

INTELLIGENT CONTROL OF DOUBLE PENDULUM BASED ON HUMAN KNOWLEDGE

Seiji Yasunobu¹ Takayuki Iwasaki¹

1. Department of Intelligent Interaction Technologies, University of Tsukuba, Ibaraki 305-8573, Japan

ABSTRACT: Human can carry out a good control for a nonlinear system which is difficult for conventional control. However, it is difficult to incorporate human control into controller. In this paper, we propose an intelligent control method based on human knowledge of control. This control method is applied to the swing up and stabilization control of double pendulum which is an unstable nonlinear system. The effectiveness of this method was confirmed by experiments.

Keyword: Intelligent control, Swing up control, Double pendulum

1 Introduction

Most systems in the real world are nonlinear so that it is difficult to control. However, human can acquire knowledge of operation of such systems by operating several times. A control based on human knowledge is flexible and good control for nonlinear systems. For instance, an automatic train's operation system[1] had succeeded in the past with control based on human knowledge.

The pendulum is widely used for researches of control for as a typical nonlinear system. The control of double pendulum is difficult in particular because of its especially strong nonlinearity. Using the double pendulum, the control methods using modern control theory[2], neural network[3], etc have been proposed. The control method using modern control theory needs the accurate mathematical model of the double pendulum, and the control method using neural network is not easy to understand for human.

Human can operate nonlinear systems without considering their motion equations, and a control based on human knowledge is easy to understand. Applying the fuzzy control system that considers human knowledge of operation, swing up and stabilization control of single pendulum has been done[4]. Human can also acquire knowledge of operation of the double pendulum.

In this paper, we acquire suitable knowledge of operation for various situations by constructing the model of double pendulum on the computer and operating many times at extended simulation-time. Using the acquired human knowledge of operation, we proposed the intelligent control method based on human knowledge. This method swings up the first pendulum by predictive fuzzy control[1] and swings up the second pendulum and sta-

bilizes by using fuzzy model. In order to confirm the effectiveness of this control method, simulation and experiment are conducted.

2 Double Pendulum

The model of double pendulum which used in this research is shown in figure 1. The first pendulum is jointed at the cart, and the second pendulum is jointed at the first pendulum. The cart is moved by the DC motor through the driving belt. The double pendulum is swung up by moving the cart left or right in the straight line.

The purpose of the control in this research is to execute a suitable control according to the situation by judging the situation from six variables (position and velocity of cart, angle and angular velocity of each first and second pendulum) so that the pendulum is upright in target position. The outline of the control of double pendulum is shown in figure 2 and the parameters is written in table 1.

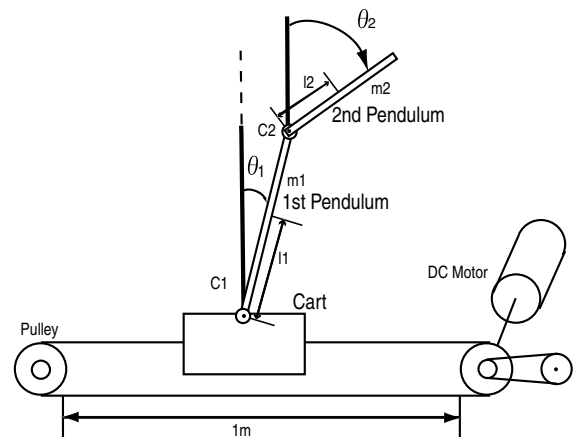


Figure 1: Model of Double Pendulum

3 Human Knowledge

When human swing up the single pendulum, there are knowledge of operation as follows[4].

When the pendulum is in the upside-down position, the operators move the cart and enlarge the angle of the pendulum. The cart is moved in the direction where the pendulum is laying to maintain the upright pendulum. Moreover, if the position of the cart is different from the target

