Robotic Machining: Material Removal Rate Control with a Flexible Manipulator

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Abstract—**Practical material removal rate (MRR) control strategies for industrial robot are presented in this paper. Based on a force control platform, both force signal and spindle power information could be used for MRR measurement. Three different control methods, PI control, adaptive control and fuzzy control, are implemented to satisfy various process requirements. Performance and experimental results are presented and compared. With controlled material removal rate (CMRR), the productivity of robotic machining process could be increased dramatically.**

Keywords—**CMRR, force control, robotic machining**

I. INTRODUCTION

Cleaning and pre-machining operations are major activities and represent a high cost burden for casting producers. The cleaning operations account for 20-40% of the overall casting manufacturing cost. Subsequent machining operations may lead to expenditure equivalent to a further 40% of casting production costs. Machining processes, such as cleaning, milling, grinding, deburring, and saw cutting are promising applications for industrial robot with the drive from foundry automation.

On the other hand, industrial robots are rarely used in machining process nowadays, if compared with their widely usage in assembly, painting, wielding, material handling process, which does not require intensive contact between robot and its workpiece. There are huge advantages of using industrial robots to do machining tasks, such as, their programmability, adaptability, flexibility, and relatively low cost. But compared with CNC machine, the low stiffness and narrow stability region of industrial robots also presents challenges in designing control system for industrial robots used in machining process. [1]

One of the major hurdles preventing the adoption of robots for machining processes is the low material removal rate limited by the capability of robot (mostly due to its low stiffness) and motor spindle power. Machining processes are basically accomplished by applying process-specific tools to workpieces with certain amount of force. The machining force usually varies dramatically during the process due to the complex geometry of workpiece and variation of material engaged in the cutting.

The MRR in machining process is usually controlled by adjusting the tool feedrate. In robotic machining process, this means regulate robot feed speed to maintain a constant MRR. Machining force and spindle power are two variables proportional to MRR, which could be used to control robot feed speed. With 6-DOF force sensor fixed on robot wrist, cutting force is ready on real-time. Most spindles have an analog output whose value is proportional to the spindle current. With force feed back or spindle current feed back, MRR could be controlled to avoid tool damage and spindle stall.

In most cases, the relationship between process force and tool feedrate is nonlinear, and the process parameters, which describe the nonlinear relationship, are constantly changing due to the variations of the cutting conditions, such as, depth-of-cut, width-of-cut, spindle motor speed, and tool wearing condition, etc. Most of the time, conservative gains have to be chosen in order to keep the close-loop system stability but trading off control performances.

In this paper, three different control strategies, PI control, adaptive control and fuzzy control, are designed based on a force control platform to satisfy various process requirements. PI control is easy to tune and is very reliable. Adaptive control provides a more stable solution for machining process. Fuzzy control, which provides a much faster response by sacrificing control accuracy, is the best method for applications require fast robot feed speed.

This paper is organized as follows. Section II introduces the dynamic model of robot and force process. In Section III, the concept of material removal rate control is first introduced. Then three different control strategies are presented in detail. Section IV gives experimental results for various controllers. Finally, Section V provides some conclusion.

II. PROCESS MODELING

A. Robot dynamic model

A robotic milling process using industrial robot is shown in Figure 1. The robot used in the process is ABB IRB 6400 robot. The cutting force of this milling process is regulated by adjusting the tool feedrate. Since the tool is mounted on robot end-effector, the tool feedrate is controlled by commanding robot end-effector speed. Thus, the robot dynamic model for this machining process is the dynamics from the command speed to the actual end-effector speed. The end-effector speed is controlled by robot position controller. A model is identified via experiments for this position controlled close-loop system,

which represents the dynamic from command speed to actual end-effector speed.

Figure 1. Robotic end milling process

The dynamic model identified is given as

$$\frac{f(s)}{f_c(s)} = \frac{63s^2 - 45800\,s + 4330000}{s^3 + 575\,s^2 + 98670\,s + 4313000} \qquad (1)$$

Where f(s) is the actual end-effector speed, $f_c(s)$ is the commanded end-effector speed.

