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Adaptive Hybrid Position/Force Control for Grinding Applications

M. Fazeli and M. J. Sadigh
Department of Mechanical Engineering
Isfahan University of Technology
Isfahan, Iran
Email: m.fazeli@me.iut.ac.ir and jafars@cc.iut.ac.ir

Abstract— **Application of robotic manipulators for grinding purposes may cause unreasonable behavior during grinding of uneven surfaces such as damaging workpiece surface, or following undesired roughness of the surface depending on the control strategy. This paper presents an adaptive control strategy which is a combination of a closed loop position control to track the desired path, an open loop force control to compensate for contact forces and an adjustable closed loop force control term. The third part of this control strategy, which can be considered the main contribution of this work, makes it possible to choose between position or force control strategy in the normal direction. Several numerical examples are provided to show versatility of this control in confrontation with different type of uneven surfaces.**

Keywords— robotic grinding; adaptive; position/force control.

I. Introduction

Grinding applications is a challenging task for robotic systems which has gained lots of attention in last three decades [1-11]. Two categories of position control and hybrid-position/force control can be identified among these researches.

The first control strategy looks very good for grinding purposes, why it causes the disk to follow a prescribed path both in normal and tangential directions and leaves a grinded surface exactly as expected. However, this strategy does not work well in confrontation with large steps up. In such cases a sudden increase in material removal may cause serious damage to the surface such as burning or even damage of the grinding disk.

The other strategy, on the other hand, is based on the idea of closed-loop force control normal to the surface and position control in tangential direction. This idea of hybrid position-force control, which was first introduced by Raibert and Craig [12], does not cause any damage to the workpiece. However, this strategy has its own disadvantages such as following the pattern of surface and leaving the uneven form of the surface unaltered which is apparently in contradiction with finishing purpose of grinding. In other words this control strategy causes the manipulator to keep material removal dept constant, regardless of uncertainties in surface, to keep the normal force close to its desired value. This made researchers to devise adaptive control strategies to circumvent this problem.

Elbatsavi et al. [13] used an adaptive force control for this purpose. They tried to make necessary correction in desired path by the force feedback. Jenkin et al. [14] designed a robust control based on separate control of velocity of the tool and normal force, in order to control the normal force through velocity of the tool. Whitney et al. [15] employed a structured light vision system to devise a desired value for force control profile. In another attempt to solve this problem Brown and Whitney [16] used a stochastic dynamic programming approach. Srivastava et al. [17] proposed an adaptively force control strategy to optimize the rate of material removal in order to avoid burning in the surface. In a recent attempt to solve this problem Nahavandi et al. [18] incorporated a compliant system in the robotic system. Although this method could be considered as a safe and cheap solution to the problem it may causes some unwanted vibration or even chattering in confrontation with rough surfaces. The work by Chen et al. [19] can also be mentioned as a recent attempt to solve this problem, in which they used cubic splines to estimate the constraints of motion such that the desired path is adaptively adjusted during the process.

This paper presents a simple, yet sophisticated, control strategy which can solve the above mentioned problem. The control law is combination of a closed loop position control augmented with an open loop force control. A third part is added to this control which can be used to make a trade-off between force and position control in normal direction. The basic idea for this controller comes from the point that end-effector of a robotic manipulator with closed-loop position control and open-loop force control makes a position error in opposite direction of force error. It means that if the normal force applied on the end-effector is less than the desired value, the end-effector moves toward surface and vice versa. This part of control is adjusted by a feedback from the normal force and as soon as the normal force passes a critical value turns the control law on which makes the end-effector back off to keep the normal force at maximum value. This process is reversed as soon as the normal force becomes smaller than the maximum possible value. In other words, this control law enforces closed-loop position control while the normal force is less than an acceptable value and switches to a force control normal to the surface as soon as the normal force is greater than certain safe value to prevent damage to surface and the tool.

After this introduction, dynamic modeling is presented in section two followed by the control synthesis in section three. Some numerical simulations are presented in fourth section to show versatilities of the method. The paper is finished by some concluding remarks in fifth section.

