南京航空航天大学

论文集

（二〇〇五年） 第11册

自动化学院

（第1分册）

南京航空航天大学科技部编

二〇〇六年三月

自动化学院

031 系

序号	姓名	职称	单位	论文题目	刊物名称	年卷期	类别
1	李医民 胡寿松	副教授 教授	031	T-S fuzzy fault-tolerant control via Riccati eqution	World Journal of Modeling and Simulation	2005, 1(1)	
2	杜贞斌 胡寿松	博士生 教授	031	Fuzzy adaptive H∞ control for a class of uncertain nonlinear time-delay systems	World Journal of Modeling and Simulation	2005,1(2)	
3	李医民 胡寿松	副教授 教授	031	Genetic algorithms research and application based on the mechanics of natural selection	Far East Journal of Application Mathematics	2005,20(1)	
4	胡寿松 何亚群	教授 教授	031	Compatibility rough-fuzzy set and compatibility fuzzy-rough set	DCDIS Proc	2005, 3	
5	杜贞斌 胡寿松	博士生 教授	031	Tracking control for a class of uncertain nonlinear time-delay systems	DCDIS Proc	2005, 3	
6	张正道 胡寿松	讲师 教授	031	Modeling time series based fault prediction for model-unknown nonlinear system	DCDIS Proc	2005, 3	
7	张正道 胡寿松	讲师 教授	031	Fault prediction of fighter baset on nonparametric density estimation	Journal of Engineering andElectronics	2005年16卷4期	
8	刘亚 侯霞 胡寿松	博士 教授	031	基于自适应AGBFN的不确定非线性系统的跟踪控制	控制理论与应用	2005, 22(1)	
9	朱其新 胡寿松	讲师 教授	031	网络控制系统的可镇定性和可检测性	系统工程学报	2005, 20(1)	
10	张正道 胡寿松	讲师 教授	031	基于未知输入观测器的非线性时间序列故障预报	控制与决策	2005, 20(7)	
11	肖迪 胡寿松	博士生，教授	031	基于相近关系的粗糙因子神经网络的模式识别方法	应用科学学报	2005, 23(5)	
12	李医民 胡寿松	副教授 教授	031	模糊神经网络技术在故障诊断中的应用	系统工程与电子技术	2005, 27(5)	
13	何亚群 胡寿松	教授 教授	031	自修复飞行控制系统效能评估的相容粗糙模糊集方法	系统工程	2005, 23(2)	
14	侯霞 胡寿松	博士生 教授	031	隐层小波元神经网络的非线性跟踪特性	信息与控制	2005, 34(1)	
15	杜贞斌 胡寿松	博士生 教授	031	基于模糊观测器T-S模型和自适应模糊逻辑系统的一类非线性系统的H∞控制	信息与控制	2005, 34(2)	
16	张绍杰 胡寿松	博士生 教授	031	一种基于粗糙约简的分形几何容错故障诊断方法	计算机测量与控制	2005, 13(6)	
17	杜贞斌 胡寿松	博士生 教授	031	一类非线性系统的模糊自适应跟踪控制	南京航空航天大学学报	2005, 37(3)	
18	张正道 胡寿松	讲师 教授	031	基于未知输入观测器的不确定非线性系统故障检测	南京航空航天大学学报	2005, 37(3)	
19	文博武 胡寿松	硕士生 教授	031	基于再励学习的歼击机安全着陆横侧向协调控制	东南大学学报	2005, 35（增刊Ⅱ）	
20	陈韵雪 胡寿松	硕士生 教授	031	基于自适应神经网络的歼击机模糊跟踪控制	东南大学学报	2005, 35（增刊Ⅱ）	
21	许洁 胡寿松 申忠宇	讲师 教授	031	歼击机操纵面故障的灰色识别法	南京理工大学学报	2005, 29（增刊）	
22	张震 胡寿松	正营 教授	031	动态系统故障诊断方法的灰色层次评估法	南京师范大学学报	2005, 5(1)	
23	盛守照 王道波 黄向华	讲师 教授 副教授	031	限定记忆的前向神经网络在线学习算法研究	控制与决策	2005,20(3)	
24	盛守照 王道波 王志胜 黄向华	讲师 教授 副教授	031	基于函数集信息量的模型选择研究	电子与信息学报	2005,4	

