Human Simulated Intelligent Controller with Fuzzy Online Self-Tuning of Parameters and its Application to a Cart-Double Pendulum

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***Abstract*—Using the basic concepts and design methods of Human Simulated Intelligent Control (HSIC), we have designed the master control level of an HSIC controller for the swinging-up and handstand control of a cart-double pendulum. Then, the self-tuning structure of the self-tuning level of the HSIC Controller is implemented using fuzzy logic rules. This structure has fuzzy self-tuning abilities in the swing-up control of a cart-double pendulum system and achieves online self-tuning of the control parameters of the HSIC controller efficiently with a hierarchical and multi-mode control structure. The computer simulation and real-time experiments of the swing-up control of a cart-double pendulum system show that the fuzzy online self-tuning of the control parameters markedly enhances the robustness and adaptability of the HSIC.**

***Index Terms*—human simulated intelligent control, cart-double pendulum system, fuzzy logic rule, online parameter self-tuning**

I. INTRODUCTION

There are many examples that successfully use fuzzy control in the handstand stability control of a pendulum. For controlling goals in single, double, triple, and even quadruple pendulums, the studies have concentrated on the selection of control variable dimensionality, the choice of the universe of discourse and the established fuzzy rules [1-17]. There are, however, very few examples showing how to apply fuzzy control to realize the swing-up and handstand control of a pendulum. Muskinja and Tovornik [13] have introduced the swing-up control of a single pendulum using a fuzzy adaptive control method and have compared the fuzzy algorithm to energy-based swinging strategies. The results of this comparison show the advantages of fuzzy control. Yi *et al.* [14] constructed a dynamic fuzzy controller for stabilizing and swinging-up a cart-pendulum system based on a single input fuzzy rule module. This fuzzy controller has achieved complete stability in a wide range of cart-pendulum systems. This confirms that using fuzzy control can be very effective.

There are however, few reports on using fuzzy control for swinging-up a cart-double pendulum system. Human Simulated Intelligent Control (HSIC) theory using Sensory-Motor Intelligent Schemas (SMIS) [18-26] has successfully been applied in real-time experiments of swing-up and stabilization control of a cart-double pendulum system. HSIC based on SMIS is characterized by a hierarchical and multi-mode control structure. Li *et al.* [19] presented a design of the SMIS controller for a cart-double pendulum system. Further research on this design has been documented in [20], together with a full discussion on the relationship between the key parameters and the system's energy and the relationship between the relative motion attitude of two rods of a pendulum and the energy distribution thereof. Also discussed in [20] is the internal law of the double pendulum system, as well as the process of designing controllers and the issue of key parameters.

Hierarchical and multi-mode control structures using the characteristic identification taken from the single mapping structure of the traditional controller, solve the feasibility problems in the control of a complex system. The complex controller, however, has numerous characteristic and control parameters, making it very difficult to design and optimize. An Improved Genetic Algorithm (IGA) has been used in the design of an HSIC [24][25][26] to address this problem. A mathematical model of the controlled plant is needed to design the controller using an off-line evolutional computation. However, there will always be differences between the model and the real system, due to events that take place in the outside environment. Consequently, the controller

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parameters, obtained from the evolution calculation, need further adjustment before they can be used effectively in the control of a real system. For a nonlinear motion process like the swing-up and stabilization control of a cart-double pendulum, the control parameters need to change with the motion attitude of the two rods of the pendulum. This means that online self-tuning of the control parameters is very important for a fast, high-quality realization of real-time control.

Parameter tuning is an important part of the control process, in that it automatically alters the values of controller parameters in the different phases of the system dynamics, to adapt to the system's reliability, adjustment accuracy and needs of the design specifications.

An HSIC controller has a hierarchical structure for the information process and decision making, namely an operation control level, a parameter self tuning level and a task adaptive level. In Ref. [18], the operation control level and parameter tuning level of the HSIC are introduced in detail, and a design method for the self-tuning of parameters is presented. But the parameter self-turning strategy is a very simple delta modulation, with low efficiency and adaptability.

In this paper we present a fuzzy online self-tuning method for parameters of the HSIC controller. Based on the principle of increasing precision with decreasing intelligence (IPDI) of an intelligent system [29], by introducing fuzzy logic into the parameter tuning level of the HSIC controller to realize online parameter self-tuning, the request for control precision will be further improved and the control system will be more adaptable.

II. BASIC THEORY OF HSIC

A. Basic Concepts

An algorithm for a prototype Human Simulated Intelligent Controller was proposed by Professor Zhou in 1979, and formally published internationally in 1983 [28]. After more than 20 years of unremitting effort by the authors and others, the basic theory of and a systematical design method for an HSIC has been formalised, and it has been used successfully in many practical systems [18-26]. The algorithm for a prototype Human Simulated Intelligent Controller is:

$$u = \begin{cases} K_P e + kK_P \sum_{i=1}^{n-1} e_{m,i} & e\cdot\dot{e}>0 \cup e=0 \cap \dot{e}\neq 0 \\ kK_P \sum_{i=1}^{n} e_{m,i} & (e\cdot\dot{e}<0 \cup \dot{e}=0) \end{cases} \quad (1)$$

In the formula u is the output of the control, K_p is the scale coefficient, e is the error, $\dot{e}$ is the rate of error, $e_{m,i}$ is the i-th peak value of the error, and k is an inhibition coefficient. The static characteristic of a prototype HSIC controller is shown in Fig. 1.

