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Hierarchical Optimal Force-Position Control of a Turning Process

Bhaskar Pandurangan, Robert G. Landers, and S. N. Balakrishnan

Abstract—Machining process control technologies are currently not well integrated into machine tool controllers and, thus, servomechanism dynamics are often ignored when designing and implementing process controllers. In this brief, a hierarchical controller is developed that simultaneously regulates the servomechanism motions and cutting forces in a turning operation. The force process and servomechanism system are separated into high and low levels, respectively, in the hierarchy. The high-level goal is to maintain a constant cutting force to maximize productivity while not violating a spindle power constraint. This goal is systematically propagated to the lower level and combined with the low-level goal to track the reference position. Since the only control signal (i.e., motor voltage) resides at the lower level, a single controller is designed at the bottom level that simultaneously meets both the high- and low-level goals. Simulations are conducted that validate the developed methodology. The results illustrate that the controller can simultaneously achieve the low-level position tracking goal and the high-level force-tracking goal.

Index Terms—Aggregation, hierarchical optimal control, machining force control, servomechanism position control, turning processes.

I. INTRODUCTION

PROCESS control technologies (e.g., force control, chatter suppression) have a tremendous potential to impact machining operations by improving operation productivity and part quality. However, machining process control technologies are currently not well integrated into machine tool controllers and, thus, servomechanism dynamics are often ignored when designing and implementing process controllers. In this brief, a novel approach to the design and implementation of process control technologies is developed based upon the concepts of hierarchical control. The approach is applied to the simultaneous regulation of cutting forces and positional errors in a turning operation. A schematic of a turning operation is shown in Fig. 1. A servomechanism drives the cutting tool, thus, creating the feed that determines the magnitude of the cutting forces. The objectives are to maintain a constant cutting force corresponding to maximum productivity while tracking the tool reference trajectory.

The subject of force control has been studied extensively in the literature using many types of control methodologies. Some examples of adaptive machining force control include [1] and [2]. In these studies, model parameters were estimated online and control gains were adjusted to maintain stability over a wide range of parameter variations. As an example of direct model

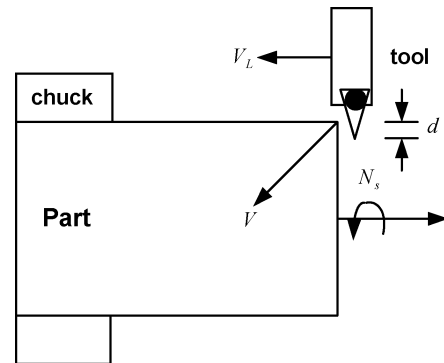


Fig. 1. Schematic of a turning operation.

based control, Landers and Ulsoy [3] developed a nonlinear controller that directly incorporated the force-feed nonlinearity. Pynyko and Bailey [4] and Rober *et al.* [5] designed quantitative feedback theory (QFT) machining force controllers in the discrete domain utilizing the delta transform. Their designs were based on a linear plant with uncertainty in pole and zero locations as well as the magnitude of a gain factor that indirectly accounts for variations in the depth-of-cut and nonlinear process parameters. While some studies [6] have directly incorporated the servomechanism dynamics into the force controller design, machining force controllers typically have been treated separately from the servomechanisms.

A. Hierarchical Systems

Complex systems are typical of the real world. Examples of such systems include airplanes, highway systems, power plants, manufacturing systems, etc. A natural hierarchy exists in most complex systems, with each level having separate requirements. However, in order to satisfy the multitude of requirements, one must rely on the relatively few physical control signals (compared to the multitude of servomechanism, process, and operation requirements), which are typically located at the lowest level in the hierarchy. The optimal hierarchical control methodology, proposed in [7], may be utilized for such problems. Aggregation techniques are utilized to propagate abstract high-level objectives to the lowest level where the physical control signals reside. Therefore, this formulation encompasses goals from all levels, provides for tracking of all requirements, and, since only one formulation is required, design complexity is reduced. A hierarchical system provides other advantages. In a complex system, the evaluation of system properties like controllability, observability, and stability are difficult to analyze [7]. The aggregated system captures the complete system behavior [8] and, thus, system properties can be evaluated from the aggregated system dynamics.

