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Research Article

Research on Fuzzy Immune Self-Adaptive PID Algorithm Based on New Smith Predictor for Networked Control System

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We first analyze the effect of network-induced delay on the stability of networked control systems (NCSs). Then, aiming at stochastic characteristics of the time delay, we introduce a new Smith predictor to remove the exponential function with the time delay in the closed-loop characteristic equation of the NCS. Furthermore, we combine the fuzzy PID algorithm with the fuzzy immune control algorithm and present a fuzzy immune self-adaptive PID algorithm to compensate the influence of the model deviation of the controlled object. At last, a kind of fuzzy immune self-adaptive PID algorithm based on new Smith predictor is presented to apply to the NCS. The simulation research on a DC motor is given to show the effectiveness of the proposed algorithm.

1. Introduction

With the development of the control technology, the network technology, and the communication technology, the structure of the control system becomes more complicated, the spatial distribution becomes more wide, and the performance requirements also become higher. Networked control system (NCS) is a cross subject which integrates the computer technology, the network communication, and the control technology. It is one of the most important research topics in the control field [1]. In the NCS, the information transmission need occupy the shared network communication lines. However, the network capacity and the communication bandwidth are limited, so they will inevitably cause the collision of the information and retransmission. At the same time, the information transmission delay may be generated when sampling, quantization, coding, and decoding are done. The existence of the time delay will degrade the control performance of the system, which makes the rise time of the system and overshoot increase and even causes the instability of the system, so the analysis of the NCS will become complex.

Although some achievements have been gotten in the research process of the NCS, so far, a mature theory has not been formed. Aiming at random, time varying, and uncertain network-induced delay, the domestic and foreign scholars put forward various methods and solutions to improve the performance of the system. Nilsson et al. transform uncertain long time delays into one of a few certain delays by using the information receiving buffer rather than into a fixed maximum delay, which reduces the degree of the delay expansion [2]. Fu et al. presented an improved predictive control method to compensate the random time delay in the NCS [3]. Wang and Chen build the random discrete time model for the system with short time delay which has the probability distribution of Markov chain and use stochastic control theory to analyze and design [4]. Aiming at the disturbance and measurement noise in the network, Zhang et al. design the robust PID tracking controller for practical models and develop the robust $H\infty$ PID control such that load and reference disturbances can be attenuated with a prescribed level. Furthermore, for the robust stabilization problem, the design of a static output feedback controller is presented by solving bilinear matrix inequalities (BMIs). In order to efficiently solve a nonconvex BMI, they propose an approach based on the linear matrix inequality technique [5, 6]. Xiong et al. build the fuzzy controller of state feedback by analyzing the delay data of the actual control system based on Internet [7]. Zhang and Hua-Jing research control system based on IP network and use the method of compensating the time delay to improve the performance of the system

[8]. Zhang and Li designed a kind of controller based on Smith compensator and signal neuron incomplete differential forward PID, and the system gets better control performance under the random time delay in forward and feedback channels [9]. In addition, Zhang et al. proposed an improved Smith predictor and Kalman filter to reduce the effect of the control interference, the measurement noise, and the time delay [10]. Huang and Chen use Smith predictor to compensate the time delay of the system and proposed a complex controller including a cerebellar model articulation controller of neural networks and a PD controller so as to further weaken the prediction error [11].

In this paper, from the control point of view, the effect of the random network delay on system performance is analyzed. Then we use the MATLAB\Simulink simulation software to set up the simulation model of the NCS and research the performance of the proposed control algorithm using a DC motor as the controlled object.

2. The Network-Induced Delay

In the NCS, data is transmitted among the controller, actuator, and sensor over the network, so there are essentially three kinds of time delay in the system: the communication delay τ^{sc} between the sensor and the controller, the computational delay τ^{c} in the controller, and the communication delay τ^{ca} between the controller and the actuator. τ^{sc} and τ^{ca} are caused by the network transmission, and they are related to the network bandwidth, the network scheduling algorithm, and the network topological structure; τ^{c} is associated with the calculating speed of controller; τ^{c} is very small compared with τ^{sc} and τ^{ca}, and it is often ignored, so the network-induced delay is expressed as $\tau = \tau^{sc} + \tau^{ca}$. The block diagram of the NCS is shown in Figure 1.