II. DYNAMIC MODELING

Let us consider a two link manipulator which is grinding a surface defined by equation y = f(x). Equations of motion of the manipulator can be written in the following form:

$$\boldsymbol{M}\,\ddot{\boldsymbol{q}} + \boldsymbol{h} = \boldsymbol{\tau} - \boldsymbol{J}^{T}\,\boldsymbol{F} \tag{1}$$

in which $\boldsymbol{M}$ is the 2×2 mass matrix, $\boldsymbol{h}$ is the 2×1 array of centrifugal, coriolis and gravitational terms, $\boldsymbol{\tau}$ is the array of joint torques. On the other hand $\boldsymbol{F} = [F_n \quad F_t]^T$ shows array of force components exerted by manipulator to the surface and $\boldsymbol{J}$ is jacobian of the end-effecter in normal and tangential direction defined by

$$\begin{bmatrix} V_n \\ V_t \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{2}$$

One should note that in deriving (1) it is assumed that actuator are collocated with joints and a proper set of generalized coordinates is used.

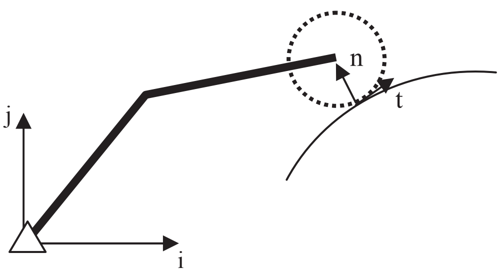

Figure 1. Schematic of two link grinding robot

According to Younis, Sadak and El-Wardani [20] normal force during grinding process in which is a function of advancement velocity of the tool and cutting dept can be written as:

$$F_n = F_{nc} + F_{nr} + F_{np} \tag{3}$$

This model consist of the normal cutting force, F_{nc} ,the normal rubbing force, F_{nr} and the normal ploughing force, F_{np}. Each of these terms are defined as:

$$F_{nc} = w\,k_1\,\frac{v_w}{v_g}\,S_n - L_a\,\frac{k_1\,v_w}{100\,v_g}\,S_n \tag{4}$$

$$F_{nr} = w\,L_a\,K_L\,l_c \tag{5}$$

$$F_{np} = w\,\alpha_f\,\frac{v_w}{v_g}\,l_c - wL_a\alpha_f\,\frac{v_w}{v_g}\,l_c \tag{6}$$

In above relation w is the width of cut. The chip thickness coefficient, k_1 [N/mm2] gives the connection between the chip surface and the cutting force. v_w [m/s] and v_g [m/s] are respectively the speed of the workpiece and the speed of grinding tool. The depth of cut is given by S_n. L_a is percentage of the total area that is loaded, i.e. the part of the total surface that actually makes contact with the workpiece. K_L [N/unitLa] is the loading force coefficient, which gives the connection between the tip area contact of the grains and the rubbing force. l_c is the contact length between grains and workpiece. Finally α_f [N/mm^2] is the coefficient that is determined by the ploughing grain geometry.

They also introduced following equation for tangential grinding force:

$$F_t = \mu\,F_{nc} + \lambda\,F_{nr} + \mu\,F_{np} \tag{7}$$

where μ is the ratio of the tangential to the normal force components and λ is friction coefficient of sliding friction between the tip area and the workpiece.

III. CONTROL

As explained before we need a control which is capable of adjusting control strategy between position control and force control in normal direction. To this end, we introduce a control law which has three components as follow:

$$\boldsymbol{\tau_c} = \boldsymbol{\tau_p} + \bar{\boldsymbol{\tau}} + \hat{\boldsymbol{\tau}} \tag{8}$$

in which τ_p is a closed-loop position control defined as:

$$\boldsymbol{\tau_p} = \boldsymbol{M}\left(\ddot{\boldsymbol{q}}_{\boldsymbol{d}} - \boldsymbol{k_v}\dot{\boldsymbol{e}} - \boldsymbol{k_p}\boldsymbol{e}\right) + \boldsymbol{h} \tag{9}$$

where $\boldsymbol{q_d}$ shows desired path, $\boldsymbol{e} = \boldsymbol{q} - \boldsymbol{q_d}$ shows position error, and $\boldsymbol{k_p}$ and $\boldsymbol{k_v}$ are proportional and derivative gain matrices.

