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An Intelligent Supervisory Control System For A Fish Processing Workcell

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Abstract

A laboratory workcell has been developed for fish cutting. The workcell, which uses a variety of sensors, actuators, and hardware for component interface and control, operates with the help of a dedicated supervisory control system. A layered architecture has been used for the system. It has several knowledge-based modules for carrying out tasks such as workcell monitoring, controller tuning, workcell conditioning, and product quality assessment. The paper describes the workcell and the intelligent supervisory control system. Performance of the supervisory system is studied through fish cutting experiments

1. Laboratory Workcell

A laboratory workcell has been developed for fish cutting [1], which possesses the following important features: (1) High cutting accuracy; obtained using mechanical fixtures, positioners, tools and associated sensors, actuators, and controllers that have been properly designed and integrated into the workcell; (2) Improved product quality; achieved through high-accuracy cutting and also through mechanical designs that do not result in product damage during handling and processing, along with a quality assessment and supervisory control system that monitors the workcell performance, determines product quality, and automatically makes corrective adjustments; (3) Increased productivity and efficiency; attained through accurate operation and low wastage, with reduced downtime and the need for reprocessing of poorly processed fish; and (4) Flexible automation; requiring fewer workers for operation and maintenance than the number needed for a conventional machine, which is possible due to the capabilities of self-monitoring, tuning, re-organization, and somewhat autonomous operation, as a result of the intelligent and hierarchical supervisory control system of the workcell.

The hardware structure of the laboratory workcell is schematically shown in Figure 1. The fish are placed one by one on the conveyor at the feeding end of the workcell. As each fish subsequently passes through the primary imaging station, an image of the fish is generated by a CCD camera and captured by a SHARP GPB image processor. Simultaneously, the thickness of the fish in the head region is sensed through an ultrasonic position sensor. The image is processed by the GPB card which occupies one slot of the primary control computer, a 486-based PC. The main image processing steps are filtering, enhancing, thresholding and labeling of the image objects. In this manner, the gill plate and correspondingly, the collarbone, of the fish are identified and gauged. This information is then used to determine the desired position of the cutter. As the fish leaves the primary imaging station it enters a positioning platform whose purpose is to deliver each fish symmetrically into the cutter unit. The desired vertical position of the delivery platform is determined according to the thickness of the particular fish, as measured by an ultrasonic sensor and read into the control computer through a PCL-711 Input/Output board. The platform is driven by a DC servomotor through a lead-screw and nut arrangement. The desired position is the reference with which the actual position, as measured by the optical encoder of the servomotor, is compared to generate the servo signal for platform control. The cutter unit consists of a pair of circular blades arranged in a V-configuration and driven by two remotely placed, 3-phase induction motors which are connected to the blades through long flexible shafts. The V-configuration allows the cutter to reach into the head region below the collarbone and recover the useful meat that is present in this region. The cutter is positioned by a DC servomotor through a lead-screw and nut arrangement, in a similar manner as the delivery platform. The two servomotors, one for the delivery platform and the other for the cutter, are controlled by means of a GALIL DMC-600 two-axis controller which receives reference commands from the PC-486 control computer and generates input signals for the two pulse-width-modulated (PWM) amplifiers which drive the motors. There is hold-down system for fish along the conveyor, starting from the primary imaging station and ending at the cutting station. This system consists of a matrix of spring loaded rollers which can apply a desired distribution of forces on the fish body so that each fish would be properly restrained. The hold-down mechanism will ensure that the configuration of a fish, as measured by the imaging system, would not change as it reaches the cutter and also provides an adequate holding force during the cutting process itself. Clearly, the restraining forces should not crush or damage the fish in any manner. The hold-down force is controlled by the supervisory control system of the workcell.