It is well known that the system stability is affected by the time delay of the NCS. In this paper, we use a DC motor as the controlled object. Under different network-induced delays, the step response of the system is first analyzed by using the simple PID control algorithm. The transfer function of controlled object is expressed as [12]

$$G(s) = \frac{2029.826}{(s+26.29)(s+2.296)}. \tag{1}$$

The controller uses PID control algorithm, and it is expressed as

$$C(s) = K_P\left(T_d s + 1 + \frac{1}{T_i s}\right), \tag{2}$$

where K_P, T_d, and T_i are, respectively, the proportion coefficient, the differential time constant, and the integral time constant. The closed-loop transfer function is shown in

$$\frac{Y(s)}{R(s)} = \frac{C(s)G(s)e^{-\tau^{ca}s}}{1+C(s)G(s)e^{-\tau^{ca}s}e^{-\tau^{sc}s}}. \tag{3}$$

Suppose that the parameters of the PID controller are $K_p = 0.1701$, $T_d = 0$, and $T_i = 0.45$. Under different time delays, the step response is shown in Figure 2.

As can be seen from Figure 2, with the increase of the time delay, the overshoot of system is increased and the adjusting time is prolonged. And when the time delay is increased to a large value, the system will produce the oscillation. The PID control algorithm has obvious shortcomings, so we put forward a kind of fuzzy immune self-adaptive PID algorithm based on new Smith predictor. This algorithm can effectively meet the requirements of control system, reduce the overshoot and the adjusting time, and enhance the system stability.

3. The Principle of the Fuzzy Immune Self-Adaptive PID Algorithm Based on New Smith Predictor

3.1. The Principle of New Smith Predictor. Smith predictor is characterized by predicting the dynamic characteristic of the system with network-induced delays, and then the delayed controlled information can be reflected into the controller in advance, so that the controller is able to take action early, which can reduce the overshoot and accelerate the response speed [13]. However, the traditional Smith predictor can be only used in the feedback control system in which the model of controlled object is known and the time delay is determined. But the NCS is a closed-loop feedback control system based on the network. It is impossible to get the accurate time delay for the network with random, time-varying, and uncertain delays. Therefore, we use a new Smith predictor, which realizes dynamic prediction of the network-induced delay. The structure of the NCS based on new Smith predictor is shown in Figure 3.

$R(s)$ is the reference signal, $C(s)$ is the transfer function of controller, $G(s)$ is the transfer function of controlled object, and $N(s)$ is the interference signal.

When $N(s) = 0$, the closed-loop transfer function of the system is expressed as

$$\frac{Y(s)}{R(S)} = \frac{C(s)e^{-\tau_{ca}s}G(s)}{1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}\left(G(s)-G_m(s)\right)e^{-\tau_{sc}s}}. \tag{4}$$

Its characteristic equation is expressed as

$$1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}\left(G(s)-G_m(s)\right)e^{-\tau_{sc}s} = 0. \tag{5}$$

When $R(s) = 0$, the closed-loop transfer function of system is expressed as

$$\begin{aligned}\frac{Y(s)}{N(s)} &= \left(1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}G_m(s)e^{-\tau_{sc}s}\right)\\ &\quad\times\left(1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}G_m(s)e^{-\tau_{sc}s}\right.\\ &\quad\left.-C(s)e^{-\tau_{ca}s}G(s)e^{-\tau_{sc}s}\right)^{-1}.\end{aligned} \tag{6}$$

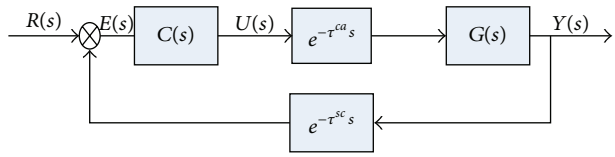


Figure 1: The block diagram of the NCS.