The second term in (8) is an open-loop control defined as:

$$\bar{\boldsymbol{\tau}} = \boldsymbol{J}^{\boldsymbol{T}}\,\mathbf{F} \tag{10}$$

This term compensates for the forces applied on the manipulator.

The third term in control law is an adjustable closed-loop force control defined as:

$$\hat{\boldsymbol{\tau}} = -k_n\,\boldsymbol{J}_{\boldsymbol{1}}^{\boldsymbol{T}}\,(F_n - F_{nd}) \tag{11}$$

in which $\boldsymbol{J_1}$ is the first row of the jacobian matrix defined in (1), F_{nd} is the desired value for the normal force and k_n is a constant which balances between position and force control in normal direction. To see how this control works let us calculate steady state position error of the end effector in terms of normal force error. To this end, let us substitute (8) into (1) to get:

$$\boldsymbol{M}\left(\ddot{\boldsymbol{e}} + \boldsymbol{k_v}\dot{\boldsymbol{e}} + \boldsymbol{k_p}\boldsymbol{e}\right) = -k_n\,\boldsymbol{J}_1^T\,e_n \tag{12}$$

in which $e_n = F_n - F_{nd}$ is the normal force error. Using this relation, the steady state error for a constant normal force error can be calculated as:

$$\boldsymbol{e_{ss}} = -k_n \boldsymbol{k_p^{-1}}\, \boldsymbol{M^{-1}}\, \boldsymbol{J}_1^T\, e_n \tag{13}$$

Considering that for small errors the relation between error in joint angles and position error in normal direction is similar to velocity relation one might write:

$$\delta = \boldsymbol{J}_1\, \boldsymbol{e} \tag{14}$$

in which δ shows position error of the end-effector in normal direction. Substituting (13) into (14) one gets:

$$\delta_{ss} = -\, k_n\, \boldsymbol{J}_1 \boldsymbol{k_p^{-1}}\, \boldsymbol{M^{-1}}\, \boldsymbol{J}_1^T\, e_n \tag{15}$$

Considering that both $\boldsymbol{k_p}$ and $\boldsymbol{M}$ are real positive definite matrices and adopting positive value for k_n one can see that δ_{ss} is always in opposite direction of normal force error. This means that:

- For $k_n = 0$ there will be no steady state error. This results is what is expected because $k_n = 0$ corresponds to a closed-loop position control with an open-loop force control which enforces end-effector to follow the desired path.
- For $k_n \neq 0$ there will be a steady state position error in opposite direction of normal force error. If the normal force is produced by a stiffness type environment, such as workpiece surface, such steady state error reduces the normal force error, so the third term in control law acts like a feedback for normal force. In this case one may easily verify from (15) that normal force error approaches zero if $k_n \to \infty$, i.e. k_n is chosen large enough.

With above conclusions we may suggest the following algorithm for choosing the value of k_n for grinding purpose:

$$k_n = \begin{cases} put\ k_n = 0\ if\ F_n \leq F_{nmax} \\ put\ k_n \neq 0\ if\ F_n \geq F_{nmax} \end{cases} \tag{16}$$

Such algorithm turns the control into a position control while F_n has not reached its maximum permitted limit, and turns it into a position/force control with a trade-off between normal force error and position error controlled by the value of k_n.