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In this brief, simultaneous force control and position control in a turning operation is performed using the optimal hierarchical architecture proposed in [7]. The force process and servomechanism system are separated into high and low levels, respectively, in the hierarchy. The high-level goal is to maintain a constant cutting force to maximize operation productivity while not violating a spindle power constraint. This goal is propagated to the lower level and combined with the low-level goal to track the reference position trajectory. This propagation requires an aggregation between the high and low levels. In this case, between the servomechanism and the cutting force process. Since there are only control signals at the lower level, in this case motor voltages, a single controller is designed at the bottom level that will meet both the high-level and low-level goals.

II. SYSTEM MODELING

This section provides models of the machining force process and servomechanism system. The cutting force depends on the cutting speed, feed, and the depth-of-cut of the cutting tool and is related to these parameters by the following nonlinear relation [3]

$$F = K f^\alpha d^\beta V^\gamma \quad (1)$$

where F is the cutting force in kN, f is the feed in mm, d is the depth-of-cut in mm, V is the cutting speed in km/min, and K , α , β , and γ are empirically determined constants. The structural vibrations are assumed to be small as compared to the feed and the cutting tool angles are constant. Also, effects due to tool wear and cutting temperature are assumed to be reflected in the force process gain.

The servomechanism system consists of an interpolator that determines the reference positions along the paths specified in the part program, the controller that determines the motor voltage, and the physical servomechanism system that consists of a motor, leadscrew, gear, table, etc. The interpolator calculates the linear axis reference position at each sample period based on the paths and velocities specified by the part program. The transfer function of the linear motion interpolator is

$$\frac{p_{\text{ref}}}{V_{L_{\text{ref}}}} = \frac{1}{s} \quad (2)$$

where $V_{L_{\text{ref}}}$ is the reference linear velocity in mm/s and p_{ref} is the reference position in mm. The reference linear velocity is related to the reference feed (f_{ref} in mm) and reference spindle speed (N_{sref} in rpm) by

$$V_{L_{\text{ref}}} = \frac{N_{\text{sref}}}{60} f_{\text{ref}}. \quad (3)$$

It is assumed that the actual spindle speed tracks the reference spindle speed through a separate regulation loop. The reference feed is calculated from (1) corresponding to the spindle speed, depth-of-cut, and maximum force. The controller (described below) outputs the motor voltage (V_0 in V) that drives the servomechanism. The servomechanism states are the feed (f in mm) and the actual cutting tool position (p_{act} in mm).

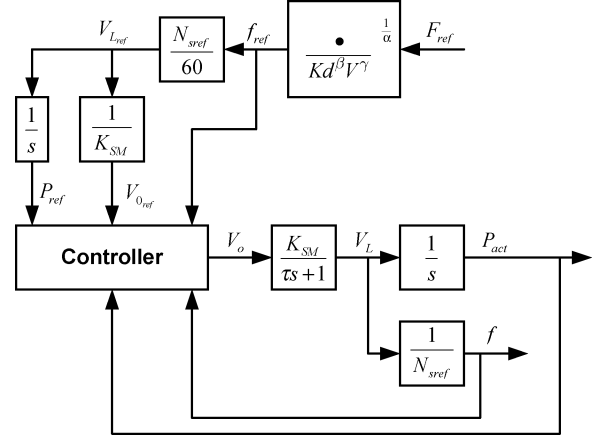


Fig. 2. System block diagram.

The servomechanism transfer function, neglecting disturbance torques and electrical dynamics, is

$$\frac{V_L}{V_0} = \frac{K_{SM}}{\tau s + 1} \quad (4)$$

where τ is the servomechanism time constant in seconds and K_{SM} is the servomechanism gain in (mm/s)/V. The relationship between the servomechanism actual position and the servomechanism actual velocity is

$$\frac{p_{\text{act}}}{V_L} = \frac{1}{s}. \quad (5)$$

The actual feed is

$$f = \frac{60V_L}{N_{\text{sref}}}. \quad (6)$$

The system block diagram is shown in Fig. 2.

