Supervisory Control of a Face Milling Operation in Different Manufacturing Environments

Robert G. Landers and A. Galip Ulsoy

Abstract: The promise of improved productivity and quality has lead to numerous research investigations in machining process monitoring and control. Recent studies have demonstrated that careful attention must be paid to the regulation of multiple process modules within a single operation such that each module performs its function properly and adverse interactions between modules do not occur. This had lead to the development of supervisory control; particularly to the development of methodologies to systematically construct and implement these controllers. However, no research study has investigated the effect of the production environment on the design of supervisory controllers. In this paper, the design of supervisory controllers for various production environments is studied. The design approach given in Landers and Ulsoy (1998) is applied to construct two supervisory machining controllers that are experimentally implemented in a face milling operation. Comparisons with an experimental implementation without process control illustrate the benefits of utilizing process controllers that are coordinated properly. The results also show that the given design approach may be used to construct supervisory controllers for different types of production environments.

Keywords: supervisory control, process control, face milling, manufacturing environments

I. Introduction

There has been a tremendous amount of research over the past few decades in process monitoring and control of machining operations (Du *et al.*, 1995; Tönshoff *et al.*, 1988; Ulsoy and Koren, 1993). While substantial improvements in productivity and quality have been demonstrated, industrial acceptance remains scarce. One reason for this lack of acceptance is the complexity involved in implementing multiple monitoring and control modules within a single operation as these modules can sometimes have adverse interactions and may not perform as expected (Landers and Ulsoy, 1998). This has lead to several investigations into supervisory control – approaches that regulate the activity of monitoring and control modules. This body of work has concentrated on the development of methodologies to design supervisory controllers and on issues encountered when implementing these controllers. However, the effect of the production environment (e.g., job–shop, high–volume transfer–line) on the design of supervisory controllers has not yet been explored.

Recently, researchers have begun to define the necessary elements for the automatic supervision of machining operations. Tlusty (1994) defined six areas necessary for the automatic supervision of milling operations: force overload, torque overload, tooth failure, tool wear, chatter vibrations, and resonant forced vibrations. These processes must be detectable on–line and a corrective procedure is needed whenever they are detected. This work concentrates on catastrophic events that may ruin the part, the cutter, or the machine tool. Lindström (1994) discussed the major processes encountered in turning and boring operations and techniques to measure, directly or indirectly, the state of these processes. The processes are tool wear, tool failure, tool collision, missing tool, cutting forces, vibrations, chip breaking, tolerances, and surface roughness. The motivation for the on–line supervision of these processes is the real–time optimization of turning and boring operations. Westkämper (1994) discussed automatic supervision of surface grinding in the context of closed–loop quality control. Quality is maintained by knowledge of pre–operation information (process variables, part state, and grinding wheel state), real–time measurements (grinding forces, cutting power, vibrations, and cutting temperature), and post–operations measurements (wheel wear, surface errors, and surface integrity). Obviously, there is not yet complete agreement as to what elements are necessary for supervisory control and what functions such a controller will serve.

Over the past decade, several research studies have investigated the supervision of machine tool controller modules. Altintas *et al.* (1996) and Altintas and Munasinghe (1996) scheduled the implementation order of monitoring and control modules via a job manager that dynamically assigned priorities to the modules. A two–level (process and supervisory) hierarchical control system was developed by Teltz and Elbestawi (1993). The process level consisted of a force controller and a chatter suppressor. Signal and alarm events were monitored in the supervisory level that utilized an inference engine to search a knowledge base and relate these events to recovery actions. Furness (1992) and Furness *et al.* (1996) cast the supervisory control problem as an off–line, constraint–based optimization problem where the activity of each module was determined *a priori*; thus, the modules were regulated in an open–loop fashion. The approach was applied to construct a supervisory controller for a through hole drilling operation where speed, feed, and torque controllers were utilized. Feed and speed controllers were utilized during drill entry to satisfy hole location error and a tool wear constraint, respectively. Torque and speed controllers were utilized between drill entry and exit to satisfy tool breakage and tool wear constraints, respectively. During drill exit, burr and tool wear constraints were satisfied via feed and speed controllers, respectively. Flores and Tsao (1998) presented a supervisory controller that

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utilized fuzzy logic to regulate the activity of various constraints and to determine the amount to increase or decrease the feedrate command to track these constraints. In an end milling application, a part was produced with a thin section that required a low force constraint to minimize deflection and another section where two sides required a high surface finish constraint to ensure proper mating with another part. Landers (1997) and Landers and Ulsoy (1998) developed a supervisory machining controller that regulated the activity (e.g., on, off, reset) of each module in the machine tool controller based on the state of the operation. The approach is outlined in this paper and applied to a face milling operation.

A variety of production environments exist in industry today. Production environments are characterized by how work material is routed through the plant, the type(s) of manufacturing stations, and the part volume and mix. At one extreme there is one–off production where a single part is produced on a station. At the other extreme are high–volume transfer–lines where a single part is produced in very large quantities using several stations in a serial configuration. In between are production environments with a wide range of volumes, which may be fixed or varying rapidly, a variety of part mixes that are produced at any give time, and configurations ranging from single stations or cells to flexible environments to dedicated transfer lines. The type of production environment will dictate the feasibility of the implementation of process monitoring and control technology and, thus, the resulting supervisory controller.

