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A Variable-Speed Deburring Robot Using the Repetitive Control

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Control methods to achieve efficient and accurate deburring robots are proposed. For efficiency, cutting speed is controlled adaptively with the cutting load. For accuracy, it adopts repetitive control. Since usual repetitive control cannot afford dynamical speed changes, the proposed method controls in an interpolating manner using several waveforms stored in the controller. Successful experimental results are shown.

1 Introduction

Since deburring of casting is often suffered from its bad environment, various studies of automatization using robots is in progress. These robots are gradually aiming to achieve efficiency and accuracy higher than manual finishing. However, robot application is limited, especially for castings with complex shapes and irregular burrs. The reasons are:

1. since large tools may interfere workpieces and load specification of robots is limited, large tools to achieve higher efficiency cannot be used;
2. usual feedback servo systems have errors varying with speed. Thus, for robots with slow response in their control system, the trajectory of motion differs with speed. This changes the finishing accuracy depending on the cutting speed.

To cope with these problems, we propose a novel scheme which:

1. detects the cutting load by the variation of tool revolutionary speed, and controls the cutting speed based on it, to obtain efficiency;
2. adopts repetitive control, to reduce errors.

However, repetitive control can enjoy its effect only when the reference period is equal to the dead time in the controller. Then, its performance degrades when the period differs with the dead time as in a variable-speed robot that changes its path speed with the cutting load. To apply the method to such robots, we propose a practical scheme that achieves control with waveforms stored in the controller for several path speeds, together with an interpolating manner if necessary.

We implemented the proposed methods on a prototype with 6 degrees of freedom. The experimental results with test models show that:

1. it can debur with a teaching speed twice or more faster than usual teaching/playback robots;
2. error is reduced down to nearly zero even when speed changes in a range of 6:1. This improves finishing accuracy.

The following descriptions include a modified repetitive control that accommodates changes in the reference period, realization of a variable-speed deburring robot based on the proposed methods, and the experimental results.

2 Variable-Speed Deburring Robot and Repetitive Control

2.1 Variable-Speed Deburring Robot

Workpieces of prime interest are aluminum castings, which are accurate in size because of metal mold, but have complicated shapes and irregular burrs. From experiment, we chose for the cutting tool a high-frequency induction motor in combination with an end mill, to remove such burrs in one pass. Induction motors have characteristics that torque increases with a slip from the synchronous speed when load acts on. Based on this property, we proposed a control method to detect the cutting load through the variation of tool revolutionary speed, and to control the cutting speed to regulate the cutting torque [1]. As the revolutionary speed directly reflects the cutting state of the tool, this method can be applied to cases with difficult force detection. These include complexly shaped works cut with ball-type end mills, whose cutting portions change so significantly to easily estimate the cutting load.

2.2 Repetitive Control Accommodating Changes in the Reference Period

Repetitive control is a method that makes use of errors in previous cycles to provide for accurate operation when its input is periodical. Some attempts have been reported to reduce trajectory errors of robots using it or learning control [2-3]. However, since path speed of a deburring robot changing with cutting load regulation corresponds to the changes in the reference period, these methods are difficult to apply to such robots. Then, as a modified repetitive control we devised the following scheme, which can adapt itself to dynamical changes in the reference period and can force the state variables, in a finite-sampling settling operation, to fit itself to the new period [4]:

1. switching the controllers, in which control variable waveforms are previously formed by enough number of repetitions, according to changes in the period (Fig. 1).
2. for cases where speed changes more than twice a cycle, excluding the compensator from the loop and repetitive control is made use of offline to form the control variable waveform.

With these improvements, robot responses can converge into their steady states in a very short time and their errors can be significantly reduced.

