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REDUCING THE IMPACT OF UNCERTAINTIES IN NETWORKED CONTROL SYSTEMS USING TYPE–2 FUZZY LOGIC

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The networked control systems (NCS) have grown in popularity in recent years. Despite their advantages over the traditional control schemes, some of their drawbacks emerged as well (time delays, packet losses). There are several ways of dealing with the time delays and packet losses in NCS, but only a few authors have ever used type-2 fuzzy controllers for this purpose to our knowledge. This paper is aimed at dealing with the negative effects that occur in NCS, by using type-2 fuzzy control systems. It is presented that this approach can be successfully used to decrease the effects of time delays and packet losses. A type-2 fuzzy controller has been designed and compared to a type-1 fuzzy controller. The intervals of type-2 fuzzy controller were optimized via genetic algorithm.

K e y w o r d s: networked control systems, packet loss, time delay, true time, type-2 fuzzy logic

1 INTRODUCTION

Networked control systems and their drawbacks have been investigated for a couple of years. The growth of their use is caused by fusing of traditional automation with the technologies of computer networks. According to [1, 2] a NCS is a distributed control structure where the communication between the nodes of the control system is provided by a communication network. The basic elements of a NCS are sensors, controllers, actuators and the communication network. The reasons for using NCS in automation are quite obviously inspired by the computer networks. The advantages stemming therefrom are: relatively cheap installation cost, use of standardized hardware, transparent infrastructure, ability to expand the system in the future, and a good resistance to interferences. The main advantage is of course the cost effectiveness [3, 4].

The most common types of NCS used are the wired systems because of their security and reliability. However, nowadays the deployment of wireless control systems is on the rise due to their massive use in computer networks, reduced installation cost, lower operating cost, installation flexibility, and scalability [5]. The wireless standards from computer networks have to be modified to be applicable in industrial environment and IWLAN or Zigbee are examples of the recent development in the industrial wireless standards. According to [6] the wireless technologies allow low cost access to additional measurements that would otherwise be too expensive to be installed. Therefore, these additional measurements contribute to the increased safety of the plant.

The problems that both the wired and wireless NCS share are the time delays and packet losses in the network. Both of these problems are addressed by a number of ways which are discussed in section II. It is shown that one way of dealing with time delays and packet losses in industrial networks is the use of type-2 fuzzy sets. We show that the type-2 fuzzy approach is capable of delivering good control results when used in NCS and is an acceptable alternative to other conventional methods. We go even further by optimizing the control performance of the controller by the use of genetic algorithms. For the simulation of real network traffic the TrueTime software was used [3]. By joining the control circuit and TrueTime network components it was possible to change the number of nodes in the network and the sampling time, thus the load of data on the network caused variable time delays of the packets and packet losses. This was helpful in checking the possibilities of type-2 fuzzy controllers in NCS.

2 VARIABLE TIME DELAY AND PACKET LOSS

Variable time delays

The variable time delay is one of the most common problems in NCS. The existence of time delay can have eminent negative impact on the performance of the control loop and can cause its instability [6-8]. The time delay in the network depends on the load of the network, packet priority, interference, and performance of the devices in the network when processing data [9]. It depends also on the design of the transfer protocol of the bus. The transfer protocol influences the timing of the packets and the priority of the media access.

Some authors lump together the delay that occurs in the controller with the delay between the controller and the actuator or with the delay between the sensor and the actuator, due to easier analysis. The lumped delays are entitled as the delay between the sensor and the controller (sensor-to-contoller) - sc and the delay between the controller and the actuator - ca [2, 9-11]. There have been several ways of dealing with the time delays in NCS based

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on fuzzy logic. A Smith prediction compensator combined with fuzzy immune PI controller is used in [12]. A Takagi-Sugeno fuzzy NCS with the compensation of time delays and packet dropouts was proposed in [13]. A similar approach but in a decentralized system is proposed in [14]. A Smith predictor and a parallel fuzzy PI controller was designed in [15].

