Fuzzy Logic Control of a Hydraulic System

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Abstract **This paper presents the implementation of a fuzzy logic controller on an automated machine for mechanical processing of salmon. The prototype machine, as developed in The Industrial Automation Laboratory, is an innovative and automated version of a fish cutting machine. It is able to considerably reduce wastage of fish meat during processing, by automatically adjusting the position of the blade of the cutter with respect to the fish that is being processed. The machine consists of an intermittent-motion conveyor system to move the fish forward, a pneumatically activated guillotine-type blade that operates in the vertical direction, an *X-Y* horizontal table which carries the cutting blade assembly and is driven by two hydraulic actuators, and a digital CCD camera that takes the image of a fish for geometric sensing before it is cut. A Proportional-plus-derivative (PD) type fuzzy logic controller is developed and implemented successfully for driving the cutter assembly. The performance of the fuzzy logic controller is investigated, with respect to the control specifications for the machine. The real time controller operates in sampling periods of 1ms; consequently, the membership functions are designed so that only four rules are fired at each sampling period, thereby enabling real time processing. Processing stability of the controller may be adjusted by 9 central rules. Criteria for choosing the membership functions of inputs and output are discussed.**

1. Introduction

The Iron Butcher, which is commonly used in the fish processing industry for fish head cutting, was designed and built at the turn of the century, and has been only slightly modified and improved since then. This machine employs a mechanical sliding mechanism to detect the gill of the fish and to align the collarbone with the cutter blade. Due to lack of active sensing and feedback control, the machine typically wastes about 5% of the useful fish meat. This represents an annual revenue loss of about 25 million dollars, in the province of British Columbia, Canada. The Industrial Automation Laboratory of the University of British Columbia has been established primarily for research and development of advanced technology in automation of the fish processing industry [1]. The industrial prototype machine that is used in the present work is an outgrowth of an activity of the laboratory. The machine consists of several parts:

An intermittent-motion ***conveyor*** system to move the fish towards the cutting zone.

- A ***guillotine type blade*** that operates in the vertical direction and is operated by a ***pneumatic actuator***.
- ***Horizontal X-Y table*** that carries the cutting blade assembly, which is driven by means of ***two hydraulic actuators***.
- A ***digital CCD camera*** that takes the image of each fish as it enters the cutting zone.

A view of the prototype machine is shown in Figure 1. The conveying mechanism has several parallel arms that are equally spaced along the belt.

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The fish are pushed forward intermittently, by means of these arms. Also there is a matrix of retaining pins that point vertically upwards. These pins can fold in one direction, only, thereby restraining any backward motion of the fish. The conveyor pushes a fish forward every 1.24s, which corresponds to the period of the cyclic motion of the mechanism. Accordingly, the rate of processing is about 48 fish/minute. During the first half period, the conveyor pushes the fish forward and in the next half period while the fish are stationary, the imaging of one fish and cutting of the previous are carried out. Also during this half period the conveying arms move backward in order to get ready to push the fish forward in the next cycle. There is an optimum position at which the blade should be located with respect to a fish so that meat wastage would be minimum. This optimum position is determined by using a computer vision system. While a fish is stationary an image of the fish is taken by the CCD camera and the corresponding digital information is acquired by a frame grabber board of the vision computer. Image processing routines automatically determine the optimum position of the cutter, according to the gill position of the fish. This point is used as the reference input (set point) for the hydraulic controller, which moves the cutting blade assembly. After the cutter assembly is moved to the desired position (optimum point), the pneumatic actuator is activated, which releases the cutter blade vertically. The operations of the system are synchronized such that, by the time a fish arrives at the cutting zone, the blade has already been positioned at the desired position. This paper develops a fuzzy controller for positioning the cutter assembly of the machine.