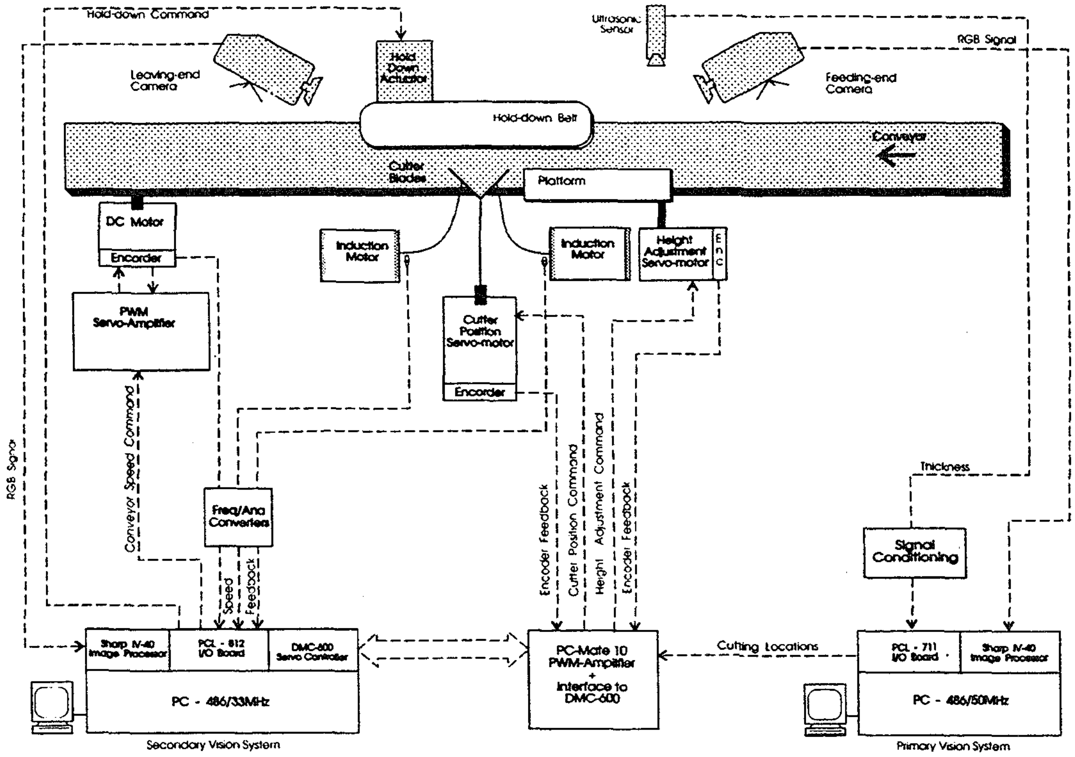

Figure 1. The Hardware Structure of the Laboratory Workcell.

A secondary CCD camera has been mounted on the product-exit side of the cutting station. The images generated by this camera are captured and processed by a dedicated SHARP GPB card which is mounted within a 486-based computer. This computer, which hosts the secondary vision system, also serves as the supervisory-control computer. The conveyor is driven by a variable-speed DC motor through a PWM amplifier, according to a speed command given by the supervisory control computer. This computer reads the optical encoders of the conveyor motor and the cutter induction motors, through frequency-to-analog conversion circuitry and a PCL-812 Input/Output board; and from this information the conveyor speed and the loads at the two cutter blades are determined. This computer also receives optical encoder signals from the cutter positioning and platform positioning servomotors. The control signals generated by the supervisory control computer, on the basis of various sensory information and other knowledge, are also transmitted to the actuators through the same PCL-812 board.

2. Supervisory Control System

The overall control system of the fish processing workcell has a variety of functions which may be organized according to an appropriate criterion. The criteria that would be appropriate here will include the required speed of control (control bandwidth), the level of detail of the information that is handled (information resolution), crispness of the knowledge that is involved (fuzzy resolution), and the level of intelligence that is needed to carry out a particular function. It may not be necessary to incorporate all such criteria in a particular system since there exists at least an intuitive relationship among these criteria. This is particularly the case if the control system is organized into a hierarchical architecture. In the present application the three-level architecture that is schematically shown in Figure 2 has been implemented. This structure may be considered as a supervisory control system. The lowest layer consists of high-resolution sensors, process actuators, and associated direct controllers. The intermediate layers primarily carry out information preprocessing, determination of the workcell status, and command transfer for operating and modifying the performance of the system components. The top layer carries out system monitoring and high-level supervisory control activities. The bottom layer of the control system of Figure 2 carries out direct control of system components in a conventional sense. Specifically, the component

