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Active Compliant Motion Control for Grinding Robot

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Abstract: A grinding robot system is presented in this paper. Active compliant motion control is applied to keep contacting between grinding tool and work pieces and auto surface tracking algorithm was developed to trace the outline of work-pieces. For real implementation of the system, the shape of work pieces are informed through barcode and the piece's dimension is measured with a laser distance sensor. Experimental results with the implemented system are also presented and discussions for further works are followed.

1. INTRODUCTION

Grinding is one of the important processes in Daewoo Shipbuilding and Marine Engineering Co. Ltd. (DSME) shipyard because grinded components in ships help to extend life cycle of ships. Since ship-owners have been very satisfied with the ships that have well grinded components, they request to grind most parts for new ordered ships. The working environment of grinding process, however, is very harmful to workers; Grinding noise is very large and dust is everywhere. Moreover, continuous vibrating force causes workers' muscle-disease. A grinding robot system was, therefore, asked to develop to replace the workers in such harmful environment.

Although the grinding process does not require highly skilled person, developing autonomous grinding robot system is very difficult. Human workers easily control contacting force between grinder and work-pieces and track any unfamiliar surface. However, force control and exact surface tracking is not easy control problem for robot system. In ideal situation if we know the exact dimension and shape of work-pieces, one can design the path of robot exactly. Work-pieces in shipyard, however, have not good tolerance: normally the dimension is different up to few millimetres from CAD information and is not serious in ship building process. Moreover, it's difficult to place work-pieces at exact location with exact orientation. Force control and auto surface tracking, therefore, are two essential techniques in developing a grinding robot system.

There are many useful algorithm and application example for the contacting force control. Hogan's impedance control (1985) is one of the most famous force control algorithm. Chang et. al. (1995) developed a hybrid force control algorithm with time delay and applied it to two degree of freedom (DOF) robot to track given surface with desired force. Kazerooni et. al. (1990,1991) proposed active compliant motion control algorithm and successfully applied it to direct drive robot. There are some result to develop robot system for grinding (Choi, 1999) and finishing (Wang, 2000) process. Grinding force control in this work was developed based on active compliance control.

Auto surface tracking was performed by estimating tangential and normal direction from the measured contacting and grinding force. Shape of work-pieces was informed by operator and dimension was measured with a laser distance sensor. The approaching position and direction was calculated with the shape and dimension information.

This paper organized in five sections. The next section introduces grinding process in shipyard, and grinding and tracking algorithm is presented at Section 3. Real implementation and experimental results are presented at section 4 and the summary and discussion on further works are followed.

2. GRINDING PROCESS

Grinding in DSME shipyard is a kind of machining process that removes materials with rotary cutter having six blades. The grinding tool operates with compressed air and nominal spindle speed is 6000 rpm. Since the cutter has six blades and rotates at 6000rpm, the cutting force vibrates at 600Hz.

Grinding tool used in this work consists of a cutter, a guide plate and a guide roller (Fig. 1). As long as guide roller and plate keep contacting to work-piece, cutter can cut work-piece to desired roundness. So, the control strategy should be to control the contacting force that the guide roller and plate does not loose contacting. Since such strategy allows the contacting force to exceed command force, it is simpler than precise force control.

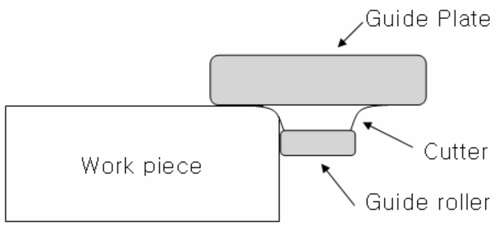

Fig. 1. Schematic of grinding tool

When human workers are working on this process, the contacting force is measured between 100N~200N and the feeding speed is about 100mm/s. Since human workers usually repeat the grinding motion twice, averaging griding-speed is regarded as 50mm/s.

From the observation above, the control strategy was determined as follows:

- Maintain the contacting force not to be below the minimum force limit to keep contacting the guide roller and plate to the work-piece.
- The contacting force must not exceed the maximum force limit to protect force sensor and other mechanical parts.
- Automatically track the outline of work-piece based on the measured force.