The type-2 fuzzy approach has also been used to suppress the effects of time delays in control systems. A fuzzy neural network based on the adaptive interval type-2 fuzzy logic was used in [16], where the authors adjusted weights, centers and widths of the proposed fuzzy neural network. The proposed scheme guarantees the H1 tracking for SISO time-delay nonlinear systems althought not necessarily NCS. The type-2 fuzzy neural structure was also successfully utilized in [17], where it was used for indentification and control of time-varying plants. The authors of [18] extended the Takagi-Sugeno fuzzy model approach to the stability analysis and controller design for interval type-2 fuzzy systems with time-varying delays. Delay-dependent robust stability criteria were developed in terms of linear matrix inequalities by using the improvement technique of free-weighting matrices.

Packet loss

The other common problem that occurs in NCS is packet loss. Like time delay in the system, packet loss has also impact on the performance of the control loop and it can cause instability [19]. Packet loss in the network usually occurs when the signal on the medium is distorted (interference, deffective medium), when the network is overloaded, the data packets are defective, or some of the network hardware is defective. If the network is overloaded, some of the data packets are omitted from the communication to free up the medium, free up the buffers and to inform the transmitting nodes to lower their demands for the medium [19].

The packet loss is more likely in the networks where the access to the medium is nondeterministic, in the networks where for the interconnection of the nodes switches or routers are used and of course in wireless networks. Wireless networks are less resistant to interference. The circumstances that lead to the reduction of signal intensity are also an adverse factor. The authors of [20] verified the increase of packet loss in the ZigBee network by interfering the transmission by another transmission in the same frequency band. They explored the dependence of packet loss on the distance of the transmitting nodes and on the frequency deviation of the nodes.

The packet loss can be divided according to the area where it originates into:

- packet loss between the sensor and the controller
- packet loss between the controller and the actuator

The authors are often treating the packet loss and the time delay together because of the similar effects they have on the network. In the literature there have been a number of ways of designing controllers capable of treating packet losses in the network. The packet losses in fuzzy systems are dealt with in [21], where a new digital controller using the intelligent digital redesign for nonlinear systems is proposed. Another fuzzy approach is the T-S fuzzy model-based fault detection for NCS with time delays and packet losses.

An interval type-2 Takagi-Sugeno FLC design for a class of nonlinear singular NCS encountering data-transmission delay and packet loss problems was proposed in [22], where the concept of parallel distributed compensation was employed to design the interval type-2 T-S FLC. Another example of using type-2 fuzzy approach to suppress packet losses in the systems includes video streaming across IP networks [23] where interval type-2 fuzzy logic congestion control was utilized. In the next sections the existing results will be improved with the use of genetic algorithms. It will be shown that the type-2 fuzzy approach is very useful in NCS controller design when time delays and packet losses are present in the network.

3 TYPE–2 FUZZY LOGIC SYSTEM

Past research has shown that the type-1 fuzzy logic controllers may have difficulties in modeling and minimizing the effects of uncertainties. Type-2 fuzzy sets, characterized by membership grades that are themselves fuzzy, were introduced by Zadeh in 1975 to better handle uncertainties [24, 25]. Type-2 fuzzy logic controllers have been extensively studied since then and it has been proven that they are able to eliminate oscillations in the control loop and can better cope with modeling uncertainties [26, 27].

A type-2 fuzzy set in the universal set X is denoted as $\tilde{A}$, which is characterized by a type-2 membership function $\mu_{\tilde{A}}(x)$, in (1), that can be referred to as a secondary membership function (MF) or also as a secondary set, which is a type-1 set in [0, 1]. In (1) $f_x(u)$ is a secondary grade, which is the amplitude of a secondary MF; *ie* $0 \le f_x(u) \le 1$. The domain of a secondary MF is called the primary membership of x. In (1), J_x is the primary membership of x, where $u \in J_x \subseteq [0,1]$ for $\forall \in X$; u is a fuzzy set in [0,1], rather than a crisp point in [0,1], [28].

$$\tilde{A} = \int_{x\in X} u_{\tilde{A}}(x)/x = \int_{x\in X} \left[\int_{u\in J_x} f_x(u)/u \right] /x, \quad J_x \subseteq [0,1] \tag{1}$$

When $f_x(u) = 1, \forall u \in J_x \subseteq [0,1]$, the secondary MFs are interval sets such that $\mu_{\tilde{A}}(x)$ in (1) can be called an interval type-2 MF, [34]. Therefore, type-2 fuzzy set $\tilde{A}$ can be rewritten as

$$\tilde{A} = \int_{x\in X} \left[\int_{u\in J_x} 1/u \right] /x, \quad J_x \subseteq [0,1]. \tag{2}$$