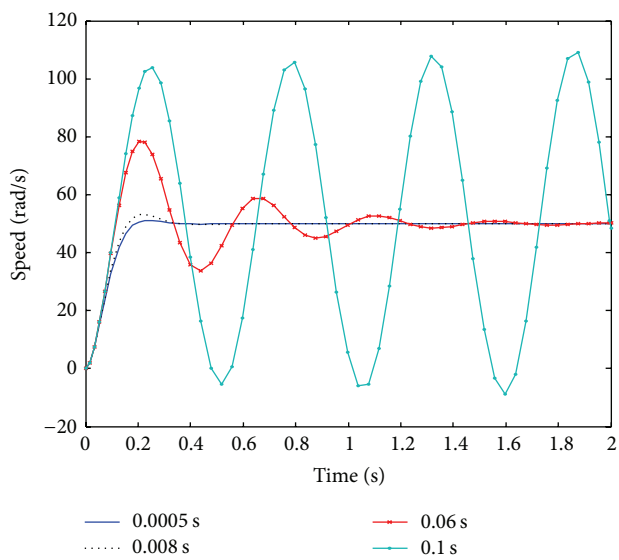


Figure 2: The step response under different network time delays.

Its characteristic equation is expressed as

$$1 + C(s)G_m(s) + C(s)e^{-\tau_{ca}s}G_m(s)e^{-\tau_{sc}s} - C(s)e^{-\tau_{ca}s}G(s)e^{-\tau_{sc}s} = 0. \quad (7)$$

In (5) and (7), they both include the controlled object $G(s)$ and the predicted model $G_m(s)$. When the system satisfies $G_m(s) = G(s)$, (4) and (6) are simplified and get the following relation:

$$\frac{Y(s)}{R(s)} = \frac{C(s)e^{-\tau_{ca}s}G(s)}{1 + C(s)G(s)}. \quad (8)$$

$$\frac{Y(s)}{N(s)} = \frac{1 + C(s)G(s) + C(s)e^{-\tau_{ca}s}G(s)e^{-\tau_{sc}s}}{1 + C(s)G(s)}. \quad (9)$$

Then their characteristic equation of (8) and (9) is expressed as

$$1 + C(s)G(s) = 0. \quad (10)$$

Equation (10) shows that all exponential functions with the time delay are removed from the closed-loop characteristic equation, so that the performance of the control system will be improved no matter the size of the time delay [14].

3.2. The Realization of the Fuzzy Immune Self-Adaptive PID Algorithm. In Section 3.1, we know that new Smith predictor can remove the exponential function with the time delay in the closed-loop characteristic equation when the system satisfies $G_m(s) = G(s)$. In fact, it is difficult to get the precise model of the controlled object, so the self-adaptive PID control algorithm need be introduced into the control system to compensate the influence of the model deviation of the controlled object.

3.2.1. The Principle of the Fuzzy Immune Control Algorithm. The immune controller is a kind of nonlinear controller based on the immune mechanism of the biological system. The controller mainly uses the immune feedback mechanism. The mutual collaboration between the inhibitory mechanisms and the feedback mechanism is completed through the rapid response of immune feedback mechanism of the antigen and the stability of the immune system. The immune system is complex, but its resistance to the adaptive ability of antigen is very obvious. The intelligent behavior of the biological information system provides the theoretical reference and the technical methods for the science and engineering [15]. Then the immune feedback control algorithm is expressed as

$$u(k) = K\{1 - \eta f[u(k), \Delta u(k)]\}e(k) = k_{p1}e(k), \quad (11)$$

where $k_{p1} = K\{1 - \eta f[u(k), \Delta u(k)]\}$, K represents the response speed of the system, and η represents the stability of the control system. Once the reasonable variables K and η are selected, a better control performance can be obtained. $f[u(k), \Delta u(k)]$ is a nonlinear function about $u(k)$ and $\Delta u(k)$.

Thus, it can be seen that the controller based on the mechanism of the immune feedback is a nonlinear proportional controller. The proportion varies with the output of the controller. Using the output of the controller to adjust the input, the system has better adaptive ability.

