Experimental Implementations of Decoupling Self-Organizing Fuzzy Control to a TITO Pneumatic Position Control System*

Ying-Tsai WANG** and Ming-Kun CHANG**

The coupling and pneumatic compressibility effects cause strong parameter variety in a two-input two-output (TITO) pneumatic control system. Thus, it is difficult to design a controller using conventional control method. In this paper, self-organizing fuzzy control (SOFC) is applied to a TITO pneumatic position control system. By using the concept of decentralized control, a TITO control structure is decomposed into two separate control channels. Each channel is associated with a SOFC for single-axial pneumatic control system and a decoupling SOFC for structure interactions. Experimental results show that the proposed control algorithm can achieve high control accuracy. And, it is robust to various operating conditions.

Key Words: Decoupling Self-Organizing Fuzzy Control, TITO Pneumatic Control System

1. Introduction

A two-input two-output (TITO) pneumatic control system shown in Fig. 1 basically includes two sets of single-axial electro-pneumatic servo control subsystems and a flexible connected plate. This experimental setup is used to simulate two-axial pneumatic driving systems, such as material testing machine and multiple-vibration plate-form. And, the coupling plate and loading springs are used to simulate various loading effects. Due to pneumatic compressibility and interactions between subsystems, system parameters are strongly time-variant and thus it is very difficult to identify its true model. Recently, some advanced control algorithms, including optimal control⁽¹⁾, self-tuning control⁽²⁾, adaptive-fuzzy control⁽³⁾ etc. have been used in pneumatic control systems to improve the control performance. However, they only emphasized on single-input single-output (SISO) systems,

and did not concern with the noise effect and interactions between actuators. They could not be implemented for TITO or multi-input multi-output (MIMO) pneumatic control systems.

The fuzzy control approach has been found to be an effective alternative to deal with complicated, ill-defined and poorly mathematically modeled dynamical process. Without relying on detailed mathematical model, the fuzzy control algorithm is developed by incorporating human knowledge and experience directly into implementations. Hence, fuzzy control can be used to overcome difficulties of parameter identification. Nie etc.^{(4),(5)} used conventional decoupling fuzzy control to a multivariable servomechanism. Huang and Lian⁽⁶⁾ applied the similar control structure to a multi-degree dynamic absorber. However, conventional decoupling fuzzy control associated with fixed fuzzy rules can not cover all operating conditions in this TITO pneumatic control system.

Based on the evaluation of system's performance, self-organizing fuzzy control (SOFC)⁽⁷⁾ has a learning mechanism to generate and modify fuzzy rules. In this paper, we will develop a decoupling control structure for a TITO pneumatic control system. The

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** National Taiwan University of Science and Technology, Department of Mechanical Engineering, 43, Keelung Road, Section 4, Taipei, Taiwan, R. O. C.
E-mail: ytwang@mail.ntust.edu.tw

decoupling control structure is composed of two separate control channels. Each channel is associated with a SOFC for single-axial pneumatic control subsystem and a decoupling SOFC for structure coupling. To examine its effectiveness and robustness, the performance of proposed decoupling self-organizing fuzzy control will be compared with conventional decoupling fuzzy control⁽⁴⁾⁻⁽⁶⁾. Experimental results indicate its superior performance both in the transient and in the steady state, and prove its feasibility for various operating environments.

2. Control Strategy

A two-axial pneumatic control system shown in

Fig. 1 The schematic diagram of TITO pneumatic control system

Fig. 2 Block diagram of proposed control algorithm

Fig. 3 Control structure of SOFC

Fig. 1 has two control inputs (u_1 and u_2) and two position outputs (x_1 and x_2). From the physical viewpoint, this system can be decomposed into two individual SISO subsystems. Thereby, each subsystem can be considered as a typical single-axial pneumatic driving system and a decoupling mechanism is added to compensate coupling effects between subsystems.

Figure 2 indicates the block diagram of proposed control algorithm and all controllers are designed by linguistic-approach self-organizing fuzzy control algorithm^{(7),(8)}. The actual input voltage u_i to the servo amplifier is

$$u_i = \sum_{j=1}^2 u_{ji}, \quad i=1, 2, \quad (1)$$

where u_{11} (or u_{22}) is the input voltage obtained from individual single-axial pneumatic driving subsystem and u_{12} (or u_{21}) is the input voltage induced by structure interactions.