IV. NUMERICAL SIMULATION

To show how this control algorithm works let us consider a two-link planar manipulator which is used to grind a vertical surface as shown in Fig. 2. Both links of manipulator are identical and are 0.4m long and their masses are 2Kg. Position of workpiece surface and the desired path are as follow:

$$\begin{aligned} X_w &= 0.600000m \\ X_d &= 0.600145m \\ Y_d &= 0.1m \end{aligned} \tag{17}$$

which means a cutting depth of 0.145 mm. To show how the control can work in case of uneven surfaces three different situations are considered

Case 1) there is a pit of 1mm on the surface
Case 2) there is a lump of 0.1mm on the surface
Case 3) there is a lump of 1mm on the surface

The maximum permitted normal force is considered to be 150N. All parameters of normal force is similar as those in [20]. The controller parameters are chosen as:

$$\begin{aligned} \boldsymbol{k_p} &= 10{,}000 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ \boldsymbol{k_v} &= 100 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ k_n &= \begin{cases} 0 & for\ \ F_n \leq 150N \\ 10 & for\ \ F_n > 150N \end{cases} \end{aligned} \tag{18}$$

Simulation results for case 1 are shown in Fig. 3. In this case a normal force of 60N is generated which is reduced to zero once end-effector reaches the pit and again reaches the value of 60N. As expected during the process k_n remains zero and the desired path is exactly followed.

The results for the second case are shown in Fig. 4. In this case a normal force 60N is generated which is increased to 90N once the disk tries to remove the lump of 0.1mm. Here also k_n remains zero and again desired path is exactly followed. As can be seen in this figure the lump is completely removed by grinding process and the surface is finished.

In the third case the lump is large such that the normal force reaches the value of 150N once the tool reaches the lump as shown in Fig. 5. As we expected in this case the controller does not let the normal force to exceed the maximum permitted value of 150N at the cost of leaving part of lump for a second run of finishing. As shown in the figure in the first run of grinding only 0.5mm of lump is removed. Clearly a second run of grinding with a similar desired path will remove the rest of lump. To show what would be the result with a simple position control, a similar situation is considered with k_n always equal to zero. Simulation results for this case are shown in Fig. 6 which shows that the lump is completely removed in the first run at the cost of increasing normal force to an unacceptable value of 300N which might damage surface and the disk.