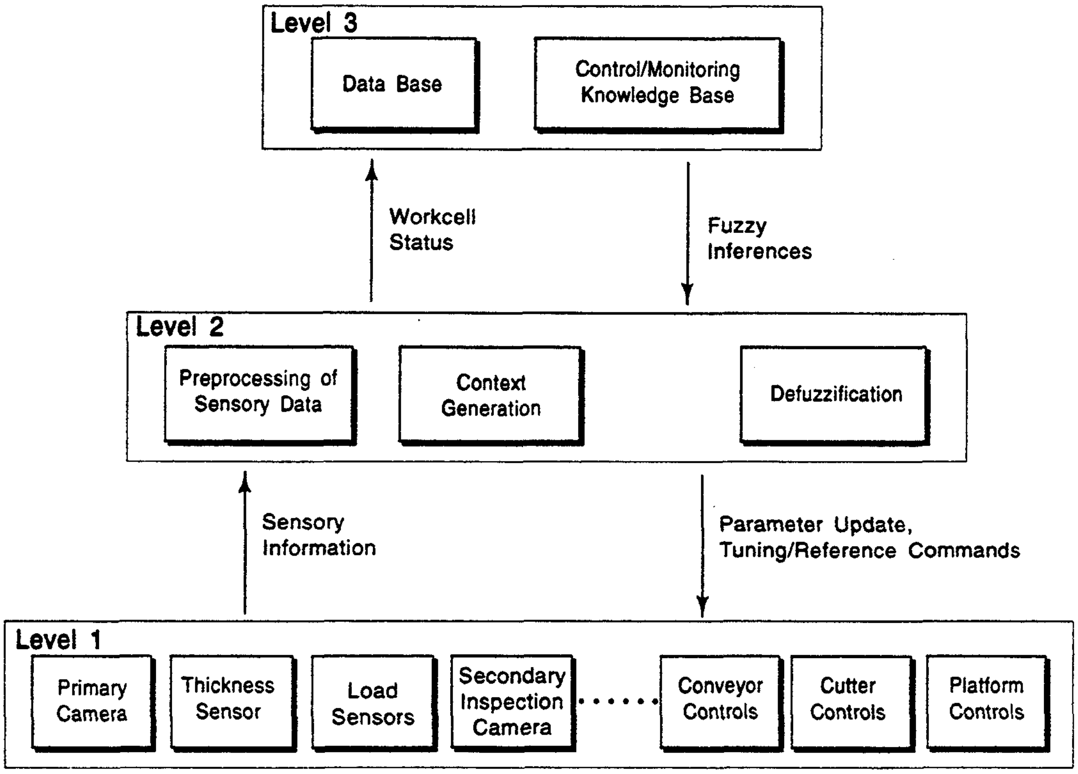

Figure 2. Hierarchical Supervisory Control System of the Workcell.

responses are sensed at high resolution, control commands are generated on this basis at high speed, according to hard (i.e., crisp) algorithms, and the components are directly actuated using the control commands. These high-resolution, high-bandwidth, direct control operations do not need a high degree of intelligence for their execution. Specifically, in the prototype workcell that has been developed by us, the following sensory information is acquired in the bottom layer; (1) Position and speed information of the positioning servo systems and the conveyor, from the respective optical encoders; (2) Cutter load information from the induction motors that drive the cutter blades; (3) Visual images from the position sensing CCD camera (primary); (4) Visual images from the task monitoring CCD camera (secondary); (5) Thickness information from the ultrasound height sensor. The associate raw signals are characterized by the following properties: (1) Large quantities of data points are collected; (2) Data points are generated in rapid succession; (3) The sensory signals have a high resolution and tend to be quite precise, in the absence of noise. For example, an image may contain about 250 kbytes of information, and may be captured every 0.5 seconds. This will represent an information rate of 500 kb/s for this optical sensor alone. Within the bottom layer, some sensory signals would be directly used, without "intelligent" preprocessing, for device control. This is the case with the encoder signals from the servomotors, and the ultrasonic-thickness signal which are directly used in feedback for positioning control.

The high resolution information from the crisp sensors in the bottom layer of the workcell have to be converted into a form that is compatible with the knowledge base in the top layer before a matching process could be executed [2]. The intermediate layer of the hierarchy of Figure 2 accomplishes this task of information abstraction, where the sensory information from the bottom layer is preprocessed, interpreted, and represented for use in inference-making in the top layer. Each stream of sensory data from the bottom layer is filtered using a dedicated processor which identifies trends and patterns of a set of representative parameters in these signals. The operations performed by the preprocessors may include averaging, statistical computations such as standard deviation and correlations, peak detection, pattern recognition, and computation of performance attributes such as rise time, damping ratio, and settling time of a workcell component. Next these parameters are evaluated according to some performance criteria and transcribed into fuzzy quantities that are compatible with the fuzzy condition descriptors of the top level knowledge base.

The knowledge base of a fuzzy control system is primarily comprised of a linguistic rulebase. The inference making mechanism makes up the production engine which carries out reasoning using the knowledge base, and intermediates the relation between the database (input space) and the inferences (output space). The reasoning process is triggered by the context data in the database, and may be thought of as an "approximate" matching process of the "context" to the condition parts of the rules. This is the basis of the so-called "approximate reasoning" [3]. The rulebase will also infer remedial actions where necessary.

3. Performance Testing

In this section, the performance of the knowledge-based decision maker for various conditions of sensory data, such as servomotor responses of cutter and platform, and cutter load profiles, is discussed.