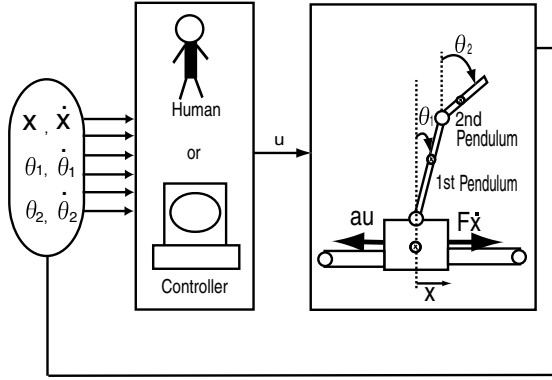


Figure 2: Control of Double Pendulum

Table 1: Parameters

$x[m]$	Position of cart
$\theta_1[rad]$	Angle of 1st pendulum from vertical line
$\theta_2[rad]$	Angle of 2nd pendulum from vertical line
$M[Kg]$	Mass of cart
$m_1[Kg]$	Mass of 1st pendulum
$m_2[Kg]$	Mass of 2nd pendulum
$l1[m]$	length from axis to the center of mass of 1st pendulum
$l2[m]$	length from axis to the center of mass of 2nd pendulum
$J1[Kg * m^2]$	moment of inertia of 1st pendulum
$J2[Kg * m^2]$	moment of inertia of 2nd pendulum
$F[Kg/s]$	Viscous friction coefficient
$u[V]$	Input voltage of amplifier
$a[N/V]$	Gain of torque
$C1[Kg * m^2/s]$	Viscous friction coefficient of 1st axis
$C2[Kg * m^2/s]$	Viscous friction coefficient of 2nd axis
$x_g i[m] (i = 0, 1, 2)$	x-coordinate of the center of mass of cart, 1st and 2nd pendulum

position of the cart, the pendulum is put in the direction of the target position to approach the target position.

In this research, we construct the model of the double pendulum on computer and swing up by input with joystick several times. As a result, we get the knowledge that human can swing up and stabilize the double pendulum when human operate as follows.

(10) If the first pendulum is in the upside-down position, the operators move the cart and enlarge the angle of the pendulum and change how to move the cart corresponding to momentum of the double pendulum.

(21) If the first pendulum is about upright, the operators stabilize the first pendulum.

(22) In addition, the operators swing up the second pendulum corresponding to swinging condition of the second pendulum. In other words, if the second pendulum is in the upside-down position, the operators swing up the second pendulum by moving the point of the first pendulum right and left.

(31) If both first and second pendulum is about upright, the operators make first and second pendulum upright.

This operation is done by reversely turning the first pendulum so that the second pendulum may turn.

(32) If both first and second pendulum is upright, the operators make the double pendulum approach the target position by putting the second pendulum in the direction of the target position, and making the angle of the first pendulum be the same angle as the angle of the second pendulum.

(40) In the other situations, the operators maintain the position of the cart.

This human operation is converted into control rules as follows

s10 Swing up the first pendulum (control), if the first pendulum is in the upside-down position.

s21 Stabilize the first pendulum (control), if the first pendulum is about upright.

s22 Swing up the second pendulum (control), if the first pendulum is about upright and the second pendulum is in the upside-down position.

s31 Make double pendulum upright properly, if both first and second pendulum are about upright.

s32 Move the cart to target position, if both first and second pendulum are upright.

s40 Maintain the cart in present position, in the other situations.

4 Outline of Control System

The control system constructed based on the above-mentioned operation knowledge (s10 ~ s40) is shown in figure 3. This control system selects suitable control part according to situations (S10 ~ S40).

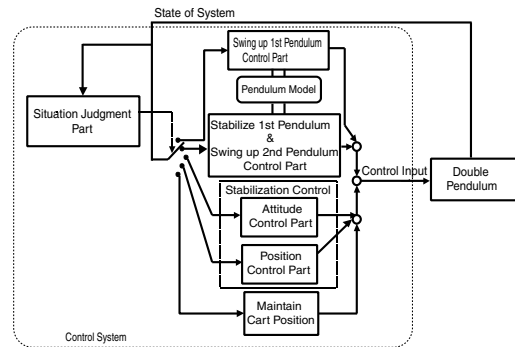


Figure 3: Outline of Control System

4.1 Situation Judgment Part

The situations are judged according to the state of the system as follows.

S10 The first pendulum is in the upside-down position (θ_1 is about π).

S21 The first pendulum is about upright (θ_1 is small [within $\pm 0.5[rad]$] & $\dot{\theta}_1$ is middle [within $\pm 20[rad/s]$]).