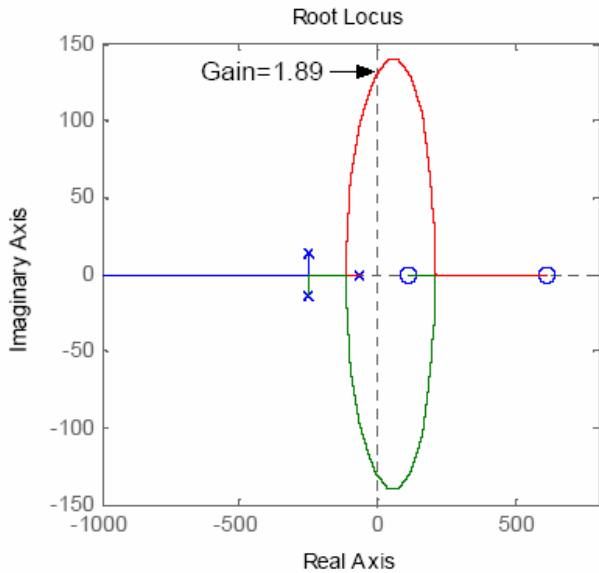The dynamic model (1) is a stable non-minimum phase system, and its root locus is shown in Figure 2.

Figure 2. Root locus of robot dynamic model

B. *Process force model*

MRR is a measurement of how fast material is removed from a workpiece; it can be calculated by multiplying the cross-sectional area (width of cut times depth of cut) by the linear feed speed of the tool:

$$MRR = w \cdot d \cdot f \qquad (2)$$

Where w is width-of-cut (mm), d is depth-of-cut (mm), f is feed speed (mm/s).

Since the value of MRR is difficult to measure, MRR is controlled by regulating the cutting force, which is readily available in realtime from a 6-DOF force sensor fixed on the robot wrist. The relationship between the machining process force and the tool feed speed is nonlinear and time-varying, as shown in the following dynamic model [2]

$$F = K_C d^{\alpha} f^{\beta} w^{\gamma} \frac{1}{\tau_m s + 1} \qquad (3)$$

Where K_C is the gain of the cutting process; α, β and γ are coefficients, and their values are usually between 0 and 1. τ_m is the machining process time constant. Since one spindle revolution is required to develop a full chip load, τ_m is 63% of the time required for a spindle revolution. [3] Since τ_m is much smaller than the time constant of robot system, it is ignored here in MRR controller design. Let,

$$K = K_C w^{\gamma} \qquad (4)$$

K is considered as a varied process gain. Then, the force model is rewritten as a static model:

$$F = K d^{\alpha} f^{\beta} \qquad (5)$$

The depth-of-cut, d, depends on the geometry of the workpiece surface. It usually changes during the machining process, and is difficult to be measured on-line accurately. The cutting depth is the major contributor that causes the process parameter change during the machining process. K, α and β depend on those cutting conditions, such as, spindle speed, tool and workpiece material, and tool wearing condition, *etc,* which are pretty stable during the cutting process. If the tool and/or the workpiece are changed, these parameters could change dramatically. But they are not changing as quickly as the depth-of-cut d does during the machining process as explained above. A force model, which is only valid for the specific tool and workpiece setup in ABB robotics lab is identified from experiment as

$$F = 23 d^{0.9} f^{0.5} \qquad (6)$$

Equation (6) models the process force very well in the lab. The tool feedrate f is chosen as the control variable, i.e., to control the process force by adjusting the feed speed. Since:

$$Fv = UI \qquad (7)$$

where F is cutting force, v is tool cutting speed, U and I is spindle voltage and current. Since v and U are constant at certain spindle RPM, spindle current I is proportional to cutting force F. Since most spindles have a current output, it could be connected to analog module of ABB controller and used as an approximation of cutting force. Using spindle current as feedback signal will reduce the cost of system by avoiding the setup of extra force sensor. Since the limit of a robotic

machining system might be either by robot structure (e.g. limited stiffness) or machine tool spindle power, using spindle current could only prevent the second limit while using force feedback could address both targets.