25	盛守照 王道波 黄向华	讲师 教授 副教授	031	一种动态筛选样本的前向神经网络快速学习算法	电子与信息学报	2005,11	
26	盛守照 王道波 王志胜 黄向华	讲师 教授 副教授	031	有限样本下模型选择理论与方法研究	系统工程与电子技术	2005,27(27)	
27	盛守照 王道波 黄向华	讲师 教授 副教授	031	基于前向神经网络的非线性平滑滤波器设计研究	中国空间科学技术	2005,25(2)	
28	盛守照 王道波 王志胜 黄向华	讲师 教授 副教授 副教授	031	基于子空间信息量准则的前向神经网络设计理论与方法研究	小型微型计算机系统	2005,26(5)	
29	范胜林 赵伟 袁信	副教授 讲师 教授	031	整周模糊度动态快速求解	电子科技大学学报	2005年34卷1期	
30	Shenghn FanKefei zhang	副教授 副教授	031	Ambiguity Resolution in GPS-based, Low-cost Attitude Determination	Journal of Global Positioning System (GPS)	Vol. 4, No. 1-2, 2005	
31	朱亮 姜长生 辅小荣	博士 教授 博士	031	具有输入时滞的关联不确定大系统的鲁棒控制	中国科学院研究生院学报	2005年1月，22（1）	
32	朱永红 姜长生	博士 教授	031	基于神经网络MIMO非线性系统自适应输出反馈控制	控制理论与应用	2005年2月，22（1）	
33	许浒 姜长生 辅小荣	硕士 教授 博士	031	基于粗神经网络的并行自适应滤波算法	盐城工学院学报	2005年3月，18（1）	
34	王岩青 姜长生	博士 教授	031	一类非线性不确定时滞系统的鲁棒H控制	信息与控制	2005年4月，32（1）	
35	高键 姜长生	博士 教授	031	一种新的云模型控制器设计	信息与控制	2005年4月，32（1）	
36	曹邦武 姜长生	博士 教授	031	基于回馈递推方法的导弹鲁棒飞行控制系统设计	宇航学报	2005年3月，26（2）	
37	王岩青 姜长生 陈海通	博士、 教授、 硕士	031	Robust Adaptive Sliding Mode Control for Noninear Uncertain Neutral Delay System	Transaction of Nanjing University of Aeronautics and Astronautics	2005年9月 Vol.22 NO.3	
38	潘锦川 姜长生	硕士、 教授	031	一种新型智能导引律及其三维可视化仿真	机械与自动化	2005年10月，No.5	
39	刘冠帮 姜长生	硕士、 教授	031	智能自主控制在航迹控制系统中的应用	机械与自动化	2005年10月，No.5	
40	李晓静 吴庆宪	硕士、 教授	031	PMAC控制程序在双轴运动平台中的实现	机械与自动化	2005年10月，No.5	
41	朱志宇 姜长生 张冰	博士、 教授、 博士	031	基于支持向量回归的混沌序列预测方法	电工技术学报	Vol.20, No.6, 2005, 6	
42	朱志宇 姜长生 张冰	博士、 教授、 博士	031	基于混沌理论的微弱信检测方法	传感器技术	Vol.24, No.5, 2005, 6	
43	赵晓凯 姜长生 朱亮	硕士、 教授、 博士	031	基于干扰观测器的空天无人飞行器鲁棒飞行逆控制器设计	弹箭与制导学报	Vol.25, No.4, 2005, 11	
44	毛丽艳 姜长生 吴庆宪	硕士、 教授、 教授	031	空战数据链通信延时产生的影响及其补偿	弹箭与制导学报	Vol.25, No.4, 2005, 11	
45	郑逸峰 姜长生	硕士、 教授	031	拦截导弹直接力和气动力复合控制问题研究	弹箭与制导学报	Vol.25, No.4, 2005, 11	
46	姜长生 吴庆宪 陈文华 王从庆	教授、 教授、 教授、 教授	031	现代鲁棒控制基础	哈尔滨工业大学出版社	2005.9	

47	张冰等	博士	031	基于小波变换的水天线提取算法研究	激光与红外	Vol. 35, NO. 4, 2005, 4	
48	张冰 姜长生	博士、 教授	031	舰船在水平面运动中非线性模型的建立	舰船科学技术	Vol. 27, No. 5，2005, 10	
49	张冰等	博士	031	舰船电力系统鲁棒励磁控制器设计与仿真	电气应用	Vol. 24, No. 3, 2005, 3	
50	王岩青 姜长生	博士、 教授	031	一类非线性不确定时滞系统的时滞相关鲁棒H控制	系统工程与电子技术	Vol. 27, No. 12, 2005	
51	曹邦武 姜长生	博士、 教授	031	一类不确定非线性系统的回馈递推滑模鲁棒控制器设计	宇航学报	2005，11，26（6）	
52	徐鸣 吴庆宪 姜长生	硕士、 教授、 教授	031	空空导弹攻击机动目标的三维最优制导律研究	航空兵器	2005，12，第6期	
53	何祥 吴庆宪	硕士、 教授	031	基于C/S与B/S模式的远程控制实验系统	电光与控制	2005，12（5）	
54	姜斌 Marcel Staroswiecki	教授 教授	031	Fault Diagnosis for Nonlinear Uncertain Systems Using Robust/Sliding Mode Observers	Control and Intelligent Systems	2005 年 33 卷 3期	
55	姜斌 Fahmida Chowdhury	教授 教授	031	Fault Estimation and Accommodation for Linear MIMO Discrete-time Systems	IEEE Transactions on Control Systems Technology	2005 年 13 卷 3期	
56	姜斌 Fahmida Chowdhury	教授 教授	031	Parameter fault detection and estimation of a class of nonlinear systems using observers	Journal of The Franklin Institute	2005 年 342 卷 7 期	
57	杨浩 姜斌 王骏	硕士生 教授 助研	031	基于神经网络与自适应控制的飞控系统重构方法	Proceeding of the 24th Chinese Control Conference	2005 年 7月	
58	杨浩 姜斌	硕士生 教授	031	基于渐进调节的容错控制	控制工程	2005 年 12 卷 4 期	
59	赵钦君 姜斌	硕士生 教授	031	基于模型的闭环系统故障检测的一种新方法	控制工程	2005 年 12 卷 7 期	
60	赵钦君 姜斌	硕士生 教授	031	基于观测器的闭环系统故障检测及其在飞控系统中的应用	东南大学学报	2005 年 35 卷 11 期	
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62	冒泽慧 姜斌	硕士生 教授	031	基于神经网络自适应观测器的一类非线性系统故障检测	自动化理论、技术与应用	2005 年 12 卷	
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64	杨忠 谭皓 樊琼剑 沈春林	副教授	031	飞行器控制软件的Statechart原型及其验证	南航学报	2005年37卷2期	
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66	杨忠 陈晔 沈春林	副教授	031	复杂嵌入式系统原型设计工具Statemate	计算机工程与应用	2005年41卷9期	
67	芮挺 沈春林 QITIAN 丁健	副教授 教授 教授 讲师	031	ICA与PCA特征抽取能力的比较分析	模式识别与人工智能	2005，Vol. 18，No. 1	