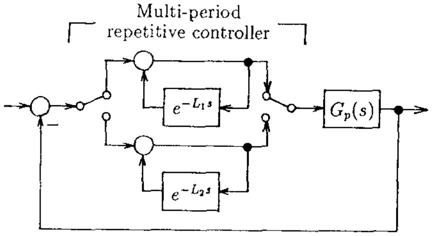


Fig. 1 Principal configuration of the repetitive control accomodating changes in the reference period

However, since this scheme is only for stepwise speed changes, it is not suitable for deburring robots that continuously change their path speed adaptively to the cutting load. In the following sections we describe some practical aspects of the novel repetitive control that can be applied to variable-speed deburring robots.

3 A Repetitive Control Method for Variable-Speed Deburring Robot

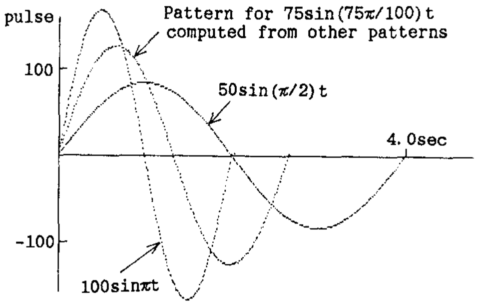
3.1 Interpolation to Cope with Continuous Speed Changes

To realize accurate variable-speed deburring robots, we use an interpolating method which compensates with several control patterns (control variable waveforms formed previously by enough number of repetitions in the repetitive controllers).

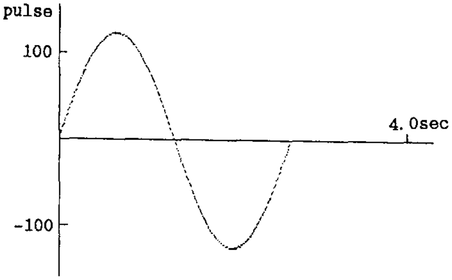
For the interpolating method to work, control variable waveforms are necessary to be nearly proportional to the path speed for the same state in the robot motion. To confirm this we simulated an axis in the block diagram shown in Fig. 5 (shown later), whose transfer function of the velocity loop is expressed by (1):

$$G(s) = \frac{280^2}{(s^2 + 2 \cdot 0.52 \cdot 280s + 280^2)}. \qquad (1)$$

We applied two sine-wave inputs, whose amplitudes are 100 and 50(mm/s), respectively, and the moving distance in half a cycle is 63.7mm. Fig. 2 (a) shows the control patterns formed in the controller after repetition, and the interpolated control pattern for an amplitude of 75. Fig. 2 (b) shows the control pattern actually formed by repetition for the amplitude. The two control patterns are nearly equal with an error of 4 pulses in the motor encoder output. Therefore, we can reduce errors with the interpolating method using two control patterns, nearest to the varying speed.



(a) Actual control patterns for 100sinπt and 50sin(π/2)t, and computed pattern for 75sin(75π/100)t



(b) Actual control pattern for 75sin(75π/100)t

Fig. 2 Effectiveness of interpolation

3.2 Practical Algorithm

Control patterns are stored as discontinuous data in the memory of a microcomputer system in the robot controller. Positional servo loop control of the robot is periodically accomplished by a computer program. Then, the control patterns are to be synchronized with the servo period. Since speed of the robot is variable, time passage cannot be used as the parameter to synchronize several control patterns in the memory, requiring some devices.

We employed a method to enable unique data for repetitive control in each axis corresponding to the control speed and resultant interpolating point from discontinuously stored control patterns. The method deals with a section between two teaching points as one control block, and controls based on the distance of the current interpolating point of the robot from the previous teaching point. Fig. 3 shows the concept of the method and the relationship among control patterns, interpolating points of the robot, and their distances.