2. Controller Specifications

Since the period of the cyclic motion of the conveyor is 1.24 seconds, the image capture and processing of a fish and the cutting of the previous fish are carried out during the return half cycle of 620ms of the conveyor. The desired position for the cutting blade assembly, has to be determined after the image processing, but the positioning command should not reach the actuators before the previous fish is cut. Positioning needs to be completed during the forward half cycle of 620ms. This means that the hydraulic positioning system has to reach the steady state at the end of the forward half cycle. Otherwise, the blade would be released while the cutting blade unit is still moving, but the fish would be in the stationary position. This may lead to such problems as poor-quality cuts or even complete entanglement of a fish with the cutter. The time required for image processing with the available hardware system is 170ms, which is well within the available time of 620ms for image capture, processing, and the generation of the set point for the cutter position. Note that the cutter can not be positioned for the next fish before the present fish is cut. The cutting time, for the pneumatic actuator is limited to less than 240ms, during which imaging and set-point computation for the next fish would be completed as well. Then a time duration of about 1.000 second would be available for positioning the cutter. Accordingly, the following specifications are used for the positioning controller:

- Time to reach the desired position in steady state ≤ 1.000s.
- Allowed offset for the cutter position (cutting accuracy) = 5mm.

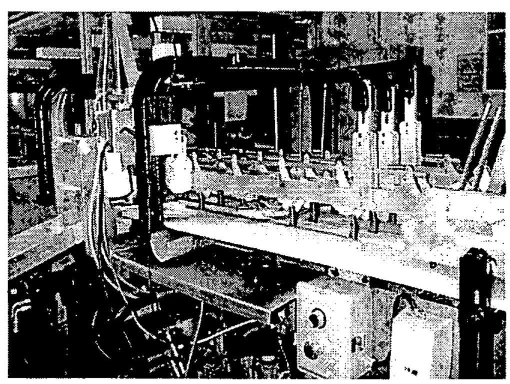

Figure 1. The prototype fish cutting machine in the Industrial Automation Laboratory.

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3. The Experimental System

The manipulator (X-Y table) that positions the cutter blade has two control inputs, which are the currents applied to the electrohydraulic proportional valves corresponding to the X and Y directions. Since the two degrees of freedom in the manipulator are quite similar and also independent, only the X direction is considered here, as shown in Figure 2. The servovalve consists of a torque motor, flapper pilot stage, and a double sliding spool boost stage. It is balanced by the centering springs which produce a spool position proportional to the differential pressure and therefore to the input current.

A Temposonics magnetostrictive linear displacement transducer at the head of the hydraulic cylinder precisely senses the position using the time interval between an interrogation pulse and the return pulse for a magnet attached to the piston. The sensor has a resolution of $0.025mm$ and a measurement update time of less than 1 ms. Two gage pressure transducers are also installed on the head and the rod sides of the cylinder, in order to measure the fluid pressures P_1 and P_2. All the sensor outputs are low-pass filtered by first order anti-aliasing RC filters. A date sampling frequency of $f_s = 1\,kHz$ is used; consequently, the cut off frequency of the filters is set to $200\ Hz$. A 12 bit PC-based data acquisition system is used for data collection. The physical parameter values of the prototype manipulator are listed in Table 1.

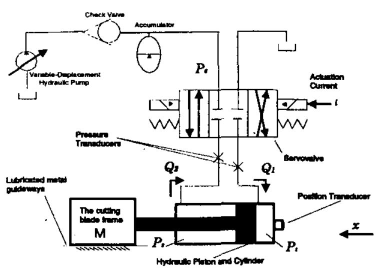

Figure 2. The high-speed electrohydraulic positioning system (X axis).

Table 1. Physical parameters of the prototype manipulator.

Parameter	Value
Measured moving mass	$M = 32.7\ Kg$
Head-side piston area	$A_1 = 1.14\times10^{-3}\ m^2$
Rod-side piston area	$A_2 = 0.633\times10^{-3}\ m^2$
Maximum piston displacement	$L = 50\times10^{-3}\ m$
Volume of each Hose between	$V_h = 8.9\times10^{-5}\ m^3$

4. Modeling of the Electrohydraulic System

There are two types of nonlinearities in the servovalve system; namely, the hysteresis resulting from electromagnetic characteristics of the torque motor and the flow forces on the valve spools [5]. Generally, servovalve dynamics can be ignored in comparison to the actuator dynamics. Newton's second law applied to the actuator yields :

$$F = P_1A_1 - P_2A_2 = M\ddot{x} + F_f \tag{1}$$

where F is the actuator force, F_f is the opposing frictional force, x is the piston displacement, and M is the moving mass in the X direction. The amount of the fluid flow to the head-side (Q_1) and from the rod-side (Q_2) of the cylinder is a function of the valve spool position and cylinder pressures. Assuming that the valve is critical center type with matched and symmetrical ports[5], the relationship can be expressed in the following form [2,4]:

$$\begin{cases} Q_1 = K.x_v.\left[s(x_v)\sqrt{P_s - P_1} + s(-x_v).\sqrt{P_1}\right] \\ Q_2 = K.x_v.\left[s(x_v)\sqrt{P_2} + s(-x_v)\sqrt{P_s - P_2}\right] \end{cases} \tag{2}$$

where x_v is the valve spool displacement, K is a fixed gain, P_s is the supply pressure, and $s(x_v)$ is a switching function defined as below:

$$s(x_v) = \begin{cases} 1 & x_v \geq 0 \\ 0 & x_v < 0 \end{cases} \tag{3}$$

Using flow continuity and taking fluid compressibility into account, we have [5]:

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$$\begin{cases} Q_1 = A_1\dot{x} + \dfrac{A_1 x + V_h}{\beta}\dot{P}_1 \\ Q_2 = A_2\dot{x} - \dfrac{A_2(L-x)+V_h}{\beta}\dot{P}_2 \end{cases} \tag{4}$$

where β is the effective bulk modulus of the fluid, and V_h is the volume of the fluid inside each of the hoses that connect the servovalve to the actuator. The state vector is

$$x \cong [x_1 \quad x_2 \quad x_3 \quad x_4]^T = [x \quad \dot{x} \quad P_1 \quad P_2]^T \tag{5}$$

By combining equations (1), (2), and (4), the following nonlinear state-space model of the system is obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{M}\left[A_1 x_3 - A_2 x_4 - F_f\right] \\ \dot{x}_3 = \dfrac{\beta}{A_1 x_1 + V_h}\left[k x_v \left(s(x_v)\sqrt{P_s - x_3} + s(-x_v)\sqrt{x_3}\right) - A_1 x_2\right] \\ \dot{x}_4 = \dfrac{-\beta}{A_2(L-x_1)+V_h}\left[k x_v \left(s(x_v)\sqrt{x_4} + s(-x_v)\sqrt{P_s - x_4}\right) - A_2 x_2\right] \end{cases} \tag{6}$$

5. PD-like Fuzzy Logic Controller Design

The conventional PD control law is:

$$u = K_P.e + K_D.\dot{e} \tag{7}$$

where e and $\dot{e}$ are the error and the rate of error, and K_P and K_D are the proportional and differential gain coefficients, respectively. Then a PD-like fuzzy logic controller consists of fuzzy rules, where inputs (context) are error and rate of error [4]; thus

if $e(k)$ is <a fuzzy state> *and* $\dot{e}(k)$ is < a fuzzy state >

then $u(k)$ is < a fuzzy state >

where < a fuzzy state > is the symbolic name of a fuzzy linguistic value. The corresponding linguistic form is:

if the value of error is <linguistic value>
and the value of change-of-error is <linguistic value>
then the value of control output is <linguistic value>

for each sampling time k. For position control of this hydraulic actuator using fuzzy logic, the inputs are position error e and changing error (velocity error) Δe, and the output is current to the servovalve. The stroke length of the hydraulic cylinder is 2 inches. Velocity is estimated by the linear observer [7] :

$$\begin{cases} \hat{v} = z_v + k_v x \\ \dot{z}_v = -k_v \hat{v} \end{cases} \tag{8}$$

A block diagram of the fuzzy knowledge-based controller (FKBC) is shown in Figure 3.

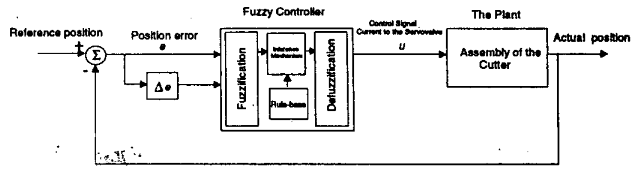

Figure 3. Block diagram of the fuzzy logic controller.

The fuzzy controller uses individual rule-based inference, not *composition based inference,* because of the lower memory requirement in real time processing. The fuzzy states of the inputs and the output, all are chosen to be equal in number and use the same linguistic descriptors:{NL, NM, NS, ZER, PS, PM, PL}; where NL = negative large, NM = negative medium, NS = negative small, ZER = zero, PS = positive small, PM = positive medium and PL = positive large. The rule base is shown in the Table 2. The rules in the center of the table are related to the steady-state behavior of the process. When both the position error and the velocity error are negative, the position is below the set-point and is moving further away. In response the control action should be positive such that it will reduce the position error.