This prototype has many intelligent properties that traditional control algorithms do not have. Generally speaking, the relationship between input and output in traditional control is a simple mapping, whereas in the

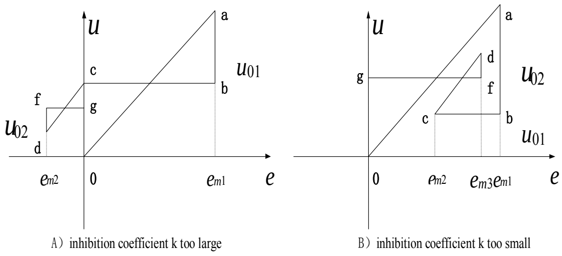


Figure 1. The static characteristics of a prototype HSIC controller

prototype HSIC controller it is a double mapping. In other words, the prototype HSIC has a double control mode with open and closed loop alternatives, where the choice and decision of control mode and control strategy, is based on the characteristic model which consists of states and error change trends.

The choice of control mode according to the characteristic model, is made by an inference chooser and information processor with double mapping, which in a process very similar to human intuition reasoning, acts like human behavior, going "from cognitive to judgment" and "from judgment to operation". Many of the basic concepts used to describe an intelligent controller were proposed in the HSIC theory, such as Characteristic Model, Characteristic Identification, Characteristic Memory, Multi-Mode Control (Decision), Intuitive Inference and Hierarchical Information Process Mechanism and so on.

Definition 1: A Characteristic Model $\Phi \in \Sigma^r$ is a model that combines the qualitative and quantitative description of the dynamic characteristics of an Intelligent Control System. It's a division of the system's dynamic information space Σ, according to the solution goal of the control problem and the difference in control specifications. Each divided area represents a characteristic state φ_i. The characteristic model is the set of all characteristic states:

$$\phi = \{\varphi_1, \varphi_2, \cdots, \varphi_r\}, \quad \varphi_i \in \Sigma^r$$

In the characteristic model, a characteristic state comprises various characteristic elements qi, where their relationship is determined by the following formula:

$$\Phi = P \odot Q \quad (2)$$

$$\varphi_i = [(p_{i1} * q_1) \wedge (p_{i2} * q_2) \wedge \cdots \wedge (p_{im} * q_m)]$$

Definition 2: Characteristic identification is the process whereby, according to the characteristic model $\Phi \in \Sigma^r$, the intelligent controller processes the sampling information and pattern recognition online, and perceives and determines to which characteristic state the system belongs.

The main task of the pattern recognition of the system dynamic characteristics is to class the dynamic characteristic schema of the control system, to divide patterns of the dynamic characteristic according to the error e and error rate of change $\dot{e}$ and other characteristic variables contained in them and to describe the system's behavior features through this schema of characteristic states. In other words, to intuit to this pattern perception to characteristic state of the system and to reflect the operation status of the dynamic process provides the basis of the decision-making of the intelligent control.

Definition 3: Characteristic Memory is the controller's memory of some characteristic variable that reflects the effect of the prophase decision and control, the request of the task of the control and the physical property of the controlled object. The set of characteristic memory is denoted as $\Lambda \in \Sigma^p$:

$$\Lambda = \{\lambda_1,\ \lambda_2, \cdots,\ \lambda_p\},\ \lambda_i \in \Sigma^p \tag{3}$$

The human control strategy is flexible and different for different targets. Even for the same object, the control mode will be different under a different dynamic response status or different request for control.

Definition 4: Multi-mode Control (Decision-Making) is a set of some qualitative or quantitative mapping relation between the output of control U, control input E and characteristic memory $\wedge$, that is, the set of control (decision-making) modes ψ.

$$\Psi = \{\psi_1, \psi_2, \cdots, \psi_r\} \tag{4}$$

$$\psi_i\!:\ u_i = f_i(e, \dot{e}, \cdots, \lambda_j)$$

or $\psi_i : f_i \rightarrow$ IF (conditions) THEN (operation or conclusion). The act of continuously changing strategy in the process of intelligent control is called Multi-mode Control (Decision-making).

In the control mode set Ψ, each control mode consists of many mode elements, the most common of which are:

$m_1 : k_p e$ proportion; $m_2 : k_d \dot{e}$ differential;

$m_3 : k_d \int edt$ integration; $m_4 : u_H$ keep of output ;

$m_5 : k \sum_{i=1}^{n} e_{mi}$ sum of peak error memory;

$m_6 : \pm k t_0 u_m$ bang-bang output;

$m_7 : u \pm a$ output pre-compensation.

The relationship between a set of control modes Ψj and a mode element vector is

$$\Psi_j : U_j = L_j M_j \tag{5}$$

where Uj is the vector of output, Mj is the vector of mode element, and Lj is the relation matrix which only has three elements 1, 0 and -1.

Definition 5: Set of Heuristic and Intuitive Inference $\Omega \in \Sigma^q$ is a kind of imitation of the human (expert) decision-making process, which, depending on the results of feature identification, makes a decision and decides the control strategy, and can be described as the production rule "IF … THEN …"

This information processing with double mapping relations is shown in Fig. 2, and can be expressed as:

$$\Omega_j : \Phi_j \rightarrow \Psi_j \qquad \Omega_j \in \Sigma^q \tag{6}$$

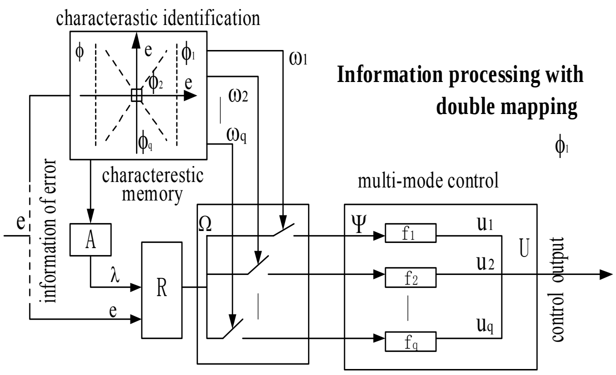


Figure 2. The Two-Order Mapping Relation of HSIC in Control and Decision-Making

where $\Omega_j = \{\omega_{j1},\ \omega_{j2}, \cdots,\ \omega_{jr}\}$

ω_{ji}: *IF* φ_{ji} *THEN* ψ_{ji} (qualitative mapping)

Ψ_j: $R_j \rightarrow U_j$ $\Psi_1 = \{\psi_{j1},\ \psi_{j2}, \cdots,\ \psi_{jr}\}$

ψ_{ji}: $u_{ji} = f_{ji}(e,\ \dot{e},\ \lambda, \cdots)$ (quantitative mapping) or $f_{ji} \rightarrow IF$ conditions THEN operation (qualitative mapping).