In this work, about 200 types of work-pieces exist and they can be categorized in 24 shapes. Since each shape has specified grinding region as shown in Fig. 2, grinding system must know what the work-pieces' shape is in order to exactly grind the specified region.

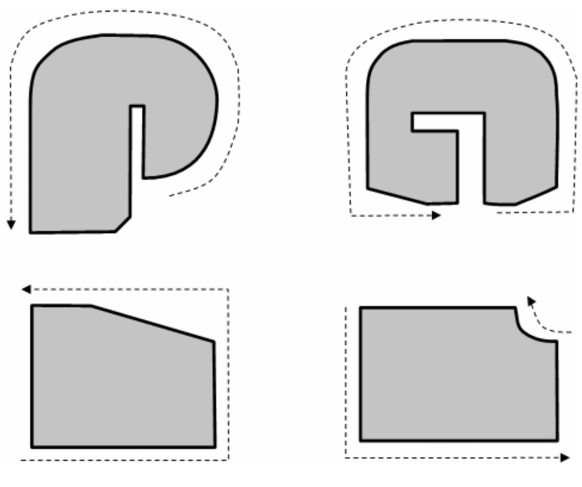

Fig. 2 Examples of work-pieces and grinding region to be grinded: dashed lines represent the grinding area

3. AUTOMATIC GRINDING CONTROL

3.1 Force control for grinding

In the developed force control system, we used position controlled servo system and controlled the contacting force by controlling the command position. While the most force control algorithm derived control input as the terms of force or torque of actuators, we used a position controlled industrial robot. It was proven that one can control contacting force with position or velocity controlled industrial robot position controlled type industrial robots (Roy, 2002, Surdilovic, 1996, Ferretti, 2000).

Since the stiffness between work-piece and robot is very high, the slight robot movement causes large force change when robot is contacting work-pieces; it makes difficult to control contacting force with position controlled robots. To decrease stiffness (or increase compliance), we imported an active compliance motion control scheme (Kazerooni et. al, 1990, 1991).

The block diagram of the applied force control system is shown in Fig. 3. x_d is the position command to the robot, K_e is the natural stiffness between robot and work-piece. A controller is added to control the compliance of the closed loop, x_r / F . The control law of active compliance controller is

$$x_d = (k_P + k_D s)\left(x_r - F \frac{\lambda H}{s+\lambda} \right) \quad . \tag{1}$$

K_P and H are control parameters to determine the magnitude of the compliance of the closed loop and K_D is to increase the stability of the system. Low pass filter is used to eliminate high frequency noise and vibration component that is induced by the rotary girding cutter.

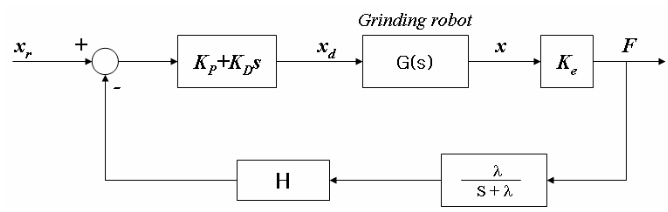

Fig. 3 Block diagram of active compliance control

Since the robot is the position controlled system the actual position, x , is follows the command position x_d with some time delay. So, the dynamics of the robot, $G(s)$, can be simplified in (2), while it has unmodelled high order terms.

$$G(s) = \frac{a}{s+a} \tag{2}$$

The resultant compliance of the closed loop, C_{CL} , is expressed as

$$C_{CL} = \frac{x_r}{F} = \frac{1}{K_e k_P G(0)} + H = \frac{1}{K_e k_P} + H \ . \tag{3}$$

So, we can get increased C_{CL} by increasing H and decreasing K_P . The maximum value of C_{CL} , however, is limited in real system because $G(s)$ has high order dynamics and it is activated when H becomes large. The optimal value of H cannot be obtained analytically for the exact dynamics of $G(s)$ is unknown. Instead, it was manually tuned by through series of experiments in this work.