S22 And the second pendulum is in the upside-down position (θ_1 is small & $\dot{\theta}_1$ is middle & θ_2 is about π).

S31 Both first and second pendulum are about upright (θ_1 is small & $\dot{\theta}_1$ is middle & $\theta_2 - \theta_1$ is small & $\dot{\theta}_2 - \dot{\theta}_1$ is middle).

S32 Both first and second pendulum are upright (θ_1, θ_2 is very small [within $\pm 0.05[rad]$] & $\dot{\theta}_1, \dot{\theta}_2$ is small [within $\pm 0.8[rad]$] & θ_1 is about θ_2).

S40 Other than the above-mentioned

4.2 Swing Up First Pendulum Control Part

The swing up first pendulum control is done when the first pendulum is in the upside-down position (S10). In the swing up first pendulum control part, the value of the control input time is determined by the predictive fuzzy control[1]. This process of swing up first pendulum is shown in figure 4. The energy model acquired from human knowledge of operation is used. The control input time ($inputtime[s]$) is length of time to give motor a constant voltage. The value of control input is defined as ($input = 10[V] \times inputtime[s]$). The cart is moved right and left when input time has positive sign and minus sign, respectively.

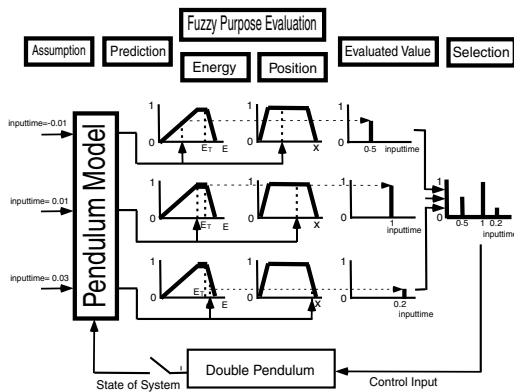


Figure 4: Process of Predictive Fuzzy Control for Swing Up 1st Pendulum

The swing up first pendulum control part predicts the increment of energy of the double inverted pendulum by using six candidates of the control input time and the energy model. The control part calculate the increment

of energy (ΔE) and the energy after swung up ($E + \Delta E$) by using the energy model and the energy in the upside-down position (E) and the control input time. The energy model used in the prediction is shown by fuzzy model based on the IF-THEN rule in the following form:

- If $inputtime$ is NB and E is NB
then ΔE is 0.052
- ⋮
- If $inputtime$ is PB and E is PB
then ΔE is 0.400

Table 2 is summary of these rules when the first pendulum has clockwise angular velocity. The membership functions of IF-part have 7 fuzzy labels (NB, NM, NS, ZO, PS, PM and PB). These are shown in figure 5. The membership functions for fuzzy purpose evaluation are shown in figure 6.

Table 2: Energy model

$\Delta Energy$		EnergyNow						
		NB	NM	NS	ZO	PS	PM	PB
input time	NB	0.05	-0.02	-0.10	-0.10	-0.20	-0.30	-0.30
	NM	0.05	-0.02	-0.02	-0.05	-0.10	-0.10	-0.20
	NS	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00
	ZO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PS	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	PM	0.05	0.05	0.13	0.14	0.20	0.20	0.30
	PB	0.05	0.07	0.25	0.25	0.35	0.40	0.40

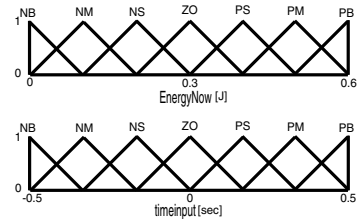


Figure 5: Membership Functions in Energy Model

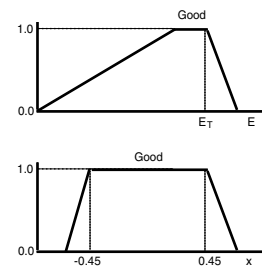


Figure 6: Membership Functions for Fuzzy Purpose Evaluation

The swing up first pendulum control part carries out the multipurpose fuzzy evaluation for predicted energy

of the double inverted pendulum after swung up and predicted cart's position. The evaluation of the energy is whether it is close to the target energy value which the first pendulum has in upright position. The swing up first control part determines that the candidate of control input time with highest evaluation value is appropriate and selects it as a control instruction.