II. SMC design approach overview

This section provides an overview of the supervisory machining control design approach developed by Landers and Ulsoy (1998). The supervisory controller regulates the activity of the machining modules to ensure that each module performs properly and that adverse interactions between modules do not occur. The supervisory controller (Figure 1) consists of a state supervisor and an operation supervisor (described below). The machine tool controller manipulates the machining variables (i.e., speed, feed, and depth–of–cut) and hence, the operation, via a set of servo and process control modules. The process modules manipulate the reference values of the servo modules, while the servo modules directly manipulate the machine tool servomechanisms. Measurements from the machining operation are fed back to the state supervisor and machine tool controller where they are utilized in raw or filtered form. The operator is able to alter the machining operation via real–time inputs to the state supervisor.

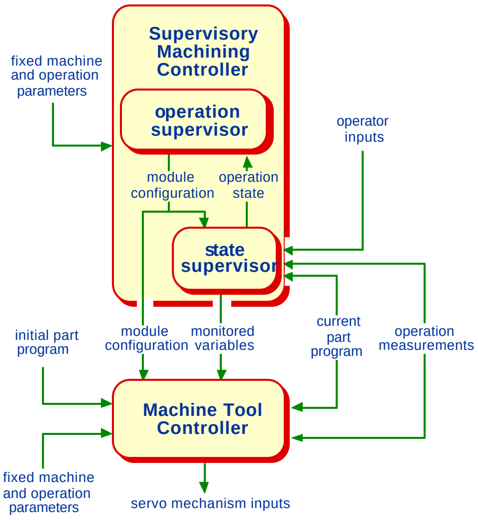

Fig. 1. Structure of supervisory machining controller.

1. State supervisor

The state supervisor monitors the state of the machining operation by utilizing a set of monitoring modules that are selected *a priori* by the designer. Given operation measurements, fixed machine and operation parameters, and operator inputs, the state supervisor determines 1) the instantaneous operation state (e.g., cutting tool–part contact, chatter) and 2) the monitored parameters (e.g., force process gain). The instantaneous operation state is input to the operation supervisor.

2. Operation supervisor

The operation supervisor is a state–based logic controller that regulates the activity of the monitoring and control modules. The designer constructs the supervisory controller based upon knowledge gained through a variety of sources (e.g., experience, simulations). Given the current operation state from the state supervisor, the operation supervisor regulates the activity (e.g., on, off, initialize) of each machining module.

3. Design approach

The designer is given the machining operation specifications (i.e., machine tool, cutting tool, constraints, part, and part program that specifies the nominal cutting parameters and tool path) as well as a set of operation objectives. Finally, the designer is given the available monitoring and control modules.

The designer constructs the supervisory controller via the following steps:

1) Select Monitoring and Control Modules: The designer chooses the monitoring and control modules to be implemented in the machining operation. The modules are selected to meet the design objectives.

2) Construct Fixed Machine and Operation Parameter Modules: The designer constructs modules containing the necessary fixed parameters (i.e., parameters that will not change during the operation) given the particular machine tool and machining operation. These parameters will be utilized by the monitoring and control modules.

3) Construct Operation Supervisor: The designer constructs the operation supervisor via the following steps: a) form rules for how, given each operation state, the activity of each module should be regulated and how the modules should interact, b) specify a logic controller based upon the developed rules, and c) convert the logic controller into a module to be implemented in the machining system. In this paper, Grafcet (see David and Alla, 1992) is used to specify the logic controller and the operation supervisor is implemented as a “C” module.

4. Grafcet

This section briefly describes the tool Grafcet (refer to Figures 4 and 5). Each system state is represented with a box. For instance, state 2 is encountered when the tool and part are not in contact. A double box denotes an initial state; in this case, state 1 is the initial state. A token (darkened circle) is placed in the active state(s) denoting the current situation (i.e., collection of active states). The thick horizontal lines, which are numbered in parentheses on the left, are transitions whose receptivities are represented by a Boolean function on the right. The symbol ‘ to the right of a Boolean variable denotes the complement of the Boolean variable. A transition is enabled when all proceeding state(s) are active. A transition is firable if it is enabled and its receptivity is true (i.e., its Boolean function has a value of 1). New states are then entered and the situation changes. The lines joining the states are called arcs and are directed downward unless otherwise indicated with an arrow. The small boxes connected to the right of each state represent actions. The capital letter is a Boolean variable denoting the activity of the particular action. When the state is active, the variable takes a value of 1 and the action is active. When the state is inactive, the variable takes a value of 0 and the action is inactive. Level actions (i.e., actions whose time duration is finite) are represented by Boolean variables without asterisks (*) while impulse actions (i.e., actions whose time duration is infinitesimal) are represented by Boolean variables with asterisks.