The detail of SOFC is functionally shown in Fig. 3. Here, SOFC is associated with a conventional fuzzy control structure and a learning mechanism to modify fuzzy rules. The gains GE_{jm} , GCE_{jm} and GU_{jm} are used to normalize between system variables and the universal of fuzzy sets. Fuzzification is adopted the triangle-type membership function⁽⁹⁾ to obtain linguistic variables. The fuzzy inference is based on the Max-Min product composition⁽¹⁰⁾ to operate the fuzzy control rules. In order to reduce computer load, fuzzy control rules based on a 7×7 fuzzy rule table as Table 1. To defuzzify the fuzzy sets, the height method⁽¹¹⁾ is used to attain the control signal.

Instead of using the performance decision table, we adopt error (e) and error change (ce) as input variables to modify fuzzy rules⁽⁸⁾. First, it defines a learning rate r to compensate the position error as

$$\Delta x(k) = r[x_d - x(k)] = re(k), \quad 0 < r \leq 1. \quad (2)$$

To allow the output x to approach the desired output x_d gradually, the learning rate r should be properly chosen in order to compromise the overcorrection and convergent speed of output response. Similarly,

$$\Delta v(k) = -\frac{r}{T} ce(k), \quad (3)$$

where T is the sampling time and v represents the position change rate. Then, to reduce the computer

Table 1 Fuzzy control rules

U_{jm}		E_j						
		NB	NM	NS	ZO	PS	PM	PB
CE_j	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NM	NM	NS	ZO	PS
	NS	NB	NM	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PM	PB
	PM	NS	ZO	PS	PM	PM	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

Fig. 4 The excitation modules of fuzzy rules

load in parameter identifications, the controlled system is simplified as a 0th-order.

$$\Delta u_e = \frac{1}{M} \Delta x \quad (4)$$

$$\Delta u_{ce} = \frac{T}{M} \Delta v \quad (5)$$

Here, the limits of Eqs. (4) and (5) are $\Delta x \approx 0$ and $\Delta v \approx 0$, respectively. If these are not satisfied, the input reinforcement Δu is incorrect. When x and v are departure, a single control input does not allow x to approach the desired point x_d and v to approach the desired point v_d , simultaneously. Thus, the input reinforcement Δu should be defined by these corrections as

$$\begin{aligned} \Delta u &= (1 - \zeta) \Delta u_e + \zeta \Delta u_{ce} \\ &= \frac{\gamma}{M} [(1 - \zeta) e(k) + \zeta ce(k)] \quad 0 \leq \zeta < 1, \end{aligned} \quad (6)$$

where ζ is the weighting factor. Since every output state in the universe, e or ce , can be excited by 2 modules. Therefore, the rule modification is excited by four rules as Fig. 4. The correction of each rule is modified by its excitation intensity W_i , which can be obtained by the linear interpolation technique⁽¹²⁾. Thus, the input u_{jm} of i th rule is

$$\begin{aligned} u_{jmi}(k+1) &= u_{jmi}(k) + W_{jmei} W_{jmeci} \frac{\gamma_{jm}}{M_{jm}} [(1 \\ &\quad - \zeta_{jm}) e_j(k) + \zeta_{jm} ce_j(k)]. \end{aligned} \quad (7)$$

This equation is the basic learning algorithm. In term of linguistic-approach, this rule base can be expressed as

$$\begin{aligned} RULES_{jm}(k+1) &= RULES_{jm}(k) \\ &\quad + W_{jmei} W_{jmeci} \frac{\gamma_{jm}}{M_{jm}} [(1 - \zeta_{jm}) e_j(k) \\ &\quad + \zeta_{jm} ce_j(k)]. \end{aligned} \quad (8)$$

Table 2 Component specifications

single-side actuator	$A_{rod} = 9.366 \text{ cm}^2$, $A_p = 12.57 \text{ cm}^2$, stroke = 20cm
servo-valve	-20mA~20mA, bandwidth=20Hz
linear scale	resolution=0.005mm
supply pressure	6 bars
D/A converter	12 bits, settling time :25 μ s
spring loading	$Ks1=Ks2=0.376 \text{ kgf/mm}$
counter	24 bits
connected plate	mass=0.27kg, material: aluminum length=33.5cm, thickness=0.6cm, width=5cm

Table 3 Typical fuzzy rules

U_{jm}		E_j						
		NB	NM	NS	ZO	PS	PM	PB
CE_j	NB	-4	-4	-4	-4	-2	-1	0
	NM	-4	-4	-2	-2	-1	0	1
	NS	-4	-2	-2	-1	0	1	2
	ZO	-4	-2	-1	0	1	2	4
	PS	-2	-1	0	1	2	2	4
	PM	-1	0	1	1	2	4	4
	PB	0	1	2	4	4	4	4

3. Experimental Results

In this paper, component specifications of this TITO pneumatic control system are summarized and listed in Table 2. Spring loading ($Ks1$ and $Ks2$) and a flexible coupling plate are used to simulate various loading conditions. Proposed controllers in Fig. 2 are implemented on Intel-80586 microcomputer system, and the sampling time is 2.5 ms.