4.3 Stabilize First Pendulum and Swing up Second Pendulum Control Part

The stabilize first pendulum and swing up second pendulum control is done when the first pendulum is about upright and the second pendulum is in the upside-down position (S21). The second pendulum is swung up by changing the target position in position control of the first pendulum. The target position (x_T) is set by using the swing up second pendulum model and the maximum swing up angle of the second pendulum (θ_{2max}) and cart's position (x). The swing up second pendulum model based on the IF-THEN rule in the following form:

- If θ_{2max} is NB and x is NB then x_T is 0.3

⋮

- If θ_{2max} is PB and x is PB then x_T is -0.3

Table 3 is summary of these rules. The membership functions of IF-part have 7 fuzzy labels. These are shown in figure 7.

Table 3: Swing Up 2nd Pendulum Model

x_T		Cart Position						
		NB	NM	NS	ZO	PS	PM	PB
θ_{2max}	NB	0.30	0.30	0.30	0.30	0.30	0.20	0
	NM	0.40	0.40	0.40	0.40	0.40	0.35	0
	NS	0.50	0.50	0.50	0.50	0.50	0.40	0
	ZO	0.50	0.50	0.50	0.50	0.50	0.50	0
	PS	0	-0.40	-0.50	-0.50	-0.50	-0.50	-0.50
	PM	0	-0.35	-0.40	-0.40	-0.40	-0.40	-0.40
	PB	0	-0.20	-0.30	-0.30	-0.30	-0.30	-0.30

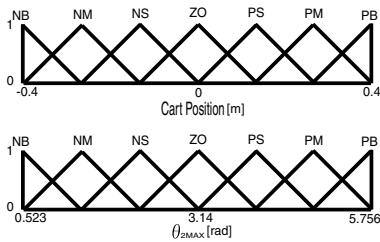


Figure 7: Membership Functions in Swing Up 2nd Pendulum Model

4.4 Stabilization Control Part

The stabilization control part (it is shown in figure 8) has four fuzzy inference parts and executes position control and attitude control according to the state of the double inverted pendulum (S31,S32). The control input is the magnitude of input voltage ($-10 \sim 10[V]$).

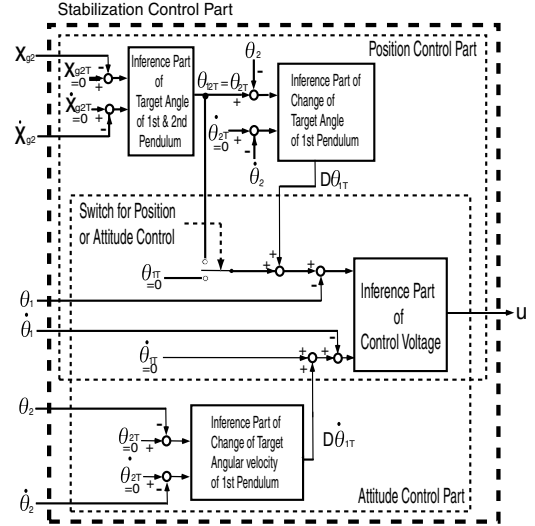


Figure 8: Stabilization Control Part

4.4.1 Attitude Control Part

The attitude control part is executed when both first and second pendulum are about upright (S31). The purpose of this part is to make first and second pendulum be upright together ($\theta_1, \theta_1, \theta_2, \theta_2 = 0$). First, the target angular velocity of the first pendulum is changed from 0 to the value enough to make the second pendulum be upright ($\dot{\theta}_{1T} = \Delta\theta_{1T}$). Next, the control input is determined by the fuzzy inference which uses the difference between the target angle and the angle of the first pendulum ($\theta_{1T} - \theta_1$) and the difference between the target angular velocity and the angular velocity of the first pendulum ($\dot{\theta}_{1T} + \Delta\theta_{1T} - \dot{\theta}_1$).

