Human Simulating Intelligent Control and Its Application to Swinging-up of Cart-Pendulum

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Abstract

On the basis of the Human Simulating Intelligent Control (HSIC for short) proposed by the author, this paper discusses the Swinging-up control of Cart-Pendulum. The theoretical analysis and simulation results have verified the universal validity of the HSIC theory which aims at the emulating human "motor sensory preview intelligence" for the nonlinear system such as Cart-Pendulum, walking robots etc.

1 Introduction

As a mechanical system, Cart--Pendulum is always used to test and verify the feasibility and applicability of the control theory. There still is the stabilization problem of Cart-Pendulum around the upright position in posture control of walking robot. In fact the swinging-up control of Cart-Pendulum from the pendent position to the upright and being stabilized finally in the setting point can be regarded as one of the complicated postures of acrobat and gymnastic robot. So it is worth while to develop thorough investigation into the Cart-Pendulum problem. As a result many fundamental control problems of walking robot can be made clear correspondingly. For example at first we can study the stabilization mechanism of walking robot, then make robot complete some more complex operations. Therefore there are considerable technical and practical values in the Cart-Pendulum researches [1, 2].

For the time being the robot is still clumsy. The robot's ability is not equal to its ambition even for those natural and simple movements for human. So it is necessary to improve its motive performance by learning and emulating the human agile activities. Because the swinging-up control of Cart-Pendulum is completely nonlinear, we can't expect a proper control law by mathematical analysis. However human can accomplish many difficult operations with satisfaction by repetitious learning and training. In fact the swinging-up of single pendulum under limited torque has been solved by manual control[2]. Qijian Zhou[7] and Zushu Li [8] etc. have proposed a novel intelligent control theory--Human Simulating Intelligent Control (HSIC) by emulating human behavior in manual control. The theory has been applied successfully in many perplexing processes and plants (such as delay system, multivariable system and nonlinear system etc.). With HSIC method, Zushu Li etc.[10] have solved the swinging-up control of the single pendulum under limited torque. In this paper the authors attempt to abstract some human more profound knowledge and set up some models of the human "motor sensory preview intelligence" by emulation of the general dynamics of manual control. And so an intelligent controller can be devised. The simulation results verify that the HSIC controller can perfectly finish the swinging-up tasks of Cart-Pendulum.

2 HSIC controller

The HSIC theory aims at emulating human behavior based on the human macro control structure, and starts with the lowest level of hierarchical intelligent control, constructs the model of the "motor sensory preview intelligence" in manual control. Consequently the HSIC controller also possesses some excellent control properties like a human operator. The HSIC theory is different from the conventional methods. It does not only possess the property of the parallel problem solving, logic and language control, but also comprises of the analytical quantitative control of the traditional ways. Generally speaking, it holds the following fundamental structures and functions:

★ information processing and decision making with hierarchical structure (high order production system);

★ characteristic identification and characteristic memory on line;

★ Multi-mode control with combination of open and close loop control, positive and negative feedback control, qualitative decision and quantitative control;

★ using heuristics and intuition;

The hierarchical information processing and decision making structure is one of high order production system. The framework can be divided into three levels: the Central Commanding level (CC), the Organizing and Coordinating level (OC) and the Unit Controller UC

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(see Fig.1). The UC and OC are subordinate to OC and CC respectively. They formulate together the integrated cooperation architecture with 4th order production system structure, further can formulate multi-integrated systems in different hierarchical frameworks. They can be dealt with by higher production system to solve more complex problems. The difference between order and efficiency of the production system does really reflect the knowledge level and the "intelligence quotient" of an intelligent control system in a sense.

The HSIC theory believes that the lowest level in human motion control is a structure of hierarchical information processing and decision making, shown as Fig.2. This is called as UC. Actually it is a second order production system that solves the movement problems in a parallel way. The UC is composed of the run-time level master controller MC, the self-tuning level ST and task adaptive TA. Each level has its own data base DB, characteristic identifier CI and inference engine IE. A common data base CDB is implemented to serve as a quick information communication center among all levels. The performance base PB stores all kinds of prior performance index and transient performance index.

