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Intelligent Control of Cybernetic Below-Elbow Prosthesis

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Abstract

In this paper, an intelligent control scheme with multistage fuzzy inference is developed for a myoelectric prosthesis to achieve natural control with tactile feedback based on fuzzy control strategies. Strain gauges and a potentiometer are added to the prosthesis for tactile feedback with a PWM motor driver developed to save the battery power. According to the multi-stage fuzzy inference, the prosthesis can determine the stiffness of the object and hold an object without injuring it, meanwhile, the hysteresis phenomenon is also resolved. The controller is implemented by software in an 80196KC single-chip microcontroller to replace the original controller.

1. Introduction

The myoelectric prosthesis is operated by surface electromyogram signal (SEMG) of the amputee's remaining muscle to control an electric motor for opening or closing the artificial hand. However, the SEMG signal is quite complex and may change for different amputees. Furthermore, no tactile sensors are utilized in the commercial prosthesis to provide the tactile feedback like human's skin. Therefore, long trying time is required for the amputee to adapt to the prosthesis. In this study, an intelligent control scheme is presented to achieve some intelligent functions with tactile feedback for the prosthesis by compliance control.

The first practical myoelectrically controlled prosthesis was demonstrated by Reinhold Reiter at the Exportmesse in Hannover in 1948 [1]. It was not until 1970 that some investigations were devoted to myoelectric control in the USA, England, Sweden, Japan, and Canada. From the development of the early conventional mechanical cable-operated arm to the cybernetic prostheses, control methods in the past for the prostheses were still quite different from the natural motion of the normal limb. Nowadays, some commercial prostheses such as Otto Bock, Hosmer, and Utah Arm [2] still adopt on-off or some kinds of proportional control in the open loop way [3]. Hogan and Abul-haj [4] in M.I.T. presented a novel control scheme called "natural control" to attempt to make the prosthesis respond as the natural elbow by the concept of impedance control. Scott et al. [5] has studied prosthesis for many years and presented the myoelectric control system with sensory feedback systems. Yeh et al. [6] did a study on the neural network controller using a single-chip microcontroller for proportional force control of the myoelectric prosthesis. So far no studies of compliance control with sensory feedback in the prosthesis have been reported using fuzzy control strategies.

In this study, an intelligent control scheme which utilizes a multi-stage fuzzy inference is presented to control prosthesis to achieve compliance and natural control with tactile feedback. Strain gauges and a potentiometer are mounted on the cybernetic prosthesis for tactile feedback. According to these signals, some intelligent strategies are developed to achieve natural control by fuzzy reasoning. A pulse width modulation (PWM) method is used to control electrical current in the motor to prolong the service time of the battery. Besides, the phenomenon of the hysteresis in the transmission mechanism of Otto Bock hand is resolved in this study by fuzzy control. Finally, the controller is implemented by software in an 80196KC single-chip microcontroller to replace the original controller in the Otto Bock hand.

2. System Architecture

The whole architecture of control system is shown in Fig. 1, including a below-elbow prosthesis with two EMG preamplifiers, tactile sensors, motor driver, fuzzy inference program, and 80196KC single-chip microcontroller.

2.1 Prosthesis with EMG preamplifiers

A commercial product of the Otto Bock below-elbow prosthesis is adopted as the experimental equipment in this study. The original Otto Bock hand is controlled by switching the motor on and off in an open loop way based on the EMG signals processed by the preamplifiers. In this study, an amputee can control for opening or closing the artificial hand based on the half-wave rectified EMG signals of flexor or extensor muscles integrated per 0.1 seconds.

2.2 Tactile Sensors

For achieving natural control, strain gauges and a potentiometer shown in Photo 1 are mounted on the original prosthesis to provide the tactile feedback with the information of acting force and displacement. The force transducer has been designed using two semiconductor strain gauges (gauge factor: 146, gauge resistance :356.7 Ω) on two sides of the thumb of the Otto Bock hand to measure the compression and tension on the thumb caused by the bending moment. A circuit of the half-bridge for the strain gauges with temperature compensation is used with the adjustable offsets and gain. The force levels is represented by voltage (1 N as 25 mV).

Position transducer has been designed using a potentiometer mounted on the Otto Bock hand mechanism to measure the displacement between thumb and index finger. The displacement can be sensed from the potentiometer with sensitivity of 270 mV/cm.