3.1 Servomotor Tuning Examples

Several test runs were carried out on the cutter servomotor in order to investigate the behavior of the rulebase for servomotor tuning [4]. A series of step inputs of magnitude 4000 encoder pulses was applied to the cutter servomotor, and the response was preprocessed to obtain the context database. Then, using this information as the context for the rulebase, a new set of parameters for the lead compensator and integrator was inferred. These parameters were then converted to their digital equivalent and the corresponding parameters of the servomotor controller (DMC-620) were updated to reflect the new values. This procedure was repeated for each test input.

Initially Overdamped System: Figures 3 (a) through (f) show six consecutive responses of the cutter servomotor for a series of step inputs of magnitude 4000 encoder pulses, while the on-line tuning procedure is active. For this test, the initial controller parameters were chosen such that the cutter servomotor exhibited an overdamped response in the beginning. Table 1 shows the context, as generated by the preprocessor for the servomotor response. The columns (a) through (f) of Table 1 list the context generated for the responses in figures 3 (a) through (f), respectively. Table 2 shows the controller parameters inferred by the knowledge-based servotuner for the response curves shown in Figure 3. The values listed are in the Z-domain.

Initially Underdamped System: Figures 4 (a) through (f) show six consecutive responses of the cutter servomotor for a series of step inputs of magnitude 4000 encoder pulses. For this test, the initial controller parameters were chosen such that the platform servomotor exhibited an underdamped response in the beginning. Table 3 gives the context as generated by the preprocessor corresponding to the servomotor response as shown in Figure 4. Table 4 gives the controller parameters (in the Z-domain) as inferred by the knowledge-based tuner, in this case.

The performance of the knowledge-based servomotor tuner, as illustrated in figures 3 and 4, appears to be quite satisfactory. The tuner has managed to bring the servomotor response to comply with the specifications, in approximately 5 to 6 cycles of tuning. For the purpose of these experiments, the initial controller parameters were set significantly off their normal operating values. In practice, however, perfect tuning is achieved much faster since the operating conditions usually remain close to their tuned performance.

Table 1. Context Corresponding to the Servomotor Responses in Figure 3.
UN - Response is Unsatisfactory, PR - Poor, MD - Moderate, IS - Within Specification, OS - Over Specification.

Performance Parameter	Context Database					
	(a)	(b)	(c)	(d)	(e)	(f)
Rise Time	UN	IS	IS	IS	IS	IS
Damping Ratio	UN	MD	IS	OS	IS	IS
Damped Natural Frequency	UN	MD	IS	IS	OS	OS
Overshoot	OS	UN	MD	OS	OS	OS
Offset	UN	MD	OS	OS	OS	OS

Table 2. Inferences of the Knowledge-Based Servomotor Tuner for Responses in Figure 3.

Controller Parameter	Z-domain Value					
	(a)	(b)	(c)	(d)	(e)	(f)
Gain	0.413	1.666	8.678	13.605	18.482	19.551
Pole	-.07950	-0.5675	-0.7950	-0.8232	-0.8485	-0.8485
Zero	0.9783	0.9483	0.9783	0.9830	0.9844	0.9844

The performance shown in figures 3 and 4 was obtained for the cutter servomotor (*X*-axis) that has been installed in the prototype workcell. This servomotor is characterized by a high inertia load, arising due to the mass of the cutter assembly that is supported by the lead-screw, and a low-level of damping. Also, there is a perturbation load that acts on the servomotor due to the flexible shafts of the cutter induction motors. This perturbation load varies in magnitude with the movement of the servomotor. A knowledge-based system similar to the one for the *X*-axis carries out tuning of the delivery platform (*Y*-axis) servomotor. Experiments conducted on this servomotor have shown that the performance is very much similar to that shown in figures 5 and 6. In this case, however, perfect tuning is achieved in a fewer number of cycles since the *Y*-axis servomotor carries a considerably smaller inertia load.

3.2 Workcell Tuning Example

Performance of the workcell tuner is illustrated now, using an example. First, several cutter load profiles were obtained through experimentation. Then, by the use of cutter-load preprocessor, a context database, corresponding to each load profile, was generated. Next, the rulebase for workcell tuning was used to obtain the inferences pertaining to the conveyor speed and hold-down force.

Figures 5 (a) through (d) show four cutter load profiles corresponding to actual fish cutting experiments carried out using the workcell. Each curve in Figure 5 has been obtained under different operating conditions of holding force and conveyor speed, as indicated. The numerical parameters resulting from preprocessing of these cutter load profiles are given in Table 5. The corresponding fuzzy linguistic context, as generated by the cutter-load preprocessor, is shown in figures 6 (a) through (d).