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69	芮挺 沈春林 丁健 江南	副教授 教授,, 讲师, 教授	031	独立分量重建模型的手写数字字符识别	计算机辅助设计与图形学学报	2005, Vol. 17, No. 3	
70	芮挺 张金林 丁健	副教授 副教授 讲师	031	基于主分量分析的手写字符识别	小型微型计算机系统	2005, Vol. 26, No. 2	
71	芮挺 TIANQI 沈春林 丁健	副教授 教授, 教授, 讲师	031	基于ICA的特征不变性目标识别	小型微型计算机系统	2005, Vol. 26, No. 3	
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73	芮挺 沈春林 QITIAN 丁健	副教授 教授 教授 讲师	031	基于HMM的击键特征用户身份认证	计算机工程	2005, Vol. 31, No. 2	
74	芮挺 王金岩 沈春林 丁健	副教授 教授 教授 讲师	031	基于线性分析的特征不变性目标识别	计算机工程	2005, Vol. 31 No. 15	
75	罗德林 沈春林 王彪 吴文海	博士生 教授 讲师 外单位	031	Air combat decision making for cooperative multiple target attack using heuristic genetic algorithm	Proceedings of 2005 International conference on machine learning and cybernetics	2005年第1卷	
76	罗德林 沈春林 吴文海 李玉峰	博士生 教授 外单位 博士后	031	基于遗传算法的飞行器追踪拦截模糊导引律优化设计	吉林大学学报（工学版）	2005年35卷第4期	
77	罗德林 吴文海 沈春林	博士生 外单位 教授	031	空战多目标攻击决策综述	电光与控制	2005年12卷第4期	
78	施连军	硕士生	031	三维空间视域变换实现方法的研究	电脑开发与应用	2005年18卷第12期	
79	陈超 罗德林 沈春林	硕士生 博士生 教授	031	多目标攻击排序算法研究	飞机设计	2005年第4期	
80	王第伟 沈春林	硕士 教授	031	基于Direct3D的雾化效果实现	电脑开发与应用	2005年18卷11期	
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85	谭浩 李玉峰 王金岩 何亦证 沈春林	博士生 博士后 外单位 外单位 教授	031	AC-PSO algorithm for UAV mission planning	Transactions of Nanjing university of aeronautics & astronautics	2005年22卷3期	

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87	谭浩 王金岩 何亦证 沈春林	博士生 外单位 外单位 教授	031	一种基于子群杂交机制的粒子群算法求解旅行商问题	系统工程	2005年23卷4期		
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93	于秀芬 段海滨 龚华军	硕士 博士 副教授	031 031 031	移动机器人视觉定位方法的研究与实现	数据采集与处理	2004年19卷4期		
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96	刘春生	副教授	031	最小相位不确定非线性系统的观测器设计	系统工程与电子技术	2005,27(11)		
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COMPATIBILITY ROUGH-FUZZY SET AND COMPATIBILITY FUZZY-ROUGH SET

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Abstract. This paper presents the conception of compatibility rough-fuzzy set based on compatibility relation and the conception of compatibility fuzzy-rough set based on fuzzy compatibility relation, considering that the fuzzy information exists in the decision system which may be influenced by noise and random disturbance. The definitions of compatibility rough-fuzzy set and compatibility fuzzy-rough set are proposed, at the same time their corresponding membership functions are also given and their properties are proved. An example is given to illustrate the effectiveness of the proposed method.
Keywords. Rough set; compatibility relation; fuzzy compatibility relation; compatibility rough-fuzzy set; compatibility fuzzy-rough set

1. Introduction

The rough set method[1] presented by Polish mathematician Z.Pawlak in 1982, offers a new way for decision-making and analysis, which can find out the useful decision-making rules from large numbers of data so that it attracts great attention of people[2]. This classical rough set theory regards indiscernibility relation as the core and is suitable for the case that neither the condition attribute nor the decision attribute is fuzzy in decision table.