III. Face milling application

The face milling operation (see Figure 2) and the machine tool (Figure 3) used for the experimental implementations are described in this section. The operation objectives are to avoid or suppress chatter and not violate the spindle power constraint. The programmed spindle speed and feedrate are 1500 *rpm* and 10 *mm/s*, respectively. The depth–of–cut will be either 1 *mm* or 2 *mm*, depending on the production environment (discussed below). There is an operation constraint on the maximum feed of 0.6 *mm/tooth* given in a machinist handbook (Machinability Data Center, 1980). The machine tool is a three–axis vertical milling machine with constraints on the maximum feedrate (36 *mm/s*) and spindle power (745.7 *W*). The available process monitoring and control modules are listed in Table 1. The capital letters in parenthesis are Boolean variables that indicate the activity of each action (e.g., a value of 1 indicates the action is active). The instantaneous force

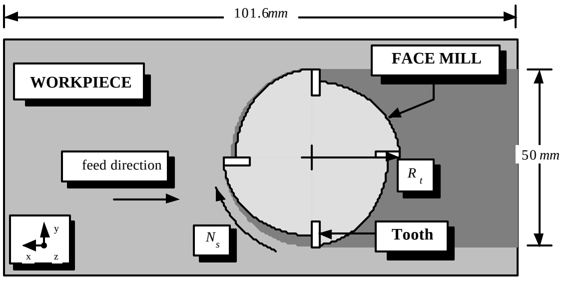

Fig. 2. Face milling operation schematic (top view). The part is 6061 aluminum. The face mill has four carbide teeth and a radius (R_t) of 25 *mm*. The spindle speed (N_s) is 1500 *rpm*, the depth of material to remove (in *z* direction) is 2 *mm*, and the programmed feedrate is 10 *mm/s*.

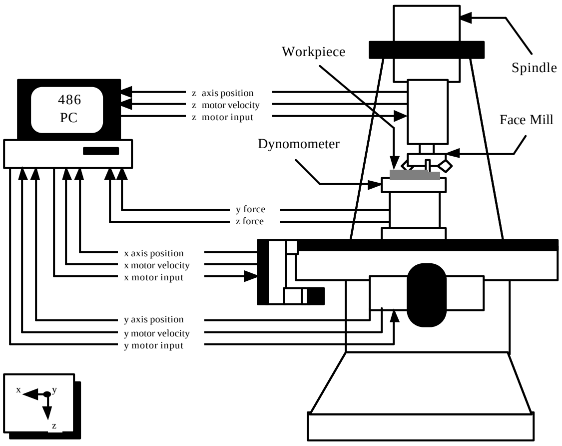

Fig. 3. Experimental system schematic.

Table 1. Machining modules.

Module	Function	Period
Feedrate Routine (A)	Select the feedrate to be the programmed feedrate, zero if a feed hold is invoked, or overriden if a force controller is invoked	10 *ms*
Operator Input Monitor (B)	Determine if the operator has signaled chatter detection or a feed hold	10 *ms*
Feed Hold (C)	Hold axes at a constant position	–
Operator Chatter Detector (D)	Signal chatter via operator keyboard input	–
Automatic Chatter Detector (E)	Determine chatter via thresholding the sprectral density of the samples of the signal F_z during a spindle revolution where the signal F_z is sampled every 0.5 *ms*	40 *ms*
Chatter Suppresser (F)	Rewrite part program to decrease depth–of–cut by an amount such that one additional pass is added to the operation	–
Chatter Suppression Routine (G)	Invoke chatter suppresser and then invoke feed hold for 200 *ms*	–
Parameter Estimator (H)	Estimate feed–force process gain (i.e., the term $Kd^{\hat{a}}$ in equation [1])	40 *ms*
Force Signal Processor (I)	Determine F_Y = max{abs(F_y)} during spindle revolution where the signal F_y is sampled every 0.5 *ms*	40 *ms*
Contact Monitor (J)	Determine cutting tool and part contact via thresholding F_Y (i.e., J = 1 if $F_Y > 50$ *N*)	40 *ms*
Adaptive Force Controller (K)	Regulate machining force level via an adaptive control technique	40 *ms*
Model–Based Force Controller (L)	Regulate machining force level via a model–based control technique	40 *ms*

acting on the cutting tool in the *y* direction (F_y) is sampled every 0.5 *ms*, antialised via a low–pass filter with a cut–off frequency of 250 *Hz* and then processed by the force signal processor to determine the signal F_Y (i.e., the maximum magnitude of F_y during a spindle revolution). The instantaneous force acting on the cutting tool in the *z* direction (F_z) is sampled every 0.5 *ms*, antialised via a low–pass filter with a cut–off frequency of 1000 *Hz* and then processed by the automatic chatter detector. Note that the utilization of the automatic chatter detector depends on the production environment and, thus, is not used in both implementations. The software modules are implemented on a 66 *MHz* Xycom 486 computer with various sampling periods (see Table 1). A detailed description of each module and the experimental conditions may be found in Landers (1997).