The HSIC controller with hierarchical information processing and decision-making structure consists of a task self-adaptive level TA, parameter self-tuning level ST, and master control level MC. Fig.3 shows that each of the MC, ST and TA has its own distinguishing database (DB), rule base (RB), characteristic identifier (CI), and inference engine (IE). The MC, ST and TA exchange information through the common database (CDB). This concurrent operation mechanism with compact coupling is convenient for the fast self-adaptive process of the HSIC controller.

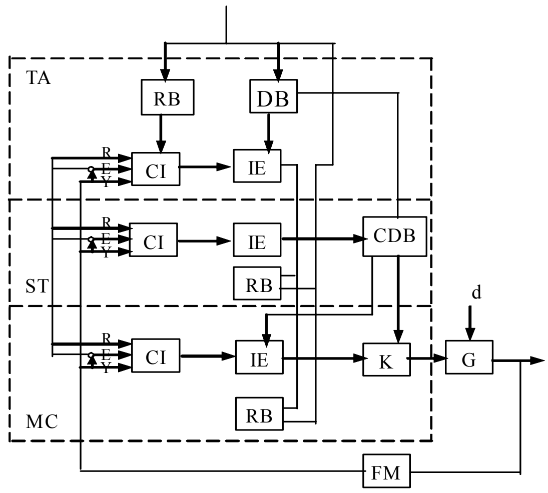


Figure 1. Hierarchical structure of HSIC controller

B. Design of HSIC Controller

The design steps for the HSIC controller are the following:

(a) To establish an ideal error target trajectory in the error phase plane of control system. According to the control specifications of the system, an ideal unit-step response process is established, and mapped onto the $e-\dot{e}$ phase plane, as an error phase trajectory. This is the target trajectory for designing the HSIC controller. Every point on the trajectory can be seen as a transient control specification of the HSIC controller.

(b) To design the characteristic model of the HSIC controller. According to the position of the target trajectories in the $e-\dot{e}$ phase, determine characteristic elements, divide characteristic states, and then compose the characteristic model of the different levels of the HSIC controller. Figure 4 describes the typical design process of a characteristic model. The curve (a) + (b) show an ideal constant value control process, and the curve (b) show an ideal dynamic process of servo control. If we make this trajectory the target to design the controller, the ideal situation is: the controller forces the system's dynamic response to slip onto this trajectory. But because of the uncertainty of the system, the moving trajectories can only be in one belt around the ideal trajectory. So the design task is altered to, according to the position of this belt on the error plane, divide the regions of the characteristic states.

(c) To design the control rules and the set of control modes. Once the characteristic model has been established, the design task becomes that of, according to the moving tendency of the target trajectory and the errors between the system's dynamic response and the transient control specifications (the ideal target trajectory) emulating the human control and decision-making behavior, design the control and decision-making mode of the controller and confirm the parameters of these control modes (Fig. 4).

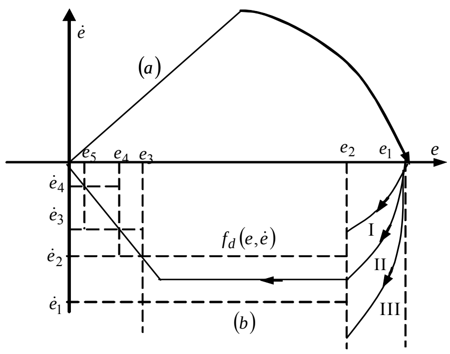


Figure 4. Error phase locus in the HSIC design

III. DESIGN OF SWING-UP AND HANDSTAND CONTROLLER FOR THE HSIC OF A CART-DOUBLE PENDULUM SYSTEM

By dynamically analyzing a cart-double pendulum system, the motion involved in the swing-up and handstand of the pendulum can be divided into four phases. These are the initial movement phase, the swinging-up phase, an attitude adjusting phase, and the balance control phase (see Fig. 5) [20].

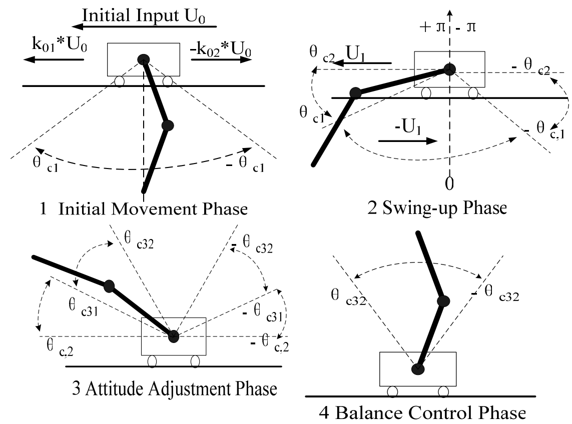


Figure5. Four phases of swing-up and handstand control process of cart-double pendulum

(a) Initial movement phase: With the two rods of the pendulum in a freely pendulous state, the cart is made to move to one side by applying a small force. The inertia of the cart initially makes the two rods move. Then, according to the velocity and position of the inner rod, the controller drives the cart and the two rods of the pendulum using positive feedback control. This increases the swinging amplitude of both rods.