Different types of interval type-2 fuzzy membership functions are described in several papers. In this paper

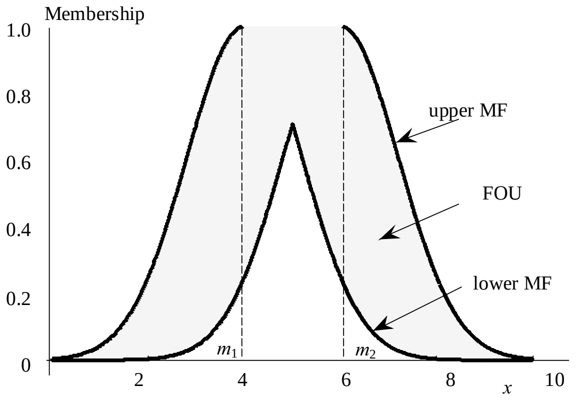

Fig. 1. Gaussian MF with uncertain mean (3)

the Gaussian membership functions with uncertain mean values are used, Fig. 1.

$$\mu_{\tilde{A}}(x) = \exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right], \quad m \in [m_1, m_2]. \tag{3}$$

As one can see in Fig. 1 the region of the Gaussian MF with uncertain mean can be bounded by upper $\overline{\mu}_{\tilde{A}}(x)$ and lower $\underline{\mu}_{\tilde{A}}(x)$ MF and it is called the footprint of uncertainty (FOU). Type-2 fuzzy logic system is similar to type-1 fuzzy logic in its structure. It consists of these five main parts: fuzzifier, rule base, inference engine, type-reducer, and defuzzifier.

The type-2 fuzzy rule base consists of a collection of IF-THEN rules where the antecedents and the consequents are represented by type-2 fuzzy sets. With M rules, p inputs and one output the lth rule has the form

$$\begin{aligned} R^l:\ \text{IF } x_1 \text{ is } \tilde{F}_1^l \text{ and } \dots \text{ and } x_p \text{ is } \tilde{F}_p^l, \\ \text{THEN } y \text{ is } \tilde{G}^l, \quad l = 1, \dots, M \end{aligned} \tag{4}$$

The inference engine combines the rules and gives a mapping from input type-2 fuzzy sets to output type-2 fuzzy sets. The inference engine in type-2 fuzzy logic systems uses the extended sup-star composition. The output of the inference engine block is a type-2 set. Type reduction is used to reduce the type-2 fuzzy set to a type-1 fuzzy set. Many type reductions like centroid, height or modified weight have been presented but the center-of-sets is a commonly used one.

$$\begin{aligned} Y_{cos}(x) = [y_l\ y_r] = \\ \int_{y^1} \cdots \int_{y^M} \int_{f^1} \cdots \int_{f^M} 1 / \frac{\sum_{i=1}^{M} f^i y^i}{\sum_{i=1}^{M} f^i} \end{aligned} \tag{5}$$

The whole procedure for computing y_l and y_r is described in [35]. The crisp value can be computed as

$$y(x) = \frac{y_l + y_r}{2} \tag{6}$$

In this paper the type-2 fuzzy logic system as a controller for the networked control system is used. It will be shown that if network problems are considered as uncertainties, the use of the type-2 fuzzy logic controller can a be beneficial solution.

4 GENETIC ALGORITHMS

The genetic algorithm (GA) is a stochastic algorithm based on the principles of evolution and it has been applied to various optimization problems. To solve a problem, a GA maintains a population of individuals and probabilistically modifies the population by genetic operators such as selection, crossover and mutation, with the intent of seeking a near-optimal solution to the problem [31].

In each generation for which the GA runs, each individual in the population is evaluated against the unknown environment. The fitness values are associated with the values of the objective function. Genetic operators drive the evolutionary process of a population in GA, after the Darwinian principle of survival of the fittest and naturally occurring genetic operations. To perform genetic operators, one must select individuals in the population to be operated on. The selection strategy is based on the fitness level of the individuals actually presented in the population or random. After a new population is formed by the selection process, some members of the new populations undergo transformations by means of genetic operators to form new solutions (a recombination step) [31].

