Sensing and Control for Automated Robotic Edge Deburring

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Abstract— **This paper describes the sensing and control elements of a system for automated robotic edge deburring. The deburring path, automatically generated by a task planner, is corrected on-line by an active end effector with the objective of controlling the chamfer depth. The sensing system combines the information from force and vision sensors during deburring to provide an improved depth measurement. The vision sensor is then used to verify the deburring performance during an inspection pass. The control system incorporates a new form of adaptive Generalized Predictive Control (GPC) combined with learning control, termed GPC with Learning (GPCL). The system is tested through computer simulations and deburring experiments. The experiments were performed on steel parts with one-dimensional (1-D) and two-dimensional (2-D) edges. For the 1-D edges the depth's standard deviation measured on-line was 0.015 mm with nonadaptive GPC, 0.009 mm with adaptive GPC, and 0.006 mm with adaptive GPCL. With adaptive GPCL and the 2-D edge the deviation was 0.017 mm. This was confirmed by the inspection pass measurements which reported a mean of 0.39 mm and a deviation of 0.019 mm.**

I. Introduction

EVEN in today's most fully automated factories it is still a common sight to see dozens of workers manually deburring parts produced by CNC machines. Automated robotic deburring systems have been investigated for a number of years as a replacement for the costly and unpleasant manual operation. In manual deburring machining burrs are often removed from part edges by chamfering. The deburring specifications can require the chamfer depth to be within tight tolerances. Consequently, much of robotic deburring research has been concerned with controlling the depth of cut when chamfering with non-compliant cutting tools. Due to the poor accuracy of most industrial robots, part positioning errors, and deflections of the robot arm due to cutting forces, position control cannot be used alone to control the depth. Hybrid position/force control has been used by several researchers, [1]–[4] for example. The deburring force has been shown to be approximately proportional to the material removal rate (the feedrate times the chamfer plus burr areas). It can therefore be controlled by adjusting the feedrate tangential to the edge. This strategy is most suitable to applications where the burr area is variable and is a large percentage of the chamfer area. An alternate approach has been to control the normal force by making position corrections to the robot's path normal to the part edge. If the burr size, material hardness, and feedrate variations are small, this approach results in a controlled chamfer depth. The normal force component is preferable to the tangential one, as it has been shown to be less sensitive to burr area variations [5]. These corrections may be performed by the robot itself, or by an independently controlled active end effector mounted between the robot and the tool. Several researchers have developed active end effectors that are able to achieve much greater positioning accuracy and actuator bandwidth than most industrial robots [1], [4], [6]. At the present time, mostly nonadaptive control algorithms have been used. For good performance these schemes require the robot arm and deburring process dynamics to be relatively time invariant. In practice, however, the robot arm's stiffness is known to vary with configuration, and the deburring process is affected by changes in cutting conditions and part material. A simulation study by Bone *et. al.* [7] concluded that parameter adaptive control provided significant improvements in control bandwidth and robustness over nonadaptive schemes for deburring. Robust, high bandwidth control is required for deburring complex part contours at high feedrates. An adaptive Smith Predictor and a form of Model Reference Adaptive Control were investigated. Duelen, Münch, and Sirdilovic [3] simulated a hybrid position/force control algorithm which adapted to changes in the deburring process. Their results show greatly improved robustness in comparison to the non-adaptive case. Liu and Asada [8] have developed an adaptive controller for deburring based on a human skill model. On-line process parameter estimates were used to evoke the appropriate control actions from associative memories trained from human demonstration data. In deburring experiments the system outperformed a system in which the feedrate was held constant. One limitation of these control approaches is that the cutting force was used alone to monitor the deburring process. When the variations in burr size, material hardness, or feedrate are large, the normal force can no longer be used as an accurate measure of the chamfer depth. Force control is also prone to overshoot or even instability at the time of initial contact [2], [3]. Despite these facts, few alternative or additional sensors have been investigated.

Dornfeld and Erickson [9] have used acoustic emission feedback for controlling very shallow chamfers, with results comparable to those of Hollowell and Guile [1] using force control. Seleck and Loucks [2] used a vision sensor to determine the part orientation prior to deburring under force control. They also inspected the chamfer width and angles (top and bottom) at a rate of 2 Hz. Vision sensing has been

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