The state-space realization of the servomechanism system is given by

$$\begin{bmatrix} \dot{p}_{\text{act}} \\ \dot{f} \end{bmatrix} = \begin{bmatrix} 0 & \frac{N_{\text{sref}}}{60} \\ 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} p_{\text{act}} \\ f \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{60K_{SM}}{\tau N_{\text{sref}}} \end{bmatrix} V_0. \quad (7)$$

Since the aggregation relation will be described in terms of perturbed variables, the state variables chosen are the perturbed actual position $\Delta p_{\text{act}} = p_{\text{ref}} - p_{\text{act}}$ and the perturbed feed $\Delta f = f_{\text{ref}} - f$. The state-space representation in terms of the perturbed state variables is

$$\begin{bmatrix} \Delta \dot{p}_{\text{act}} \\ \Delta \dot{f} \end{bmatrix} = \begin{bmatrix} 0 & \frac{N_{\text{sref}}}{60} \\ 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} \Delta p_{\text{act}} \\ \Delta f \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{60K_{SM}}{\tau N_{\text{sref}}} \end{bmatrix} \Delta V_0 \quad (8)$$

where $\Delta V_0 = V_{0_{\text{ref}}} - V_0$ and $V_{0_{\text{ref}}} = V_{L_{\text{ref}}}/K_{SM}$ is the equilibrium voltage. Equation (8) may be written compactly as

$$\Delta \dot{X} = A_{\text{bot}} \Delta X + B_{\text{bot}} \Delta V_0 \quad (9)$$

where

$$\Delta X = \begin{bmatrix} \Delta p_{\text{act}} \\ \Delta f \end{bmatrix}. \quad (10)$$

III. HIERARCHICAL CONTROLLER DESIGN

The equilibrium feed can be calculated from (1) corresponding to the maximum allowable force (F_{\max} in kN). If P_{\max} , in kW, is the maximum power that can be supplied by the spindle, the reference force and feed, respectively, are

$$F_{\text{ref}} = F_{\max} = \frac{P_{\max}}{V} \quad (11)$$

$$f_{\text{ref}} = \left[\frac{F_{\text{ref}}}{KV^\gamma d^\beta} \right]^{1/\alpha}. \quad (12)$$

Note that P_{\max} is the maximum continuous power. The actual power can exceed the maximum continuous power for short periods of time as long as the actual power does not exceed the maximum peak power. Linearizing (1) about the operating (i.e., equilibrium) conditions yields

$$\Delta F = [KV^\gamma d^\beta \alpha f_{\text{ref}}^{\alpha-1}] \Delta f = \Theta \Delta f \quad (13)$$

where $\Delta F = F_{\max} - F$. The linearized force-feed relation (13) is used to aggregate the perturbed cutting force with the perturbed feed. The aggregation matrix is

$$C = [0 \quad \Theta] \quad (14)$$

that maps the state variables of the lower level (i.e., Δf and Δp_{act}) to the state variables of the upper level (i.e., ΔF). Thus

$$\Delta F = [0 \quad \Theta] \begin{bmatrix} \Delta p_{\text{act}} \\ \Delta f \end{bmatrix} = C \Delta X. \quad (15)$$

The goal at the top level of the hierarchy is to maintain a constant cutting force (i.e., $\Delta F = 0$) such that productivity is maximized within the spindle power constraint. The next step is to propagate this goal to the lower level. Thus, the feed trajectory at the lower level should produce the cutting force trajectory such that $\Delta F = 0$. Due to the aggregation given by (13), there is a constraint on the lower level to track the trajectories of the upper level. This constraint is the goal propagation from the upper level to the lower level. The optimal control problem at the lower level can now be formulated as, minimizing the following cost function:

$$J_{\text{bot}} = \frac{1}{2} \left[\Delta F(t_f)^T S \Delta F(t_f) \right] + \frac{1}{2} \int_0^{t_f} \left\{ [\Delta F - C \Delta X]^T Q_{\text{bot}} [\Delta F - C \Delta X] + \Delta V_0^T R_{\text{bot}} \Delta V_0 + \Delta X^T Q \Delta X \right\} dt \quad (16)$$

subject to the dynamics given by (9). The first term under the integral in (20) is the cost associated with satisfying the aggregation relation (13). In other words, the trajectory of ΔX should be such that the aggregation relation (13) is satisfied. The second term under the integral in (16) is the control effort cost. The third term under the integral in (16) is the cost associated with maintaining the objectives at the bottom level (i.e., driving p_{act} to p_{ref} and f to f_{ref}).