To emphasis on all possible implementations of this two-axial pneumatic position control system, four cases based on various operating conditions will be presented. And, to evaluate the efficacy and robustness of proposed control algorithm, experiments of conventional decoupling fuzzy control are also included. Conventional decoupling fuzzy control basically has the same decoupling control structure as Fig. 2. And, the only difference is to substitute the conventional fuzzy controller, which is associated with fixed fuzzy rules as given in Table 3, into the self-organizing fuzzy controller. For both proposed control algorithm and conventional decoupling fuzzy control, gains of GE , GCE , and GU are given as $GE_{11} = GE_{22} = 0.5$, $GCE_{11} = GCE_{22} = 0.5$, $GU_{11} = GU_{22} = 0.25$ and $GE_{12} = GE_{21} = 0.1$, $GCE_{12} = GCE_{21} = 0.1$, $GU_{12} = GU_{21} = 0.1$. And, to compromise the overcorrection and convergent speed of output response, other parameters are optimally chosen as $\gamma_{jm}/M_{jm} = 0.1$ and $\zeta_{jm} = 0.5$ via plenty of tests.

© Case 1: Synchronous position motion without connected plate

First, we will study the synchronous control of

Table 4 Fuzzy rules of Case 1
(a) Steady extending process at $t=11$ sec.

$U_{22} \backslash U_{11}$		$E_1 \backslash E_2$							$U_{12} \backslash U_{21}$		$E_1 \backslash E_2$						
		NB	NM	NS	ZO	PS	PM	PB			NB	NM	NS	ZO	PS	PM	PB
CE_1 CE_2	NB	-4	-4	-4	-4	-4	-1	0	CE_1 CE_2	NB	0			-1.8	-1.94	-5	
	NM	-4	-4	-2	-4	-1.69	0	1		NM	0			-1	-1.4	-39	-4
	NS	-4	-2	-2.01	-2.08	-1.12	1	2		NS	0			0	-1.1	-29	-28
	ZO	-4	-2	-2.29	-1.7	-1.1	2	4		ZO	0.02			-1.01	.9	0.02	
	PS	-2	-1	-.99	.43	2	2	4		PS	.32			-.23	1.04	0	
	PM	-1	0	.23	2.23	2	4	4		PM	.28	.32		1.23	1.57	0	
	PB	0	1	.43	4	4	4	4		PB	.38	.41	.9	1.47	1.86	0	
											.92	.9		1.65			

(b) Steady retracting process at $t=7$ sec.

$U_{22} \backslash U_{11}$		$E_1 \backslash E_2$							$U_{12} \backslash U_{21}$		$E_1 \backslash E_2$						
		NB	NM	NS	ZO	PS	PM	PB			NB	NM	NS	ZO	PS	PM	PB
CE_1 CE_2	NB	-4	-4	-4	-4	-4	-1	0	CE_1 CE_2	NB	0			-1.8	-1.64	-55	-64
	NM	-4	-4	-2	-4	-1.69	0	1		NM	0			-1.64	-1.45	-39	-39
	NS	-4	-2	-2.04	-1.18	-1.12	1	2		NS	0			-1.27	-.47	-29	-28
	ZO	-4	-2	-2.04	-.8	-1.02	2	4		ZO	.02			-.14	.9	-.02	
	PS	-2	-1	-.12	.4	2.01	2	4		PS	.61			.74	1.1	0	
	PM	-1	0	1.62	4	2	4	4		PM	.57	.88		.98	1.69	0	
	PB	0	1	1.69	4	4	4	4		PB	.81	.81	1.19	1.83	1.86	0	
											1.3			1.86

Fig. 5 Response of Case 1, (a): proposed control algorithm, (b): conventional decoupling fuzzy control (—: command, —: actuator 1,: actuator 2)

two independent single-axial pneumatic driving systems. The connected plate thus is taken out, and there are completely no coupling interactions. U_{12} and U_{21} of Table 3 for conventional decoupling fuzzy control are set to zeros. Their position responses of a 0.125 Hz square command are shown in Fig. 5. Obviously,

responses x_1 and x_2 of conventional decoupling fuzzy control are different. Because of unexpected minor difference, these two single-axial subsystems can not simultaneously attain optimal response by using the same fuzzy rules. Because $U_{ii}=0$ at $E_i=ZO$ and $CE_i=ZO$ in typical fuzzy rules as Table 3, there is no

control signal into servo valve to drive the actuator in the steady state and thus the steady-state error can not be overcome.