For the nonlinear function $f[u(k), \Delta u(k)]$, we use the fuzzy algorithm to approximate it, so as to achieve the destination of parameter self-tuning. In the immune controller, we take the output of system and the output rate as the controller input. Domain of inputs is set at $[-1, 1]$, and the domain of $f[u(k), \Delta u(k)]$ is set at $[-1, 1]$. The fuzzy rules of $f[u(k), \Delta u(k)]$ are shown in Table 1.

3.2.2. The Fuzzy Immune Self-Adaptive PID Algorithm. The pure fuzzy immune controller cannot completely eliminate the control error which is caused by the nonlinear interference or noise because of the lack of integral term of the deviation.

In addition, the fuzzy PID control algorithm has faster response speed and better robustness. But its performance of tracking of a given value is less than fuzzy immune

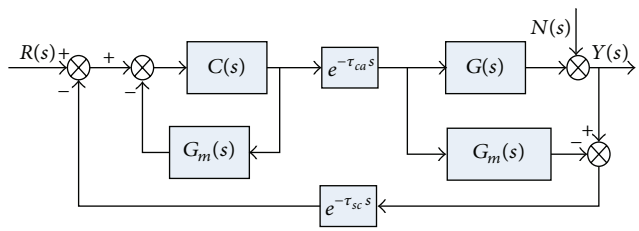


Figure 3: The structure of the NCS with new Smith predictor.

algorithm, so we use the fuzzy immune algorithm to improve the proportion coefficient of the fuzzy PID control algorithm in the NCS.

So we combine the fuzzy PID control algorithms and the fuzzy immune algorithm and get the fuzzy immune self-adaptive PID algorithm. The fuzzy immune self-adaptive PID algorithm is expressed as

$$u(k) = k_{p1}e(k) + k_i \sum e(k) + k_d [e(k) - e(k-1)], \quad (12)$$

where k_{p1} is the proportion coefficient and we use the fuzzy immune algorithm to get it. $k_i = k_{i0} + \Delta k_i$ is integral coefficient, and $k_d = k_{d0} + \Delta k_d$ is differential coefficient; they are both gotten by the fuzzy adaptive algorithm. k_{i0} and k_{d0} are the initial value of the fuzzy self-adaptive PID parameters.

In the system, the fuzzy control algorithm uses the error e and the error rate ec as the input linguistic variables and uses Δk_i, Δk_d as the output linguistic variables [16]. The input and output variables are divided into seven sets, namely, {NB, NM, NS, ZO, PS, PM, PB}. The domains of the input variables are set at $[-1, 1]$, and the domains of Δk_i and Δk_d are, respectively, set at $[-0.06, 0.06]$, $[-3, 3]$. Then we build the control tables of the fuzzy rules, according to the stability, the response, and the overshoot. The fuzzy rules tables of Δk_i, Δk_d are shown in Tables 2 and 3.

3.2.3. The Fuzzy Immune Self-Adaptive PID Algorithm Based on New Smith Predictor. According to the PID control theory, increasing the proportion coefficient can accelerate the response speed of the system, increasing the integral coefficient can reduce the steady-state error of the system, and increasing the differential control can reduce the overshoot. Due to the difficulty of the nonlinear function selection in the immune algorithm, we use the fuzzy algorithm to approximate nonlinear function, so we use the fuzzy immune feedback mechanism to adjust the proportion coefficient of the PID controller. At the same time, the integral and differential coefficient of PID controller are gotten by using online self-tuning of the fuzzy controller, which makes the controlled object have good dynamic and static performance, so as to realize the adaptive control [17].

So we combine the fuzzy immune self-adaptive PID algorithm and new Smith predictor and get the fuzzy immune self-adaptive PID algorithm based on new Smith predictor. The structure of the control system is shown in Figure 4.

In the control process, the parameters of PID algorithm are corrected online by using the fuzzy rule tables, which achieve the goal of self-tuning of PID parameters.

Table 1: The fuzzy rules of $f[u(k), \Delta u(k)]$.