(b) Swinging-up phase: When the inner rod swings close to the horizontal position, the dynamics of the system change. In response to this change, the controller exerts a stronger positive feedback force on the cart, causing the rods to cross the horizontal, and after reaching a certain level of motion, the attitude adjustment phase is entered.

(c) Attitude adjustment phase: Depending on the relative motion and dynamic features of the cart and the inner rod, a proportional derivative (PD) controller, using different parameters, can be designed by a well-phased linearization of the mathematical model of the system. The control objective of this phase is to align the two rods vertically in a straight line.

(d) Balance control phase: This starts when the two rods are both in a vertical upright position. The controller achieves handstand balance control of the two rods of the pendulum using PD control with three rotational degrees of freedom for both modes.

The control laws of the four phases in the multi-mode HSIC controller, together with the total control law, are given in (7).

$$S_{KG}=\begin{cases}\begin{cases}u=U_0 & e_{\theta_1}=e_{\theta_2}=0,\dot{e}_{\theta_1}=0\\ u=\mathrm{k}_{01}\cdot U_0 & 0<\left|e_{\theta_1}\right|<\theta_{c1},\dot{e}_{\theta_1}<0,\dot{e}_{\theta_2}<0\\ u=-\mathrm{k}_{02}\cdot U_0 & 0<\left|e_{\theta_1}\right|<\theta_{c1},\dot{e}_{\theta_1}>0,\dot{e}_{\theta_2}>0\end{cases}\\ \begin{cases}u=U_1 & \theta_{c1}<\left|e_{\theta_1}\right|<\theta_{c2},\dot{e}_{\theta_1}<0,\dot{e}_{\theta_2}<0\\ u=-U_1 & \theta_{c1}<\left|e_{\theta_1}\right|<\theta_{c2},\dot{e}_{\theta_1}>0,\dot{e}_{\theta_2}>0\end{cases}\\ \begin{cases}u=k_{11}\cdot e_x+k_{12}\cdot e_{\theta1}+k_{13}\cdot e_{\theta2}+d_{11}\cdot e_{\dot{x}}+d_{12}\cdot e_{\dot{\theta}1}+d_{13}\cdot e_{\dot{\theta}2} & \theta_{c2}<\left|e_{\theta_1}\right|<\theta_{c31}\\ u=k_{21}\cdot e_x+k_{22}\cdot e_{\theta1}+k_{23}\cdot e_{\theta2}+d_{21}\cdot e_{\dot{x}}+d_{22}\cdot e_{\dot{\theta}1}+d_{23}\cdot e_{\dot{\theta}2} & \theta_{c31}<\left|e_{\theta_1}\right|<\theta_{c32}\end{cases}\\ \left\{u=k_{31}\cdot e_x+k_{32}\cdot e_{\theta1}+k_{33}\cdot e_{\theta2}+d_{31}\cdot e_{\dot{x}}+d_{32}\cdot e_{\dot{\theta}1}+d_{33}\cdot e_{\dot{\theta}2}\right. & \left|e_{\theta_1}\right|>\theta_{c32}\end{cases} \tag{7}$$

In (7), the attitude adjustment phase incorporates two different linear optimum control modes for the different objectives [20]. The LQR optimum method is used to determine the initial control parameters when the rods reach two different positions above the horizontal. Using a well-phased linearization design and incorporating the improved genetic algorithm, superior control parameters are evolved off-line. The control mode of the balance controller also makes use of a genetic algorithm to determine the 3 rotational degrees of freedom in the balance position, for the related PD parameters. In order to overcome the problems with the off-line calculation, and to further raise the robustness and adaptive ability of the system, this paper discusses a means whereby the parameters can employ online self-tuning in the swing-up and handstand control of the cart-double pendulum. This means that the pendulum can successfully swing-up and handstand even when the control object's physical parameters or the environment has changed.

According to the error and error ratio of the system, HSIC theory plots the characteristic state regions and designs a characteristic model of the adjusting level of the parameters of a typical servo controller. This is shown in Fig. 6 [18].

Using the characteristic model of the tuning level of the parameters, HSIC theory gives both the effective tuning structure of the control parameters, and a detailed qualitative description of the rules for adjusting the parameters. As the characteristic state is naturally uncertain, we can formalize this using fuzzy logic.

The data in Table I are the relevant characteristic states in the presence of the error and the change in velocity errors.

The qualitative adjusting rules, used by the characteristic model, are as follows:

Area 1: Bang-bang control: No need to revise the parameters.

Area 2: Beyond the limits of deflection velocity; increase PD control.

Area 4: Deflections reduce velocities to less than setting range; increase the proportional operation.

Areas 5 and 6: Deviation is very small, while velocity remains large; enhance both PD and positive feedback control.

Area 8: Deflection is small, but velocity is not; decrease PD operation.

Area 9: Deflection's velocity lower than that requested; increase the proportional operation slightly.

Area 11: Deflection has reached the controller's request, but velocity has not; decrease the proportional operation slightly.

Area 12: Deflection's velocity is too low; increase proportional operation slightly through parameter adjustment.

Area 14: Overshoot has occurred but deflection's velocity still high; enhance differential control, and decrease proportional operation slightly.

Area 15: Overshoot has occurred but deflection and velocity still high; increase differential and proportional operation.