To reach the synchronous function, the decoupling SOFC included in Fig. 2 is designed to eliminate the imbalance between actuators. Initial fuzzy rules are also given as Table 3. In Fig. 5, responses of proposed control algorithm are much symmetric and synchronous in both extending and retracting processes. Tables 4 (a), (b) show their self-modified fuzzy rules in the steady state. Here, U_{12} and U_{21} are unequal, which means these two single-axial pneumatic subsystems require various coupling units. Their steady state errors are summarized in Table 5, and it indicates that all steady errors of proposed control algorithm are near to the sensor's resolution.

© Case 2: Synchronous position motion with connected plate

This case is a typical application of a two-axial pneumatic driving system, such as a pneumatic vibration plate-form. Because of the connected plate, the structure interactions between actuators are inevitably. U_{12} and U_{21} representing coupling effects thus can not be ignored. Experimental results are shown in Fig. 6. It is evident that decoupling units are capable

to simulate the structure interactions. However, conventional decoupling fuzzy control still can not attain appropriate responses, which are always worse than those of proposed control algorithm.

In the transient process at $t=0.6$ sec., modified fuzzy rules are shown in Table 6. It is very similar to typical fuzzy rules as Table 3. In the proposed control algorithm, responses are convergent after 0.85 sec. and their fuzzy rules in the steady state are shown in Tables 7. To compare with Tables 4, the most significant variety exists only at linguistic variables ZO, i.e. $U_{11}=1.7$ in Case 1 and $U_{11}=0.75$ in Case 2 of the steady extending process, and $U_{22}=0.19$ in Case 1 and $U_{22}=0.8$ in Case 2 of the steady retracting process. Although both Case 1 and Case 2 have the same loading in the steady state, their structure interactions are still different. They require different input signals to overcome steady state errors. In other words, typical fuzzy rules can be implemented only in the transient process. To improve the steady state performance, fuzzy rules at the linguistic variables ZO should be modified for different environment.

© Case 3: Synchronous position motion with asymmetric springs

To simulate asymmetric loading conditions of Case 2, asymmetric springs $K_{s1}=0.376$ kgf/mm and $K_{s2}=0.112$ kgf/mm are used. Here, although these two actuators are in the synchronous motion, their loading effects are different. The maximum force difference is 7.92 kgf in the steady extending process. Figure 6 shows their responses of the same command as Case 2 and steady state errors are listed in Table 5. Again, the proposed control algorithm is superior. To examine the variations of modified fuzzy rules in the steady extending process of 1st actuator, the

Table 5 Steady-state errors of Cases 1-4 (unit: mm)

		Conventional		Proposed	
		extending	retracting	extending	retracting
Case 1	Actuator 1	0.57	0.22	0.005	0.01
	Actuator 2	0.43	0.38	0.005	0.005
Case 2	Actuator 1	0.27	0.42	0.005	0.005
	Actuator 2	0.3	0.67	0.005	0.01
Case 3	Actuator 1	0.76	0.185	0.01	0.005
	Actuator 2	0.145	0.59	0.01	0.015
Case 4	Actuator 1	0.78	0.1	0.005	0.01
	Actuator 2	0.02	0.3	0.005	0.005

Fig. 6 Response of Case 2 (for symbols please see Fig. 5)

Table 6 Fuzzy rules of Case 2 in the transient process at $t=0.6$ sec.

$U_{22} \backslash U_{11}$		$E_1 \backslash E_2$							$U_{21} \backslash U_{12}$		$E_1 \backslash E_2$							
		NB	NM	NS	ZO	PS	PM	PB			NB	NM	NS	ZO	PS	PM	PB	
CE_1	NB	-4	-4	-4	-4	-2	-1	0	CE_2	NB	-4	-4	-4	-4	-2	-1	0	
	NM	-4	-4	-2	-2	-1	0	1		NM	-4	-4	-2	-2	-1	0	1	
	NS	-4	-2	-2	-1	0	1	2		NS	-4	-2	-2	-1	0	1	2	
	ZO	-4	-2	-1	0	1	2	4		ZO	-4	-2	-1	0	1	2	4	
	PS	-2	-1	0	1	2	2	4		PS	-2	-1	.34	1	2	2	4	
CE_2	PM	-1	0	1.05	1.44	2	4	4	CE_2	PM	-1	0	.33	1.46	3.5	2	4	4
	PB	0	1	1.03	1.27	4	4	4		PB	0	1	1.38	3.14	4	4	4	

Table 7 Fuzzy rules of Case 2
(a) Steady extending process at $t=11$ sec.