III. MRR CONTROL STRATEGY

In roughing cycles, maximum material removal rates are even more critical than precision and surface finish. Conventionally, feed speed is kept constant in spite of variation of depth-of-cut during the pre-machining process of foundry part. This will introduce a dramatic change of MRR, which induces a very conservative selection of machining parameters to avoid tool breakage and spindle stall. The idea of MRR control is to adjust the feed speed to keep MRR constant during the whole machining process. As a result, a much faster feed speed, instead of conservative feed speed based on maximal depth-of-cut position, could be adopted. Figure 3 illustrates the idea of MRR control while depth-of-cut changes during milling operation. The parallel blue curves are constant force contours and the red curve is the power limit of the spindle driver. [4]
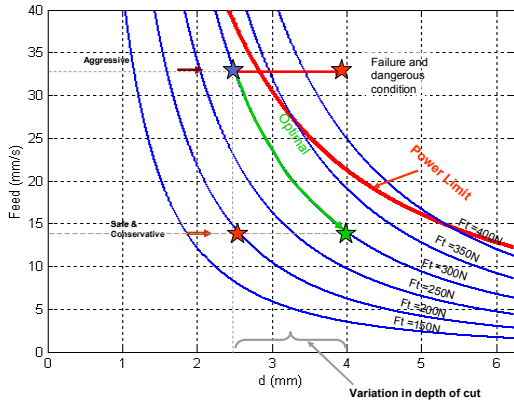

Figure 3. Controlled material removal rate

A. Force control sturcture

The active force control platform is the foundation of various CMRR strategies. It is implemented on the most recent ABB IRC5 industrial robot controller, which is a general controller for a series of ABB robots. As shown in Figure 1, an ATI 6 DOF force/torque sensor is equipped on the wrist of the robot to close outer force loop to realize implicit hybrid position/force control scheme. While the conventional position control is realized in joint space, force controller is implemented in Cartesian space. The force controller could be configured differently for various applications. CMRR is one of its functions in machining process control. The block diagram of CMRR is shown in Figure 4.

The cutting force is controlled by varying the robot end-effector speed in tool feed direction. The difference between the reference force and the measured cutting force is input to the MRR controller. In actual implementation, the robot motion is planned in advance based on a pre-selected command speed. The output of MRR controller is a term called speed_ratio, which is a ratio (e.g. from 0 to 1) of the actual robot feed speed to interpolate the reference trajectory in order to adjust the tool feedrate. Thus the command speed is the greatest speed robot

can move. If the measured cutting force is larger than reference force, robot will slow down; otherwise robot will speed up until it reaches command speed. The CMRR function may implement several control approaches under the indirect force control framework. Three different control strategies, classical control (PID), adaptive control, and fuzzy control, will be introduced in the following sessions.
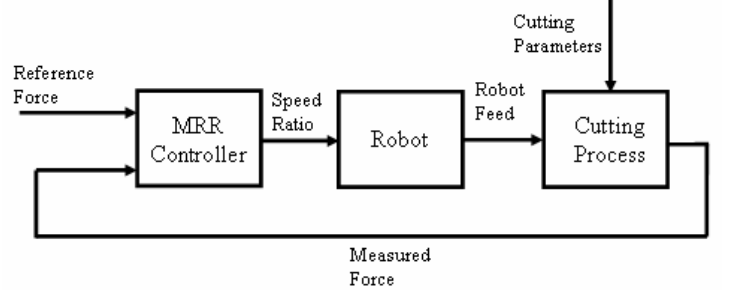

Figure 4. The Force Control Loop

B. PI control

The cutting force model is nonlinear as described in (5), for controller design, it can be rewritten as

$$F = Kd^{\alpha} f^{\beta} = K_f f^{\beta} \qquad (8)$$

Where $K_f = Kd^{\alpha}$. The effect of parameters K, d, and α to the process force is lumped into one parameter, force process gain K_f.

Define

$$F' = (F)^{1/\beta} \qquad (9)$$

Together with (8), we get

$$F' = (F)^{1/\beta} = (K_f)^{1/\beta} f = kf \qquad (10)$$

Where $k = (K_f)^{1/\beta}$ is time-varying. Instead of controlling cutting force F, we control F' to follow the new command force, i.e., $F_r' = (F_r)^{1/\beta}$, which is equivalent as controlling F to follow the original reference force F_r. By using (10), the nonlinear system is exactly linearized, and the linear system design technique can be applied to design a controller for the nonlinear system. PI type control is selected to achieve null steady-state error. The derivative term is not desirable due to the large noise associated with force readings.