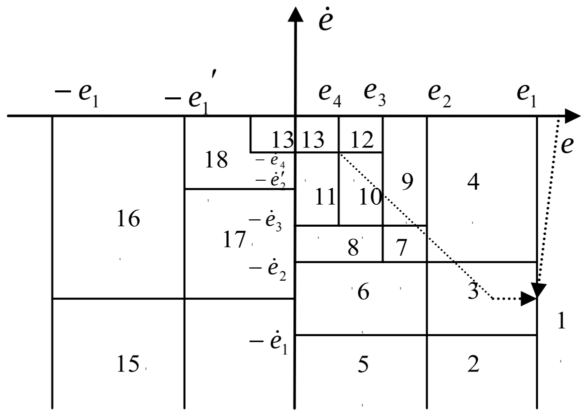


Figure 6. Characteristic model of Self-Tuning Level for HSIC
(Note: first and second quadrants have parallels to third and fourth.)

TABLE I
FUZZY QUERY OF ERROR PHASE PLANE

$\dot{e}$ \ ϕ \ e	nb	nm	ns	0	ps	pm	pb
nb	15	14	14	6	5	5	2
nm	15	17	17	8	6	6	3
ns	16	17	18	11	10	7	4
0	16	18	13	13	12	9	4
ps	5	6	10	12	18	17	14
pm	5	6	7	9	17	17	14
pb	2	3	4	4	16	15	15

Area 16: Overshoot has occurred, deflection is high but velocity is not so high; enhance the proportional operation slightly and decrease differential operation.

Area 17: Overshoot is small, as is velocity; increase differential operation slightly.

Area 18: Deflection and velocity are small, but they have not reached the requested level; increase proportional operation slightly.

Area 3, 7, 10 and 13: System functions under ideal conditions; no need to alter parameters. Retain this model.

In the rules given above, we refer to "enhance slightly" "increase slightly" and "increase" with s, m, and b. In the cart-double pendulum system, we can use fuzzy logic to formalize these qualitative rules, and design the online parameter self-tuning controller. This controller causes the parameters to change with the swing-up and handstand process, and also realizes a highly accurate handstand balance. If we merge phases three and four of the HSIC controller into one phase called the pose adjusting and handstand balance phase, the HSIC controller can be designed according to the structure shown in Fig. 7. The third component of this design is the parameter self-tuning structure. The total control rules for this are expressed in (8).

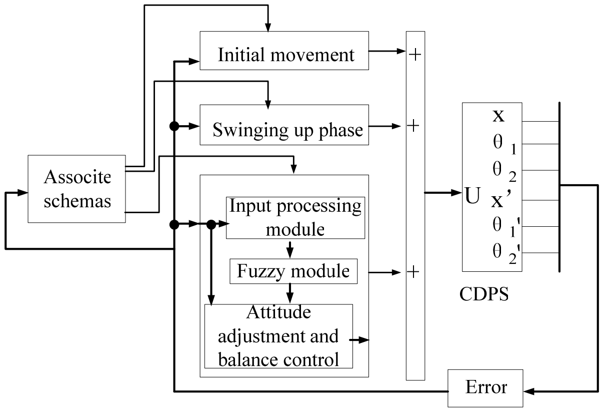


Figure 7. Structure of fuzzy, online self-tuning of parameters for HSIC

$$S_{KG}=\begin{cases} \begin{cases} u=U_0 & e_{\theta_1}=e_{\theta_2}=0, \dot{e}_{\theta_1}=0 \\ u=k_{01}\cdot U_0 & 0<|e_{\theta_1}|<\theta_{c1}, \dot{e}_{\theta_1}<0, \dot{e}_{\theta_2}<0 \\ u=-k_{02}\cdot U_0 & 0<|e_{\theta_1}|<\theta_{c1}, \dot{e}_{\theta_1}>0, \dot{e}_{\theta_2}>0 \end{cases} \\ \begin{cases} u=U_1 & \theta_{c1}<|e_{\theta_1}|<\theta_{c2}, \dot{e}_{\theta_1}<0, \dot{e}_{\theta_2}<0 \\ u=-U_1 & \theta_{c1}<|e_{\theta_1}|<\theta_{c2}, \dot{e}_{\theta_1}>0, \dot{e}_{\theta_2}>0 \end{cases} \\ \{u=k_1\cdot e_x-k_2\cdot e_{\theta 1}+k_3\cdot e_{\theta 2}+d_1\cdot e_{\dot{x}}-d_2\cdot e_{\dot{\theta} 1}+d_3\cdot e_{\dot{\theta} 2} & \theta_{c2}<|e_{\theta_1}| \end{cases} \quad (8)$$

In the third component of Fig. 7, the input processing module changes the error information into four signals, namely the position error of car e_x (input1); the angle error of the inner-rod e_{θ_1} (input2); the error of the inner and outer rods' angle error $e = e_{\theta_1} - e_{\theta_2}$ (input3); and the angle velocity error between the inner and outer rod $\dot{e} = \dot{e}_{\theta_1} - \dot{e}_{\theta_2}$ (input4). These inputs enter the fuzzy calculation module, which uses the pre-established fuzzy rules to self-tune the six output parameters online, namely $k_1, k_2, k_3, d_1, d_2, d_3$ (output1,2,3,4,5,6). Finally the output parameters are used by the PD control during the pose adjusting and handstand balance phase.

The sets of the four input variables in the fuzzy calculation module are: e_x is {nb,0,pb}; e_{θ_1} is {nb,nm,0,pm,pb}; e and $\dot{e}$ are {nb,nm,ns,0,ps,pm,pb}. Similarly, in order to simplify the rules but not affect the system behavior, the fuzzy sets of the six output variables ($k_1, k_2, k_3, d_1, d_2, d_3$) are all sets of {s, m, b}.