The indiscernibility relation is still the core of rough-fuzzy set. It divides objects into equivalent classes and forms rough-fuzzy set by decision fuzzy attribute values. Fuzzy-rough set developed from rough-fuzzy set, replacing indiscernibility relation by fuzzy equivalent relation, divides objects into fuzzy equivalent classes and forms fuzzy-rough set. These two kind rough sets are separately based on indiscernibility relation and fuzzy equivalent relation. But some problems will emerge when there is noise or random disturbance in the system, the strict relation usually being unsatisfied. Therefore, the

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paper extends indiscernibility relation and fuzzy equivalent relation to compatibility relation and fuzzy compatibility relation and presents compatibility rough-fuzzy set and compatibility fuzzy-rough set[3-6].

2. Fuzzy decision information system

Let an information system be represented by $\{U, A, V, f\}$,where $U = \{x_1, x_2, \cdots, x_n\}$ be a finite non-empty objects set, and $A = \{q_1, q_2, \cdots, q_k\}$ is a non-empty attributes set ; $V = \{v_q, q \in A\}$is the value of attribute which may be a certain value, or a value of membership function. If the value of attribute is that of membership function, under the condition attribute q, the attribute value of object x can be denoted by $\mu_q(x) \in [0, 1]$; f denotes a mapping, $f : U \times A \to V_q$. Suppose $A = C \cup D$,where $C = \{a_1, a_2, \cdots, a_m\}$ denotes condition attribute, while $D = \{d_1, d_2, \cdots, d_l\}$ represents decision attribute, the information system is the fuzzy decision information system.

3. Compatibility rough-fuzzy set

3.1 *Compatibility relation and compatibility class*

For an object in the field of objects, a neighborhood is defined, in which two objects are regarded compatible, and R denotes the compatibility relation.

Definition 1 $\forall x, y \in U, \forall a_j \in C(j = 1, 2, \cdots, m)$,defining threshold by $t(a_j)$,if $d(a_j(x), a_j(y)) \leq t(a_j)$, then the relation can be denoted by xRy, where $d(a_j(x), a_j(y)) = |a_j(x) - a_j(y)|$.Obviously, relation R satisfies: (1) reflexive: xRx; (2)symmetric: $xRy \to yRx$.

But it does not satisfy transitive, so such kind of relation R is the compatibility relation. In view of practical decision system, the compatibility relation can be redefined as follows:

Definition 2 $\forall x, y \in U$, under the condition attribute $P \subseteq C$,a threshold is defined by $t(a)$, and if $D(x, y) = \frac{1}{|P|} \sum_{a \in P} d(a(x), a(y))$, then the relation can be denoted by xRy, where $d(a(x), a(y)) = |a(x) - a(y)|$, and $|P|$ is the amount of elements in condition attribute subset.

Obviously the relation R also satisfies:(1)reflexive; (2)symmetric. But not satisfying transitive, so relation R is the compatibility relation.

Definition 3 $\forall x \in U$, compatibility class is defined by:

$$RS(x) = \{y \in U | xRy\} \tag{1}$$

Then, we divide the set of objects into h compatibility classes, $U = \{F_1, F_2, \cdots, F_h\}$.

3.2 *Compatibility rough-fuzzy set*

Similar to the rough-fuzzy set based on equivalent relation[9], the compatibility rough-fuzzy set can be defined.

Definition 4 Given $U = \{x_1, x_2, \cdots, x_n\}$, X is a fuzzy set on U, under the compatibility relation R, the compatibility rough-fuzzy set is defined by:

$$R(x) = (\underline{R}(X), \overline{R}(X)) \tag{2}$$

For $x \in U$,the membership functions of compatibility class $RS(x)$ in the compatibility rough-fuzzy set are expressed as:

$$\mu_{\underline{R}(X)}(RS(x)) = \inf\{\mu_X(x)|x \in RS(X)\} \qquad \forall x \in U \tag{3}$$

$$\mu_{\overline{R}(X)}(RS(x)) = \sup\{\mu_X(x)|x \in RS(X)\} \qquad \forall x \in U \tag{4}$$

3.3 *Compatibility rough-fuzzy membership function and its properties*

Definition 5 Given $U = \{x_1, x_2, \cdots, x_n\}$, X is a fuzzy set on U, under the compatibility relation R, the compatibility rough-fuzzy membership function of object $x \in U$ for X is defined by:

$$\eta_X(x) = \frac{|F \cap X|}{|F|} \tag{5}$$

Where $F = RS(X)$, is the compatibility class of x.

Property 1 $0 \leq \eta_X(x) \leq 1$.

Property 2 For $\forall A, B \subseteq U, \eta_{A\cup B}(x) \geq \max\{\eta_A(x), \eta_B(x)\}$.

Property 3 For $\forall A, B \subseteq U, \eta_{A\cap B}(x) \leq \min\{\eta_A(x), \eta_B(x)\}$.

Using compatibility rough-fuzzy membership function, the possible value of every object in the different decision classes can be acquired, so that the decision rules are obtained.

3.4 *Example 1*

Consider a fuzzy decision system $\{U, C, D\}$, where $U = \{1, 2, \cdots, 8\}$ denotes object, $C = \{a_1, a_2, a_3\}$ denotes condition attribute, $D = \{d_1, d_2\}$ denotes decision attribute, the values of condition attribute are certain, while those of decision attribute are fuzzy, the detailed data of decision system are shown in table 1.