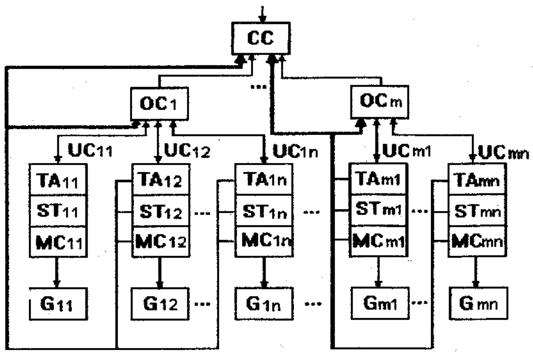


Fig. 1 : high order production structure of HSIC

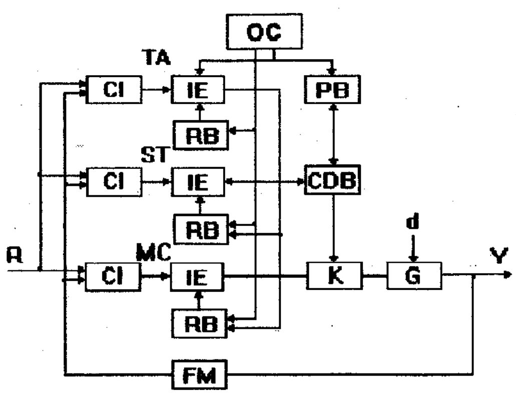


Fig. 2 : 2nd order production system structure of UC

In decoupling control of multivariable system a complex control task can be simplified into several easy sub-questions. We can fulfill the original task only if we can integrate and coordinate these subtasks. The human excellent functions just rely on the excellent abilities in the efficient information acquisition, management and exploitation, the capabilities of coordinating different complex movement requirements; and the abilities of quick learning and adaptation to the surroundings. To some extent the human control behavior is a hierarchical information acquisition, processing and exploitation process, which combines the qualitative inference and decision ("cognition to judgment") with the quantitative control ("judgment to operation"). It is really a double mapping processing courses (see Eq. (1) and Fig.3).

$$
\begin{array}{llll}
IC=<\Phi,\Psi,\Omega> & & \Psi=<R,F,U> & \\
\Omega & \Phi\rightarrow\Psi & \Omega=\{\omega_1,\omega_2,\cdots\omega_r\} & \\
\omega_i: & IF\ \ \varphi_i\ \ THEN\ \ \psi_i & (qualitative\ \ mapping) & (1) \\
\Psi: & R\xrightarrow{F}U & \Psi=\{\psi_1,\psi_2,\cdots\psi_r\} & \\
\psi_i: & u_i=f_i(e,\dot{e},\lambda,\cdots) & (quantitative\ \ mapping) & \\
\psi_i & f_i\rightarrow IF\ \ r_i\ \ THEN\ \ u_i & (qualitative\ \ mapping) &
\end{array}
$$

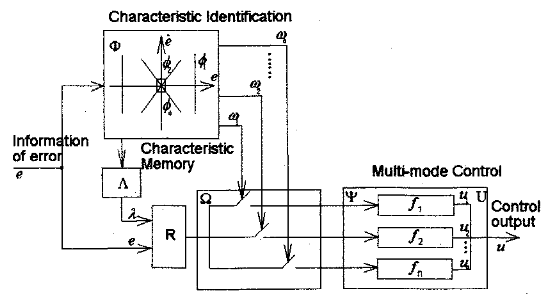


Fig. 3 The double mapping process of information processing

Where the characteristic model Φ is a division of the information space $\Sigma=(e(t)\ \ \dot{e}(t)\ \ t)$, and comprised by the characteristic states such as $\varphi_1,\varphi_2,\cdots,\varphi_r$; Ψ is a set of the control (or the decision) modes $\psi_1,\ \psi_2,\ \cdots,\ \psi_r$ presented by the qualitative rule f_i or quantitative function $f_i(e,\dot{e},\lambda,\cdots)$;The inference rule Ω is really the mapping relationship between the characteristic model and the control mode. R is a set of the input informations (error e, $\dot{e}$ and characteristic memory λ), while U is the controller's output.