IV. Supervisory controller designs

Two supervisory machining controllers are now constructed, using the design approach, for the face milling operation described above. The two supervisory controllers will be constructed for two very different production environments. The first controller, denoted SMC I, is designed for a high–volume transfer–line production environment where the situation is very *static* (i.e., the same product is produced via the same sequence of operations over a long period of time). The second controller, denoted SMC II, is designed for a job–shop production environment where the situation is very *dynamic* (i.e., products are produced in small batch sizes and, hence, the products, tooling, technology, etc. change very rapidly).

1. SMC I design

In the first design, it is assumed that the face milling application is performed in a high–volume transfer–line production environment. It is often economically feasible to model the force process in this type of environment and utilize this information to meet the design objectives. For this situation, force process and structural vibration models are utilized to perform chatter analysis (see the Appendix) allowing the designer to plan a chatter–free operation. For this application, two tool passes with equal depths–of–cut of 1 *mm* each are programmed. A static force process model

$$F_Y = Kd^b f^a = 0.76 d^{0.65} f^{0.63} \qquad (1)$$

is employed by a model–based force controller (Landers and Ulsoy, 2000) that adjusts the operation feed to maximize productivity given the spindle power constraint. The force signal F_Y bounds the cutting force (Landers, 1997). Thus, the SMC I design harnesses process information to avoid the occurrence of chatter and to maintain the spindle power constraint.

The SMC I design is as follows:

1) The monitoring modules are B, I, and J, and the control modules are A, C, and L.

2) The fixed machine parameter module contains the maximum spindle power and maximum feedrate. The fixed operation parameter module contains the maximum feed, force process model parameters, number of cutting tool teeth, cutting tool radius, module sample periods, and controller time constants.

3a) The following rules are developed:

i) Implement A and B during the entire machining operation.

ii) Implement I and J unless state 5 is active.

iii) When cutting tool–part contact is detected, reset L.

iv) Implement L while the cutting tool and part are in contact.

3b) The Grafcet representation of the logic controller is given in Figure 4. A list of the actions is given in Table 1 and a list of the transition receptivities and states is provided in Table 2. The actions and transition receptivities are denoted by Boolean variables. When the corresponding variable takes the value of 1, the action is active or the transition receptivity is true. The transitions from states 2 and 4 are not uniquely defined (i.e., if two or more receptivities become simultaneously true, multiple states would become active). While multiple

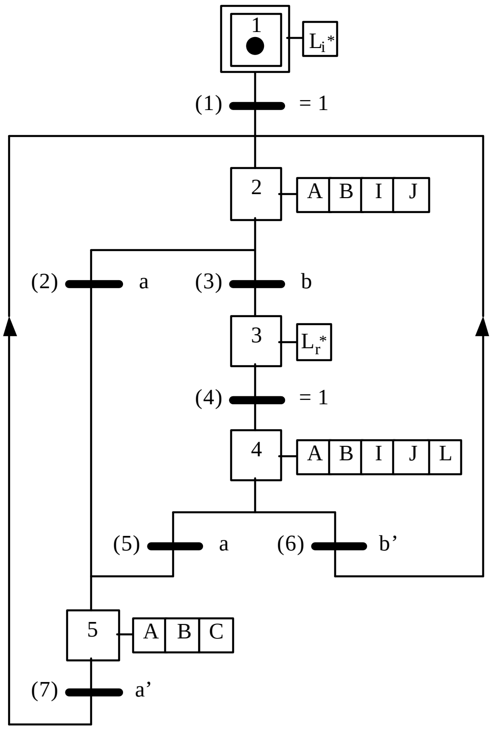

Fig. 4. Grafcet of supervisory machining controller 1).

Table 2. Transition receptivities and states for grafcets in figures 3 and 4.

Transition Receptivities	**States**
Operator Feed Hold Activated (a)	Initialize Modules (1)
Cutting Tool–Part Contact Detected (b)	No Contact and No Chatter (2)
Chatter Manually Detected (c)	Reset Modules (3)
Chatter Automatically Detected (d)	Contact and No Chatter (4)
Chatter Suppression Routine Complete (e)	Operator Feed Hold Active (5)
	Chatter Suppression Routine Active (6)

states are possible in a Grafcet representation, this situation is undesirable in this example and, thus, the designer must decide the order in which the possible transitions receptivities for each of these states should be checked. Since the feed hold always takes precedent, the receptivity of transitions (2) and (5) will be checked first when states 2 and 4, respectively, are active.

The model–based force controller is initialized in state 1. The situation immediately becomes state 2 where the feedrate routine, operator input monitor, force signal processor, and contact monitor are active. If the operator input monitor detects a request for a feed hold, then the feed hold is activated in state 5. The feedrate routine and the operator input monitor remain active and the force signal processor and contact monitor become inactive. Once the operator input monitor receives a request to deactivate the feed hold, the situation again becomes state 2. From state 2, if the contact monitor detects the cutting tool and part are in contact, the situation becomes state 3 where the model–based force controller is reset. From state 3, the situation immediately becomes state 4 where the feedrate routine, operator input monitor, force signal processor, contact monitor, and model–based force controller are active. From state 4, a feed hold may be activated, as discussed above, or contact may cease. In the later case, the situation again becomes state 2.