Table 1 fuzzy decision-making system

U	a_1	a_2	a_3	d_1	d_2
1	3.4	5.6	1.2	0.3	0.7
2	5.2	8.9	2.4	0.1	0.9
3	3.3	5.7	1.2	0.2	0.8
4	6.7	7.6	3.2	0.6	0.5
5	5.2	9.0	2.35	0.2	0.9
6	3.35	5.7	1.25	0.4	0.8
7	6.8	7.5	1.25	0.7	0.4
8	1.4	2.5	3.6	0.9	0.1

Using (3) and (4), the membership functions of compatibility equivalent classes in the compatibility rough-fuzzy set can be obtained.Using (5), the value of compatibility rough-fuzzy membership function is obtained.

Table 2 compatibility rough-fuzzy membership functions values

Sequence number	compatibility class	$\eta_{d_1}(F)$	$\eta_{d_2}(F)$
1	{1,3,6}	0.3	0.77
2	{2,5}	0.15	0.9
3	{4,7}	0.65	0.45
4	{8}	0.9	0.1

4 Compatibility fuzzy-rough set

4.1 *Fuzzy compatibility relation and fuzzy compatibility class*

Definition 6 $\forall x, y \in U$, for a certain attribute $a_j \in C(j = 1, 2, \cdots, m)$, define the fuzzy relation $R_j(U \times U \to [0, 1])$ as:

$$xR_jy = \{(x, y) \in U \times U | \mu_{R_j}(x, y) \geq \alpha_j\} \tag{6}$$

Where:$\mu_{R_j}(x, y) \geq \alpha_j \Leftrightarrow |\mu_j(x) - \mu_j(y)| \leq 1 - \alpha_j, \forall a_j \in C; \alpha_j(j = 1, 2, \cdots, k)$is a prescribed constant, called threshold.

It is easy to prove that relation R_j satisfies reflexive and symmetric, but not transitive. So R_j is fuzzy compatibility relation.

That indicates $x, y \in U$ is fuzzy compatible under the condition attribute $a_j \in C$.

Definition 7 $\forall x \in U$, for a certain attribute $a_j \in C(j = 1, 2, \cdots, m)$, under the fuzzy compatibility relation R_j, the fuzzy compatibility class is written in the form:

$$U/a_j = \{y \in U | xR_jy\} \tag{7}$$

In this way, under the condition attribute a_j, object set U is divided into h_j fuzzy compatibility classes, $U/a_j = \{F_{j1}, F_{j2}, \cdots, F_{jh_j}\}$.

Definition 8 $\forall x \in U$, under the condition attribute $C = \{a_j, j = 1, 2, \cdots, m\}$, the relevant fuzzy compatibility class is written as:

$$FR(x) = U/C = U/a_1 \cap U/a_2 \cap \cdots \cap U/a_m = \{F_1, F_2, \cdots, F_h\} \quad (8)$$

Where,$\forall x, y \in U$, fuzzy compatibility relation $R : U \times U \longrightarrow [0, 1]$ is defined as:

$$xRy = \{(x, y) \in U \times U |\, \mu_R(x, y) \geq \max(\alpha_j), j = 1, 2, \cdots, m\} \quad (9)$$

Obviously, superposition may be exists between $F_i(i = 1, 2, \cdots, h)$, i.e. for arbitrary object, it probably belongs to different fuzzy compatibility classes at the same time.

4.2 *Compatibility fuzzy-rough set*
Similarly to the fuzzy-rough set [12], the compatibility fuzzy-rough set can be defined.

Definition 9 Setting $U = \{x_1, x_2, \cdots, x_n\}$, X is a fuzzy set on U. Under the fuzzy compatibility relation R , the compatibility fuzzy-rough set is defined as:

$$R(x) = (\underline{R}(X), \overline{R}(X)) \quad (10)$$

For fuzzy compatibility class $F_i(i = 1, 2, \cdots, h)$, the lower approximation and the upper approximation of compatibility fuzzy-rough set is expressed as:

$$\mu_{\underline{R}(X)}(F_i) = \inf_x \max\{1 - \mu_{F_i}(x), \mu_X(x)\} \qquad \forall i \quad (11)$$

$$\mu_{\overline{R}(X)}(F_i) = \sup_x \min\{\mu_{F_i}(x), \mu_X(x)\} \qquad \forall i \quad (12)$$

For $\forall x \in U$, the lower approximation and the upper approximation of compatibility fuzzy-rough sets are expressed as:

$$\mu_{\underline{R}(X)}(x) = \sup_{F \subseteq U/R} \min(\mu_F(x), \inf_{y \in U} \max\{1 - \mu_F(y), \mu_X(y)\}) \quad (13)$$

$$\mu_{\overline{R}(X)}(x) = \sup_{F \subseteq U/R} \min(\mu_F(x), \sup_{y \in U} \min\{\mu_F(y), \mu_X(y)\}) \quad (14)$$

4.3 *Compatibility fuzzy-rough membership function and its* properties
Compatibility fuzzy-rough membership function can be defined by the same way of fuzzy-rough membership function[13].