Using optimal control principles [9], the Hamiltonian has the form

$$H_{\text{bot}} = J_{\text{bot}} + \lambda_{\text{bot}}^T (A_{\text{bot}} \Delta X + B_{\text{bot}} \Delta V_0) \quad (17)$$

where

$$\lambda_{\text{bot}} = P_{\text{bot}} \Delta X + h_{\text{bot}} \quad (18)$$

is the Lagrange multiplier at the bottom level. The values of P_{bot} and h_{bot} are determined by integrating the following differential equations backward in time

$$\dot{P}_{\text{bot}} = -P_{\text{bot}} A_{\text{bot}} - A_{\text{bot}}^T P_{\text{bot}} + P_{\text{bot}} B_{\text{bot}} R_{\text{bot}}^{-1} B_{\text{bot}}^T P_{\text{bot}} - C^T Q_{\text{bot}} C - Q \quad (19)$$

$$\dot{h}_{\text{bot}} = -A_{\text{bot}}^T h_{\text{bot}} + P_{\text{bot}} B_{\text{bot}} R_{\text{bot}}^{-1} B_{\text{bot}}^T h_{\text{bot}} + C^T Q_{\text{bot}} \Delta F. \quad (20)$$

The terminal boundary conditions [10] are

$$P_{\text{bot}}(t_f) = \frac{\partial H_{\text{bot}}}{\partial \Delta X} = C^T S C \quad (21)$$

$$h_{\text{bot}}(t_f) = -C S \Delta F(t_f). \quad (22)$$

Thus, the matrix P_{bot} and the vector h_{bot} are integrated backward in time using the boundary conditions in (21) and (22). These trajectories are utilized to calculate the control law and integrate the equations of motion forward in time, given the state initial conditions.

In order to find the optimal control signal at the bottom level, (16) is partially differentiated with respect to V_0 and equated to zero. Thus, the optimal control law is

$$\Delta V_0 = -R_{\text{bot}}^{-1} B_{\text{bot}}^T \lambda_{\text{bot}} = -R_{\text{bot}}^{-1} B_{\text{bot}}^T [P_{\text{bot}} \Delta X + h_{\text{bot}}]. \quad (23)$$

Since $\Delta F(t_f) = 0$ and $h_{\text{bot}}(t_f) = 0$, $h_{\text{bot}} \equiv 0$. Therefore, the control law may be written as

$$\Delta V_0 = -R_{\text{bot}}^{-1} B_{\text{bot}}^T P_{\text{bot}} \Delta X. \quad (24)$$

Therefore, the problem is converted from a tracking problem to a regulation problem.

A. Simulation Studies

Simulation studies are now conducted to illustrate the utility of the hierarchical controller. The force process is given by $F = 1.17 d^{0.877} V^{-0.273} f^{0.891}$. This data is based on machining experiments conducted for a steel part using a coated carbide insert [11]. The maximum power is 10 hp (7.46 kW) and the operation parameters are $N_{\text{sref}} = 6000$ rpm, $d = 1$ mm, and $V = 0.938$ km/min. The servomechanism time constant and gain are $\tau = 0.055$ s and $K_{SM} = (20 \text{ mm/s})/V$, respectively. The value of the maximum force, determined from the maximum cutting power and cutting velocity, is $F_{\max} = 0.4772$ kN, the equilibrium feed is $f_{\text{ref}} = 0.3571$ mm, and the aggregation matrix is $C = [0 \quad 1.186]$. Using the servomechanism parameters and (8), $A_{\text{bot}} = \begin{bmatrix} 0 & 100 \\ 0 & -18.2 \end{bmatrix}$ and $B_{\text{bot}} = \begin{bmatrix} 0 \\ 3.64 \end{bmatrix}$, and the weighing matrices are $Q_{\text{bot}} = 4$, $S = 0.05$, $R_{\text{bot}} = 2$, and $Q = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix}$.

The system is simulated for a final time of 2.5 s and the results are shown in Figs. 3 and 4. In Fig. 3, it is seen that the feed tracks the reference feed and, thus, the force tracks the reference force. Also, the servomechanism position tracks the reference