3c) The logic controller is then converted into a software module in the "C" computing language and experimentally implemented in the next section.

2. SMC II design

In the second design example, it is assumed that the face milling application is performed in a job–shop production environment. It is typically infeasible to model the force process or machine tool and part structures in this type of environment. Therefore, the operation must be completed without this information. Since stable depths–of–cut cannot be determined, the planned operation will consist of a single tool pass with a depth–of–cut of 2 *mm*. A means for chatter detection and suppression is now required and, thus, an operator chatter detector, automatic chatter detector, and a chatter suppressor are utilized in the SMC II design to meet the chatter suppression objective. Further, an adaptive force controller, that does not require force process information, is required to meet the spindle power constraint objective. This force controller is more complex than the model–based version since a parameter estimation routine is required. Thus, the SMC II design seeks to meet the design objectives with no process information. It should be noted that the SMC II design is more complex, but also more flexible, than the SMC I design.

The SMC II design is as follows:

1) The monitoring modules are B, D, E, H, I, and J, and the control modules are A, C, F, G, and K.

2) The fixed machine and operation parameter modules are the same as those given in the SMC I design.

3a) The following rules are developed:

i) Implement A during the entire machining operation.

ii) Implement B unless state 6 is active.

iii) Implement I and J unless states 5 or 6 are active.

iv) When cutting tool–part contact is detected, reset E and K.

v) Implement D, E, H, and K while the cutting tool and part are in contact.

vi) If chatter is detected, activate G.

3b) The Grafcet representation of the logic controller is given in Figure 5. The transition receptivities, states, and actions are the same as those for the SMC I design. Note that a chatter suppression state (6) is included in the design. Again, the feed hold always takes precedent and, thus, the receptivity of transitions (2) and (5) will be checked first when states 2 and 4, respectively, are active. Since chatter will not be sustained if contact between the tool and part ceases, the receptivity of transition (7) is checked before that of transition (6) when state 4 is active.

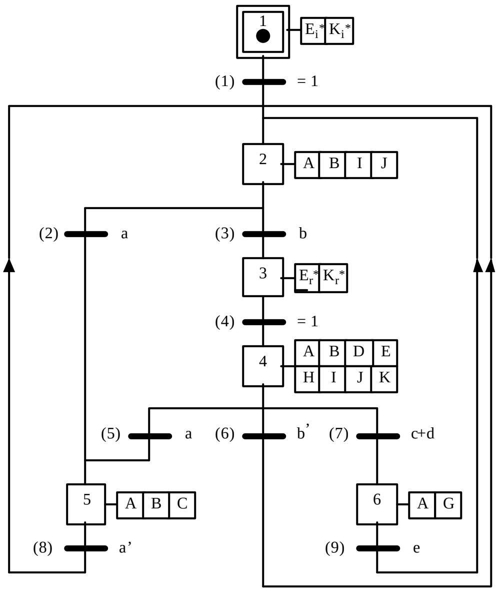

Fig. 5. Grafcet of supervisory machining controller 2).

The automatic chatter detector and adaptive force controller are initialized in state 1. The situation immediately becomes state 2 where the feedrate routine, operator input monitor, force signal processor, and cutting tool–part contact monitor are active. If the operator input monitor detects a request for a feed hold, then the situation is state 5 where the feedrate routine, operator input monitor, and feed hold are active. After the feed hold is deactivated, the situation again becomes state 2. If contact occurs, then the situation becomes state 3 where the adaptive force controller and automatic chatter detector are reset. From state 3, the situation immediately becomes state 4 where the feedrate routine, operator input monitor, force signal processor, contact monitor, operator chatter detector, automatic chatter detector, parameter estimator, and adaptive force controller are active. From state 4, a feed hold may be activated, as discussed above, or contact may cease and the situation becomes state 2. From state 4, chatter may be detected. In this case, the feedrate routine remains active and the chatter suppression routine is activated. After the chatter suppression routine is complete, the situation again becomes state 2.

3c) The logic controller is then converted into a software module in the "C" computing language and experimentally implemented in the next section.

V. Supervisory controller implementations

The two supervisory machining controllers designed above are now implemented in the face milling operation. For comparison, an experiment is conducted without process control where the programmed spindle speed and feedrate are constant throughout the operation and a depth–of–cut of 2 *mm* is used. Figure 6 shows a plot of F_Y for this experiment. Since the process plan does not account for the specific machine tool, the spindle power constraint was violated during the entire operation (by as much as 224%) and sustained chatter was encountered (as evidenced by the large amplitude vibrations seen in Figure 6 and the high pitch noise heard by the operator). These results demonstrate that process control and/or process knowledge is required to meet the design objectives.