Definition 10 Setting $U = \{x_1, x_2, \cdots, x_n\}$, X is a fuzzy set on U, $U/R = \{F_1, F_2, \cdots, F_h\}$, under the fuzzy compatibility relation R, the compatibility fuzzy-rough membership function is expressed as:

$$\rho_X(x) = \begin{cases} \frac{1}{H}\sum_{j=1}^{k} \mu_{F_i}(x)\eta_X^j & if \quad \exists j, \mu_{F_i}(x) > 0 \\ 0 & else \end{cases} \tag{15}$$

Where, $\eta_X^j = \frac{|F_j \cap X|}{|F_j|} = \frac{\sum_{x\in U} \min(\mu_{F_j}(x), \mu_X(x))}{\sum_{x\in U} \mu_{F_j}(x)}$, H is the number of the compatibility fuzzy classes which contain x and $\mu_{F_j}(x) \neq 0 (j = 1, 2, \cdots, h)$.

Property 4 $0 \leq \rho_X(x) \leq 1$.

Property 5 For $\forall A, B \subseteq U, \rho_{A\cup B}(x) \geq \max\{\rho_A(x), \rho_B(x)\}$.

Property 6 For $\forall A, B \subseteq U, \rho_{A\cap B}(x) \leq \min\{\rho_A(x), \rho_B(x)\}$.

4.4 *Example 2*

Both the values of condition attribute and those of decision attribute are fuzzy. The detail data of information system are shown in table 3.

Table 3 fuzzy information system

U	a_1	a_2	a_3	d_1	d_2
1	0.1	0.8	0.9	0.5	0.7
2	1.0	0.5	0.3	0.2	0.9
3	0.6	0.3	0.8	0.2	0.8
4	0.1	0.5	0.6	0.6	0.5
5	0.2	0.9	0.9	0.4	0.6
6	0.5	0.2	0.8	0.3	0.7
7	0.8	0.9	0.5	0.7	0.2
8	1.0	0.6	0.2	0.1	1.0

Using the formula (13) and (14), the lower approximation and the upper approximation of the objects can be obtained relatively to compatibility fuzzy-rough set.

The membership functions of the compatibility fuzzy-rough set can be obtained by formula (15), as shown in table 4.

Table 4 membership functions of the compatibility fuzzy-rough set

Object	$\rho_{d_1}(x)$	$\rho_{d_2}(x)$
1	0.10	0.10
2	0.18	0.30
3	0.24	0.24
4	0.10	0.10
5	0.20	0.20
6	0.16	0.16
7	0.50	0.20
8	0.12	0.20

5. Conclusions

The compatibility rough-fuzzy set and the compatibility fuzzy-rough set presented in the paper are the extension of rough-fuzzy set and fuzzy-rough set cited in [9-12] separately. For fuzzy decision system, the compatibility relation is the core of the compatibility rough-fuzzy set, while the fuzzy compatibility relation is the core of the compatibility fuzzy-rough set, which make the decision system be able to apply this kind of method effectively when noise and random disturbance exists, so that the practicability of the rough set is more distinct.

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Fuzzy adaptive H_∞ control for a class of uncertain nonlinear time-delay systems *

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Abstract. Combining both kinds of fuzzy logic forms including fuzzy T-S model and adaptive fuzzy logic systems, this paper presents an observer-based H_∞ control scheme for a class of uncertain nonlinear time-delay systems. Firstly, the fuzzy T-S model is used to approximate the nonlinear systems, and an observer is designed to observe the system states, and the fuzzy control law of the fuzzy model is derived by the LMI. Secondly, the adaptive time-delay fuzzy logic systems are constructed, and the modeling errors and the uncertain nonlinear parts are eliminated by a compensator based on the adaptive time-delay fuzzy logic systems with three adjustable parameters: weights, centers and widths. It is proved that the closed loop system satisfies the anticipant H_∞ performance, The simulation results demonstrate that the control scheme is effective.

Keywords: fuzzy T-S model, adaptive fuzzy logic systems, nonlinear systems, time-delay.

1. Introduction

In engineering, the existence of time-delay and uncertainties deteriorates the system performance. Time-delay and uncertainties pose great difficulties to the stabilization control design. Therefore, the problem of controller design for uncertain nonlinear time-delay systems has attracted considerable attention.

A typical approach of effective control for nonlinear time-delay systems is the local fuzzy-T-S- model-based linearization approach, and this approach has been successful applied in [1-2]. However, the modeling error is neglected in these studies. Therefore, the designed controller does not always guarantee the stability of the original system. Besides, in nonlinear modeling, the paper [3] considers that the modeling error has the upper bound, the papers [4-5] consider that the modeling error satisfies the matching condition, However, the upper bound and the matching condition are difficult to find in practice. The paper [6] designs a neural network compensator to compensate the modeling error. With regard to the uncertain nonlinearities in nonlinear systems, it is often required to satisfy the certain constraint in [7]. In fact, it isn't easy to look for the constraint condition. Meanwhile, the system states cannot be often directly measured in engineering. It is necessary to design the observer-based H_∞ control scheme.

The adaptive fuzzy logic systems have the universal approximation property and could uniformly approximate nonlinear continuous functions to an arbitrary accuracy. The adaptive fuzzy logic systems could sufficiently make use of the linguistic information and the expert information. The adaptive fuzzy logic systems are used to model uncertain nonlinear systems by a set of fuzzy "if-then" rules. When a proper control is given to the model, an anticipant output is produced from the nonlinear systems. At present, the adaptive fuzzy logic systems have been successfully used in nonlinear control [8-9].