3.2 Auto tracking algorithm

Basic idea of auto tracking is to generate a motion command based on measured cutting force. Fig. 4 illustrates various force and direction while grinding work (Choo, 2006). Cutting force, $\mathbf{F}_c$, is measured from force sensor and the direction of cutting force, ϕ , is calculated from (5).

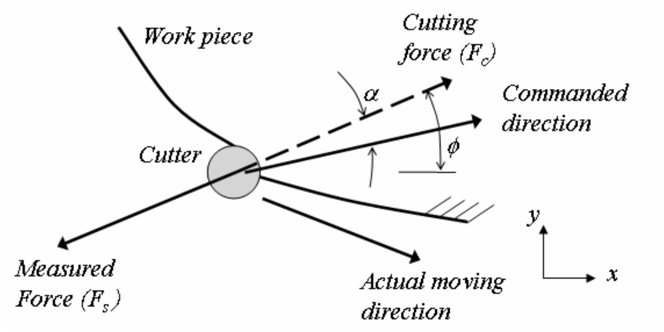

Fig. 4 Force and moving direction in grinding process

$$\mathbf{F}_c = -\mathbf{F}_s \tag{4}$$

$$\phi = \operatorname{atan2}\left(F_{cy}, F_{cx}\right). \tag{5}$$

When the cutting force and direction is obtained, the reference position command of (1), (x_r, y_r) , is calculated using following equation

$$\begin{pmatrix} x_r \\ y_r \end{pmatrix} = A \begin{pmatrix} \cos(\phi-\alpha) \\ \sin(\phi-\alpha) \end{pmatrix}, \tag{6}$$

where A and α are constants number that are determined from desired tracking speed and normal force. Since appreciate A and α are depends on the tools and work-pieces' condition they should be tuned through trial and error in real system.

An acceleration algorithm shown in (7) and (8) is added to increase the grinding speed, where A and α are to replace those in (6). If the changing rate of force direction, $\dot{\phi}$, is low it might mean striated surface and the feeding speed is near maximum. Otherwise, rapid change of measured force means not striated surface and the feed rate is decreased to keep contacting.

$$\alpha = \alpha_0 - k_\alpha \operatorname{sat}\left(\frac{\dot{\phi}}{\tau_\phi s + 1}\right), \tag{7}$$

$$A = A_0 - k_A \operatorname{sat}\left(\frac{\dot{\phi}}{\tau_\phi s + 1}\right), \tag{8}$$

where α_0 and A_0 are nominal values of α and A , respectively; k_α and k_A are constant values, and

$$\operatorname{sat}(x) = \begin{cases} -1 & \text{for } x < -1 \\ 1 & \text{for } x > 1 \\ x & \text{otherwise} \end{cases}.$$

Full block diagram including auto-tracing and active compliance control is shown in Fig. 5.

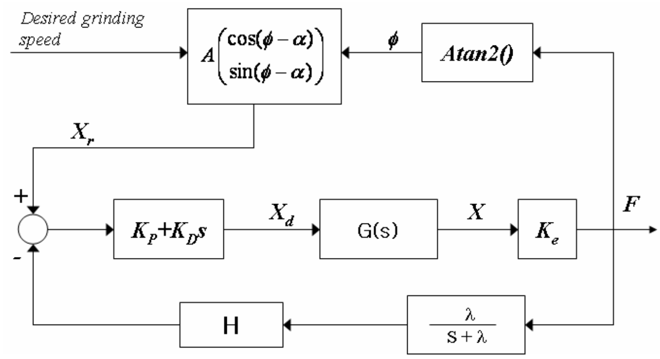

Fig. 5 Block diagram of the auto-tracking grinding force control system

4. IMPLEMENTATION OF GRIDING SYTEM

4.1 Implementation issues

There are eight sub-tasks in grinding process that we concerned in this work. Those are

a. Bring a palette with work-pieces to working area. A palette usually contains 100 to 300 work-pieces in one to six different shapes.
b. Load a work-piece to the working place.
c. Recognize the shape and size of work-pieces. The edges to be grinded are specified is worker's manual according to the shape.
d. Grind the edges.
e. Turn over the work-piece.
f. Grind turned work-piece.
g. Arrange the finished work-piece to the output palette for the next process.