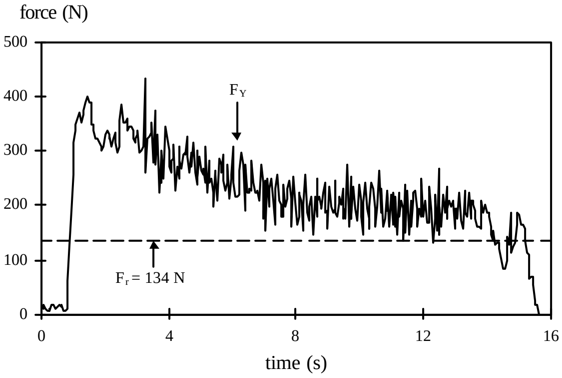

Fig. 6. History of F_Y with no process control.

The results of the SMC I and the SMC II implementations are shown in Figures 7 and 8, respectively. Note that whenever the chatter suppressor and feed hold were invoked, the force processor was inactive and, thus, the signal F_Y appears to remain constant. The operator feed hold was invoked during the second tool pass for both implementations to demonstrate that this action is not detrimental to the performance of other modules. The reference force was tracked in the operation steady–state in both implementations. The SMC I implementation was programmed with two tool passes with equal depths–of–cut (1 *mm*); thus, chatter never occurred. In the SMC II implementation, the original part program has one tool pass with a depth–of–cut of 2 *mm*. Since this depth–of–cut is unstable, chatter occurred and was detected via the automatic chatter detector which thresholds the spectrum of the force signals in the *z* direction collected during a spindle rotation. Subsequently, the part program was reprogrammed on–line via the chatter suppressor. Therefore, in the SMC II implementation, the chatter suppressor reprogrammed the part program to have two tool passes with equal depths–of–cut (1 *mm*) which are stable. It should be noted that while the reference force was tracked in both implementations, much greater force overshoot was encountered in the SMC II implementation (113%) than in the SMC I implementation (28%) due to the occurrence of chatter when SMC II was utilized. Thus, the incorporation of process knowledge allowed the SMC I approach to avoid the potential problems of chatter and severe force overshoot that may lead to tooth chippage.

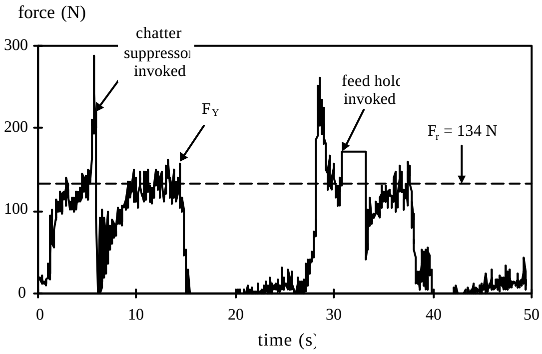

Fig. 7. History of F_Y with SMC I implementation.

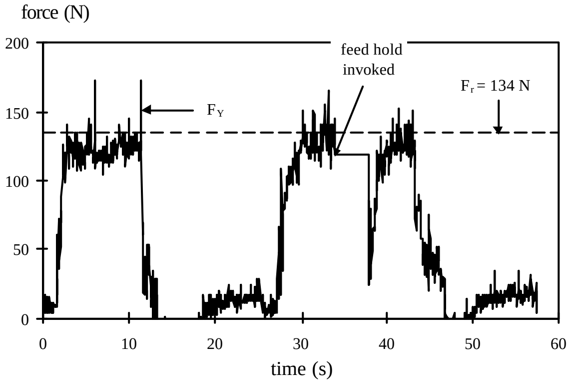

Fig. 8. History of F_Y with SMC II implementation.

Two supervisory machining controllers were constructed for a face milling operation. The experimental implementation of these two controllers, as compared to an implementation where process control was not utilized, demonstrated that careful use of process control was required to satisfy the spindle power and chatter constraints. The first controller (SMC I) was designed for a high–volume transfer–line production environment while the second controller (SMC II) was designed for a job–shop production environment. Force process and structural models were employed by the SMC I design to plan a chatter–free operation. Further, a force process model was utilized to design a model–based force controller to ensure the spindle power constraint was not violated. For a high–volume transfer–line production environment, the development of these models can be economically justified since the cost will be spread out over hundreds of thousands or even millions of parts. However, the model development, in general, will not be economically feasible in a job–shop environment since the cost is spread out over only a few, if not one, part. Therefore, in the SMC II design, chatter detectors and a chatter suppressor were utilized to ensure the chatter constraint was not violated and an adaptive force controller, which employed a parameter

rameter estimator, was utilized to ensure the spindle power constraint was not violated. Since the development of force process and structural models is economically infeasible for the job–shop production environment, SMC I cannot be utilized in this production environment and, thus, SMC II was utilized. Supervisory Machining Controller II is more complex than SMC I (i.e., there are more modules and the typical module has more complex algorithms); however, SMC II is more general since it is applicable to a wider range of operations.