$f(u(k), \Delta u(k))$	Δu						
	NB	NM	NS	ZO	PS	PM	PB
e							
NB	PB	PB	PB	PM	PS	PS	ZO
NM	PB	PB	PM	PS	ZO	ZO	ZO
NS	PB	PM	PS	ZO	ZO	NS	NS
ZO	PM	PS	ZO	ZO	NS	NS	NM
PS	PS	ZO	ZO	NS	NS	NM	NB
PM	PS	ZO	NS	NS	NM	NB	NB
PB	ZO	ZO	NS	NM	NB	NB	NB

Table 2: The fuzzy rules of Δk_i.

Δk_i	ec						
	NB	NM	NS	ZO	PS	PM	PB
e							
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

4. Simulation Results

In order to show the effectiveness of the proposed method, in the MATLAB/Simulink, the simulation is done using a DC motor as the controlled object. The sampling period $T = 10$ ms, the reference input $R = 50$ rad/s, and the network-induced delay is produced by gauss random generator in the Simulink toolbox. In addition, the input field is $e = ec = \{-3, -2, -1, 0, 1, 2, 3\}$; the fuzzy rules tables from Table 1 to Table 3 are adopted, the fuzzy reasoning uses "Mamdani," and the defuzzification uses "centroid." The initial value of parameters of the fuzzy immune self-adaptive PID algorithm is $K = 0.03$, $\eta = 2.5$, $k_{i0} = 0.282$, and $k_{d0} = 0.0008$. Using the fuzzy PID algorithm, the fuzzy PID algorithm based on Smith Predictor, the fuzzy PID algorithm based on new Smith predictor, and fuzzy immune self-adaptive PID algorithm based on new Smith predictor, respectively, we observe the waveform of the step response of the motor speed, and the results are shown in Figures 5, 6, and 7.

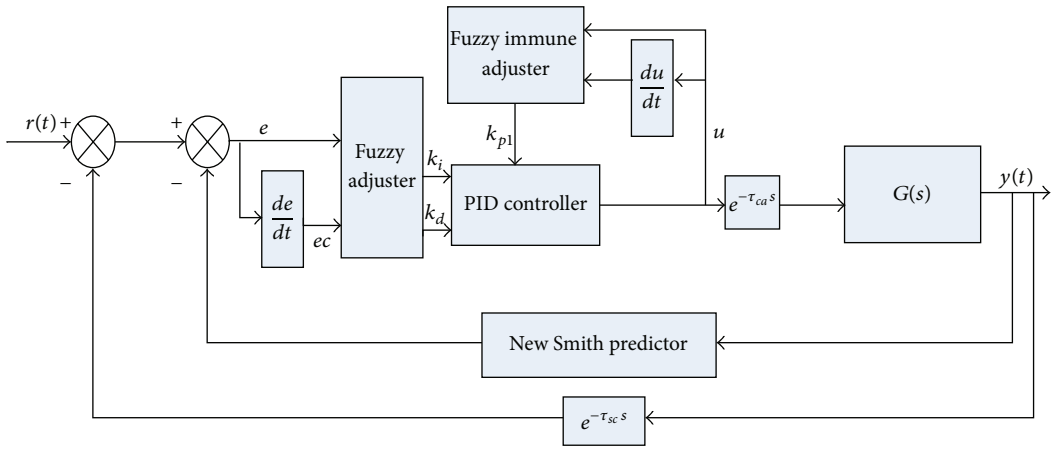
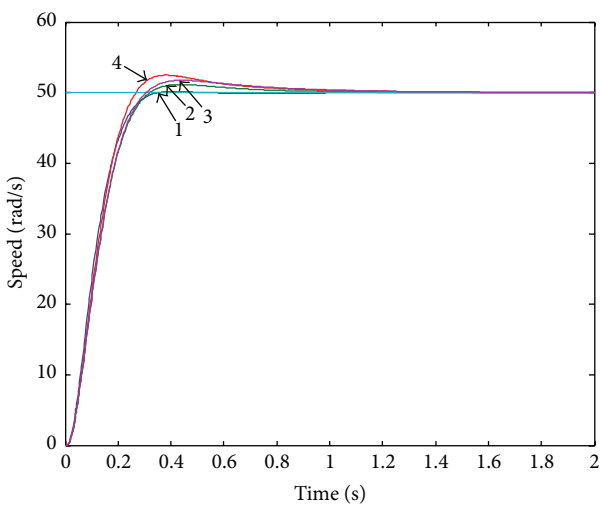
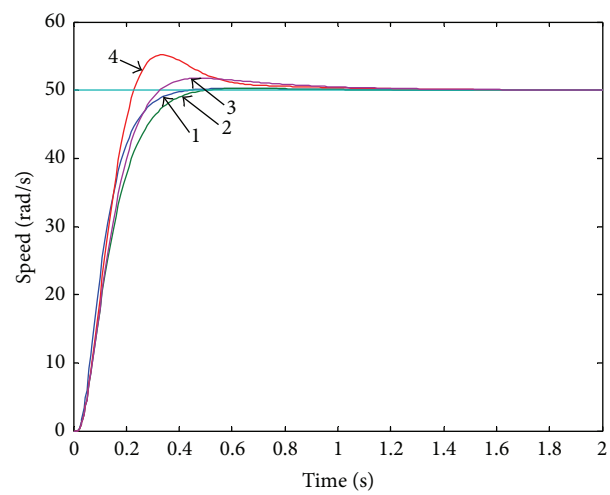