It is very difficult to develop fully automated grinding system for the all sub-tasks above; For example, it's hard to select and load a work-piece from the palette that contains mixed work-pieces in various shapes and different sizes. In this work, therefore, we developed a grinding system for the selected sub-tasks and left others as human worker's portion, so that we can implement the grinding system in given period and budget. Table 1 shows the property of the sub-tasks and our strategy to develop auto-grinding system.

Table. 1. Properties of sub-tasks and strategy for system development

Sub-Task	Property	Strategy
a	Automatic handling of palettes with few tons is not good approach.	Let workers move it using overhead crane.
b	It's difficult to select and load one from a stock of mixed work-pieces.	Ask workers to stock work-pieces in a specified cartridge. Load/unload device moves them from the cartridge to working place.
c	It takes long time and expensive to develop auto shape recognizing system.	Let workers input the shape number.
d,f	It is needed to control contacting force and to track the surface of work-pieces in various shapes.	Develop a grinding robot with auto tracking function.
e	It must turn over work-pieces of weight 20kg	Develop a turn-over device.
g	It is a simple task if system knows the shape and orientation of work-pieces.	Load/unload machine moves the work-pieces in working place to the palettes.

As a result, human worker does the first three sub-tasks in the developed system and the grinding robot system does the others; Human workers take work-pieces from a palette, stack them in a specified place, a cartridge cell, and inform the grinding robot system the shape of the work-pieces. Note that a cartridge cell must include only one shape in predefined orientation. The grinding robot system, then, moves the work-pieces to work place, grinds them and stacks them on an output palette.

4.2 Components in grinding robot system

The developed grinding robot system consists of three mechanical components and two sensing components. Mechanical components are a load/unload device, a grinding robot and a turn-over device. Two sensing components are a barcode scanner and a laser distance sensor that are for informing shape number and measuring the dimension of work-pieces, respectively.

Load/unload device is to move work-pieces from cartridge cell to work place and from work place to output palette. It can carry work-pieces up to 20kg with its electro-magnetic hands. Since cartridge cells and work place are located in fixed place. The load/unload device simply travels between the pre-programmed positions. If it touches the bottom of the cartridge cell when it tries to pick up work-pieces, it regarded that there is no more work-pieces left.

Grinding robot has six degree of freedom (DOF) and is equipped with a force torque sensor to measure grinding force. It is droved with position control type servo controllers and trajectory and grinding process is controlled by DSME's universal controller (Kim, 2005). Work-piece that was grinded by robot is turned over by a turn-over device and the robot grinds the backside.

In order to inform the shapes of work-pieces to the robot, operator must place a appreciate barcode at the specified place and robot controller recognize the shape number through barcode reader. A laser sensor was attached to the tip of robot hand to measure the size, thickness and the location of work-pieces. Since the shape and orientation of the pieces are informed by operator, the size and location can be estimated by measuring few critical points according to the shape. Fig. 5 shows an example of the critical points for two types of work-pieces and scanning path of laser sensor to measure the points. The dimension information is sent to the grinding robot controller so that it generates grinding information such as approaching point, approach direction, ending condition and total grinding distance.

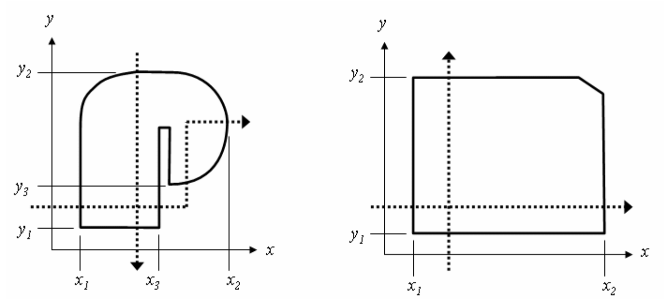

Fig. 5 Critical points to measure the dimension of work-piece and scanning path of laser distance sensor

4.3 Real implementation and experimental results

Schematic of grinding robot system and real system are shown in Fig. 6 and 7, respectively. Force torque sensor used in this work is ATI 660/60 with IP65 specification and barcode scanner is from Datalogic. A laser sensor of Kience, LB301, is used to measure the dimension of work-pieces.