3 Cart-Pendulum

The Cart--Pendulum discussed in this paper is shown in Figure 4. Generally speaking it could be a single pendulum or a compound pendulum (double- pendulum, even triple). We will devote our efforts to the cart-pendulum system. The plant's kinetic and power equations are listed in Eq. (2)--(3), where the means of all variables are listed in Tab. 1.

$$\begin{cases} (M + m)\ddot{r} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta) = u \\ ml\ddot{r}\cos\theta + mgl\sin\theta + (J + ml^2)\ddot{\theta} = 0 \end{cases} \quad (2)$$

$$\begin{cases} \frac{(M+m)}{2}[\dot{r}^2]_{t_1}^{t_2} + ml\int_{t_1}^{t_2} \dot{r}\frac{d^2\sin\theta}{dt^2}dt = \int_{r_1}^{r_2} u dr \\ ml[\dot{r}\frac{d\sin\theta}{dt}]_{t_1}^{t_2} + mgl[1-\cos\theta]_{t_1}^{t_2} + \frac{(J+ml^2)}{2}[\dot{\theta}^2]_{t_1}^{t_2} = ml\int_{t_1}^{t_2} \dot{r}\frac{d^2\sin\theta}{dt^2}dt \end{cases} \quad (3)$$

Tab. 1 the variable list of the cart - pendulum

notation	Parameter
M	equivalent mass of cart and driving system
m	equivalent mass of single pendulum
J	rotating inertia of single pendulum when centered is rotating axes
l	distance between the centered and the axes of the single pendulum
f	equivalent frictional coefficient of cart
c	equivalent frictional torque coefficient of pendulum
u	control force (u is commonly limited)
r	displacement of cart
θ	angle of pendulum

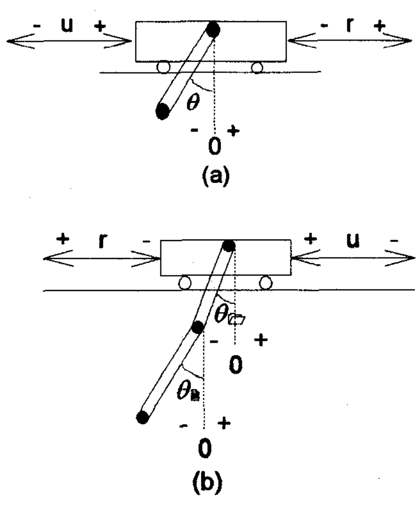


Fig. 4 the illustration of Cart-Pendulum

. It can be seen that there is a strong coupling effect between the cart and single pendulum . Just due to the coupling effect, the pendulum can be controlled indirectly through manipulating the cart's movement. So the torque of the swinging-up control of pendulum is limited. However this coupling also would perplex the accurate positing and even distort the stable property of the whole system. Obviously the crux to solve swing-up control of cart--pendulum is to attack this complex coupling affection successfully.

4 Design of HSIC Controller for Swinging-up of Cart-Pendulum

According to the general design methodology of the HSIC controller [9], and analytical methods [12], firstly we can equivalently simplify the complicated swinging-up control question of cart-pendulum into two simple sub-questions, shown as Figure 5 .

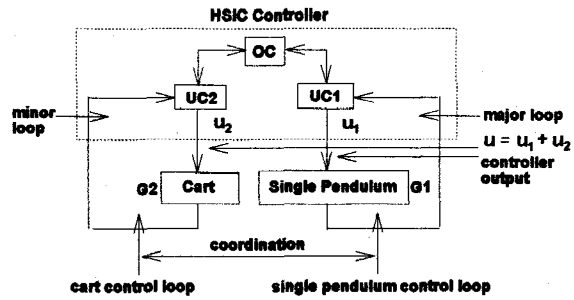


Fig. 5 HSIC controller's architecture for the cart - pendulum

Although we introduce two control forces u_1, u_2 respectively, the real control force applied to the cart will be one force u. Lots of efforts should be devoted to the coordination decoupling between the cart and pendulum, that is $u = u_1 + u_2$. The swinging-up control of Cart-Pendulum can be divided into two steps: the first step is to swing the pendulum up to the top, as well as to avoid overdriving ; the second step is to stabilize the pendulum and cart around the setting position.