In this paper we use a GA to optimize the parameters of a Type-2 FLC. We consider to tune the parameters of an interval singleton type-2 FLS when the antecedent membership functions are Gaussian primary membership functions with uncertain means m_1, m_2. The Centers Of Sets (COS) of consequents c_1, c_2 are optimized too according to Mendel [30]. We encoded a total of 35 parameters for each individual (FLC) of our population. The number of chromosomes in each generation was set to 25 and the number of generations was 1000. Distributed computing methods for speeding up the simulations were used as well.

5 EXPERIMENTS AND RESULTS

This section presents the experimental comparison of fuzzy systems deployed in network control. The Matlab/Simulink simulation environment has been used to construct the simulation schemes and to perform the experiments. The schemes consisted of blocks that represented the controlled plant, the FLC, and the network components. Furthermore, we have chosen the contolled plant to be the plant from [2] as follows

$$G_p(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \tag{7}$$

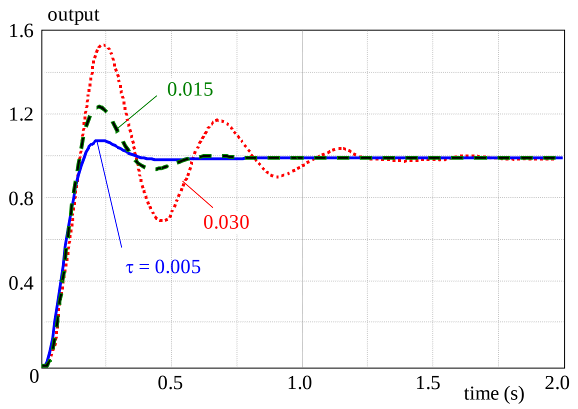

Fig. 2. Impact of time-delay in the network on Type-1 FLC

Table 1. Mean values for input MF

	NB	NS	Z	PS	PB
e	−1.20	−0.60	0	0.60	1.20
ie	−0.12	−0.06	0	0.06	0.12

Table 2. Output MF height values

e/ie	NB	NS	Z	PS	PB
NB	−0.2495	−0.2268	−0.2041	−0.1814	−0.1588
NS	−0.1417	−0.1247	−0.1021	−0.0794	−0.0567
Z	−0.0454	−0.0227	0	0.0227	0.0454
PS	0.0567	0.0794	0.1021	0.1247	0.1474
PB	0.1588	0.1814	0.2041	0.2268	0.2495

The NCS has been created by means of TrueTime, which is a toolbox that provides models of various communication networks and their components. The basic attributes of the wireless networks are located in the TrueTime Wireless Network block, where we altered the type of the network, number of nodes or the probability of packet loss during the simulations. The individual nodes are represented by the TrueTime Send and the TrueTime Receive blocks, which are designed to exchange data. We found out that the ZigBee wireless network suits our needs due to the sufficient number of attributes that can be altered.

The type-1 FLC was designed as a conversion of the PI controller from [2]. The corresponding fuzzy system uses a singleton fuzzifier, a product-inference rule, and a height defuzzifier to obtain the crisp output value. The intervals of the universes for the controller error and the integral of error were covered with 5 type-1 Gaussian membership functions. The standard deviation was 0.3 for the error and 0.03 for the integral of error. The mean values and the heigth values for the output membership functions were set according to following tables.

Similarly as in [2], we have verified how the type-1 FLC can handle growing time-delay. However, neither the FLC can completely suppress the influence of time-delay on the controlled system, as is shown in Fig. 2. The time-delay in the network is denoted by and consists of the sum of the time-delays between the sensor and the controller and between the controller and the actuator. We omitted the computational delay because it is negligible compared to the time-delay in the network.

The parameters of the control system that cause performance degradation can be considered as uncertainties. These parameters can vary arbitrarily and therefore they have to be considered during the design of the control system. Mendel has shown in [35] that type-1 FLCs can not cope with these uncertainties. However, the uncertainties can be included in type-2 FLCs.

A custom designed type-2 FLC can improve the performance of the control system, but we wanted to compare the maximum possible improvement. Therefore we used genetic algorithm optimization, as it is one of the most popular optimization methods. The authors of [32] also presented that the use of GA optimization to evolve the type-2 FLCs can outperform type-1 FLCs that have more design parameters. Thus, the type-2 FLC is more appealing than its type-1 counterpart with regards to accuracy and interpretability.