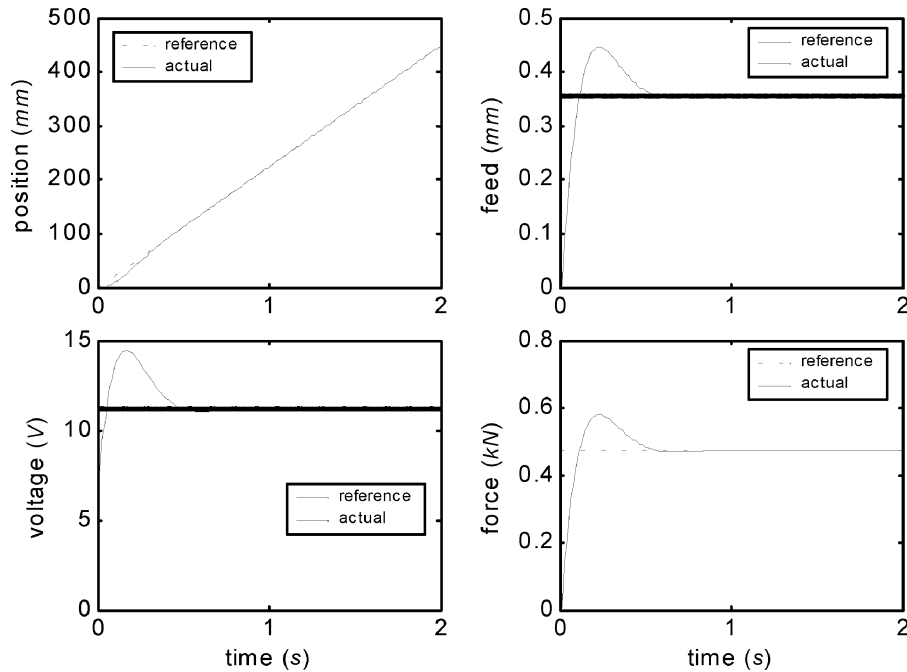


Fig. 3. Simulation results for time varying P_{bot} .

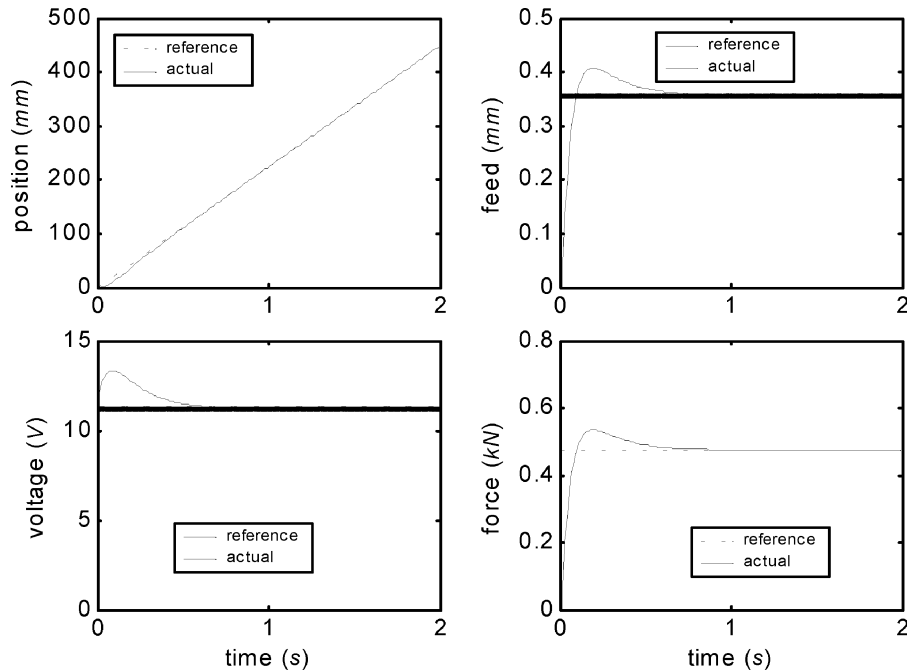


Fig. 4. Simulation results for constant P_{bot} .

position trajectory. Thus, the hierarchical controller is able to simultaneously meet the upper level and lower level objectives. For the results in Fig. 3, the dynamic solution of P_{bot} was utilized. Next, the steady-state solution of P_{bot} is utilized and the results are shown in Fig. 4. A comparison of Figs. 3 and 4 illustrates that there is no difference when utilizing the steady-state solution of P_{bot} . Therefore, the steady-state solution of P_{bot} may be utilized, relieving an excessive computational burden and greatly aiding controller implementation. Also, since the feed is adjusted to maintain a constant cutting force, it is not possible to predict the exact cycle time of the machining oper-

ation and, thus, utilizing the dynamic solution for P_{bot} would not be practical.