Table 2. The rule base of the Fuzzy Controller.

Δe

e \ Δe	NL	NM	NS	ZER	PS	PM	PL
NL	PL	PM	PM	PS	PS	PS	ZER
NM	PM	PM	PS	PS	PS	ZER	ZER
NS	PM	PS	PS	PS	ZER	ZER	NS
ZER	PS	PS	PS	ZER	ZER	NS	NS
PS	PS	PS	ZER	ZER	NS	NS	NM
PM	PS	ZER	ZER	NS	NS	NM	NM
PL	ZER	ZER	NS	NS	NM	NM	NL

When the velocity error is positive, while the position error is negative, the cutter is moving towards the set-point and control action should be low enough to slow down the

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approach to the set-point. The remaining segments of rules in Table 2 may be similarly explained. Note from Figure 2 that, dynamics of each hydraulic actuator is not symmetric, due to the difference in the effective area of the rod side and the head side of the piston. The designed rulebase of the fuzzy controller accounts for this asymmetry as well.

6. Choice of Membership Functions

For computational effectiveness, efficient use of memory, and the relative ease of performance analysis, a representation of membership functions with uniform shape and parametric functional definition has been realized in the present application. As can be seen in Figure 4, the triangular membership functions used have an overlap between every adjacent pair. This means that every crisp value of an input to the controller will belong to at least one membership function with the degree of membership strictly greater than zero. If this was not the case, then there would be a crisp input value which could not be matched to a rule-antecedent during the fuzzification phase, and none of the rules would fire. This will cause discontinuities in the control output. The present system has been designed in such a way that two adjacent membership functions have a cross-point level of 0.5 and cross-point ratio of 1, (i.e., symmetric 50% overlap) since this choice provides significantly less overshoot and faster rise-time. Furthermore, for each antecedent, two rules will fire and in this way, continuity of the control action would be guaranteed. The membership functions of the nine central rules, are responsible for the steady state response of the controller. It follows that the peaks of these membership functions are among the parameters that need to be tuned carefully. The membership functions of the controller output (rule-consequent) have been taken uniform and symmetric as well, in order to maintain a symmetry in the control action. In this case the peak and the centre of gravity of each membership function are identical [4].

The implication is based on Mamdani's method (Min-Max). The centre of gravity method is used for defuzzification. With the form of the membership functions that are used for the controller inputs, at each sampling period only two rules will fire for each input value. With two inputs, at each sampling period (1 ms), the processor will deal with only four rules. This choice of inference and membership functions significantly reduces the complexity of computation of the fuzzy control law. The computer is an IBM compatible machine with DOS operating system, and the code is written in WATCOM C. A 12 bit PC-based data acquisition system is used for data collection.

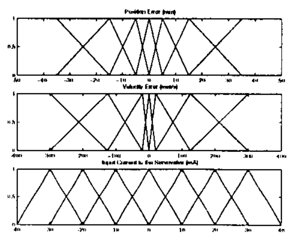

Figure 4. Membership Functions of controller inputs (Position Error and Velocity Error) and output (Input Current to the Servovalve).

7. Experimental Results

As clear from the experimental result given in Figure 5, control specifications have been achieved successfully. In particular, the maximum offset has been limited to about 3mm. The test was carried out, starting at different initial positions. By properly adjusting the membership functions of the central rules in the table of rules, a stable response was achieved. Different rulebases were tried and the one that provided the best performance among them was adopted for control of the prototype system.

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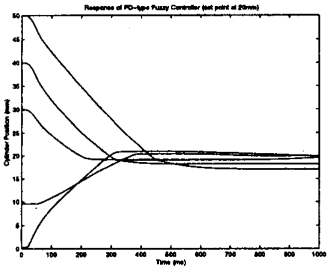

Figure 5. A Typical Experimental Result of the PD-Type Fuzzy Controller.

8. Conclusion

In this paper, fuzzy logic control of an industrial hydraulic manipulator that has been implemented in real time was discussed. The effect of deadband of the servovalve was added to the control signal, which reduced the position offset to an acceptable level. The asymmetry of the hydraulic actuators was taken into consideration in designing the control rulebase. Consequently, the rulebase was not strictly symmetric.

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