(1) First step: the following qualitative rules are easily concluded in the .manual swing-up control

$$if \quad |\theta| \le \frac{\pi}{2} \Rightarrow e > 0 \quad then \quad \begin{cases} u < 0 \Rightarrow \ddot{\theta} > 0, \ddot{e} < 0, \ddot{r} < 0 \\ u \ge 0 \Rightarrow \ddot{\theta} \le 0, \ddot{e} \ge 0, \ddot{r} \ge 0 \end{cases} \quad (4)$$

Where the $e = \pi - \theta$ is supposed to be the error of the swing-up angle. On the basis of the above qualitative conclusion the control rules for swing the pendulum up can be selected as:

$$e \cdot \dot{e} \ge 0 \Rightarrow u = \beta, \quad e \cdot \dot{e} < 0 \Rightarrow u = -k\beta \quad (5)$$

Where β is a positive force. Obviously the control force continuously increases the swinging kinetic energy, enhances the swinging movement of the pendulum and so will be able to swing the pendulum from the pendent position to the upright. To avoid overdriving, a strategy emulating human behavior as known "wait a moment and watch a while " (let $u=0$) can be used sometimes.

Because cart's movement is not symmetrical in the first step, we suggest using an unequal Bang-Bang control to compensate the asymmetrical motion of the cart and to overcome the friction's resistance. The proper k can eliminate the cart's error away from its destination after the first step is over.

(2) Second step: There is two control loops (the cart's and the pendulum's) and a coupling loop between the above two logic loops (presented in Fig. 6 and 7). If the cart's control loop and the pendulum's are negative feedback loops, a positive feedback coupling loop will occur. We have analyzed this relation in detail in Fig. 6, where

$$u_1 = K_{p1}e_1 + K_{d1}\dot{e}_1, \quad u_2 = K_{p2}e_2 + K_{d2}\dot{e}_2 \quad \text{and}$$

$$e_1 = \pi - \theta, \quad e_2 = r_T - r \cdot \tag{6}$$

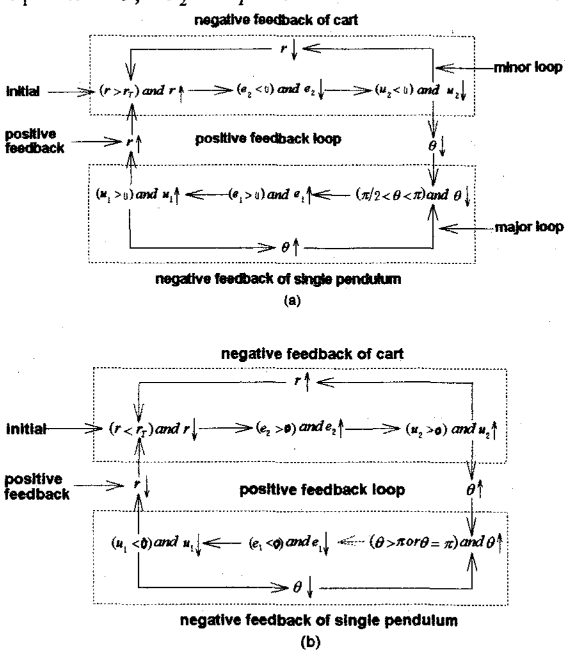


Fig. 6 the coupling illustration of cart-pendulum system

Around the upright position, a positive feedback coupling loop would destroy the stability of whole system very easily. But if we change the cart's control into the positive feedback compensation control and let $u_2 = -K_{p2}e_2 - K_{d2}\dot{e}_2$ (Fig. 7), then whole control system will finally tend to be negative.

In short, when the pendulum is close the upright point, a proper positive feedback compensation by cart's movement will be helpful to make the whole control process evolve to the desired status. So the coordination control algorithm for cart-pendulum should be as follows:

$$u = K_{p1}e_1 + K_{d1}\dot{e}_1 - K_{pr}e_r - K_{dr}\dot{e}_r \tag{7}$$

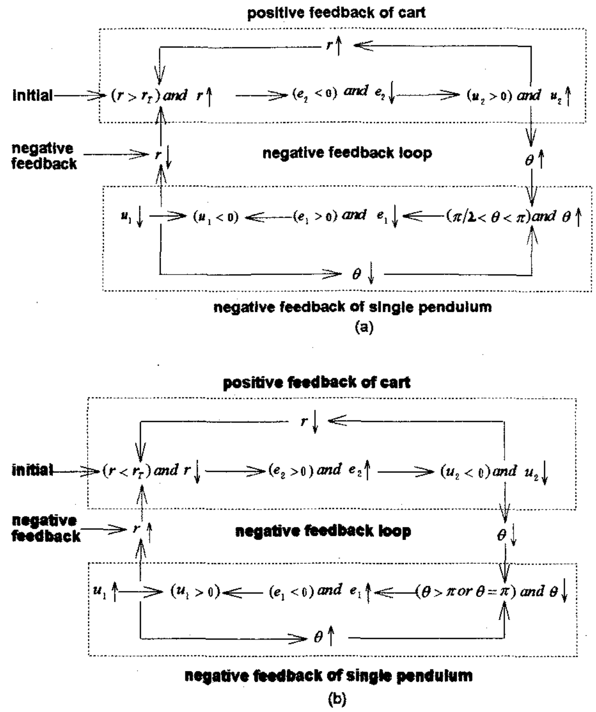


Fig. 7 the coordination decoupling of cart and single pendulum

Sum up, the HSIC's characteristic model Φ on the error phase plane in swinging-up control is shown as Fig. 8 and Eq. (8):

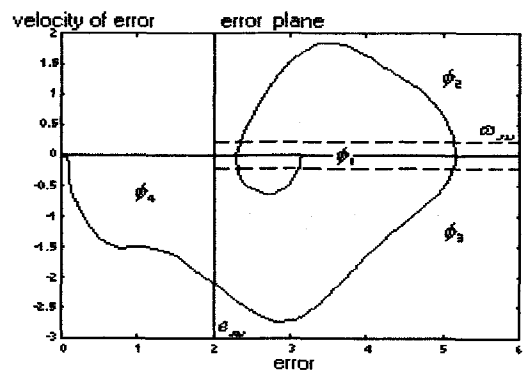


Fig. 8 the error phase plane of cart- pendulum in swinging-up

$$\begin{aligned} &\phi_1: |e_1| \geq e_{sw} \; and \; |\dot{e}_1| < \omega_{sw}, \\ &\phi_2: |e_1| \geq e_{sw} \; and \; |\dot{e}_1| \geq \omega_{sw} \; and \; e_1 \cdot \dot{e}_1 > 0, \\ &\phi_3: |e_1| \geq e_{sw} \; and \; |\dot{e}_1| \geq \omega_{sw} \; and \; e_1 \cdot \dot{e}_1 < 0, \\ &\phi_4: |e_1| < e_{sw} \end{aligned} \tag{8}$$

The corresponding multi-mode control tactic Ψ is as below:

$$\psi_1 : u = 0 \quad \psi_2 : u = U \quad \psi_3 : u = -kU \tag{9}$$
$$\psi_4 : u = K_{p1}e_1 + K_{d1}\dot{e}_1 - K_{p2}e_2 - K_{d2}\dot{e}_2$$

Where ψ_1, ψ_2, ψ_3 are the swinging-up modes, ψ_4 is the stabilization mode. ψ_1 is introduced in order to restrain overdriving during the swinging up. Generally the control force of u is limited, or:

$$if \quad |u| \geq u_{\max} \quad then \quad u = \mathrm{sgn}(u)u_{\max} \tag{10}$$

Tab. 2 the parameters of HSIC controller

notation	physical representation
k	reverse coefficient in swinging up control
K_{p1}	P coefficient in stable control of pendulumm
K_{d1}	D coefficient in stable control of pendulum
K_{p2}	P coefficient of cart's positive compensation
K_{d2}	D coefficient of cart's positive compensation
$u_{\max}$	maximum of the system output
e_{sw}	threshold of the angle difference of the single pendulum
ω_{sw}	threshold of angular speed difference of the single pendulum

The control system also needs a propelling force in a short time to initialize the whole system: $\psi_0 : u = -u$. And so the inference rules Ω can be determined as below:

$$\begin{aligned} & t \leq t_s: \quad \psi_0, \\ & t > t_s: \quad \omega_1 : \phi_1 \rightarrow \psi_1, \quad \omega_2 : \phi_2 \rightarrow \psi_2, \\ & \qquad \omega_3 : \phi_3 \rightarrow \psi_3, \quad \omega_4 : \phi_4 \rightarrow \psi_4, \end{aligned} \tag{11}$$

The initial values of an intelligent controller can be chosen according to the following qualitative guiding principles:

(1) Determination of initial values of e_{sw} ω_{sw}:

The determination of e_{sw}, ω_{sw} is of importance for the final positing of the pendulum. However their initial values should be in a region determinated by following equations:

$$\begin{cases} e_{sw} \leq tg^{-1} \dfrac{mg}{u_{\max}} \\ \omega_{sw}^2 \leq 2gl(1 - \cos e_{sw}) \end{cases} \tag{12}$$

(2) determination of initial value of k:

The choosing of k materializes the compensating ideas for the asymmetry of cart's movement during swinging process. The proper value of k can diminish the error of the cart's movement as possible. Generally speaking, the appropriate choice of k also relies on the cart's destination: if the final setting position is equal to the original, 1.4 is not a bad choice; if not, proper increasing or decreasing will be necessary.

(3) Determination of initial values of $K_{p1}, K_{d1}, K_{p2}, K_{d2}$:

The restraint of the mutual perturbing by positive feedback and the appropriate coordination between the cart and the pendulum will rely largely on the proper choosing of $K_{p1}, K_{d1}, K_{p2}, K_{d2}$. Generally repetitious caliberating of controller's values is necessary for the final accpetable extent. Fortunately there are some useful qualitative experiences: during the stabilization of the pendulum, once big error of pendulum's angle displacement or its speed occured, the pendulum's control requirment should be prior to the cart's. And so the values K_{p1}, K_{d1} of the pendulum's controller should be larger than the values K_{p2}, K_{d2} of the cart's controller. Our studies reveals that for a special cart-pendulum system, $\left|\dfrac{K_{p1}}{K_{p2}}\right|$ and $\left|\dfrac{K_{d1}}{K_{d2}}\right|$ respectively have a rational value region. The determination of this value region will be a main task in swinging--up and positing control of the cart-pendulum.

5 Simulation Results

We have built up a simulation system for the cart-pendulum based on the above controller's structure, shown as Fig.9. The relevant CAD learning and training system is software of "MATLAB/SIMULINK".

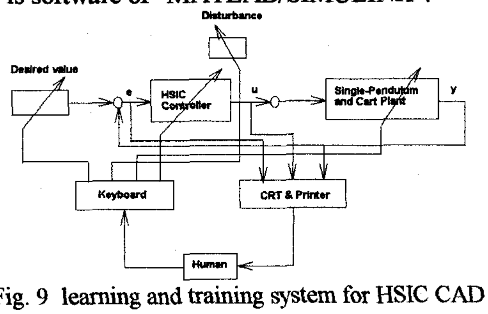


Fig. 9 learning and training system for HSIC CAD

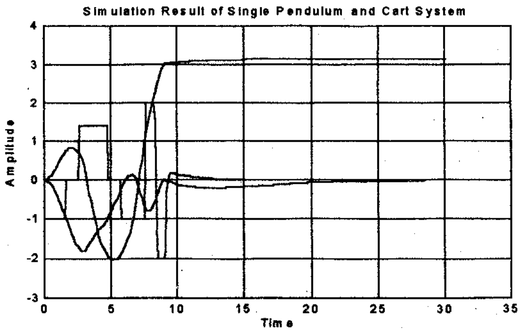
In equation (1) suppose:

$$ml = J + ml^2, \quad (M + m) = 2ml,$$
$$\beta = u / ml\omega^2 \quad \omega^2 = mgl / (ml^2 + J)$$

The non dimensional model of the cart-pendulum system would be as follows:

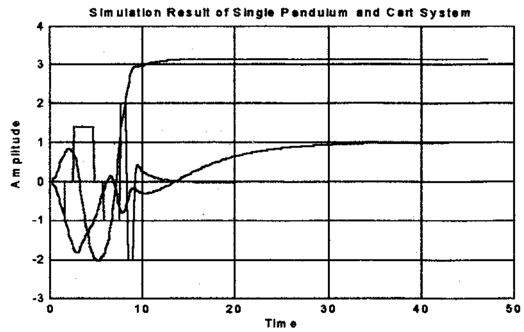
$$\begin{cases} \ddot{\theta} + \ddot{r}\cos\theta + \sin\theta = 0 \\ \ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta + 2\ddot{r} = \beta \end{cases} \quad (13)$$

If $|\beta| \geq 2$ then $\beta = \text{sgn}(\beta)2$. The simulation results of cart- pendulum are presented in Fig. 10.