According to the information of force and position, the stiffness of the object can be distinguished. Different objects, which correspond to the different stiffness, may themselves have a minimum force value (F_p) for picking up an object and a maximum force value (F_b) beyond which the object may break. Because stiffness of the object is not directly sensed by an amputee wearing a prosthesis, unproper motion of the prosthesis may sometimes injure the objects. Therefore, multi-stage fuzzy control strategies are developed to achieve natural motion of the human hand.

2.3 Motor driver for prosthesis

A motor driver is developed by the PWM method to drive motor to prolong the service time of the battery and to replace the original linear driver circuit. The desired output force is controlled by varying the duty cycle of the PWM pulses through software implemented in an 80196KC single-chip microcontroller. The average motor current is modulated so that the force in the artificial hand is controlled. The output pulse signals are transmitted with PWM period of 0.01 seconds by two high speed output (HSO) ports in an 80196KC single-chip microcontroller to turn the transistors on and off in an H-bridge circuit in an unipolar way.

2.4 Hysteresis phenomenon

Hysteresis phenomenon is found to exist in the transmission mechanism of the Otto Bock hand. It can provide auto-lock function with a holding torque even when the motor current is small. This causes some hysteresis relations as shown in Fig. 2 between the duty cycle D of the PWM driver for the motor and the acting force F of prosthesis. From Fig. 2, it can be noticed that the characteristics of hysteresis are different for different objects (A: plastic bottle, B: tennis ball, and C: aluminum) of various stiffness. The duty cycle is roughly proportional to output force in the small force level when the duty cycle is increasing. But the force level may suddenly jump to high values when the duty cycle is beyond about 60%. While the force remains the same value within the dead zone until the duty cycle decreases to negative values. This phenomenon may yield some information to control the prosthesis by fuzzy reasoning. Therefore, some fuzzy control strategies are developed to resolve these problems.

2.5 Prosthetic controller

The controller is implemented using an 80196KC single-chip microcontroller. The I/O ports of the microcontroller are used to send or receive EMG signals and sensor signals. The control scheme and signal processing is realized by software programming, including a PWM driver control program, programs for multi-stage fuzzy inference with control strategies, and a program to process the EMG signals. These programs are developed in C96 language with the aid of the EV80C196KC microcontroller evaluation board.

3. Fuzzy Control Strategies

Human can easily grasp an unknown object without visual feedback and also achieve the task without injuring the object. In this study, to achieve the tasks through the prosthesis, fuzzy control strategies are developed by the multi-stage inference as shown in Fig. 3 to complete several tasks including mild force control, stiffness estimation, object holding and releasing. In small force level, an amputee can control the acting force proportionally based on EMG signal. But in large force level without injuring the object, the multi-stage fuzzy inference is used, in a way that the membership functions of the antecedence and consequence in later stage are determined dynamically based from the results of the defuzzification of the former stage.

3.1 Mild force control by EMG

Since the characteristics of the small force region are similar even for various objects, proportional force control can be easily achieved [6] based on the EMG signal of an amputee by controlling the duty cycle D of PWM driver. The fuzzy rules are developed below, in which the EMG1 and EMG2 represent the EMG signal of flexor and extensor muscles respectively.

If EMG1 is zero, then D is zero.
If EMG1 is small, then D is positive small.
If EMG2 is small, then D is negative small.
If EMG2 is big, then D is negative big.

A positive duty cycle is used to close artificial hand, whereas a negative duty cycle is used to open the artificial hand.

3.2 Determining the stiffness of the object

While in the task of mild force control, the prosthesis is activated to lightly press the object after the object is detected to be touched with the force is greater than a threshold value. Then a force change ΔF is detected from the strain gauges, the deformation ΔX is measured from the potentiometer to estimate the stiffness of the object. The stiffness K of the object can be estimated based on fuzzy rules below:

If $\Delta X/\Delta F$ is big, then K is small.
If $\Delta X/\Delta F$ is medium, then K is medium.
If $\Delta X/\Delta F$ is small, then K is big.

Different objects with different stiffness have themselves a minimum force value F_p for holding them for pick-up and a threshold value of maximum force F_b beyond which the object may cause some permanent deformation or even breaks. To achieve the task of holding the object for picking up, the basic holding condition is that the force should be larger than the threshold value of F_p, for example, a desired holding force F_h, while it must be less than F_b in order not to break the object.

