The use of this methodology will monitor the degradation of robot performance, reduce unexpected shutdowns, and help the optimization of maintenance strategy to improve productivity.

The workflow of the quick health assessment development is shown in Fig. 2. The workflow contains the development of advanced sensing used to take measurements (will be presented in Section 3 and 4), a test method, algorithms for data processing and health assessments, the root cause analysis, and PHMC remedy techniques.

To address the second and the third challenges previously listed, a test method with a fixed loop motion was developed. An important feature of the test method is that it requires the robot movements to be evenly distributed in both joint space and Cartesian space. The even distribution in joint space prevents missing errors or adding too heavy weights on errors. The even distribution in Cartesian spaces enables the evaluation of the arm accuracy and rigidity throughout the robot working volume. A fixed loop motion is designed to satisfy those requirements. In the meantime, collision avoidance of the robot arm with

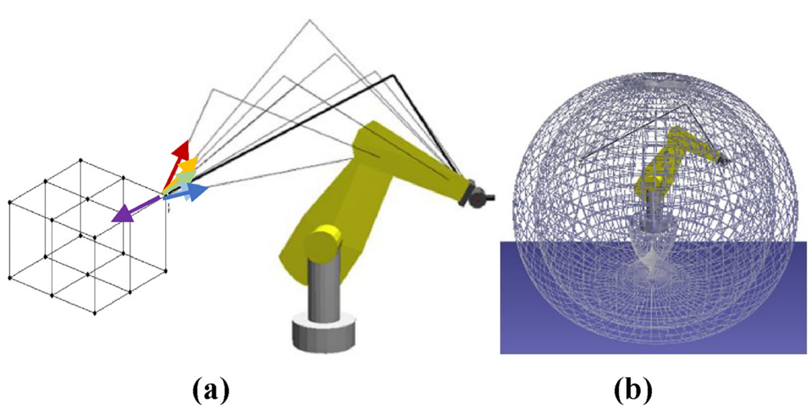

Fig. 1. Robot working volume and multiple inverse kinematic solutions in Cartesian space.