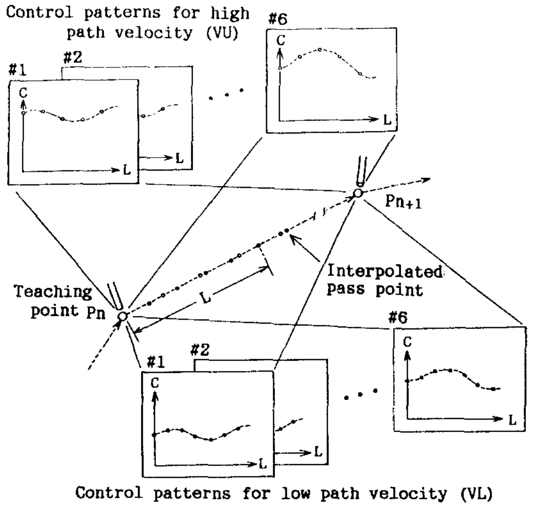


Fig. 3 Control patterns for various path velocity and teaching points

In the course of variable-speed deburring, control data C^* for each axis can be calculated with:

$$CU = \begin{cases} CU_j + \\ \quad (CU_{j+1} - CU_j)\dfrac{(L^* - LU_j)}{(LU_{j+1} - LU_j)} & (j \geq 1) \\ CU_0 + \\ \quad (CU_1 - CU_0)\dfrac{L^*}{LU_1} & (j = 0) \end{cases} \tag{2}$$

$$CL = \begin{cases} CL_k + \\ \quad (CL_{k+1} - CL_k)\dfrac{(L^* - LL_k)}{(LL_{k+1} - LL_k)} & (k \geq 1) \\ CL_0 + \\ \quad (CL_1 - CL_0)\dfrac{L^*}{LL_1} & (k = 0) \end{cases} \tag{3}$$

$$C^* = CU + (CL - CU)\frac{(V^* - VU)}{(VL - VU)}, \tag{4}$$

where

V^* and L^* denote the path speed and the interpolating distance, respectively,

CU and CL are upper and lower control data at L^*, respectively, calculated from the control patterns sandwiching V^*,

LU and LL are distances for which control data is to be formed,

suffixes ${}_0$ and ${}_1$ indicate to be at the previous teaching and interpolating points, respectively,

suffixes ${}_j$ and ${}_{j+1}$ indicate to be nearest and next to the interpolating point within L^* for VU, and

suffixes ${}_k$ and ${}_{k+1}$ denote similarity for VL.

4 Implementation of a Variable-Speed Deburring Robot

4.1 Configuration of the Experimental Robot

Fig. 4 shows the configuration of the prototype, which has been developed especially for deburring of aluminum castings to achieve efficient and high-speed deburring. It is of the cylindrical-coordinate type with six degrees of freedom. Tool is drived by a high-frequency induction motor with rated revolutionary speed of 17,500 rpm and rated output power of 0.6kW. The speed is detected with a pulse generator built in the tool. Robot controller accepts the revolutionary data via an A/D convertor and controls the path speed of the robot to regulate the loading torque.

To achieve highly responsive control, we employed a 16-bits, 2-CPU microcomputer system with a floating-point coprocessor, to allow servo and repetitive controls with a period of 10 ms.

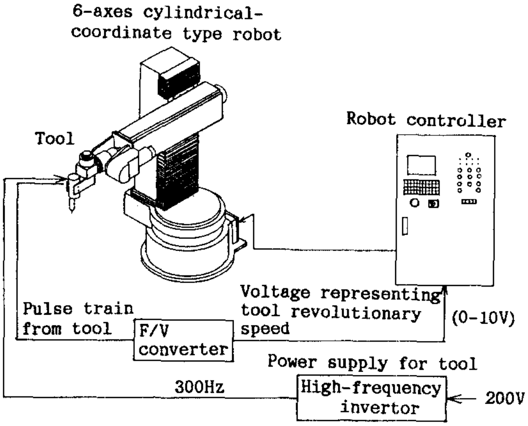


Fig. 4 Configuration of a variable-speed deburring robot

4.2 Control Methods

Fig. 5 shows the block diagram of the deburring robot using the variable-speed repetitive control and tool revolutionary speed regulation. The latter system includes gain varying with burr size and cutting speed. Gain constant shown is for a 2-teeth end mill. Transfer function of the tool was experimentally determined, and the time constant is between 0.1 and 0.25. Velocity loop characteristics of the servo motors were derived by its frequency response, to be approximated by a second-order lag for all the axes. In Fig. 5 only the transfer function of the 3rd axis is shown. The robot controller can be configured to