The principle of GA optimization has been used in the experiments to optimize the parameters of type-2 FLC for the purpose of improving the performance of the control system. In order to correctly evaluate the results of the experiments, the parameters of the intervals were found in the vicinity of the original type-1 FLC. The experiments to compare the performance of type-1 and type-2 FLC were carried out and they are presented in the next sections.

Network delays

The networked control systems usually consist of a vast number of network nodes. There can even be several independent control systems in the same network. If there is a high number of nodes in the network, it is usual that some of them want to transmit data at the same time. Therefore, depending on the Media Access Protocol (MAC) method, the samples from the sensor or the controller can be delayed. For example, the CSMA/CD method uses exponential backoff that can delay the packet transmission for a long time and causes nondeterministic packet transmissions. However, some of the protocols exploit the priority of devices and alleviate the problem.

The network in the next experiment consisted of a number of nodes with periodic data transmissions. The intervals for the input and output fuzzy sets of type-2 FLC are in the following tables.

The setup of the simulation scheme and the number of nodes in the scheme has naturally caused that some of the nodes have been trying to transmit data at the same time, resulting in network overload and communication delay. Therefore, the performance of the control system was significantly deteriorated, with the deterioration mainly emerging in the step responses. Fig. 3 presents the graphical result of such an experiment where the type-1

Table 3. Optimized MF input values $\{M_1, M_2\}$

	NB	NS	Z	PS	PB
e	$\{-1.24, -1.16\}$	$\{-0.67, -0.53\}$	$\{-0.31, 0.31\}$	$\{0.37, 0.83\}$	$\{0.69, 1.71\}$
ie	$\{-0.20, -0.04\}$	$\{-0.01, -0.02\}$	$\{-0.03, 0.03\}$	$\{0.02, 0.10\}$	$\{0.11, 0.13\}$

Table 4. Optimized MF input values $\{C_1, C_2\}$

e/ie	NB	NS	Z	PS	PB
NB	$\{-0.30, -0.20\}$	$\{-0.41, -0.04\}$	$\{-0.51, 0.10\}$	$\{-0.44, 0.08\}$	$\{-0.40, 0.08\}$
NS	$\{-0.24, -0.05\}$	$\{-0.20, -0.04\}$	$\{-0.76, 0.56\}$	$\{-0.60, 0.44\}$	$\{-0.93, 0.82\}$
Z	$\{-0.99, 0.89\}$	$\{-0.14, 0.10\}$	$\{-0.89, 0.89\}$	$\{-0.65, 0.70\}$	$\{0.01, 0.07\}$
PS	$\{-0.91, 1.01\}$	$\{-0.72, 0.87\}$	$\{-0.26, 0.46\}$	$\{-0.03, 0.28\}$	$\{-0.24, 0.53\}$
PB	$\{-0.04, 0.35\}$	$\{-0.79, 1.15\}$	$\{-0.32, 0.73\}$	$\{-0.09, 0.55\}$	$\{-0.18, 0.68\}$

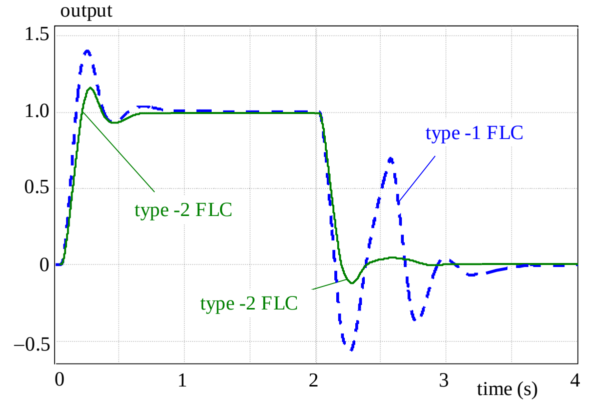

Fig. 3. Control performance of a system with multiple nodes

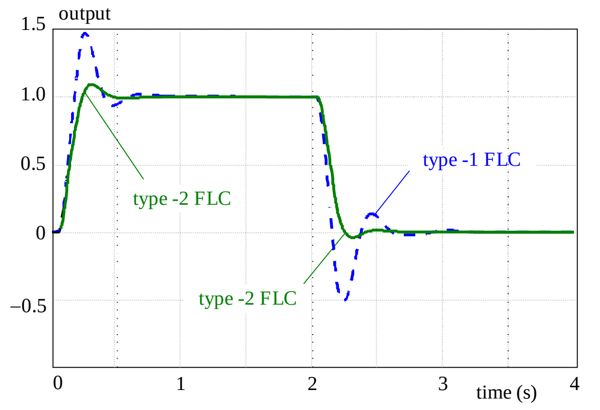

Fig. 4. Control performance of a system with packet dropout

FLC can not handle the communication delays very well, particularly in the second half of the simulation. However, the type-2 FLC exhibited much lover overshoot and oscillation rate.