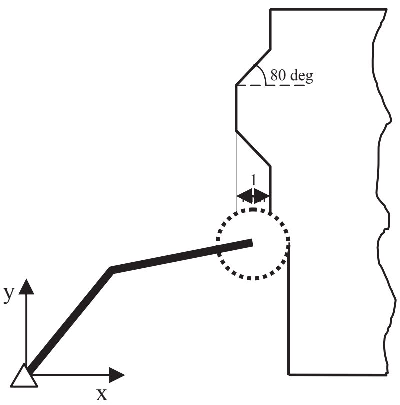

Figure 2. Schematic of two link grinding robot

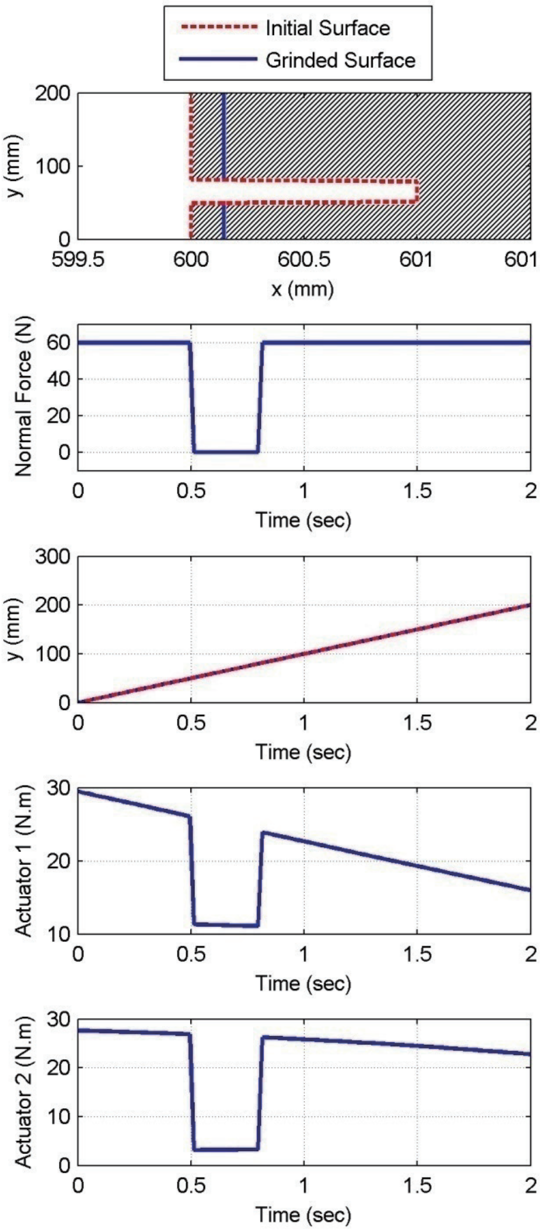

Figure 3. Simulation results for grinding a surface with a pit of 1mm

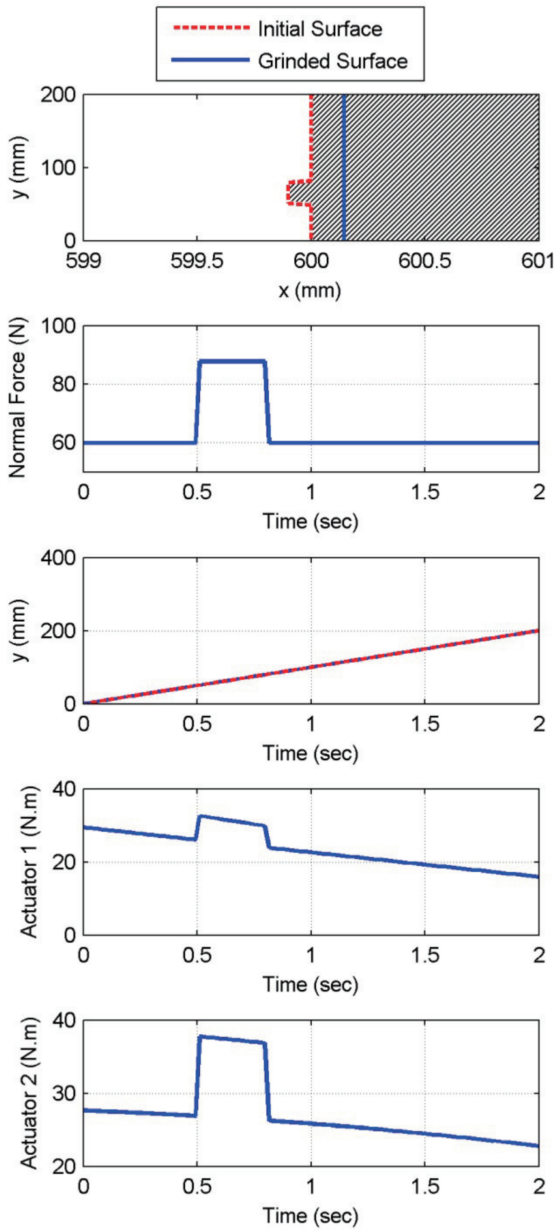

Figure 4. Simulation results for grinding a surface with lump of 0.1mm

V. CONCLUSION

This paper presents a control strategy for grinding uneven surfaces. The control law has three parts. The first part is a simple computed torque position control. The second part is an open-loop force control which is planned to compensate for normal and tangential forces which are generated due to contact of grind disk with surface while following desired path. To keep the normal force below a certain permitted value which is safe for the disk and workpiece, a third part is considered in the control law which can balance between tendency of closed loop position control and force control in normal direction. Several numerical examples are provided to show versatility of the method in different situations of uneven surfaces.