10.

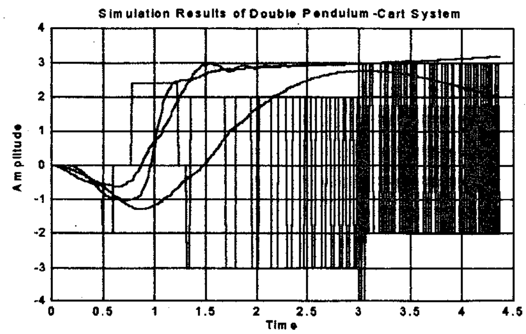
$r_0 = 0, r_T = 0$



$r_0 = 0, r_T = 1$

Fig. 10 the simulation results of cart-pendulum

We have also made some progress in the swinging-up of cart and double pendulum. Fig. 11 is one of the simulation results.



$r_0 = 0, r_T = 2$

Fig. 11 the simulation results of cart and double pendulum

6 Summary and Conclusions

The coordination is a most important " motor sensory preview intelligence" owned by people, which can help us to deal with different types of complex coupling plant. Learning, utilizing and using this kind of method for reference will surely help us to solve those complex multi-variable control problems. Analyzing the method further will also be useful for understanding the essence of the coupling effects, for accumulating control experiences and enhancing the capabilities in other applications.

Our successful practice has also verified the promising future of the HSIC theory that aims at the learning and emulating human "motor sensory preview intelligence" in the nonlinear control field.

References

[1] Zushu Li, Qingchun Chen, "The intelligent control study of the inverted pendulum system and its development" (in Chinese), Proc. of the 2nd Chinese World Congress on Intelligent Control and Intelligent Automation (CWC ICIA'97), pp. 14-19, Xian China, 1997.

[2] T.Takahashi, H.Inooka, "Swinging-up control of a pendulum", The International Conference on Advanced Mechantronics, May 21-24, pp. 815-819, Tokyo, Japan, 1989.

[3] R.Ikeura, H.Inooka, "Manual Control Approach to the Teaching of a Robot Task", .IEEE Trans. on Systems Man. and Cybernetics, Vol. 24, No.9, pp. 1339-1346, 1994.

[4]Hikaru Inooka, Yoshinobu Shito, Kee-Ho Yu, "Manual Control of the Two-link Arm with a Free Joint", Trans. IEEE International Conference on System, Man and Cybernetics, pp. 2324-2328, Oct. 22-25, 1995.

[5] Shozo Mori, Hiroyoshi Nishihara, Katsuhisa Furuta, "Control of unstable mechanical system-Control of pendulum", INT. J. Control, Vol. .23, No.5, pp.673-692, 1976.

[6]Masayuki Nishida, Akihiro Kaneshige, Kazuhiko Terashima, "Control System of Nonlinear Process to Swing Up and Stabilize Inverted Pendulum", Trans. of the Society of Instrument and Control Engineers, Vol. 31, No.9, pp.1452-1461, 1995.

[7] Zhou, Q.J. and Bai, J.K, "An Intelligent Controller of Novel Design", Proc. of Multi-National Instrumentation Conference, Prt.1, Shanghai, 1983.

[8] Zushu Li, "The theoretical study of Intelligent Control" (in Chinese), Information and Control, No 5, pp. 27-37, 1991.

[9] Li, Zu-shu etc. "Design and Application of Controllers Based on Methods for Emulating Human Intelligence", (TC7) 8th International Symposium on AIMaC'91, pp.327-332, Japan, 1991.

[10] Zu Shu Li, etc. "Control of a Pendulum under Torque Limitation (Swinging up Control by Intelligent Controller)", Trans. of the Japan Society Mechanical Engineers, Vol. 58, No. 556, C, pp. 3621-3626, 1992.

[11] Qingchun Chen, "The Human Simulating Intelligent Control Study of Inverted Pendulum System" (in Chinese), the master thesis of Chongqing University, 1997.

[12] Minglian Zhang, Weidong He, Chenzhi Shen, "The Human Simulating Control Based on the Synthesization Rules" (in Chinese), Proc. of the 1ts Chinese World Congress on Intelligent Control and Intelligent Automation (CWC ICIA'93), pp. 291-296, Beijing, 1993.