The rulebase for workcell tuning has two fuzzy inferences; namely, the change of conveyor speed and the magnitude of hold-down (grasping) force. Figures 7 (a) through (d) illustrate the corresponding inferences when the knowledge-based system operates on the context shown in Figure 6.

Figure 5 (a) shows a case where the conveyor speed is quite high, as can be gauged from the peak load that is higher than normal. Also, in this case, it is clear that the fish has been delivered asymmetrically into the cutter, since there is a mismatch of peak loads corresponding to the top and the bottom load profiles. Furthermore, it is seen that the two peak values do not occur simultaneously because of the slight offset that has been provided in the placement of the two circular blades, with an overlap, so as to achieve a complete cut. The load profile of the top blade (solid curve) also shows a slight degree of slipping as can be seen from the higher than normal trailing region of the load profile. The fuzzy linguistic context obtained after preprocessing the load profile confirms those visual observations, as seen in Figure 6 (a). The inferences corresponding to this context, shown is Figure 7 (a),

Table 3. Context Corresponding to the Servomotor Responses in Figure 4.

Performance Parameter	Context Database					
	(a)	(b)	(c)	(d)	(e)	(f)
Rise Time	IS	OS	IS	OS	IS	IS
Damping Ratio	PR	PR	MD	MD	IS	IS
Damped Natural Frequency	IS	MD	IS	IS	IS	IS
Overshoot	UN	UN	UN	UN	UN	IS
Offset	OS	OS	OS	OS	OS	OS

Table 4. Inferences of the Knowledge-Based Servomotor Tuner for Responses in Figure 4.

Controller Parameter	*Z*-domain Value					
	(a)	(b)	(c)	(d)	(e)	(f)
Gain	3.0939	4.3373	5.8941	8.2921	12.306	19.985
Pole	0.1298	0.0388	-0.0494	-0.1523	-0.2747	-0.4234
Zero	0.7750	0.8094	0.8380	0.8666	0.8954	0.9245

Table 5. Preprocessed Cutter Load Information.

Load Profile	Mean Load %	Asymmetry %	I^{ry} Peak (%)/Time (s)		II^{ry} Peak (%)/Time (s)	
			Top	Bottom	Top	Bottom
(a)	118	47	146/0.58	91/0.67	33/1.22	None
(b)	149	22	166/0.44	133/0.48	71/1.85	None
(c)	55	11	58/0.70	52/0.70	None	32/1.93
(d)	65	7.6	63/0.72	68/0.78	62/0.79	None

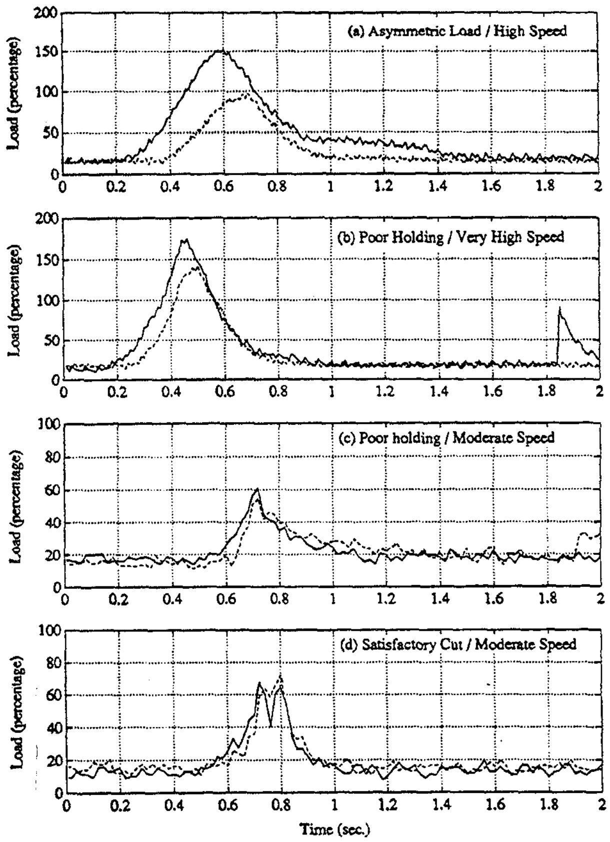

Figure 5. Cutter Load Profiles (Solid Curves - Top Blade, Dashed Curves - Bottom Blade).

recommend a large reduction in conveyor speed and a moderate increase in hold-down force. Figures 5 (b) and (c) illustrate two cases where slipping occurs towards the tail end of the cutter load profiles. Here, as well, the fuzzy linguistic context shown in figures 6 (b) and (c) captures the information as expected. Consequently, the knowledge-based system recommends tight holding and a reduced speed, as can be seen from figures 7 (b) and (c). Figure 5 (d) shows a satisfactory cut at a moderate conveyor speed. In this case, the two closely placed peaks visible on the load profile of the top blade are not due to slipping of fish, and the preprocessor correctly interprets this. The corresponding inferences suggest a soft holding force and a slight increase in conveyor speed to take into account the fact that the capacity of the cutter motors is underutilized in this case. Further details are found in [5].