All the membership functions of the variables are shown in Fig. 8. Input1 e_x uses a membership function with overlapped, symmetrical and asymmetrical distribution. Its distribution is given as follows: at the two ends, a trapmf type membership function is used for a small area, while in the large middle area a gaussmf type membership function is used. Input2 e_{θ_1} uses a gaussmf type membership function with overlapped, symmetrical and asymmetrical distribution. Input3 and input4, e and $\dot{e}$ respectively, use trimf type membership functions with overlapped, symmetrical and equable distribution. Because of its simplicity and uniform

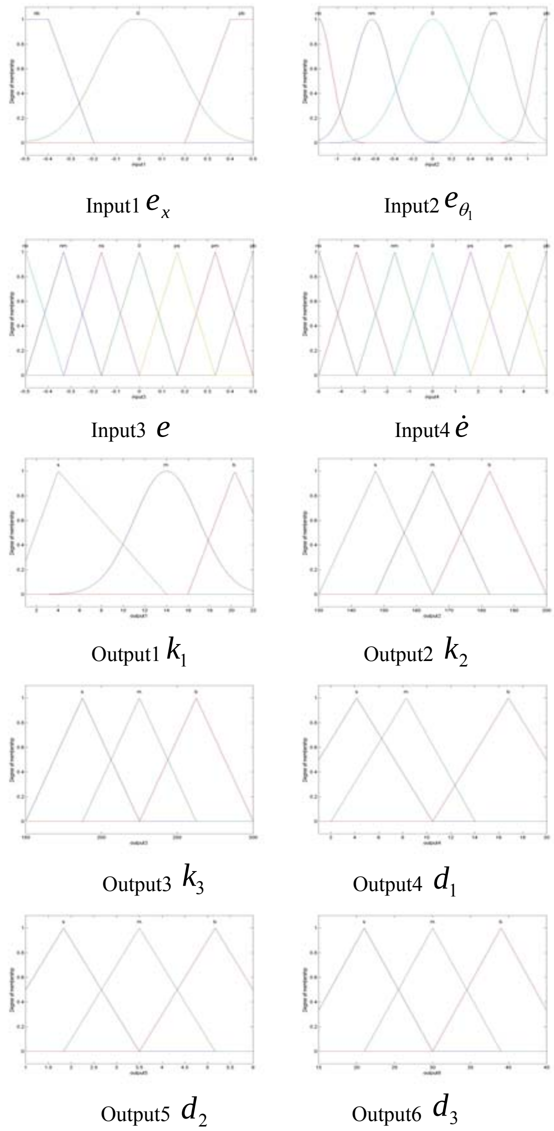


Figure 8. Membership functions for input and output variables

distribution, this function makes it easy to design the rules. The output parameter k_1, uses a membership function with overlapped and asymmetrical, but without uniform distribution. In addition, s and b use a trimf type while m uses a gaussmf type. Output parameter d_1 uses a trimf type membership function with overlapped and asymmetrical, but without uniform distribution. The remaining parameters k_2, k_3, d_2, d_3 use a trimf type membership function with overlapped, symmetrical and uniform distribution.

The universes of all the fuzzy variables are determined from the parameters of the cart-double pendulum model. Their concrete values are then given in the simulation experiment.

After determining the fuzzy set form and membership functions of the parameters, we can design the fuzzy adjusting rules as follows. The parameter tuning module has 4 input and 6 output variables. We divide the input variables into three phases and set them up independently.

These three phases are then combined to determine the values of the parameters.

(a) The error of angle error of the inner and outer rods e, and the angle velocity error between the angle error of the inner and outer rods $\dot{e}$:

The emphasis of the design rests here. In the swing-up and handstand control of the cart-double pendulum, this phase is very important for the relative posture control of the two rods. We can properly design the self-tuning level of the preceding parameters for an HSIC based on fuzzy logic.

Therefore, we introduce e and $\dot{e}$ into the online control to adjust parameters k_2, k_3, d_2, d_3. Based on the fuzzy query table of error phase planes e and $\dot{e}$, we design the set of rules which are shown in Table II.

In the swing-up and handstand control of a cart-double pendulum, the control objective, with posture adjustment of the two rods and balance control, is that the error of the two rods is satisfied with the ideal movement track as given in Fig. 6. In other words, control does not enter the first and third quadrants of the error phase plane, with the result that no entries exist in Table II. The adjusting rules for the parameters k_2, k_3, d_2, d_3 are given in Table II. These rules are defined as follows. If (Input3 (e) and Input4 ($\dot{e}$)) exist in a certain fuzzy state, Then (Output2 (k_2), Output3 (k_3), Output5 (d_2) and Output6 (d_3)) are given corresponding values.

(b) The error of inner angle e_{θ_1}:

Depending on the deflection between the angle of the inner rod and its corresponding target, the HSIC is divided into many control phases, which are controlled by the corresponding control module. We make use of this tendency to change control of each parameter in a large area. The corresponding rules are shown in Table III.

The adjusting rules can be expressed as follows:

If (Input2 (e_{θ_1})) exists in a certain fuzzy state, Then (Output1 (k_1), Output2 (k_2), Output3 (k_3), Output4 (d_1), Output5 (d_2) and Output6 (d_3)) are given corresponding values.

(c) The displacement error of the cart e_x:

In the swing-up and handstand control of a cart-double pendulum, the most difficult part is the posture control of the two rods. While our demands on the cart are not high, we need to be aware of any deviation of the cart from the target position. Otherwise we keep the values of the corresponding two parameters. This also affects the selection of membership function. The appropriate rules are:

If e_x is nb, then k_1 is b and d_1 is b.

If e_x is 0, then k_1 is m and d_1 is b.

If e_x is pb, then k_1 is b and d_1 is b.