Based on fuzzy rules above, the F_b, F_h, and F_p of an object are estimated by the fuzzy rules as listed in Table 1. The corresponding required duty cycles D_p, D_h, and D_b to handle the hysteresis characteristics can also be determined through fuzzy inference from Table 1.

3.3 Object holding

The F_b, F_h, and F_p form three vertices of fuzzy sets. They are determined from the results of previous defuzzification stages. The membership functions of the antecedence are then dynamically established for the fuzzy sets of the F_b, F_h, and F_p. Similarly, the membership functions of the consequence of the D_b, D_h, and D_p are also dynamically determined by the singleton sets.

The real acting force F is then checked to determine the duty cycle D to handle the hysteresis characteristics by the fuzzy rules below:

If F is small, then D is positive small.
If F is medium, then D is positive medium.
If F is O.K. for holding(H), then D is zero.
If F is big, then D is negative medium .

The fuzzy rules are same for different objects but with different membership functions for F_b, F_h, F_p, D_b, D_h, and D_p. While the second rule is used for holding the object using the auto-lock function of the prosthesis in order to conserve battery power. Beside, when an amputee wants to open the prosthesis at any time, a fuzzy rule below is simultaneously checked to turn the motor loose to open the artificial hand when the rule is fired.

If EMG2 is big, then D is negative big.

4. Results and Discussions

To check the effectiveness of the control system, a book is used as the test object for grasping. The results are recorded as shown in Fig. 4. With 3 seconds of closing movement, the artificial hand touches the object. When the object is lightly pressed, its stiffness is estimated. After the force level is above F_p level through mild force control, the force is automatically increased to reach the desired value for holding. Then the duty cycle is decreased to zero in order to save the battery power as controlled by an 80196KC single-chip microcontroller. It can be noticed from Fig. 4(a) that at the start of holding process, the force higher than the holding value is automatically decreased by the negative duty cycle as can be seen from Fig. 4(d). After 5 seconds of holding time, the prosthesis is opened up caused by a large EMG2 signal. When force history of the grasping process for a book is compared with those of three sample objects from Fig. 5, it noticed that the holding force (and also the stiffness) is between aluminum and tennis ball.

5. Conclusions

An intelligent control scheme which utilizes multi-stage fuzzy inference is presented for prosthetic control to achieve natural control with tactile feedback developed fuzzy control strategies. Strain gauges and a potentiometer are mounted to the prosthesis for tactile feedback to provide the information of the multi-stage fuzzy inference. Prosthesis can determine the stiffness of the object and hold an object without injuring it using an 80196KC single-chip microcontroller. In addition, the hysteresis phenomenon is also resolved.

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References

[1] Reiter, R., "Eine neue Elektrokunsthand," Grenzgebiete der Medizin, Vol. 1, No. 4, 1948, pp. 133-135.

[2] Jacobsen, S. C., Knutti, D. F., Johnson, R. T., and Sears, H. H., "Development of the Utah Artificial Arm," IEEE Trans. Biomed. Eng., Vol. BME-29, Spr. 1982, pp. 249-269.

[3] Sears, H. H. and Shaperman, J., "Proportional Myoelectric Hand Control: An Evaluation," Am. J. Phys. Med. Rehabil., Vol. 70, No. 1, 1991, pp. 20-28.

[4] Hogan, N. and Abul-haj, C. J., "An Emulator System for Developing Improved Elbow-Prosthesis Designs," IEEE Trans. Biol. Eng., Vol. 34, No. 9, 1987, pp. 724-736.

[5] Scott, R. N., Brittain, R. H., Caldwell, R. R., Cameron, A. B., and Dunfield, V. A., "Sensory-Feedback system Compatible with Myoelectric Control," Med. & Biol. Eng. & Comput., Vol.18, 1980, pp. 65-69.

[6] E. C. Yeh, W. P. Chung, R. C. Chan, and C. C. Tseng, "Development of Neural Network Controller for Below-Elbow Prosthesis Using Single-Chip Microcontroller," 1992 International Symposium Biomedical Engineering in the 21st Century, Taipei, R.O.C., 1992.