The examples in this paper have considered the design of supervisory machining controllers that utilize force control, chatter detection, chatter suppression, and contact monitoring, among other, modules. While these examples provided rich illustrations with which to compare supervisory controllers to machining implementations without process control and in different types of production environments, an industrial application would require a more sophisticated supervisory controller with more modules (e.g., tool wear and breakage, burr formation). However, the design approach in this paper may be utilized to design more comprehensive supervisory controllers that would be required in industry.

VI. Summary and conclusions

In this paper the supervisory machining control design approach (Landers and Ulsoy, 1998) was summarized and then applied to construct two supervisory controllers for a face milling operation. The supervisory controllers were implemented experimentally and the results were compared to a baseline experiment where no process controllers were utilized (i.e., the process variables were constant).

The experimental results demonstrated that process control was required to meet the operation objectives and that both supervisory control designs were able to meet those objectives. The experimental implementations also demonstrate the design tool's applicability to both high–volume transfer–line and job–shop production environments. In the first design, process knowledge, in the form of force and structural vibration models, was incorporated to meet the operation objectives while the second design did not utilize this information. Since process model development cannot be economically justified for small batch and one–off operations, SMC I cannot be utilized in job–shop environments and, thus, the more complex, but more general, SMC II was utilized. However, while both designs met the operation objectives, a comparison of the two implementations illustrates the benefits of incorporating force process knowledge: no chatter and less force overshoot.

Appendix

This section outlines the chatter analysis technique known as Time Domain Simulation (TDS) used to plan a chatter–free machining operation in the SMC I design. Refer to Figure 9 for a schematic of the face milling operation. The cutting and thrust pressures, respectively, acting on the i^{th} tooth are

$$P_{C_i} = 0.29 f_i^{-0.25} d^{-0.13} \left(\frac{V}{1000} \right)^{-0.72} \quad (A1)$$

$$P_{T_i} = 0.16 f_i^{-0.40} d^{-0.41} \left(\frac{V}{1000} \right)^{-0.58} \quad (A2)$$

where the cutting pressure, thrust pressure, feed of the i^{th} tooth, depth–of–cut, and cutting velocity (i.e., P_C, P_T, f_i, d, and V) are in units of kN/mm^2, kN/mm^2, mm, mm, and m/min, respectively. The total forces acting on the part in the x and y directions, respectively, are

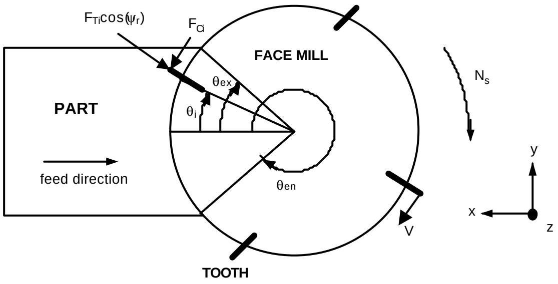

Fig. 9. Top view of a face milling operation.

$$F_x = \sum_{i=1}^{N_t} \left[-P_{T_i} f_i d \cos(y_r) \cos(q_i) + P_{C_i} f_i d \sin(q) \right] g(q_i) \quad (A3)$$

$$F_y = \sum_{i=1}^{N_t} \left[-P_{T_i} f_i d \cos(y_r) \sin(q_i) - P_{C_i} f_i d \cos(q_i) \right] g(q_i) \quad (A4)$$

where the forces acting in the x and y directions, the lead angle, and the angle of the i^{th} tooth (i.e., F_x, F_y, y_r, and q_i) are in units of kN, rad, and rad, respectively. The parameter N_t is the number of teeth and the function $g(q_i)$ determines if the i^{th} tooth is in contact with the part. This function is

$$g(q_i) = \begin{cases} 1 & if \quad q_i \le q_{ex} \\ 1 & if \quad q_{en} \le q_i \\ 0 & if \quad q_{en} \ge q_i \ge q_{ex} \end{cases} \quad (A5)$$

where the entry and exit angles (i.e., q_{en} and q_{ex}) are measured in rad. The machine tool and part structures are each represented by two, uncoupled second order linear differential equations

$$\ddot{x}_t(t) + 2(0.07)(4500)\dot{x}_t(t) + (4500)^2 x_t(t) = -\frac{(4500)^2}{14} F_x(t) \quad (A6)$$

$$\ddot{y}_t(t) + 2(0.11)(4100)\dot{y}_t(t) + (4100)^2 y_t(t) = -\frac{(4100)^2}{14} F_y(t) \quad (A7)$$

$$\ddot{x}_p(t) + 2(0.09)(2600)\dot{x}_p(t) + (2600)^2 x_p(t) = \frac{(2600)^2}{9.5} F_x(t) \quad (A8)$$

$$\ddot{y}_p(t) + 2(0.22)(2100)\dot{y}_p(t) + (2100)^2 y_p(t) = \frac{(2100)^2}{9.5} F_y(t) \quad (A9)$$

where the displacements in the x and y directions (i.e., x and y) are in mm. The subscripts t and p denote machine tool and part, respectively, and the single dot and double dots denote, respectively, single and double differentiation with respect to time. The instantaneous feed of the i^{th} tooth is

$$f_i = f_t \cos(q_i) + \Delta x \cos(q_i) + \Delta y \sin(q_i) \tag{A10}$$

$$\Delta x = \left[x_t(t) - x_t(t-T) \right] - \left[x_p(t) - x_p(t-T) \right] \tag{A11}$$

$$\Delta y = \left[y_t(t) - y_t(t-T) \right] - \left[y_p(t) - y_p(t-T) \right] \tag{A12}$$

where the nominal feed/tooth and period for one spindle revolution (i.e., f_t and T) are in units of *mm* and *s*, respectively.