IV. ROBUSTNESS TO PARAMETER VARIATIONS

The force model given by (1) includes model parameters (i.e., K , α , β , and γ) that must be determined empirically and process parameters (i.e., d and V) that are functions of the machine tool's linear axis and the spindle motions. The controller derived above assumed no variation in these parameters; however, these parameters naturally vary during a machining operation. For ex-

ample, the model gain K strongly depends on the tool wear and cutting temperature. Also, the depth-of-cut depends on the part geometry and the cutting speed will change when machining a taper part if the spindle speed is held constant. When a model parameter varies, monitoring techniques must be used to determine the amount of variation, while process parameter variations may be determined from the part drawing and sensing the machine variables. When there is parameter variation, the linearized relation given by (13) is not valid. In this section, controllers are derived for uncertainties in the model gain and in the depth-of-cut.

A. Variations in Model Parameters

Variations in the force process model gain are considered first. Expanding the force-feed relation given by (1) in a Taylor series expansion about the reference feed and the nominal value of the force process model gain (K_0)

$$\begin{aligned} \Delta F \cong & [K_0 \alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma] \Delta f + [f_{\text{ref}}^\alpha d^\beta V^\gamma] \Delta K \\ & + \frac{1}{2!} [K_0 \alpha (\alpha - 1) f_{\text{ref}}^{\alpha-2} d^\beta V^\gamma] \Delta f^2 \\ & + [\alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma] \Delta f \Delta K \end{aligned} \quad (25)$$

where $\Delta K = K - K_0$. Assuming the second-order term in Δf in (25) is negligible, we get

$$\begin{aligned} \Delta F - [f_{\text{ref}}^\alpha d^\beta V^\gamma] \Delta K & \\ = [K_0 \alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma + \alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma \Delta K] \Delta f & \\ = [K \alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma] \Delta f. \end{aligned} \quad (26)$$

The term $- [f_{\text{ref}}^\alpha d^\beta V^\gamma] \Delta K$ can be regarded as a bias. The goal propagated from the top level of the hierarchy is $\Delta F_{\text{eff}} = 0$ where

$$\Delta F_{\text{eff}} = \Delta F - [f_{\text{ref}}^\alpha d^\beta V^\gamma] \Delta K. \quad (27)$$

The actual model gain K is estimated using monitoring techniques such as an observer or measurements and, thus, ΔK may be calculated. The effective aggregation matrix is

$$C_{\text{eff}} = [0 \quad K \alpha f_{\text{ref}}^{\alpha-1} d^\beta V^\gamma]. \quad (28)$$

Note this is the same aggregation matrix as given in (14) except the force process gain varies with time. The cost function to minimize at the lower level is

$$\begin{aligned} J_{\text{bot}} & \\ = \frac{1}{2} & \left[\Delta F_{\text{eff}}(t_f)^T S \Delta F_{\text{eff}}(t_f) \right] \\ & + \frac{1}{2} \int_0^{t_f} \left\{ [\Delta F_{\text{eff}} - C_{\text{eff}} \Delta X]^T Q_{\text{bot}} [\Delta F_{\text{eff}} - C_{\text{eff}} \Delta X] \right. \\ & \left. + \Delta V_0^T R_{\text{bot}} \Delta V_0 + \Delta X^T Q \Delta X \right\} dt. \end{aligned} \quad (29)$$

The controller given by (23) is implemented where the steady-state solution for P_{bot} is updated each time the model gain estimate is updated. The vector h_{bot} is again identically zero since $\Delta F_{\text{eff}}(t_f) = 0$.

B. Variations in Process Parameters

Variations in the depth-of-cut are now considered. Expanding the force-feed relation given by (1) in a Taylor series expansion about the reference feed and the nominal value of the depth-of-cut (d_0)

$$\begin{aligned} \Delta F \cong & [K \alpha f_{\text{ref}}^{\alpha-1} d_0^\beta V^\gamma] \Delta f + [K \beta f_{\text{ref}}^\alpha d_0^{\beta-1} V^\gamma] \Delta d \\ & + \frac{1}{2!} [K \alpha (\alpha - 1) f_{\text{ref}}^{\alpha-2} d_0^\beta V^\gamma] \Delta f^2 \\ & + \frac{1}{2!} [K \beta (\beta - 1) f_{\text{ref}}^\alpha d_0^{\beta-2} V^\gamma] \Delta d^2 \\ & + [K \alpha \beta f_{\text{ref}}^{\alpha-1} d_0^{\beta-1} V^\gamma] \Delta f \Delta d \end{aligned} \quad (30)$$

where $\Delta d = d - d_0$. Assuming that the second-order term in Δf in (30) is negligible, we get