The PI control in is given as

$$G_c = K_p + \frac{K_i}{s} \qquad (11)$$

We put the zero of PI controller at −66.5 to cancel the slow stable pole of the robotic dynamic model. Since the zero of the PI controller is fixed, the proportional and integral gains will be given as

$$K_p = 0.015\alpha, \quad K_i = \alpha \qquad (12)$$

Where α will be chosen to make the open loop gain of the whole system at the desired value. The magnitude of open loop

gain, defined as kK_p determines the stability of the system. Conservative K_p and K_i are selected to ensure system still stable while the force process gain k takes the maximal value. The desired system response is that small overshot for command feed speed.

C. Adaptive control

Since depth-of-cut and width-of-cut are likely to change dramatically due to the complex shape of workpiece and varied bur size, the force process gain k will vary dramatically during the machining process. The fixed-gain PI control will surely have problems to maintain the stability and consistent system performance for wide range of cutting conditions. From Figure 2, the close loop system becomes unstable when the open loop gain is greater than 1.89, which is consistent with our observations in machining experiments. So it is very important to adjust controller gains to compensate process parameter changes, in order to maintain close-loop system stability during the machining process.

A self-tuning mechanism is proposed here to adaptively adjust the gain of PI controller to maintain a stable machining process. The self-tuning PI controller is shown in Figure 5. There is low positive speed_ratio output limit (because negative or larger than 1 speed_ratio is meaningless) assigned for tool feedrate command to avoid "stop and go" situation. So saturation nonlinearity is introduced into the control system. The anti-windup scheme is also necessary for the PI control to avoid the integration windup.

Let V_r be the maximum feed speed that the tool can be commanded. The saturation nonlinearity is defined as

$$sat(u) = \begin{cases} 1 & u \geq 1 \\ u & \delta < u < 1 \\ \delta & u \leq \delta \end{cases} \qquad (13)$$

Where $\delta \geq 0$ and δV_r is the minimum feedrate command for the machining process.

Without considering the saturation nonlinearity in the system block shown in Figure 5, we set the open loop gain at 28.84, and the close loop system will have a dominant conjugate pair of poles with a damping factor around 0.7. The close loop system will have a quick response and very small overshoot, with the above damping factor. From (1), (10), (11), and (12), the open loop gain of the system in Figure 5 is calculated as

$$\alpha \cdot V_r \cdot k = 28.84 \qquad (14)$$

Combine (12) and (14), the proportional and integral gains can be given as

$$K_I = \frac{28.84}{V_r \hat{k}}, \quad K_P = \frac{0.432}{V_r \hat{k}} \qquad (15)$$

Where $\hat{k}$ is the on-line estimation of k in (10). Equation (15) is used as the self-tuning rules for the PI controller, which aims to maintain the open loop gain at 28.84.

The following standard recursive linear least square (RLS) method is used to identify k and β of equation (10)

$$k(t) = \frac{P(t-1)x(t)}{\lambda + x^T(t)P(t-1)x(t)}$$
$$\hat{\theta}(t) = \hat{\theta}(t-1) + k(t)[y(t) - \hat{\theta}(t-1)x(t)]$$
$$P(t) = \frac{1}{\lambda}[I - K(t)x^T(t)]P(t-1) \qquad (16)$$

Where $\hat{\theta}(t) = (\ln \hat{k}(t) \quad \hat{\beta})$; $y(t) = \ln F(t)$; $x(t) = (1 \quad \ln f(t))^T$; $t = 1,2,3,...$ is the sampling point; λ is the forgetting factor, which is usually chosen between 0.95 and 0.99. The on-line identified $\hat{k}$ and $\hat{\beta}$ are used in (10) and (15) respectively as the adaptive rules.