Equations (A1)–(A12) are dynamically simulated via numerical techniques for a fixed depth–of–cut. The force and displacement signals are examined to determine if the depth–of–cut is stable. The depth–of–cut is then incremented (or decremented) and the simulation is repeated until marginal stability occurs.

References

[1] Y. Altintas and W. K. Munasinghe, “Modular CNC design for intelligent machining, part 2 – modular integration of sensor based milling process monitoring and control tasks,” *ASME Journal of Manufacturing Science and Engineering*, vol. 118, no. 4, pp. 514–521, 1996.

[2] Y. Altintas, N. Newell, and M. Ito, “Modular CNC design for intelligent machining, part 1 – design of a hierarchical motion control module for CNC machine tools,” *ASME Journal of Manufacturing Science and Engineering*, vol. 118, no. 4, pp. 506–513, 1996.

[3] R. David and H. Alla, Petri Nets and Grafcet: Tools for Modeling Discrete Event Systems, Prentice Hall, New York, 1992.

[4] R. Du, M. A. Elbestawi, and S. M. Wu, “Automated monitoring of manufacturing processes, part 1: Monitoring methods,” *ASME Journal of Engineering for Industry*, vol. 117, no. 2, pp. 121–132, 1995.

[5] M. A. Flores and T. C. Tsao, “Supervisory machining control implementation using an open architecture CNC,” *Japan–U.S.A. Symposium on Flexible Automation*, Otsu, Japan, vol. III, pp. 1157–1164, 1998.

[6] R. J. Furness, *Supervisory Control of the Drilling Process*, Ph.D. Dissertation, Department of Mechanical Engineering and Applied Mechanics, The University of Michigan, Ann Arbor, Michigan, 1992.

[7] R. J. Furness, A. G. Ulsoy, and C. L. Wu, “Supervisory control of drilling,” *ASME Journal of Engineering for Industry*, vol. 118, no. 1, pp. 10–19, 1996.

[8] R. G. Landers, *Supervisory Machining Control: A Design Approach Plus Force Control and Chatter Analysis Components*, Ph.D. Dissertation, Department of Mechanical Engineering and Applied Mechanics, University of Michigan, Ann Arbor, Michigan, 1997.

[9] R. G. Landers and A. G. Ulsoy, “Supervisory machinig control: Design approach and experiments,” *Annals of the CIRP*, vol. 47/1, pp. 301–306, 1998.

[10] R. G. Landers and A. G. Ulsoy, “Model–Based machining force control,” *ASME Journal of Dynamics Systems, Measurement, and Control*, vol. 122, no. 3, pp. 521–527, 2000.

[11] B. Lindström, “Automatic supervision in turning and boring,” *Automatic Supervision in Manufacturing*, Maciej Szafarczyk (Ed.), Springer–Verlag, Great Britain, pp. 17–34, 1994.

[12] Machinability Data Center, *Machining Data Handbook*, Cincinnati, Ohio, 1980.

[13] M. G. Mehrabi and A. G. Ulsoy, “State–of–the–Art in reconfigurable machining systems,” *ERC/RMS Technical Report #2*, University of Michigan, Ann Arbor, Michigan, 1997.

[14] M. Szafarczyk (ed.), *Automatic Supervision in Manufacturing*, Springer–Verlag, Great Britain, 1994.

[15] R. Teltz and M. A. Elbestawi, “Hierarchical, knowledge–based control in turning,” *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 115, no. 2A, pp. 122–132, 1993.

[16] H. K. Tönshoff, J. P. Wulfsberg, H. J. J. Kals, W. König, and C. A. van Luttervelt, “Developments and trends in monitoring and control of machining processes,” *Annals of the CIRP*, vol. 37/2, pp. 611–622, 1988.

[17] J. Tlusty, “Automatic supervision in milling,” *Automatic Supervision in Manufacturing*, Maciej Szafarczyk (Ed.), Springer–Verlag, Great Britain, pp. 35–66, 1994.

[18] A. G. Ulsoy and Y. Koren, “Control of machining processes,” *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 115, no. 2B, pp. 301–308, 1993.

[19] E. Westkämper, “Automatic supervision of surface grinding,” *Automatic Supervision in Manufacturing*, Maciej Szafarczyk (Ed.), Springer–Verlag, Great Britain, pp. 67–82, 1994.

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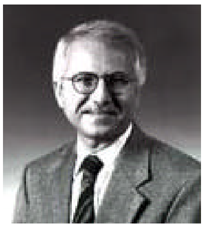

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