$$\begin{aligned} \Delta F - [K \beta f_{\text{ref}}^\alpha d_0^{\beta-1} V^\gamma] \Delta d & \\ - \frac{1}{2!} [K \beta (\beta - 1) f_{\text{ref}}^\alpha d_0^{\beta-2} V^\gamma] \Delta d^2 & \\ = [K \alpha f_{\text{ref}}^{\alpha-1} d_0^\beta V^\gamma + K \alpha \beta f_{\text{ref}}^{\alpha-1} d_0^{\beta-1} V^\gamma \Delta d] \Delta f. \end{aligned} \quad (31)$$

The term $- [K \beta f_{\text{ref}}^\alpha d_0^{\beta-1} V^\gamma] \Delta d - (1/2!) [K \beta (\beta - 1) f_{\text{ref}}^\alpha d_0^{\beta-2} V^\gamma] \Delta d^2$ again can be regarded as a bias. The goal propagated from the top level of the hierarchy is $\Delta F_{\text{eff}} = 0$ where

$$\begin{aligned} \Delta F_{\text{eff}} = \Delta F - [K \beta f_{\text{ref}}^\alpha d_0^{\beta-1} V^\gamma] \Delta d & \\ - \frac{1}{2!} [K \beta (\beta - 1) f_{\text{ref}}^\alpha d_0^{\beta-2} V^\gamma] \Delta d^2. \end{aligned} \quad (32)$$

The effective aggregation matrix is

$$C_{\text{eff}} = [0 \quad K \alpha f_{\text{ref}}^{\alpha-1} d_0^\beta V^\gamma + K \alpha \beta f_{\text{ref}}^{\alpha-1} d_0^{\beta-1} V^\gamma \Delta d]. \quad (33)$$

The cost function to minimize at the lower level is given by (29) where C_{eff} is given by (33). The controller given by (23) is implemented where the steady-state solution for P_{bot} is utilized and the controller gains are updated, based on C_{eff} , each time the depth-of-cut changes. The vector h_{bot} is again identically zero since $\Delta F_{\text{eff}}(t_f) = 0$. Often the depth-of-cut is known *a priori* and, thus, the controller gains can be calculated offline.

C. Simulations

Two simulations are conducted: one for a variation in the force process gain and another for a variation in the depth-of-cut. In the first simulation study, the force process gain increases by 25%/s to mimic extreme tool wear and it is assumed that the gain can be estimated perfectly. The length-of-cut is 600 mm and the results are shown in Fig. 5. The results demonstrate that both the low-level objective (tracking the reference position) and the high-level objective (tracking the reference cutting force) are simultaneously achieved. As the gain increases, a smaller feed is required for the cutting force to track the reference cutting force. Based on the force process gain estimate, the reference feed and the reference voltage, as well as the controller gains, are automatically adjusted. Thus, both the low- and high-level objectives may be met. In the next simulation study, the force process gain is held constant; however, the depth-of-cut is 2 mm over the first 100 mm length-of-cut, 1 mm over the