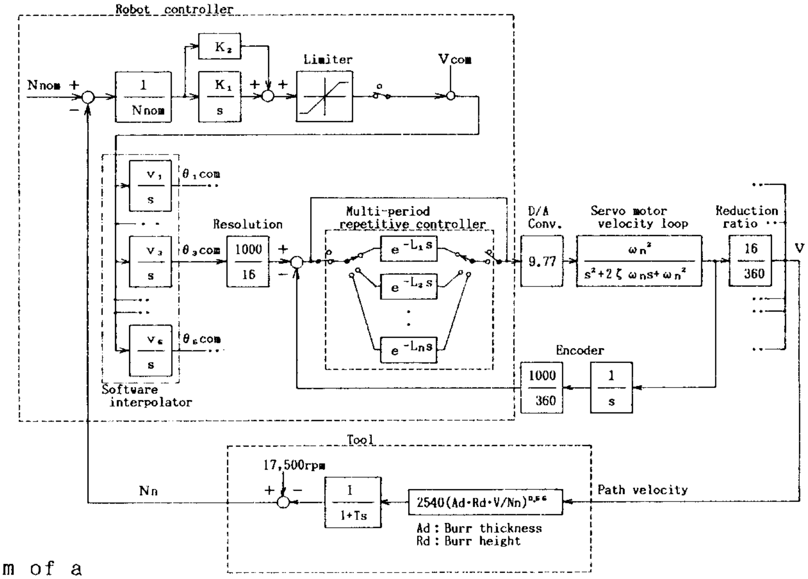


Fig. 5 Block diagram of a deburring robot using the variable-speed repetitive control

various control modes, such as making control patterns, actual deburring with cutting load control, and so on, as is shown in the figure.

Tool feed speed V_n at a periodic sample time t is derived by (5):

$$V_n = V_{n-1} - K_1\frac{(N_{nom} - N_n)}{N_{nom}} + K_2\frac{(N_{n-1} - N_n)}{(t \cdot N_{nom})}, \qquad (5)$$

where

N_{nom} is the target tool revolutionary speed,

N_n is the sampled tool speed,

N_{n-1} is the tool at the previous sample time,

and

K_1 and K_2 are proportional constants.

That is, tool feed speed is controlled to converge into N_{nom} with the PD control with its maximum limited to the taught speed.

Control patterns are made by usual repetitive control for 5 speeds, derived by multiplying the taught speed by constants. Each control pattern is stored for each axis with a period of 10 ms to synchronize to the servo control. Control data for each sample period consists of the number of pulses of the motor encoder with its sign, in 2 bytes. The data also includes interpolating distance, control data for distinguishing individual sampling data, and feeding speed, a total of 18 bytes for the 6-axes robot.

Fig. 6 shows the procedure of servo control under the variable-speed repetitive control, which is carried out every servo period. Calculation is accomplished in another task, first for the feed speed, next for the interpolating point on the path, and finally for the encoder pulse data for each axis, in the remaining time of servo control. To shorten calculation time, we devised a method of treating control pattern data as shown in Fig. 6.