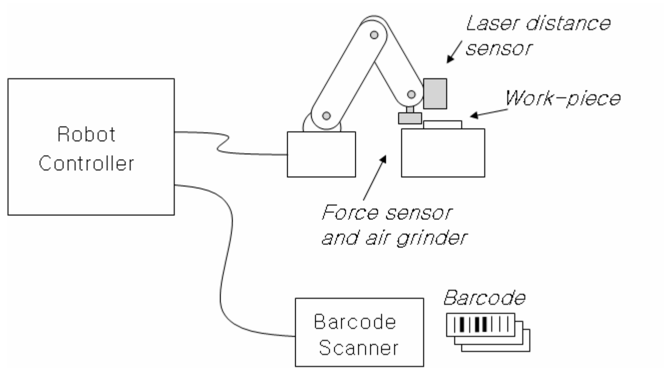

Fig. 6 Schematic of grinding robot system

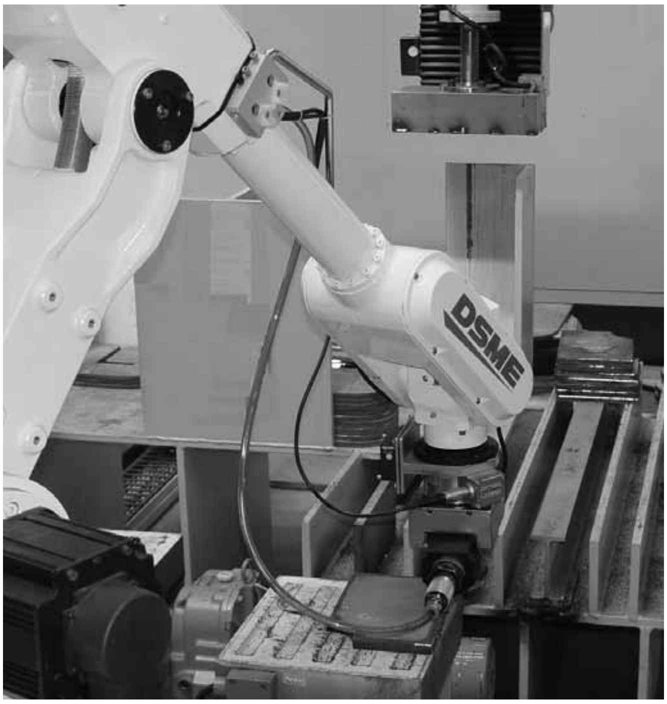

Fig. 7 Grinding robot system with loading/unloading system

24 shapes were tested in this system and successfully worked. The grinding speed was 20mm/s and measuring time for size was 10s. Grinding time was 15s for the smallest piece and 90s for the largest one. It was slower than human workers' 50mm/s for grinding speed and less than 1s for shape and dimension recognition.

5. SUMMARY AND FURTHER WORKS

The productivity is not as good as human workers'. Yet, it could remove workers from grinding work that could be a cause of muscle injury. Human operator, in the developed system, doesn't need to grind but just load work-pieces and pushed operation buttons. Additionally, it could work continuously without braking time and did not argue disease from continuous vibrating force.

There are many points to improve this system. Human workers wish to get full automated loading system that brings work-pieces from palette to work place and recognizes itself the shape of the pieces. Increasing the grinding speed and reducing the handling time are also asked for better productivity.

Optimal design of the system is another request. 3-DOF robot can replace the 6-DOF robot, because the orientation of tool is fixed during grinding work. Since the force-torque sensor is too precise and expensive for this process, simpler and more robust sensor will be appropriate such applications.

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