Combining fuzzy T-S model and adaptive fuzzy logic systems, this paper presents a new H_∞ control scheme for a class of uncertain nonlinear time-delay systems. Firstly, the fuzzy T-S model is used to approximate the nonlinear systems, and the fuzzy controller is designed by the linear matrix inequalities to guarantee the stability of the fuzzy system. Secondly, the adaptive time-delay fuzzy logic systems are

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constructed, and the modeling error and the uncertain nonlinearities are eliminated by a compensator based on the adaptive time-delay fuzzy logic systems with three adjustable parameters: weights, centers and widths. It is proved that the closed-loop system satisfies the anticipant H_∞ performance. The simulation results demonstrate that the control scheme is effective.

2. Problem formulation

Consider the following uncertain nonlinear time-delay system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_2(x, x(t-\tau_1), \cdots, x(t-\tau_r), u) + \tilde{f}_2(x, x(t-\tau_1), \cdots, x(t-\tau_r), u) + d_2 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = f_4(x, x(t-\tau_1), \cdots, x(t-\tau_r), u) + \tilde{f}_4(x, x(t-\tau_1), \cdots, x(t-\tau_r), u) + d_4 \end{cases} \quad (1)$$

$$y = Cx$$

where $x_1, x_2 \in R^{n_1}$, $x_3, x_4 \in R^{n_2}$ are the measurable state vectors, $u \in R^m$ is the control input vector, f_2, f_4 are the known smooth nonlinear functions, $\tilde{f}_2, \tilde{f}_4$ are the unknown uncertain nonlinearities of the system. τ_i (for $i = 1,2,\cdots,r$) are the time delays. d_2, d_4 denote the external disturbance. Denote $x = [x_1^T, x_2^T, x_3^T, x_4^T]^T \in R^n$, $n = 2m, m = n_1 + n_2$, $d = [0, d_2^T, 0, d_4^T]^T$.

The known part of the system (1) can be approximated by a fuzzy T-S model composed of L rules. The *ith* rule of fuzzy model is in the following form: If $z_1(t)$ is F_1^i and, $\cdots$, and $z_s(t)$ is F_s^i Then

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + \sum_{l=1}^{r} A_{il} x(t-\tau_l) + B_i u(t) + d \\ y(t) &= Cx(t) \end{aligned} \quad , i = 1,2,\cdots,L \quad (2)$$

where $z_1(t), \cdots, z_s(t)$ are the premise variables, F_j^i (for $j = 1,2,\cdots,s$) are the fuzzy sets, L is the number of If-Then rules, A_i, B_i and A_{il} are some constant matrices with compatible dimensions.

$B_i = \begin{bmatrix} 0 & b_{i1}^T & 0 & b_{i2}^T \end{bmatrix}^T \in R^{n\times m}$, $b_{i1} \in R^{n_1\times m}$, $b_{i2} \in R^{n_2 \times m}$. The final output of the fuzzy system is inferred as follows

$$\dot{x}(t) = \sum_{i=1}^{L} \mu_i [A_i x(t) + \sum_{l=1}^{r} A_{il} x(t-\tau_l)] + \sum_{i=1}^{L} \mu_i B_i u(t) + d \quad (3.1)$$

$$y(t) = Cx(t) \quad (3.2)$$

where $\mu_i = v_i(z(t)) \Big/ \sum_{i=1}^{L} v_i(z(t))$, $v_i(z(t)) = \prod_{j=1}^{s} F_j^i(z_j(t))$, $F_j^i(z_j(t))$ is the grade of membership of $z_j(t)$ in F_j^i. It is easy to find that $\mu_i \geq 0$, for $i = 1,2,\cdots,L$ and $\sum_{i=1}^{L} \mu_i = 1$ for all t. Therefore, the modeling error and the uncertain nonlinearities of the nonlinear system (1) can be expressed as

$$B\Delta(x, x(t-\tau_1), \cdots, x(t-\tau_r)) = \begin{bmatrix} 0 \\ \Delta f_2 \\ 0 \\ \Delta f_4 \end{bmatrix} = \begin{bmatrix} x_2 \\ f_2 + \tilde{f}_2 \\ x_4 \\ f_4 + \tilde{f}_4 \end{bmatrix} - (\sum_{i=1}^{L} \mu_i [A_i x(t) + \sum_{l=1}^{r} A_{il} x(t-\tau_l)] + \sum_{i=1}^{L} \mu_i B_i u(t)) \quad (4)$$

where $B = \begin{bmatrix} 0 & I_{n_1} & 0 & 0 \\ 0 & 0 & 0 & I_{n_2} \end{bmatrix}^T$, $\Delta(x, x(t-\tau_1), \cdots, x(t-\tau_r)) = \begin{bmatrix} \Delta f_2 \\ \Delta f_4 \end{bmatrix}$.