D. Fuzzy control

Although PI control and adaptive control provide stable and zero static error solutions for MRR control, they are only feasible for applications with slow feed speed, such as end milling and grinding. Their response is limited by the open
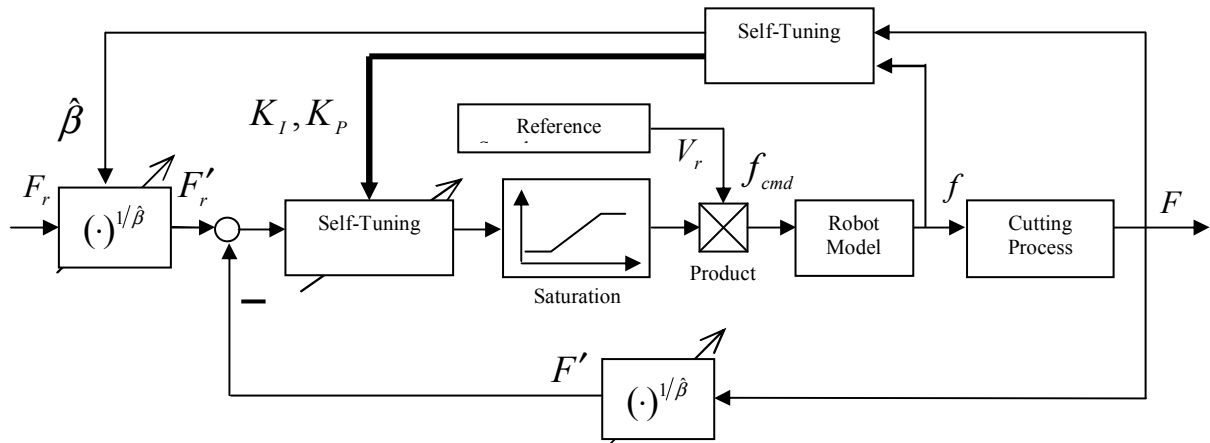

Figure 5   Robotic machining system with self-tuning PI control

loop gain to maintain a stable performance. For deburring applications, where the cycle time is critical, faster feed speed up to 200 mm/s is usually required. Also, the variation of material to be removed (bur size) is more dramatic in deburring process. Even with the largest stable gain, the PI and adaptive controller could not response fast enough to prevent spindle stall or robot vibration. Derivative term (change of force) must be included in the controller to predict the force trend and achieve faster response. Since the force/spindle current signal is very noisy, it is not practical to expand the PI control to a complete PID controller. A more intuitive control method must be adopted here to address this problem since the change of force information is only critical at the moment when the cutting tool start to engage a large bur.

Fuzzy control is a very popular approach for performing the task of controller design because it is able to transfer human skills to some linguistic rules. Therefore, fuzzy control is often applied to some ill-defined systems or systems without mathematical models. In this robotic machining situation we use a Mamdani type fuzzy PD control law to regulate the machining force. In Mamdani method, fuzzy logic controller (FLC) is viewed as directly translating external performance specifications and observations of plant behavior into a rule-based linguistic control strategy.

A FLC is a control law described by a knowledge base (defined with simple IF . . . THEN type rules over variables vaguely defined -- fuzzy variables) and an inference mechanism to obtain the current output control value. The designed FLC has three inputs, force difference, filtered change of force difference, and previous output speed_ratio, and one output change of speed_ratio. The inputs are divided in levels in accordance with the observed sensor characteristics and fuzzyfied using triangular membership functions.[5] The output is fuzzyfied in the same way. The rule base is constructed using a methodology similar to that in the work of [6]. The rule base consists three groups of rules:

a) Force limit rule: Basic rules to speed up or slow down robot based on the difference of measured force and reference force. This group of rules perform similarly to classical control method.

b) Force trend rule: This group of rules are specially implemented to detect the large burs by evaluate the trend of force difference. Proper set of force trend rule could reduce overshoot of cutting force and achieves fast response.

c) System failure protection rule: Used for safety purpose. When speed_ratio is already on lowest stage and process force is still high, robot will stop to avoid motor overload and robot vibration.

FLC generates change of speed_ratio through evaluating various rules. Instead of changing speed_ratio continuously as in classical PID control, speed_ratio is set to several stages. The reason behind this is that continuously adjusting feed speed is not desirable for machining process because it increase tool wear and deteriorate surface quality. Since a too slow feed speed will change the chip generation mechanism, that is, tool becomes rubbing instead of cutting the workpiece; the minimal feed speed is also set. Although ideally more stages means more control accuracy, five stages (0.2, 0.4, 0.6 0.8, 1.0) would

be enough for most applications. A special case is two-stage switching control which has only low or full speed. Two-stage switching control, which sacrifices control accuracy to achieve faster response, is a very attractive control method for many deburring process. One such example will be presented in the next session.