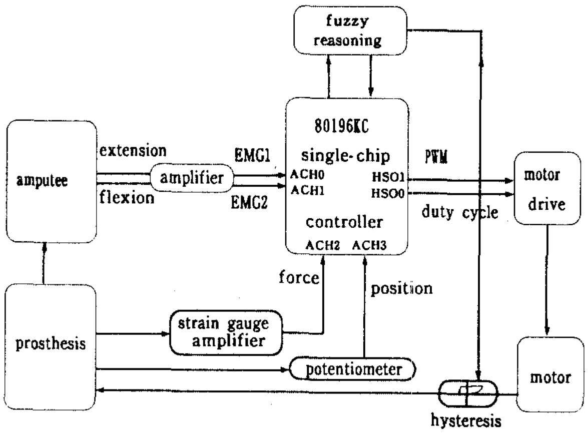


Fig. 1 Architecture of control system

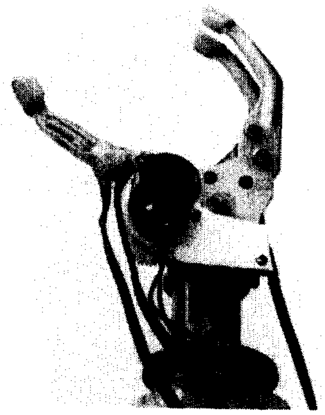
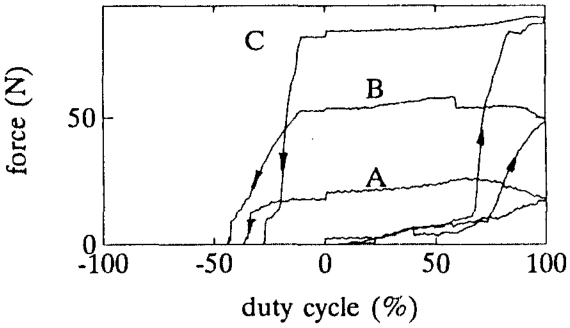


Photo 1 Tactile sensors on prosthesis



A: plastic bottle B: tennis ball C: aluminum

Fig. 2 Hysteresis phenomenon

Table 1 Fuzzy rule table

stiffness / force & duty cycle	small object A	medium object B	big object C
Fp (N)	11	32	48
Fh (N)	17	42	58
Fb (N)	28	56	88
Dp (%)	80	85	72
Dh (%)	84	90	75
Db (%)	-43	-40	-30

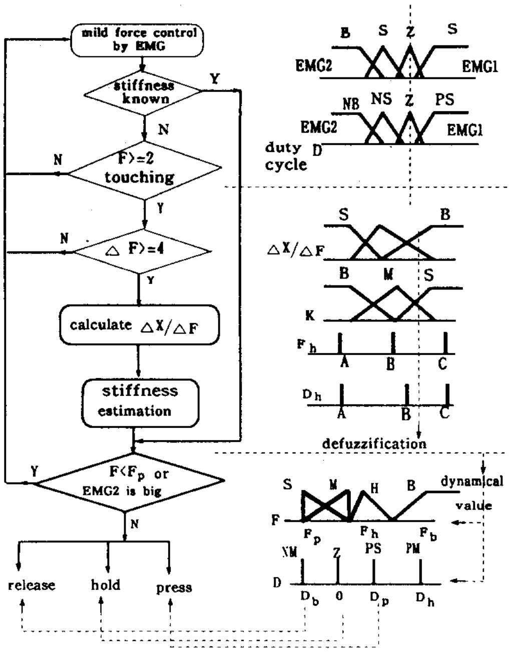
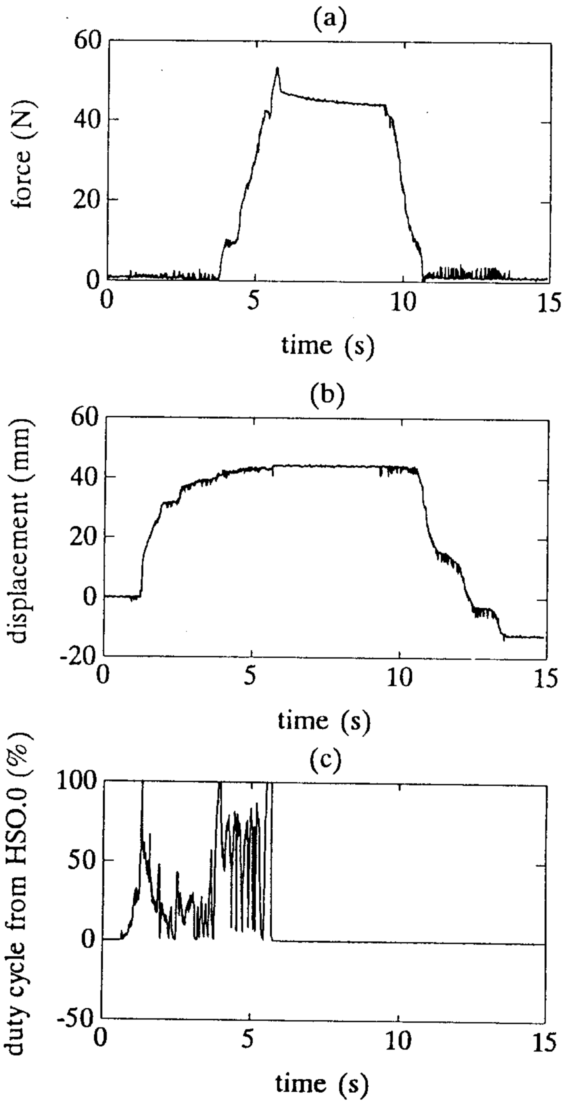