4. Conclusions

A laboratory workcell has been developed for automated cutting of fish. The workcell incorporates advanced technology of sensing, actuation and control, and operates with the assistance of a knowledge-based supervisory control system. This control system has a three-layer hierarchical architecture, with the bottom layer dedicated to low-level and high-resolution sensing and direct control of workcell components. The intermediate layer performs preprocessing of sensory information for use in various knowledge-based modules in the top layer. Servomotor tuning, workcell tuning, process performance monitoring and product quality assessment are the main functions of the knowledge-based modules of the supervisory control system. The workcell possesses important capabilities of processing accuracy, productivity, flexibility, and high product quality, which have been achieved through proper design of the system, selection and integration of components, use of appropriate technology of sensing, actuation and control, and through its "intelligent" supervisory control system.

The paper described the workcell and its supervisory control system. Performance of the workcell and its supervisory control system was illustrated by means of a series of experiments that involved actual cutting of fish.

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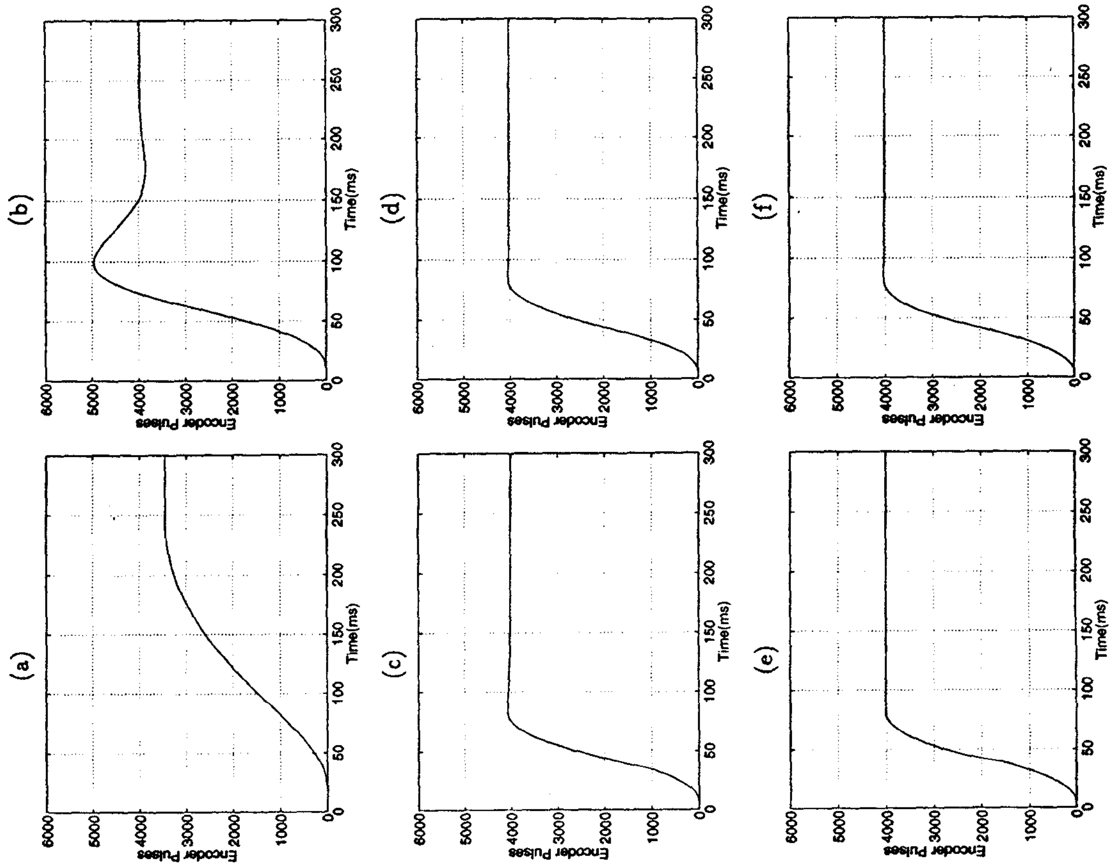

Figure 3. Performance of the Servomotor Tuner for an Initially Overdamped System.