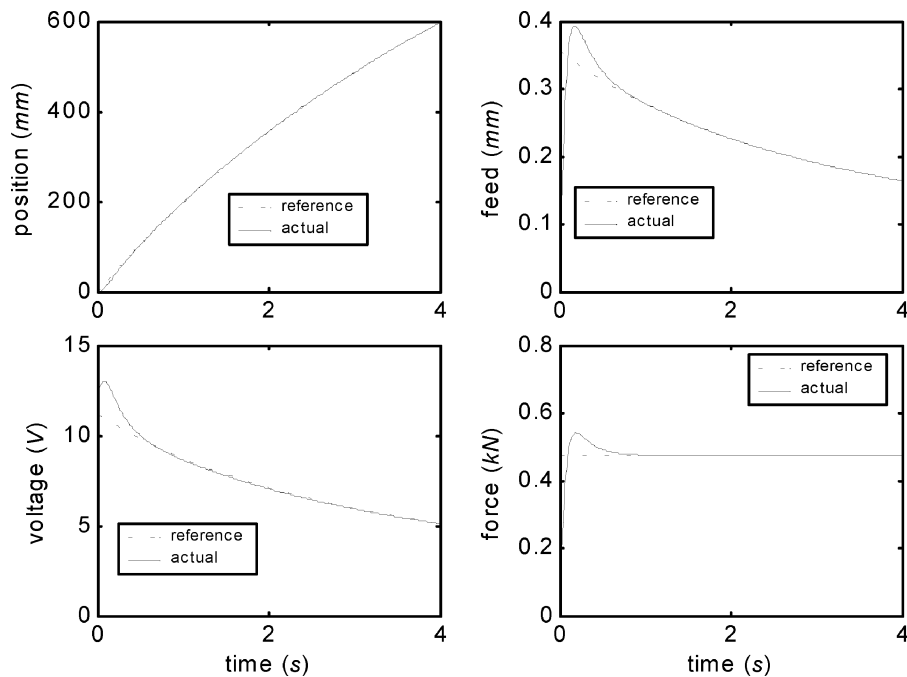


Fig. 5. Simulation results for varying force process gain.

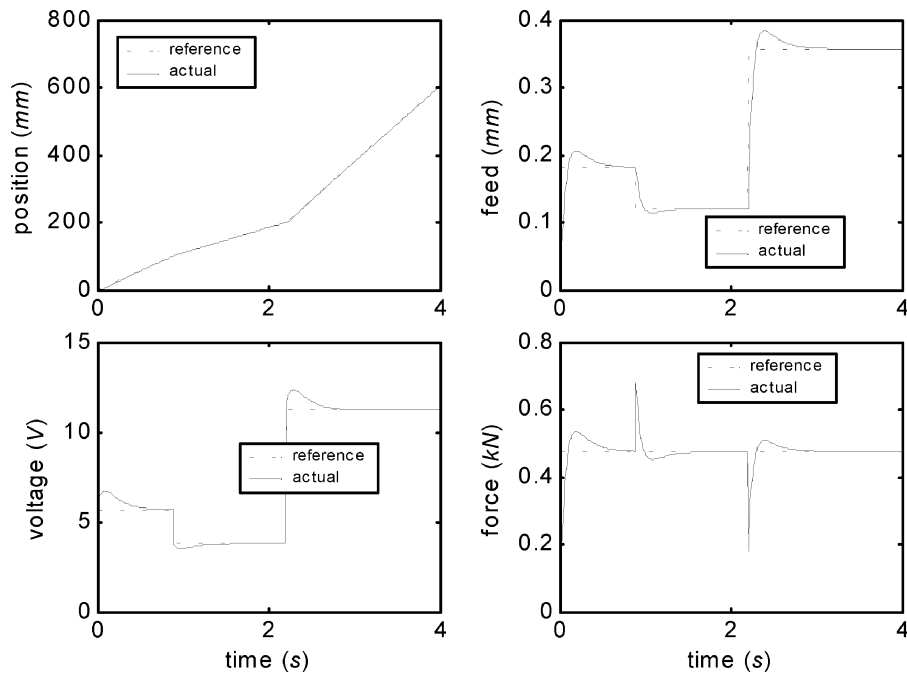


Fig. 6. Simulation results for varying depth-of-cut.

second 100 mm length-of-cut, and 3 mm over the last 400 mm length-of-cut. The results are shown in Fig. 6. Again, both the low- and high-level objectives are simultaneously achieved by automatically adjusting the reference feed and reference voltage as well as the controller gains.

V. SUMMARY AND CONCLUSION

A hierarchical multiresolutional controller was developed in this brief that simultaneously regulates the machining force and servomechanism position in a turning operation. Using

the force-feed relation, the cutting force was aggregated from the cutting tool feed and position. An optimal control problem was solved to form a control law for the voltage trajectory that guarantees the desired force and position trajectories. Simulations were conducted to verify the developed controller. The results showed that the Riccati matrix steady-state solution may be utilized, which greatly aids implementation, and that the controller can simultaneously achieve the low-level position tracking goal and the high-level force tracking goal. The controller was reformulated to account for parameter uncertainties and for known changes in process variables. In both cases, the

controller adjusted the reference feed and control voltage to again simultaneously achieve the low-level position tracking goal and the high-level force tracking goal. The simulation results demonstrate that the hierarchical controller developed in this brief is capable of regulating the force process and servomechanism position with a single controller, even when the force process varies greatly. Thus, the proposed technique greatly decreases the complexity of the overall control system. The hierarchical controller presented in this brief provides a systematic method to integrate servomechanism and process controllers in machining operations. The next phase of this work will concentrate on experimental studies, as the simulations cannot perfectly represent the actual turning process.

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