IV. EXPERIMENTAL RESULTS

Experimental studies are conducted for an end milling process to verify the stability and performance of the proposed PI control and adaptive control algorithm. The robot used in the milling process is the ABB IRB 6400, the same robot on which we have done the parameter identification. The setup of robotic end milling process is shown as Figure 1 in section II.
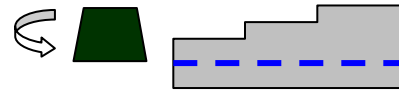

Figure 6   Robotic end milling process

During the end milling experiment, a spindle was hold by the robot arm, and an aluminum block (AL2040) is fixed on a steel table. The cutting depth of the process was changed from 1 mm to 3 mm with a step of 1 mm , as shown in Figure 6. Both fixed gain PI control algorithm and self-tuning PI control algorithm, proposed, were tested with the same experimental setup. The control system performance and stability are compared for these two controllers. The experiment results for fixed-gain PI controller and for self-tuning PI controller are shown in Figure 7 and Figure 8, respectively.
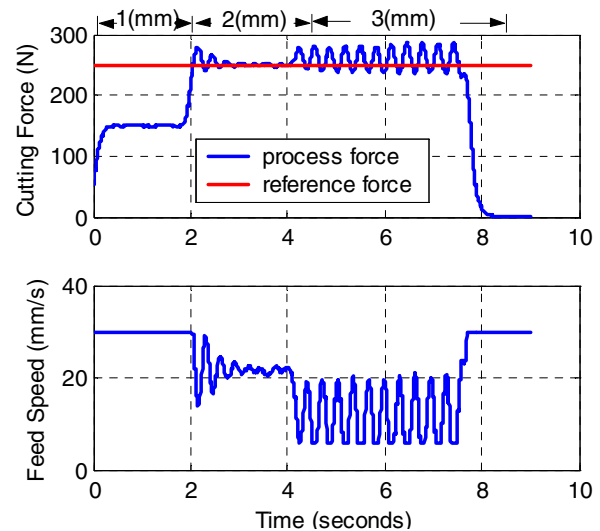

Figure 7 Fixed-gain PI control experiment result

The reference force was set at 250 N for the experiments. When the cutting depth is 1mm, both controllers are saturated with a full command speed at 30 mm/s. When the cutting depth changed to 2 mm, the fixed-gain PI controller started to

vibrate, but still stable. When the cutting depth changed to 3 mm, the fixed-gain PI controller became unstable, just as predicted in the simulation results. On the other hand, the self-tuning adaptive controller maintained the stability and performance for all the cutting depths as shown in Figure 8.
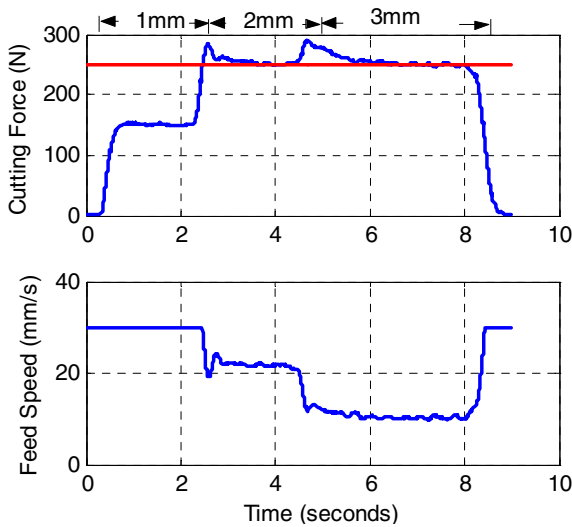