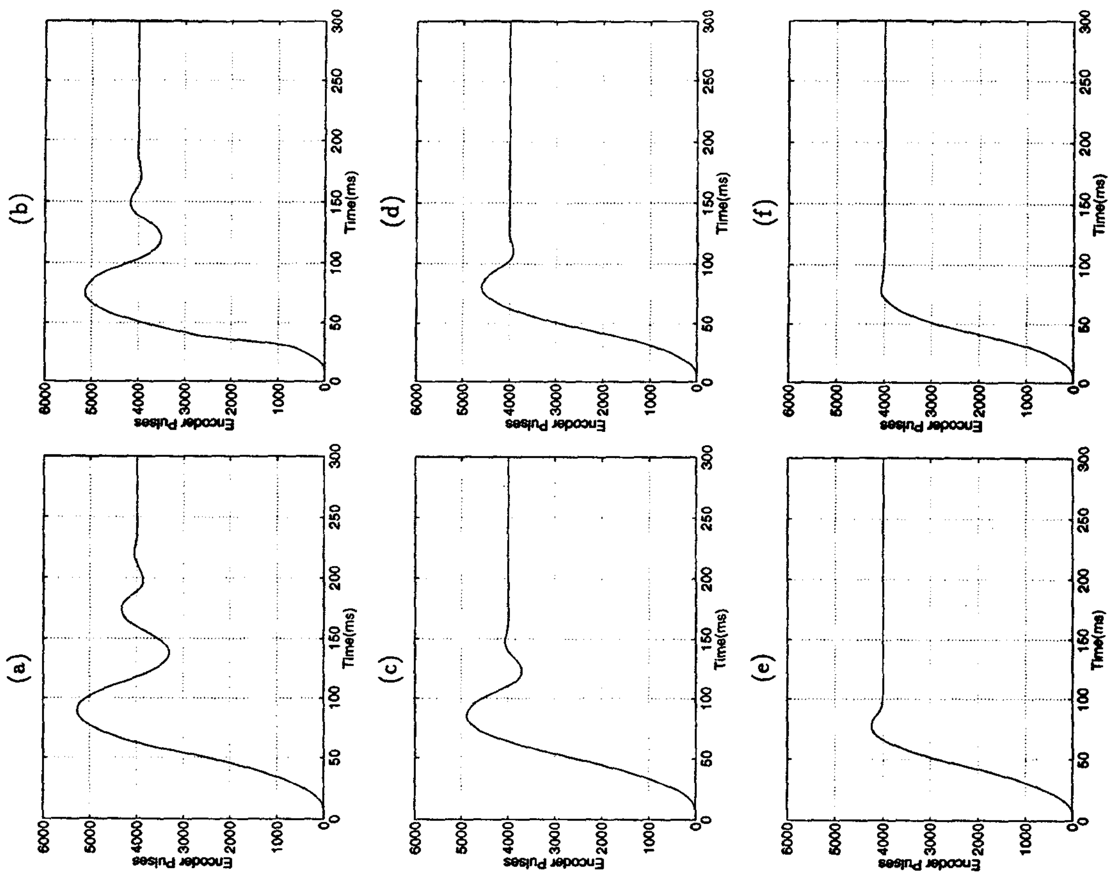

Figure 4. Performance of the Servomotor Tuner for an Initially Underdamped System.