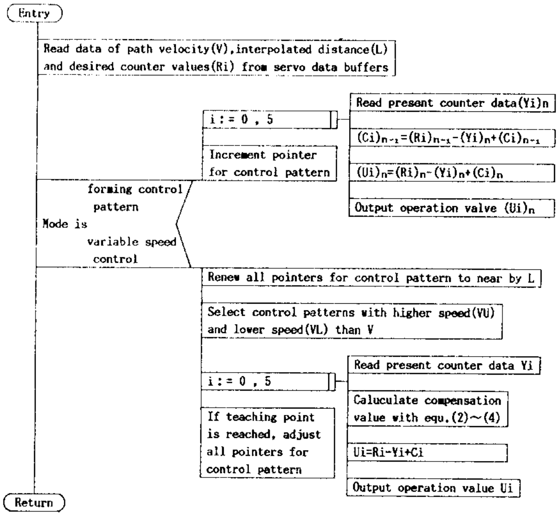


Fig. 6 Procedure of servo control under the variable-speed repetitive control

5 Experimental Results

5.1 Preliminary Experiments

One problem with the repetitive control is its strict stablity condition. It is generally difficult to control stably high-order systems with input including high-frequency component. Since the positional servo loop of the experimental robot is of 3rd order or higher, it is unstable if the gain in high frequencies is not compensated.

We investigated error profiles under usual repetitive control for all the axes without gain compensation for high frequencies. Fig. 7 shows the result for the 3rd axis when a round-trip motion with trapezoidal velocity pattern is applied. For example, when the maximum speed is 500 mm/s, rms error reduces to 1/708 of that of the basic servo system after 11 repetitions, and increases thereafter. Then, if we abort the renewal of control waveforms at this point and compensate with them in a feedforward manner since then, we can enjoy the effect of the repetitive control without stabilization.

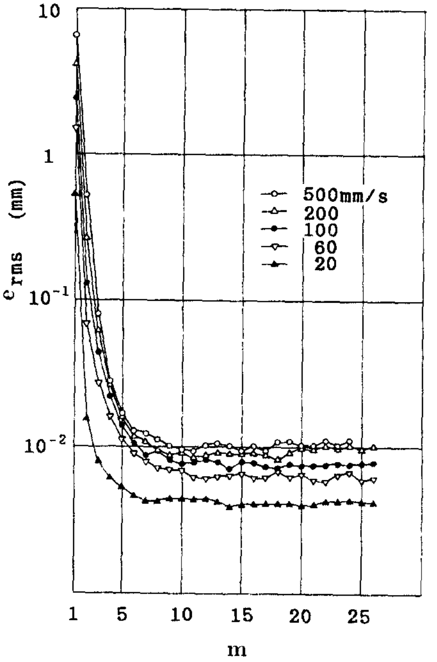


Fig. 7 Control errors as a function of the number of repetitions

5.2 Variable-Speed Cutting Experiments

Experiments were carried out with two axes of motion controlled cooperatively for test pieces of aluminum casting shown in Fig. 8. The path consists of a linear, a circular, and another linear motions connecting three teaching points. Cutting was done with an initial path speed of 100 mm/s, desired tool revolutionary speed of 17,300 rpm, cutting depth of 2.5 mm, and a situation that tool speed decreases when tool meets the test piece. The positional loop gain are set to 13 (1/s) for both the axes.

Fig. 9 shows the result only with the cutting load control. The 1st axis has a maximum error of 5.4mm and the 3rd axis 4.9mm, resulting in a 2mm offset from the taught path at the corner. On the other hand, Fig. 10 shows the result with compensation using control patterns of 5 speeds, 1.0, 0.8, 0.6, 0.4 and 0.2 of the taught speed, by 19 repetitions. Control errors are shown to be 0.5mm or less even when cutting speed decreases from 100mm/s to 65mm/s. Transitional error is caused by the lack of time at the beginning of circular interpolation calculation.

For actual aluminum castings with burr thickness and height of 1 to 2mm and 2 to 5mm, respectively, usual robots can deburr at most with 20mm/s even after rough deburring. In contrast, the prototype implementing the proposed method can deburr with 50 to 60mm/s, twice the usual teaching speed.

Since the finishing accuracy of castings for cars is about -0.5 to 1.0mm, the proposed method is enough to apply to practical deburring robots.