This means that the input e_x only affects the PD parameters of the cart.

TABLE II
SELF-TUNING RULES FOR INPUT e OR $\dot{e}$

e / k_2, k_3, d_2, d_3 / $\dot{e}$	nb	nm	ns	0	pm	pb	ps
nb	…	…	…	s,b m,m	m,b m,s	m,b m,s	s,m m,b
nm	…	…	…	m,m m,b	s,b m,m	s,b m,m	3
ns	…	…	…	b,b m,m	10	7	m,m b,s
0	m,m m,b	b,m m,b	13	13	b,b m,b	m,m s,s	m,m b,s
ps	m,b m,s	s,b m,m	10	b,b m,b	…	…	…
pm	m,b m,s	s,b m,m	7	m,m s,s	…	…	…
pb	s,m m,b	3	m,m b,s	m,m b,s	…	…	…

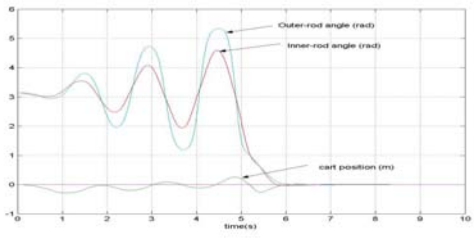
TABLE III
ANGLE ERROR OF INNER ROD TO PARAMETERS' SELF-TUNING RULES

Parameter / error	k_1	k_2	k_3	d_1	d_2	d_3
nb(pb)	s	s	s	s	b	S
nm(pm)	m	m	m	m	m	m
0	b	b	b	b	s	b

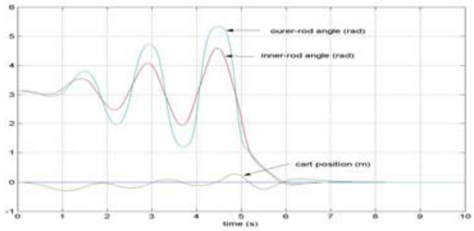
In this section, we have illustrated the design of a self-tuning parameter module for an HSIC. The fuzzy reasoning uses the max-min method, while defuzzification uses the centroid method. By combining the first 2 independent rules (A and B) with the rule that limits the displacement of the cart (C), we obtain the control parameters required for the swinging-up and handstand balance of the cart-double pendulum system.

IV. VERIFICATION OF SIMULATION AND REAL TIME CONTROL EXPERIMENTS

In order to verify the validity of this controller, we compare using simulation, the fuzzy rules algorithm to the multi-mode linearization design for constructing an HSIC. The results are shown in Fig. 9. In this experiment, the universes of e_x, e_{θ_1} e and $\dot{e}$ are (-0.5, 0.5), (-1.2, 1.2), (-0.5, 0.5) and (-5, 5), respectively. The universes of the 6 control parameters $k_1, k_2, k_3, d_1, d_2, d_3$ are given below. According to the three group parameters in [20], we design a certain range between the smallest, [1.1421 138.0530 158.0752 3.2569 6.7660 21.7986] and the largest, [14.1421 180.7532 265.8732 16.6118 1.8553 37.4161]. This range is given as (1, 22), (130,200), (150,300), (1, 20), (1, 6) and (15, 45). These are the universes of $k_1, k_2, k_3, d_1, d_2, d_3$ respectively. It can be seen from the comparison that under the condition that the required time be 5s for the first two phases, an HSIC with fuzzy online self-tuning parameters uses less than 6s, while the HSIC based on a well-phased linearization design uses about 7s. So the HSIC with fuzzy online self-

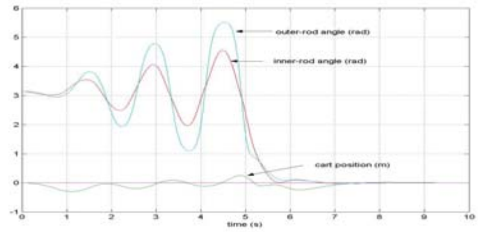


(a) HSIC with fuzzy online self-tuning parameters

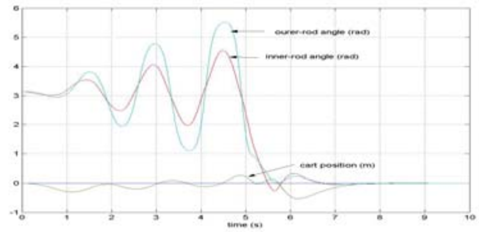


(b) HSIC using well-phased linearization design

Figure 9. Results of simulation experiments for swing-up control

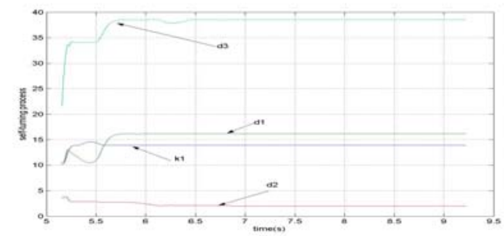


(a) HSIC with fuzzy online self-tuning parameters

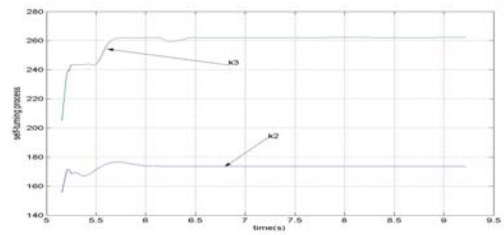


(b) HSIC using well-phased linearization design

Figure 10. Results of simulation experiments for swing-up control after changing outer rod's size by 10%.



