# An Automated Planning, Control, and Inspection System for Robotic Deburring

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Received on January 15, 1992

**Summary**

This paper describes a system for the automated planning, control and inspection of robotic edge deburring. The task planner uses an object-oriented distributed artificial intelligence approach along with computer-aided design models to plan a collision-free path. The path is adjusted on-line to maintain the desired chamfer depth of cut using a high-bandwidth active end effector. The control system incorporates: a) sensor fusion of force and vision data, b) parameter adaptive predictive control, and c) learning control. Task completion is verified through in-process inspection of the chamfered edges. Simulation as well as experimental results are presented.

**Key Words**

Robots, deburring, adaptive control.

## 1. Introduction

Manual deburring has been known to be an inefficient, and often unpleasant operation for many years, and is still part of most manufacturing environments. One of the key reasons why it has resisted automation is the lack of control systems and sensors sophisticated enough for the complex deburring operation. Recently however, researchers have made significant advances towards the goal of a fully automated robotic deburring system.

An automated deburring system involves three stages. The first stage involves high-level task planning of the robot's movements. Low-level control is then used to correct for planning errors during the deburring pass. Finally, the part is automatically inspected. The system may then accept the part or return to the task planning stage for rework.

The primary goal of task planning is to generate the robot's motion program. Three distinct approaches have been investigated which differ mainly in the amount of planning which is done off-line and the amount of a priori knowledge required. Her and Kazerooni [1] used a force sensing roller bearing to track a 2-dimensional part edge with no a priori part knowledge. This method can only be used at slow feedrates and requires surfaces adjacent to the edge suitable for position reference. Seliger and Hsieh [2] describe a sensor-assisted programming approach where the end-points of the edges are manually taught and the remaining points are generated automatically from sensor measurements. The advantages of this approach are that the downtime is reduced compared with manual teach-in, and that the programmed points are more accurate (since the actual part geometry is measured). The third approach automatically generates the motion program from the deburring specifications and Computer-Aided Design (CAD) models of the workpiece, robot and tool. Although it requires the most a priori knowledge, this approach is the most desirable since the planning is performed entirely off-line, and correspondingly is the area of greatest research interest [3-6]. A secondary goal of task planning is the selection of appropriate deburring tools [7]. This requires models of burr formation and burr removal. The burr formation model could be based on an empirical database or on-line burr measurements. Kanda *et al.* [8] developed an expert system for tool selection based on empirical burr formation and removal models. Burr removal models relate the material removal rate and edge quality produced to the workpiece material, burr measurements, cutter type and cutting conditions [7]. For edge chamfering with carbide cutters a proportional model between the cutting force and the material removal rate has been adopted by many researchers ([1,9], for example).

Low-level control is used to correct on-line for the inevitable errors in the task plan due to imperfect models. Successful low-level control requires sensor(s) which accurately measure the controlled variable, and a suitable control strategy. Hybrid position/force control is the most popular approach [5,9,10]. The force may be controlled tangential to the edge by adjusting the feedrate. Alternatively, the normal force is controlled by position adjustments normal to the edge. Several researchers have used independently controlled active end effectors to perform these adjustments [1,9,11]. Because of their small size, these end effectors are able to achieve much greater positioning accuracy and actuator bandwidth than can be obtained using the arm alone (for most industrial robots). At the present time, only fixed parameter control algorithms have been used. A simulation study by Bone *et al.* [12] concluded that parameter adaptive control could provide significant improvements in control bandwidth and robustness over fixed parameter schemes. Robust, high-bandwidth control is required for deburring complex part contours at high feedrates. More recently, Duelen, Münch, and Sirdilovic [13] 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. Implicit in the use of force control in the normal direction is the assumption that the force is proportional to the chamfer depth, so that a constant force will produce a constant edge chamfer (given a constant feedrate). When there are material hardness or feedrate variations, or the burrs are large relative to the chamfer depth the force can no longer be used as a measure of the chamfer depth. Force control is also prone to overshoot or even instability at the time of initial contact with the workpiece [5,13]. Despite these facts, few alternate or additional sensors have been investigated. Dornfeld [14] has investigated the use of acoustic emission feedback for controlling very shallow chamfers. Selleck and Loucks [5] used a vision sensor to determine the workpiece orientation prior to deburring under force control.

A further area which has received little attention in deburring research is automated inspection. Much of the benefits of an automated deburring system may be lost if the often slow and subjective manual inspection process is used. The solution to this problem is to develop a deburring system with 100% reliability (a seemingly impossible task), or to automate the inspection process. A prototype vision based inspection system has been developed by Selleck and Loucks [5] which measures the chamfer width and angles (top and bottom) at a rate of 2 Hz using a structured light technique.

This paper describes a system for the automated planning, control and inspection of robotic edge deburring. The system structure is shown in Fig. 1. The task planner uses an object-oriented Distributed Artificial Intelligence (DAI) approach along with CAD models to develop the robot's motion program. When the robot controller executes this program the tool path is adjusted on-line to maintain the desired chamfer depth of cut using a high-bandwidth active end effector. The end effector control system incorporates: a) sensor fusion of force and vision data, b) parameter adaptive control, and c) learning control. Task completion is verified through in-process inspection of the chamfered edges. The system supervisor coordinates the robot and end effector controllers, communicates with the user, and logs the system's performance.

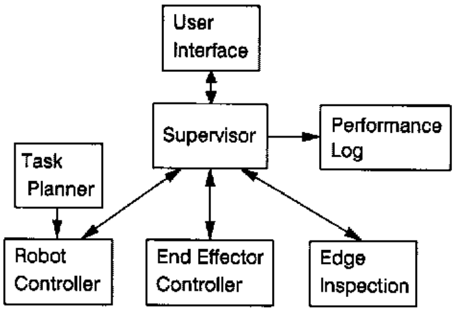

Fig. 1 Structure of the automated robotic deburring system.

## 2. Task Planning System

In this section the task planning system will be briefly described. Further details are provided in [6]. The task planner uses an object-oriented DAI approach. In DAI, a group of decentralized autonomous intelligent agents coordinate their knowledge and skill together for problem solving. Advantages of DAI systems over large monolithic systems include: increased real-time response; plus greater reliability, modularity, and reusability. Further merits of DAI for intelligent manufacturing systems were discussed by O'Hare [15]. Incorporation of object-oriented programming techniques into DAI allowed a new, more generic agent type to be developed. The current system is programmed in C++ on an engineering workstation.

### 2.1 System Structure

The organisation of the DAI task planner is shown in Fig. 2. The preprocessing module receives CAD models of the robot, tool, workspace, and workpiece, plus the deburring specifications. A blackboard data structure is used for internal information exchange. The DAI agents are objects of generic knowledge representations in that they may be small expert systems or procedural functions. These object-agents inherit their structure from a general master template, and are able to instantiate (reproduce) as required. Thus, this new type of agent has been termed an