For convenience, denote $\Delta(x, \tau) = \Delta(x, x(t-\tau_1), \cdots, x(t-\tau_r))$, therefore, the nonlinear system (1) could be rearranged as

$$\dot{x}(t) = \sum_{i=1}^{L} \mu_i [A_i x(t) + \sum_{l=1}^{r} A_{il} x(t-\tau_l)] + \sum_{i=1}^{L} \mu_i B_i u(t) + B\Delta(x, \tau) + d \quad (5.1)$$

$$y(t) = Cx(t) \tag{5.2}$$

3. The design of the output feedback controller

If we do not consider the effect of the $\Delta(x,\tau)$. Denote $\Delta(x,\tau)=0$ in (5.1). Design a controller to guarantee to stabilize the corresponding closed loop system of the linear part of the nonlinear system (5.1), and make the H_∞ performance satisfied. Because the state can not be measured, we design the observer-based output feedback controller.

The overall fuzzy observer and the overall feedback controller are given by

$$\dot{\hat{x}}(t) = \sum_{i=1}^{L}\mu_i[A_i\hat{x}(t) + \sum_{l=1}^{r}A_{il}\hat{x}(t-\tau_l)] + \sum_{i=1}^{L}\mu_i B_i u(t) + \sum_{i=1}^{L}\mu_i L_i(y(t)-\hat{y}(t)) \tag{6.1}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{6.2}$$

$$u(t) = \sum_{i=1}^{L}\mu_i K_i\hat{x}(t) \tag{6.3}$$

where L_i and K_i are matrixes with proper dimensions.

Denote $e(t) = x(t) - \hat{x}(t)$. Using (3.1) and (6) , we derive

$$\dot{e}(t) = \sum_{i=1}^{L}\mu_i[(A_i - L_iC)e(t) + \sum_{l=1}^{r}A_{il}e(t-\tau_l)] + d \tag{7}$$

Substituting (3.2) and (6.2) into (6.1), we derive

$$\dot{\hat{x}}(t) = \sum_{i=1}^{L}\sum_{j=1}^{L}\mu_i\mu_j[(A_i + B_iK_j)\hat{x}(t) + \sum_{l=1}^{r}A_{il}\hat{x}(t-\tau_l)] + \sum_{j=1}^{L}\mu_i L_i Ce(t) \tag{8}$$

Denote $\tilde{x}(t) = [\hat{x}^T(t), e^T(t)]^T$, the closed-loop system is yielded

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{L}\sum_{j=1}^{L}\mu_i\mu_j[\overline{A}_{ij}\tilde{x}(t) + \sum_{l=1}^{r}\overline{A}_{il}\tilde{x}(t-\tau_l)] + d' \tag{9}$$

where $\overline{A}_{ij} = \begin{bmatrix} A_i + B_iK_j & L_iC \\ 0 & A_i - L_iC \end{bmatrix}$, $\overline{A}_{il} = \begin{bmatrix} A_{il} & 0 \\ 0 & A_{il} \end{bmatrix}$, $d' = \begin{bmatrix} 0 \\ d \end{bmatrix}$.

Let us consider the H_∞ performance: For a prescribed attenuation $\rho > 0$, the H_∞ performance is achieved as

$$\int_0^T \tilde{x}^T(t)Q\tilde{x}(t)dt \le \tilde{x}^T(0)P\tilde{x}(0) + \sum_{l=1}^{r}\int_{-\tau_l}^{0}\alpha_l\tilde{x}^T(v)\tilde{x}(v)dv + \rho^2\int_0^T(d'^T d')dt \tag{10}$$

where P, Q are some symmetric and positive definite matrices, α_l (for $l = 1,2,\cdots,r$) are some positive scalars.

Theorem 1. There exists output feedback controller (6.3) so that the closed-loop system (9) satisfies the H_∞ performance (10), if there exist a symmetric and positive definite matrix P, a symmetric and positive definite matrix Q, and some positive scalars α_l (for $l = 1,2,\cdots,r$) satisfying

$$\overline{A}_{ij}^T P + P\overline{A}_{ij} + \sum_{l=1}^{r}\alpha_l^{-1}P\overline{A}_{il}\overline{A}_{il}^T P + \sum_{l=1}^{r}\alpha_l I + \frac{1}{\rho^2}PP + Q < 0 \quad (i,j = 1,\cdots,L) \tag{11}$$

Proof. Choose the *Lyapunov* function $V = \tilde{x}^T(t)P\tilde{x}(t) + \sum_{l=1}^{r}\int_{-\tau_l}\alpha_l\tilde{x}^T(v)\tilde{x}(v)dv$

$$\dot{V} = \dot{\tilde{x}}^T(t)P\tilde{x}(t) + \tilde{x}^T(t)P\dot{\tilde{x}}(t) + \sum_{l=1}^{r}\alpha_l\tilde{x}^T(t)\tilde{x}(t) - \sum_{l=1}^{r}\alpha_l\tilde{x}^T(t-\tau_l)\tilde{x}(t-\tau_l)$$

$$= (\sum_{i=1}^{L}\sum_{j=1}^{L}\mu_i\mu_j[\overline{A}_{ij}\tilde{x}(t) + \sum_{l=1}^{r}\overline{A}_{il}\tilde{x}(t-\tau_l)])^T P\tilde{x}(t) + \tilde{x}^T(t)P(\sum_{i=1}^{L}\sum_{j=1}^{L}\mu_i\mu_j[\overline{A}_{ij}\tilde{x}(t) + \sum_{l=1}^{r}\overline{A}_{il}\tilde{x}(t-\tau_l)])$$