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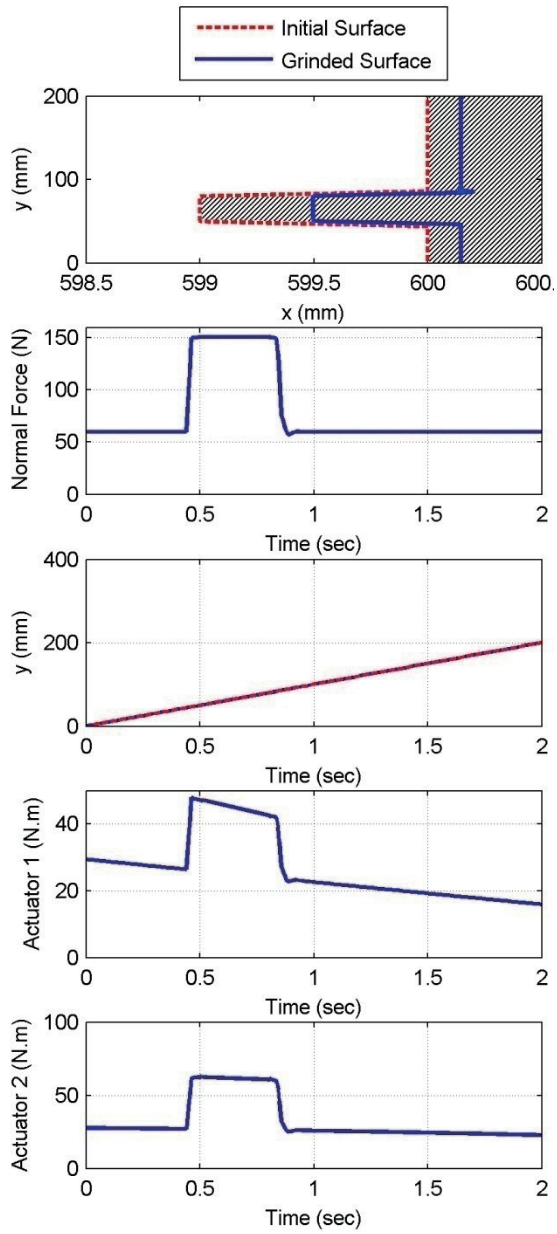

Figure 5. Simulation results for grinding a surface with lump of 1mm

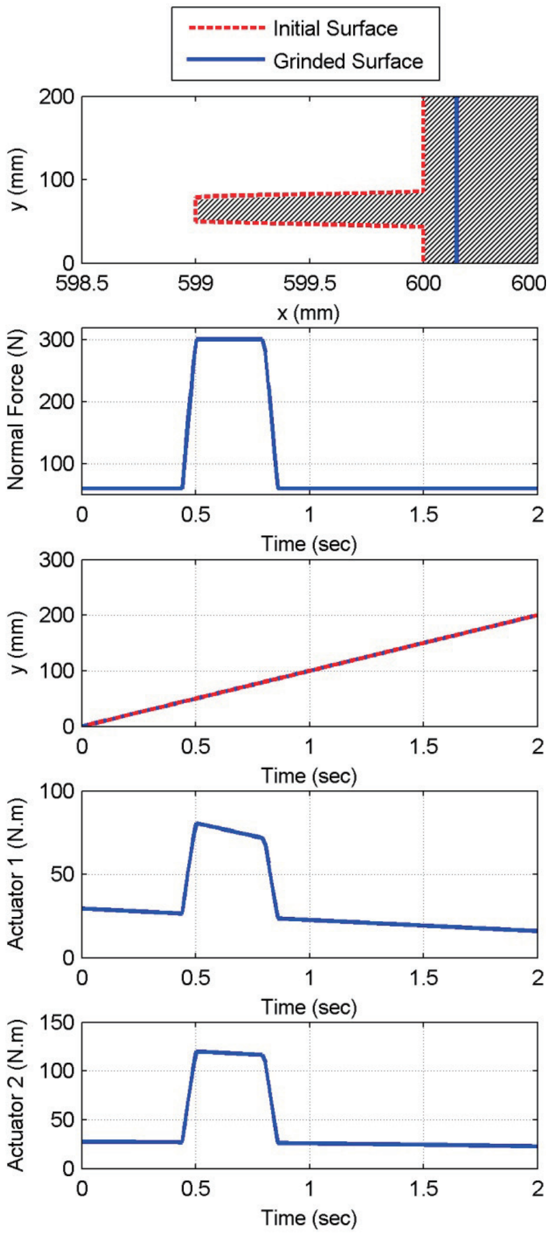

Figure 6. Simulation results for grinding a surface with a lump of 1mm with simple position control