$U_{22} \backslash U_{11}$		$E_1 \backslash E_2$							$U_{21} \backslash U_{12}$		$E_1 \backslash E_2$							
		NB	NM	NS	ZO	PS	PM	PB			NB	NM	NS	ZO	PS	PM	PB	
CE_1	NB	-4	-4	-4	-4	-4	-1	0	CE_2	NB	-4	-4	-4	-4	-4	-1	0	
	NM	-4	-4	-2	-4	-1.69	0	1		NM	-4	-4	-2	-4	-1.38	0	1	
	NS	-4	-2	-2	-1.57	-1	1	2		NS	-4	-2	-2	-4	-1.38	-41	1	2
	ZO	-4	-2	-1	-2.29	.75	1	2		ZO	-4	-2	-1	-98	3.3	1	2	4
	PS	-2	-1	.23	1.64	2	2	4		PS	-2	-1	.84	3.54	2	2	4	
CE_2	PM	-1	0	2.22	4	2	4	4	CE_2	PM	-1	0	.82	1.94	4	2	4	4
	PB	0	1	2.39	4	4	4	4		PB	0	1	1.76	4	4	4	4	

(b) Steady retracting process at $t=7$ sec.

U_{22}		U_{11}		$E_1 \backslash E_2$							U_{21}		U_{12}		$E_1 \backslash E_2$						
				NB	NM	NS	ZO	PS	PM	PB					NB	NM	NS	ZO	PS	PM	PB
$CE_1 \backslash CE_2$	NB	-4	-4	-4	-4	-4	-1	0	$CE_1 \backslash CE_2$	NB	-4	-4	-4	-4	-4	-1	0				
	NM	-4	-4	-2	-4	-1.68	0	1		NM	-4	-4	-2	-2.61	-1.38	0	1				
	NS	-4	-2	-2	-1.52	-11	1	2		NS	-4	-2	-2	-1.66	-1.64	-41	1	2			
	ZO	-4	-2	-1	-2.14	-12	1	2		4	ZO	-4	-2	-1.0	-1	1.49	1	2	4		
	PS	-2	-1	.12	.8	3.07	2	2		4	PS	-2	-1	.42	3.98	.99	2	2	4		
	PM	-1	0	1.61	4	2	4	4		PM	-1	0	1.5	.41	1.38	4	2	4	4		
	PB	0	1	1.69	4	4	4	4		PB	0	1	4	4	4	4	4	4

Fig. 7 Response of Case 3 (for symbols please see Fig. 5)

Fig. 8 Response of Case 4 (for symbols please see Fig. 5)

significant differences occur only at linguistic variables ZO , such as $U_{11}=1.58$ and $U_{21}=-2.66$ in Case 3, $U_{11}=0.75$ and $U_{21}=3.54$ in Case 2.

© Case 4: non-synchronous position motion

Figure 7 indicates experimental results of various commands for x_1 and x_2 . In the steady extending process, springs induce 1.88 kgf and the connected plate creates 2.56 kgf difference between actuators. In this case, fuzzy rules at linguistic variables ZO of 1st actuator are $U_{11}=3.58$ and $U_{21}=0.71$. Experimental results indicate that fuzzy rules strongly depend on working environments. Conventional decoupling fuzzy control associated with fixed fuzzy rules can not fit for all operating conditions.

4. Conclusions

This paper has implemented the decoupling self-organizing fuzzy control algorithm to the position control of a TITO pneumatic system. Major conclusions are summarized as following:

(1) SOFC can skip the parameter identification process. It can save computer time and is especially useful for complicated control systems.

(2) To apply conventional fuzzy control in this TITO pneumatic control system, fixed fuzzy rules at $E=ZO$ and $CE=ZO$ should be properly modified for each operating condition.

(3) The proposed decoupling self-organizing fuzzy control can tremendously improve the control performance and position accuracy in both transient and steady state processes.

(4) Then, experimental results indicate that the proposed decoupling self-organizing fuzzy control is robust and feasible for various operating environments, and the proposed decoupling technique is

expandable for multi-axial pneumatic control systems.

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