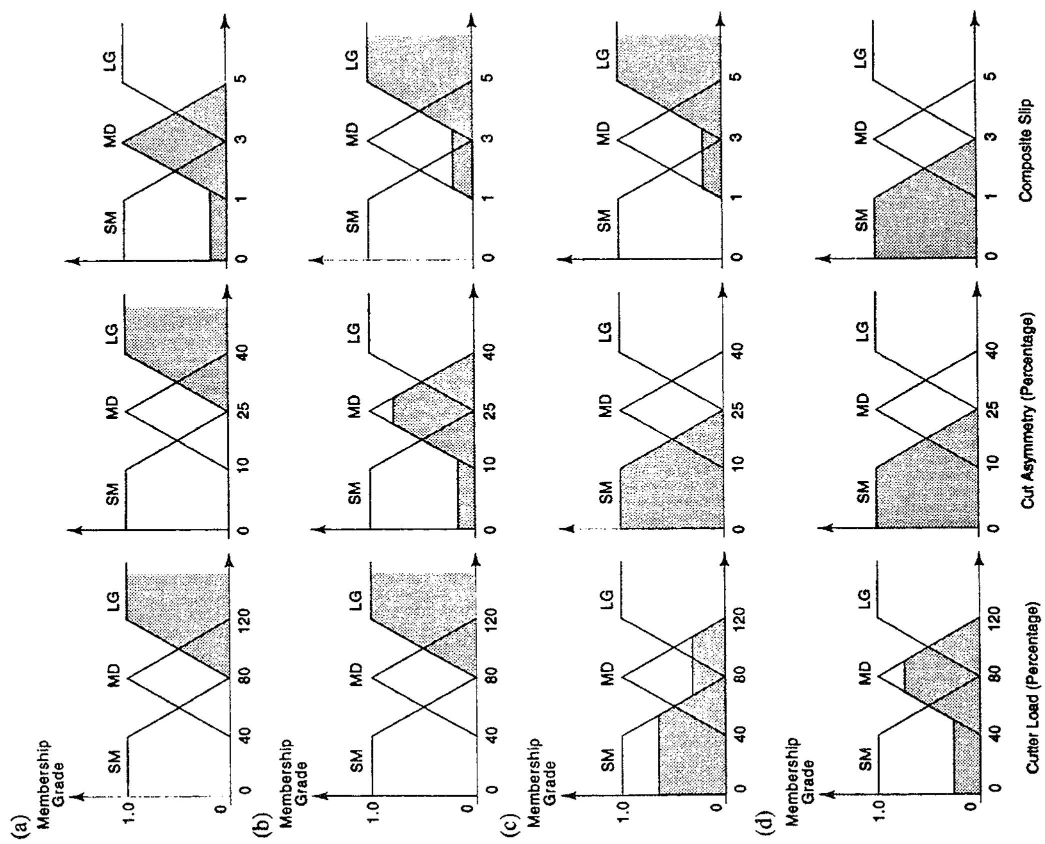

Figure 6. Fuzzy Linguistic Context Corresponding to the Experimental Cutter Load Profiles in Figure 5 (SM-Small, MD-Moderate, LG-Large).

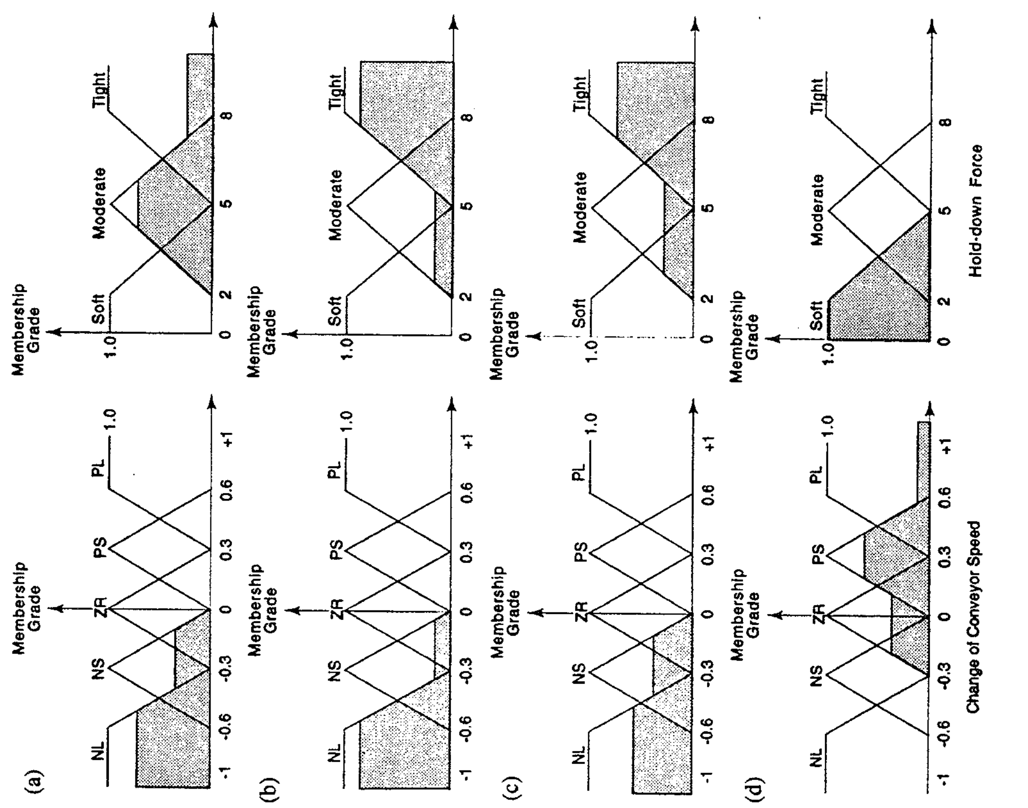

Figure 7. Fuzzy Linguistic Inferences of the Workcell Tuner.