Fig. 3 Multi-stage fuzzy inference



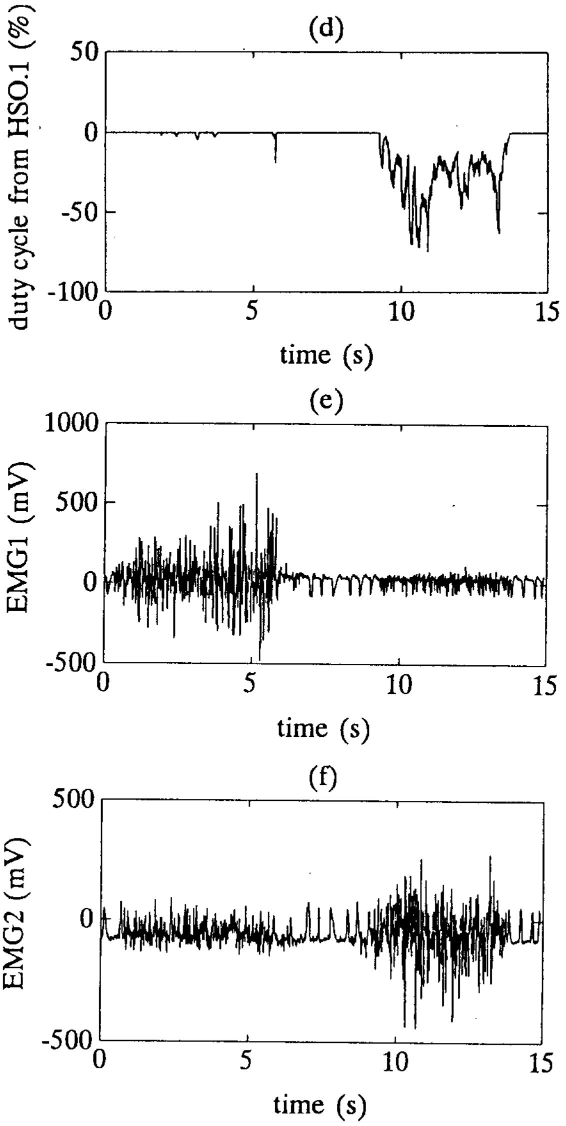
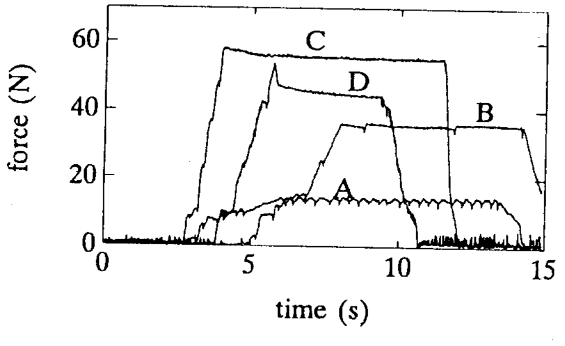


Fig. 4 Grasping process for a book

(a) touching force
(b) grasping deformatiom
(c) positive duty cycle through HSO.0
(d) negative duty cycle through HSO.1
(e) EMG1 by flexor muscle
(f) EMG2 by extensor muscle



A: plastic bottle B: tennis ball
C: aluminum D: book

Fig. 5 Force history for grasping different objects