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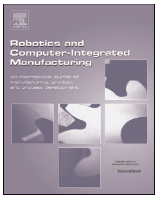

Review

A performance evaluation methodology for robotic machine tools used in large volume manufacturing

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ABSTRACT

The manufacture of large components in various industries can create health, safety and economic challenges as a result of machining operations. A potential solution is the replacement of conventional large machine tools with low-cost and portable robotic machine tools, although these lack accuracy and precision in comparison. Effort is therefore required to develop robotic machining technology to a state where it can be implemented in high tolerance applications using a variety of materials. A barrier to implementation is that there is not a standardised procedure available to robustly assess current robotic machining performance, which makes it challenging to assess the impact of technological developments. This paper develops a methodology to determine robotic machining performance based upon reviews of standards available that currently specify such guidelines for robotics and machine tool technologies used independently. It is found that useful elements from each theme can be combined and applied to robotic machine tool performance evaluation. These are presented here with the aim of forming a conceptual foundation on which the technology can be developed for large volume manufacturing.

Contents

1. Introduction

Production of large components in the oil and gas, aerospace, defence, marine, rail and energy sectors is highly capital intensive due to the requirement for large machine tools. For example,

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pressure vessels in nuclear power plants can reach 20 m in height and 5 m in diameter, weighing up to 560 tons [1]. It is beneficial to develop low cost *"process-to-part"* robotic machining technology as an alternative to conventional machine tools. With robotic machine tools, there is potentially less capital investment requirement, lower lead times, no need for remounting parts after inspection for defect correction and less dependence on heavy lifting.

A barrier to implementation is the dimensional errors associated with robotic machining, partly due to the relatively low dynamic stiffness and low resistance to machining forces [2,3]. Joint stiffness is specifically highlighted as being a influence on part quality by Dumas et al. This metric is difficult to obtain from robot manufacturers and user evaluation is recommended [4]. Geometrical errors in robot links and joints cause assembly misalignments and also influence positional accuracy, justifying robot specific kinematic model development for compensation, as discussed by Weill et al. [5]. Kinematic modelling challenges are faced for unconventional parallel robot structures as they are often complex and have many joints, despite their stiffness benefits [6–8].

Gong et al. suggest that non-geometric robot errors should also be offset by accounting for thermal variations and joint flexibility under load [9]. Thermal concerns are supported by Kamrani et al. [10]. Olabi et al. highlight that trajectory planning is a key non-geometric contributor to path error [11]. This issue and robot feed rate accuracy, as assessed by Young and Pickin [12], are key research areas for improving machined surface quality. Conventional machine tool issues, including tool deflection, gear back lash and wear [11], are exaggerated in robotic machining due to structural differences [13].

Robot machining difficulties are widely covered in the literature, with further notable research documented in [14–28]. Adopting robotic machining technology is therefore dependent on these issues being overcome through research and development of methods to offset the dimensional errors. A standardised performance evaluation procedure is desirable to facilitate a universally credible and repeatable assessment of technology improvements [29].

A challenge faced in robotic machining is that it is not supported by international codes and standards, although robotics and machine tools are supported independently. This issue is highlighted in [30] where it is noted that machine tools standards are typically not applicable to robotic kinematic structures. This paper therefore reviews the performance evaluation standards available in the two fields to determine which elements can be best applied to the combination of technologies to assess errors unique to robotic machining. For example, instead of linear guideways and gantries there are unique arrangements of joints and actuators whose sensitivity to error is not necessarily exposed using non-specific test geometry. The outcome of this paper is a robotic machining performance assessment methodology, which will reduce the barrier to usage by providing a means of quantifying the machining tolerance range of a particular system.

A performance assessment methodology is developed by reviewing robotics and machining standards, which allows for the evaluation in static and dynamic conditions. Static performance is considered, i.e. robot positional accuracy and precision without the effect of machining dynamics, because it allows a basic idea of performance to be gained at a low cost. Static assessment allows application suitability to be quickly identified if errors consume a large amount of the tolerance budget as this means it is unlikely that tolerances would be met with additional dynamic error sources. Static experiments also allow an insight to be gained into robot-specific error sensitivity, which can aid the selection of test geometry in machining performance studies.

This paper initially presents a case study in Section 2 to highlight the potential application of robotic machine tools in large component manufacturing. Robotics and machining standards are then reviewed in terms of procedures, theory and test geometry in Sections 3 and 4, respectively. A robotic machine tool performance evaluation methodology is then proposed by combining relevant standards in Section 5, with a final summary and conclusions being given in Section 6.

2. Case study

To set the context for robotic machine tool performance evaluation methodology development, two hypothetical feature-level machining operations are considered on a large vessel. Firstly, instrument penetrations must be machined in the vessel. Secondly, in preparation for hydrostatic pressure testing, these penetrations are capped by with a welded plate, which must be machined off after the test [31]. Conventionally, instrument penetration and cap machining would be done on a horizontal milling machine sized to mount the entire vessel onto it, according to the following steps [32]:

1. Vessel lifting and orientation.
2. Vessel mounting to machine tool.
3. Execute machining operation.
4. Reiterate *Steps* 1–3.

Alternatively, machining operations could be done using a robotic machine tool. This would only be sized to have a working envelope large enough to cover the individual features being machined and would not need to be built into a larger structure supporting the entire component. In this case, the following steps would be taken:

1. Lift vessel into work zone.
2. Secure vessel in place.
3. Position robot in feature region.
4. Execute machining operation.
5. Reiterate *Steps* 3 and 4.

Conventional, the component is moved and reorientated on the machine tool in situations where there are multiple vessel features inaccessible from one direction. This requires multiple machine set-ups, which demand heavy lifting and the associated health and safety risks, which increase in severity with vessel scale. In robotic machining, only the robot is repositioned around the vessel to machine individual features. This can be achieved using large volume measurement systems and the use of additional programmable axes is not necessary. Robotic machine tools can be used in this way regardless of overall component scale, as they are just repositioned to the feature region of interest. Overall, robotic machining offers an opportunity for cost reduction, although structural differences mean that the standards used to assess machine tool performance are not applicable [30].

3. Robot performance evaluation standards

A range of standardisation organisations offer robotics-based guidelines [33–39], covering issues surrounding applications far beyond those associated with industrial usage. Those that focus on industrial robotics address issues concerning the generic subsystems and components that could be applicable to a range of engineered systems as well as the following: