Robotica (1989) volume 7, pp 303–308

Robotic force control for deburring using an active end effector

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(Received: December 21, 1988)

SUMMARY

An active force control system for robotic deburring based on an active end effector is developed. The system utilizes a PUMA-560 six axis robot. The robot's structural dynamics, positioning errors, and the deburring cutting process are examined in detail. Based on ARMAX plant models identified using the least squares method, a discrete PID controller is designed and tested in real-time. The control system is shown to maintain the force within 1 N of the reference, and reduce chamfer depth errors to 0.12 mm from the 1 mm possible without closed-loop control.

KEYWORDS: Deburring; End Effector; Robot Control; Closed-loop.

1. INTRODUCTION

The formation of unwanted burrs is common to all machining, forming and casting processes. The burrs must be removed for a variety of reasons: to guarantee component fit, prevent injury to workers, enhance workpiece appearance and to improve the effectiveness of further finishing operations.[1]

The majority of machining burrs are removed by manually chamfering the burred edge with a high-speed cutting tool. The labour intensive nature and quality control problems inherent to manual deburring have prompted the development of automated deburring systems.

Robotic deburring systems, where the cutting tool is guided by the robot arm, are capable of deburring at faster rates with higher chamfer quality than possible manually.[2] By controlling the deburring force the desired chamfer depth can be maintained.

In terms of hardware there are two main methods for implementing active force control. With "through the arm" control, the force is controlled by making position adjustments normal to the part edge. In some systems the tangential speed is adjusted. The performance of this method is limited by the poor accuracy and slow response of most robot controllers. "Through the arm" control was applied to deburring in.[3–6]

With "around the arm" control, the position adjustments are performed by an independent active end effector. Since only the small end effector (and not the entire arm) is controlled, greater accuracy and control bandwidth can be achieved.[3,7]

Paul, Gettys and Thomas;[8] Zalucky and Hardt;[9] and Tlusty and Wegerif[10] have implemented active end effector based systems to reduce deflections of the robot arm under load. Hollowell and Guile[11] have implemented single and two axis end effectors for deburring with promising results; while a system by Kazerooni and Guo[12] is under development.

An excellent overview of robotic force control strategies is given by Whitney in.[13] Used initially for force control in assembly, a number of simple control laws were developed based on simplified static models for arm and environment stiffness. The first was stiffness control:

$$x_c = K_s(F_r - F_m) \tag{1}$$

$$= K_s E \tag{2}$$

Where: x_c is the commanded position,
K_s is the controller stiffness,
F_r is the reference force,
F_m is the measured force, and
E is the force error.

Stiffness control was applied by Tlusty and Wegerif[10] to control arm deflections in a routing operation. The robot's positioning errors were not eliminated.

With damping control

$$x_c = K_b \int E \cdot dt \tag{3}$$

where K_b is the controller damping, the error is integrated to eliminate any steady state offset. Hollowell and Guile[11] used a controller of this type.

A more general form incorporating both stiffness and damping terms is impedance control, with:

$$x_c = K_s E + K_b \int E \cdot dt \tag{4}$$

In this form impedance control is identical to conventional proportional-integral (PI) control. Proportional-integral-derivative (PID) control was used by Haefner et al.,[5] and Stepien et al.[6]

Kazerooni[14,15] has applied a different form of impedance control to the robotic deburring problem. He forces his end effector to behave like a passive compliance device, as follows:

$$M_e \ddot{x}_c + C_e \dot{x}_c + K_e(x_c - x_r) = -F_m \tag{5}$$

Where: M_e is the effective mass,
C_e is the effective damping,
K_e is the effective stiffness, and
x_r is the reference position.

This can be rewritten as

$$M_e \ddot{x}_c + C_e \dot{x}_c + K_e x_c = E \tag{6}$$