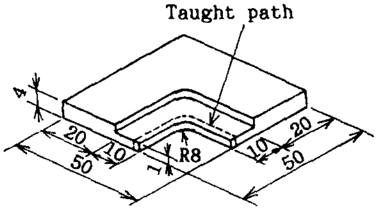
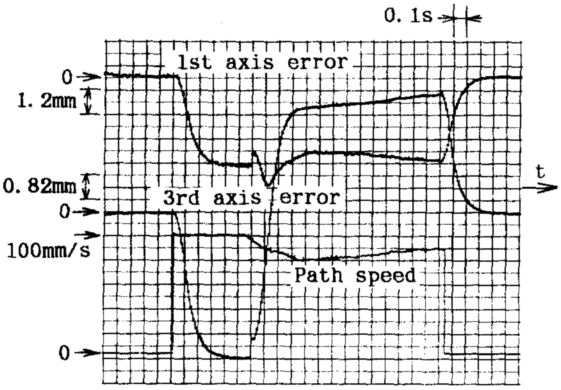
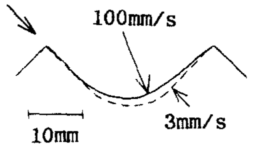


Fig. 8 Test model

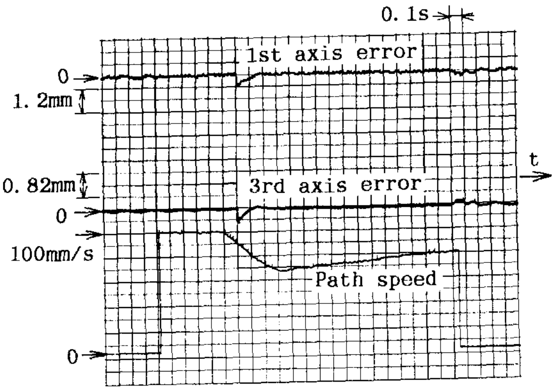


(a) Control error waveforms

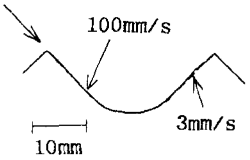


(b) Cut shape

Fig. 9 Control errors of the bare control system and a cut shape



(a) Control error waveforms



(b) Cut shape

Fig. 10 Control errors of the prototype and a cut shape

6 Conclusion

To achieve efficient and accurate deburring robots, we proposed two methods, cutting load control and repetitive control. Since the usual repetitive control is effective only when the reference period is equal to the dead time in the controller, we adopted the following schemes to apply it to variable- speed deburring robots:

1. control variable waveforms are previously formed in the controllers for several reference periods, which correspond to the taught speed multiplied by constants;
2. while deburring with speed changing continuously depending on the cutting load, control is accomplished, with interpolation if necessary, with the stored waveforms and with compensation in a feed-forward manner.

An implementation showed that:

1. by applying the proposed cutting load control, it can deburr with a teaching speed of 50 to 60 mm/s, more than twice higher than usual robots;
2. even if speed changes continuously while deburring with cutting load, control errors in each axis can be maintained below 0.5mm.

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References

[1] Y. Kimura , N. Tanabe , M. Kobayashi : Study on High-Efficient Robot with Cutting Load Control , J. of the Japan Foundrymen's Society , 61-6 , 394/399 (1989) (in Japanese)

[2] S. Arimoto , S. Kawamura and F. Miyazaki : Bettering operation of Robots by Learning , J. of Robotic Systems , 1-2 , 123/140 (1984)

[3] T. Omata , S. Hara and M. Nakano: Nonlinear Repetitive Control with Application to Trajectory Control of Manipulators , J. of Robotic Systems , 4-5 , 631/652 (1987)

[4] F. Kobayashi , Y. Kimura and S. Watanabe : A modified repetitive control accommodating changes in the reference period and its application , Trans. of the Society of Instrument and Control Engineers , while contributing (in Japanese)