Figure 4: The structure of the fuzzy immune self-adaptive PID algorithm based on new Smith predictor for the NCS.



(1) Fuzzy immune adaptive PID based on new Smith predictor
(2) Fuzzy PID algorithm based on new Smith predictor
(3) Fuzzy PID algorithm based on Smith predictor
(4) Fuzzy PID algorithm

Figure 5: The step response when the average time delay is 5 ms.



(1) Fuzzy immune adaptive PID based on new Smith predictor
(2) Fuzzy PID algorithm based on new Smith predictor
(3) Fuzzy PID algorithm based on Smith predictor
(4) Fuzzy PID algorithm

Figure 6: The step response when the average time delay is 15 ms.

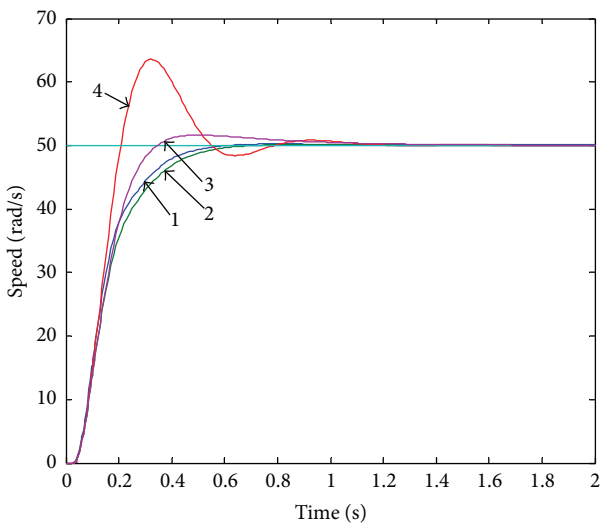
Table 3: The fuzzy rules of Δk_d.

Δk_d				ec			
	NB	NM	NS	ZO	PS	PM	PB
e							
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

The simulation results show that the fuzzy immune self-adaptive PID algorithm based on new Smith predictor is superior to the other three kinds of control algorithms comprehensively considering the response speed, the overshoot, and the adjusting time.

5. Conclusion

In this paper, the control performance and the system stability are analyzed by changing the size of network-induced delay. Then the simulation model of the NCS is built in MATLAB/Simulink. The simulation results show that the proposed control algorithm has the advantages of fast adjusting time and little overshoot, so it can improve the performance of the NCS and achieves the desired effect.



(1) Fuzzy immune adaptive PID based on new Smith predictor
(2) Fuzzy PID algorithm based on new Smith predictor
(3) Fuzzy PID algorithm based on Smith predictor
(4) Fuzzy PID algorithm

Figure 7: The step response when the average time delay is 30 ms.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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