4.4.2 Position control Part

The position control is executed when both first and second pendulum are upright (S32). The purpose of this part is to move double pendulum to target position ($x, \dot{x}, \theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2 = 0$). First, the target angle of the second pendulum is set by the fuzzy inference which uses x -coordinate (x_{g2}) and velocity (\dot{x}_{g2}) of the center of mass of the second pendulum. Next, the change of angle ($\Delta\theta_{1T}$) from the target angle of the first pendulum is set by the fuzzy inference which uses the difference between the target angle and the angle of the second pendulum ($\theta_{2T} - \theta_2$) and the difference between the target angular velocity and the angular velocity of the second pendulum ($\dot{\theta}_{2T} - \dot{\theta}_2$). The control input is determined by the fuzzy

inference which uses the difference between the target angle and the angle of the first pendulum ($\theta_{1T} + \Delta\theta_{1T} - \theta_1$) and the difference between the target angular velocity and the angular velocity of the first pendulum ($\dot{\theta}_{1T} - \dot{\theta}_1$).

4.4.3 Maintain Cart Position Part

The control system selects the maintain cart position part in situations other than above. This part maintains the position of the cart.

5 Experiments

In order to confirm the effectiveness of the proposed control method, we carried out two experiments. The appearance of the double pendulum used for this experiments is shown in figure 9.

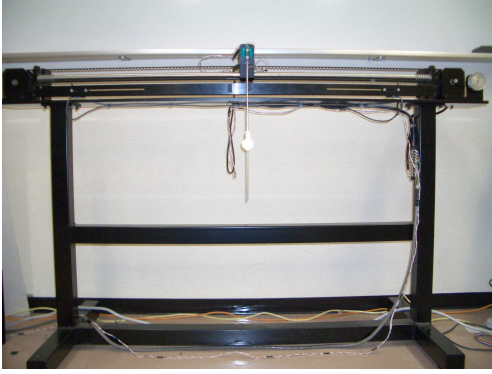


Figure 9: Double Pendulum

5.1 Simulation on Computer

First, the designed control system is simulated in SIMULINK and SimMechanics (The Math Works Inc.). The double pendulum is modeled by using SimMechanics, and the constructed control system was built into SIMULINK. table 4 is summary of value of parameters. This parameters the same as actual pendulum's.

Table 4: Value of parameters

M [Kg]	:	3.117
m_1 [Kg]	:	0.080
m_2 [Kg]	:	0.020
l_1 [m]	:	0.200
l_2 [m]	:	0.060
J_1 [Kg * m ²]	:	1.2×10^{-3}
J_2 [Kg * m ²]	:	4.2×10^{-5}
F [Kg/s]	:	23.04666
a [N/V]	:	11.1
C_1 [Kg * m ² /s]	:	8.111×10^{-4}
C_2 [Kg * m ² /s]	:	1.5×10^{-4}

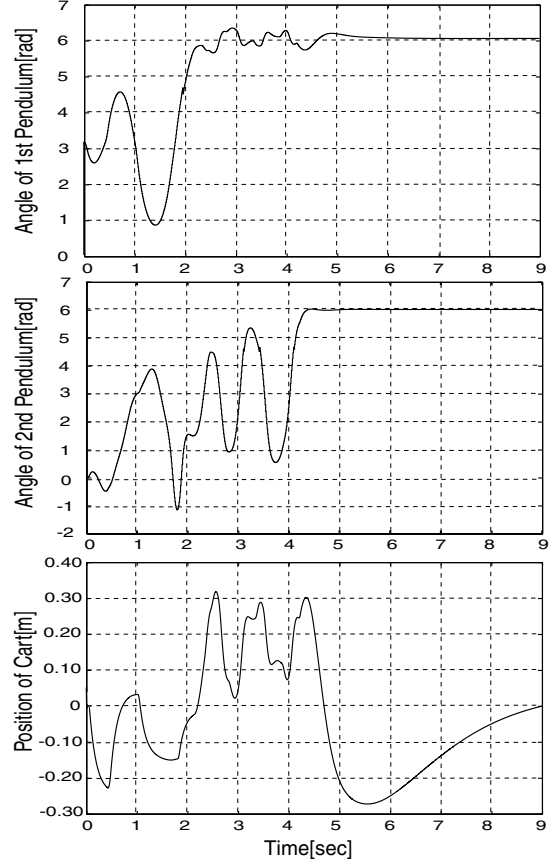


Figure 10: Simulation Result

The initial condition of the double inverted pendulum is the position of the pendulum upside-down ($\theta_1 = \pi, \dot{\theta}_1 = 0, \theta_2 = \pi, \dot{\theta}_2 = 0$) with the state of the cart at $x = 0$. The sampling interval is 10ms. The cart can move from -0.5 [m] to $+0.5$ [m]. The simulation result is shown in figure 10.