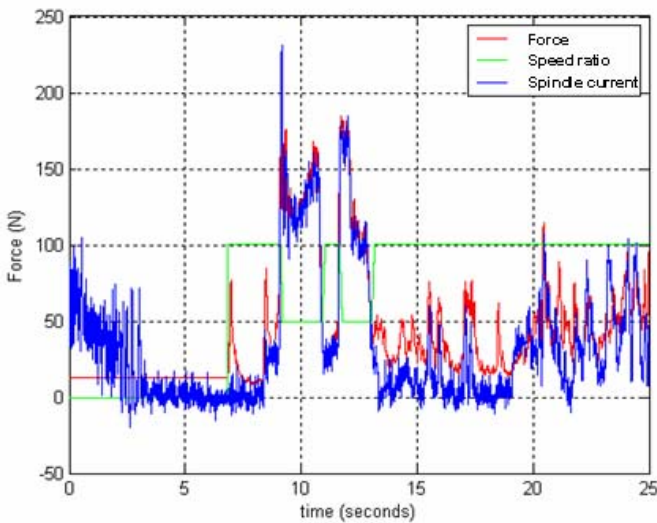Figure 8   Self-tuning PI control experiment result

Figure 19   FLC MRR control result

The FLC is tested in another setup for robotic deburring with a grinder. There two burs located in the middle of the cast steel workpiece. A single cut with straight path is supposed to remove the burs. The limit of this system is the spindle power, which is equivalent to about 300 N. Without the CMRR function, the spindle will stall at the bur location and the entire system setup will be damaged. Since the bur location and size are not predicable, normally the command feed speed is set to be a very conservative value, such as 30~40 mm/s. With FLC MRR control, command feed speed is set to 100ms. Two-stage

switch control (0.5, 1.0) is sufficient to keep the system under spindle limit. The motor current signal (blue) is also recorded for comparison purpose. It could be shown that after a linear conversion (a gain and an offset), spindle current is equivalent to machining force signal. Either signal could be used for feedback here. Note that the force measurements in the experiments were filtered with a low-pass filter before used. (Figure 9)

V.   SUMMARY

MRR control is an important feature in robotic machining processes for foundry industry. The basic idea is to control the robot feed speed according to the variation of machining force or spindle motor current. For many machining applications, especially deburring, the amount of material to be removed is not evenly distributed and the location of the large bur varies from workpiece to workpiece. If the robot feed speed is fixed, it has to be a very slow speed which makes the cutting possible even at the heaviest bur location. This makes the entire process very un-efficiency or even not practically feasible. Our solution for this problem is to real-time control the feed speed according to process force or spindle motor current.

Regulating the MRR at a constant level has many benefits, such as, increasing the productivity (e.g., material removing rate), avoiding the tool breakage, regulating robot and tool deflection, and prolonging tool life, etc. Three control methods are proposed in this paper. PI controller is easiest to implement and tune. Empirical Ziegler-Nichols turning rules could be adopted without knowing the robot and process model. Adaptive method provides a more stable control solution with the burden of modeling and tuning the system. Fuzzy control, which also does not require a system model, provides fastest response to sudden change of bur size with the sacrifice of control accuracy. It is the most feasible method for applications that high robot feed speed is critical.

REFERENCES

[1]   H. Zhang, J. Wang, G. Zhang, Z. Gan, Z. Pan, H. Cui, and Z. Zhu, "Machining with Flexible Manipulator: Toward Improving Robotic Machining Performance," in Proceeding of IEEE/ASME AIM, Monterey, 2005, pp. 1127-1132

[2]   R. G. Landers and A G. Ulsoy, "Model-based machining force control," in ASME Journal of Dynamic Systems, Measurement, and Control, vol. 122, no. 3, 2000, pp. 521-527.

[3]   L.K. Daneshmend, H.A. Pak, 1986, "Model Reference Adaptive Control of Feed Force in Turning," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 108, No. 3, pp. 215-222

[4]   Zengxi Pan, Intelligent robotic machining with force control, PhD Dissertation, Stevens Institute of Technology, NJ, USA, 2005.

[5]   Galichet, S. and Foulloy, L. (1995), "Fuzzy controllers: synthesis and equivalences", IEEE Transactions on System, Man and Cybernetics.

[6]   Li, H. and Gatland, H. (1996), "Conventional fuzzy control and its enhancement", IEEE Transactions on System, Man and Cybernetics.