(a) Control Parameters: k_1, d_1, d_2, d_3



(b) Control Parameters: k_2, k_3

Figure 11. Fuzzy online self-tuning process of control parameters

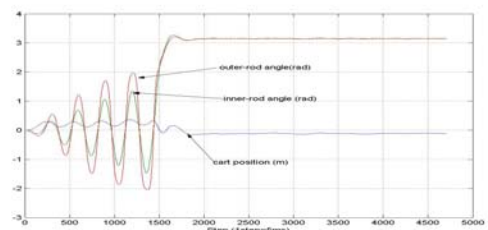


Figure 12. The real time control process of swinging-up and handstand control

tuning parameters uses about half the time for the posture adjustment and balance control phase.

At the same time, in order to prove that the controller is robust and adaptive, we change the physical characteristics of the cart-double pendulum and in so doing, simulate uncertainty. After changing the mass of the outer rod, the distance from mass center to the corresponding axis, and the length of rods by between 10% and 25%, we then repeat the simulation using both the fuzzy self-tuning parameter model and the well-phased linearization design. The results are shown in Fig. 10. From Fig. 10(a) it is obvious that the HSIC with fuzzy online self-tuning parameters has adapted more to the change of the pendulum's physical characteristics and could successfully swing-up. In Fig. 10(b) it can be seen that if the cart exceeds the trail in the HSIC based on a well-phased linearization design, real-time control of the limitation switch of the cart will fail. In real-time control experiments, a clip is put on the outer rod to verify that the controller is robust and adaptive. In the swing-up and handstand control of a cart-double pendulum, the HSIC controller with fuzzy online self-tuning parameters has continuous changing parameters, and parameters change with the posture of the pendulum (Fig. 11). This surely makes the real-time control more successful.

The equipment used was provided by the Googol (Shenzhen) company. The available length of track for the cart is 60cm, and the length of the two rods is 40cm. Control of the swing-up and handstand of the double pendulum is very difficult because the length of the moving track of the cart is limited. Using the HSIC with fuzzy online self-tuning parameters to control it, we have achieved a higher success rate and certain robustness. The control process of the swing-up and handstand stability of a double pendulum in a real-time control experiment is shown in Figs. 12 and 13.

Determining the universe of the fuzzy variables is very important in the process of real-time control, because it influences the precision of control. The fitness universes make it easy to find optimal control parameters. In the experiment, we measure the change range of e , $\dot{e}$ e_x and e_{θ_1} , and then decide the universe for each. The universes of e_x and e_{θ_1} are (-7,-6) and (-9.6,-2), respectively and the universes of e and $\dot{e}$ are (-0.2, 0.1) and (-3, 3.5), respectively. The universes of the 6 control parameters $k_1, k_2, k_3, d_1, d_2, d_3$, in the simulation are (8,

Figure 13. The control process of a double pendulum's swing-up and handstand stability in the real-time control experiment

26), (130,210), (170,300), (3, 19), (1, 5), and (20, 40), respectively. Figure 13 shows the results of real-time control.

According to the information from the sensor, the controller calculates the cart's displacement, the angle and angle velocity of the inner and outer rods, and then excites the corresponding fuzzy area. Some statistic figures of membership as given in Figs. 14, 15, 16, and 17.

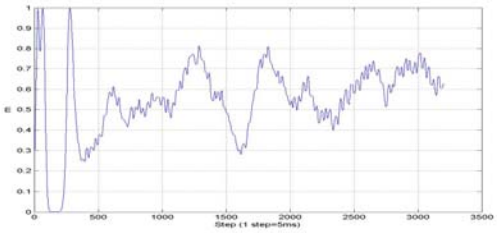


Figure 14. Fuzzy region m's membership of cart's displacement in the swing-up and handstand process

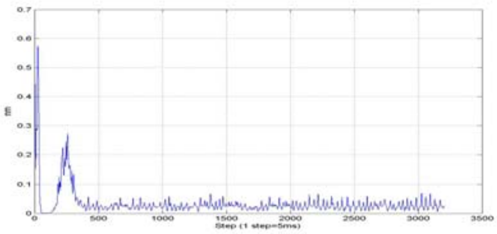


Figure 15. Fuzzy region nm's membership of inner rod's angle in the swing-up and handstand process

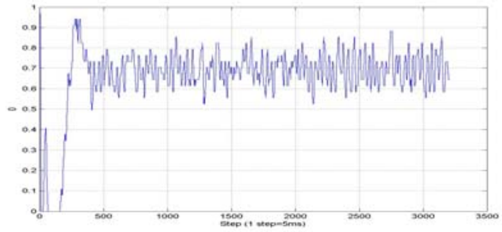


Figure 16. Fuzzy region 0's membership of inner and outer rod's angle difference in the swing-up and handstand process

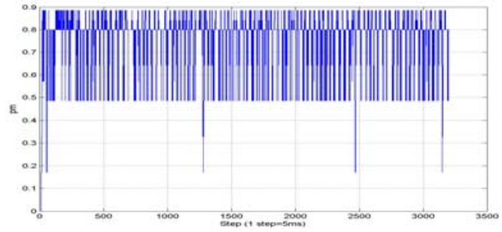


Figure 17. Fuzzy region pm's membership of inner and outer rod's angular difference in the swing-up and handstand process

V. CONCLUSIONS

We have introduced the basic concepts and controller design method for an HSIC controller simply and completely, and given a formal description of parameter tuning of the controller. A parameter self-tuning level for the HSIC controller has been designed using fuzzy logic. Thereafter, we introduced fuzzy online self-tuning into the HSIC controller of a pendulum, and designed a swing-up and handstand controller for a cart-double pendulum. The simulation and real time experiments of the swing-up and handstand control of the cart-double pendulum have proven that fuzzy online self-tuning of parameters can greatly improve the adaptive ability of an HSIC.

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