It can be confirmed that the control system swing up the first pendulum until about 2.5 seconds first and swing up the second pendulum until about 6 seconds. The control system selected the stabilization control when the first and second pendulum are about upright, and then stabilization is achieved ($x = 0, \theta_1 = 2\pi, \theta_2 = 2\pi$). The cart is also moved within the range from -0.5 [m] to 0.2 [m]. From this simulation, the effectiveness of the proposed control method is confirmed.

5.2 Experiment Using Actual Pendulum

In addition, the experiment using actual pendulum was carried out. The experimental result is shown in figure 11. It can be confirmed that the control system swing up the first pendulum until about 2.5 seconds first and swing up the second pendulum until about 5 seconds. The control system selected the stabilization control when the first and second pendulum are about upright, and then stabilization is achieved ($x = 0, \theta_1 = 2\pi, \theta_2 = 0$). The cart

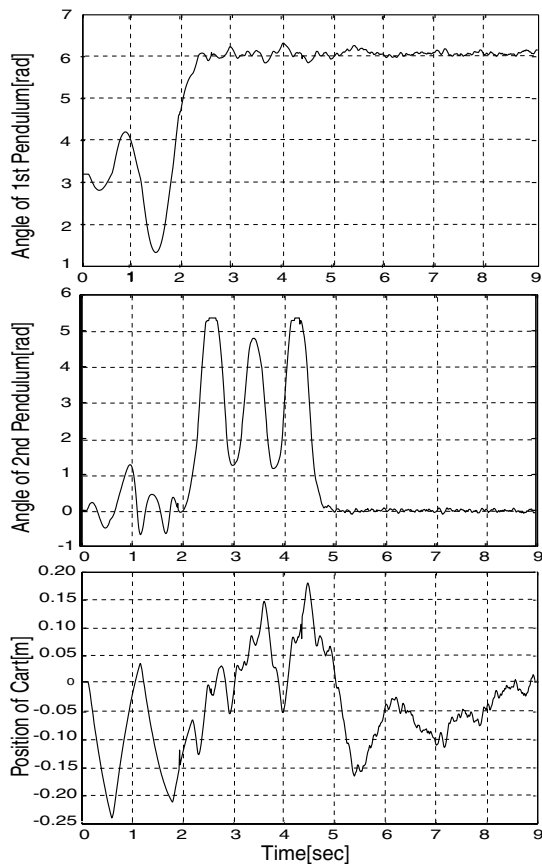


Figure 11: Experimental Result

is also moved within the range from $-0.25[m]$ to $0.2[m]$. From this experiment, it is confirmed that the proposed control method is effective for an actual nonlinear system.

6 Conclusion

In this paper, we proposed intelligent control method based on human knowledge. This method is applied to the control of double pendulum which is difficult system for conventional control. In this method, the control system which selects the control parts according to the situation. From experimental results, it was confirmed that this control method is effective for the system which has strong nonlinearity.

REFERENCE

[1] S. Yasunobu, S. Miyamoto, Automatic Train Operation System by Predictive Fuzzy Control, Industrial Applications of Fuzzy Control (M.Sugeno ed.), North-Holland, pp.1-18, 1985

[2] T. Henmi, M. Deng, A. Inoue, N. Ueki, Y. Hirashima: Reverse Order Swing-up Control of Serial Double Inverted Pedulums, Proc. of SICE Annual Conference 2003, pp.2444-2439, 2003.

[3] N. Ikeda, A. Saito and S. Kitajima: Intelligent Control Using Cubic Neural Network for Swinging up and Stabilizing Double Pendulum, Transactions of the Japan Society of Mechanical Engineers, Part C, Vol.68, No.676, pp.178-185, 2002.

[4] S. Yasunobu, T. Kitajima: The swing up control based on human experiences, Proc. of SICE Annual Conference 1998, pp.97-98, 1998.

[5] S. Yasunobu and T. Iwasaki: Swing Up Intelligent Control of Double Inverted Pendulum Based on Human Knowledge, Proc. of SICE Annual Conference 2004 in Sapporo, pp.1869-1873, 2004.