Packet dropout

The nodes of a NCS can be spaced apart unevenly, what on a large distance can cause packet losses between the nodes. The dropout is frequently caused by a damaged packet that has to be dropped because the higher level protocols can not repair its content. Altough in some cases the retransmission of the packet is possible, the rapidly operating systems usually immediately discard it.

Complete packet loss where the packets are not damaged and dropped, but completely lost during the transmission is typical for the wireless systems due to the characteristics of the environment. A very noisy environment significantly affects the quality of the transmitted signal. An example of this issue is the popular 2.4 GHz frequency band, where the technologies like ZigBee, Bluetooth or IEEE 802.11 (known as Wifi) can interfere with each other. Hence the results of the next experiment present the influence of the packet loss in a wireless control network. The input and output intervals of the fuzzy sets of the type-2 FLC are in Tab. 5 and Tab. 6.

The consequence of the packet dropouts is the performance deterioration of the control system. This deterioration is not very significant in the systems with longer sampling periods, due to sufficient time for retransmitting the packet. However, the packet dropout can significantly affect the performance and the stability of rapid control systems with very short sampling periods. The effect of the dropouts is the most significant in the step responses. Some of the controllers turn off the control action (or set it to zero) if they register packet dropouts from the sensors. A comparison of the control performances of systems with type-1 and type-2 FLCs is presented in Fig. 4. The figure shows that the type-2 FLC handles the negative effect of packet dropouts in the network better than the type-1 FLC.

Discussion

The presented simulation results show that the type-2 FLC handles the negative influences of the time delays and packet dropouts much better than the type-1 FLC. The input and output fuzzy set intervals include the delays and dropouts as uncertainties and contribute to the

Table 5. Optimized MF input values $\{M_1, M_2\}$

	NB	NS	Z	PS	PB
e	$\{-2.14, -0.26\}$	$\{-1.33, 0.13\}$	$\{-0.45, 0.45\}$	$\{0.26, 0.94\}$	$\{1.10, 1.30\}$
ie	$\{-0.21, -0.03\}$	$\{-0.12, 0.00\}$	$\{-0.01, 0.01\}$	$\{0.05, 0.07\}$	$\{0.09, 0.15\}$

Table 6. Optimized MF input values $\{C_1, C_2\}$

e/ie	NB	NS	Z	PS	PB
NB	$\{-0.69, 0.19\}$	$\{-0.97, 0.52\}$	$\{-0.43, 0.02\}$	$\{-0.02, -0.16\}$	$\{-0.22, -0.10\}$
NS	$\{-0.44, 0.14\}$	$\{-0.19, -0.06\}$	$\{-0.89, 0.69\}$	$\{-1.03, 0.87\}$	$\{-0.71, 0.60\}$
Z	$\{-1.02, 0.93\}$	$\{-0.45, 0.41\}$	$\{-0.53, 0.53\}$	$\{-0.50, 0.55\}$	$\{-0.75, 0.84\}$
PS	$\{-0.68, 0.79\}$	$\{-0.35, 0.51\}$	$\{-0.85, 1.05\}$	$\{-0.85, 1.10\}$	$\{-0.01, 0.31\}$
PB	$\{-0.20, 0.52\}$	$\{-0.78, 1.14\}$	$\{-0.69, 1.10\}$	$\{-0.16, 0.61\}$	$\{0.15, 0.35\}$

reduction of their effects on the control system. This argument is also supported by the control performance evaluation by means of the IAE and ITAE criteria (Tab. 7). The graphs of the step responses present the ability of the type-2 FLC to suppress the overshoot and to shorten the settling time.

6 CONCLUSION

The possibility of using type-2 FLCs in networked control systems has been presented in this paper. The main reason of the experiments utilizing type-2 FLCs was that there has been a number of control algorithms that deal with variable time-delays and packet losses in NCS but only a few have used type-2 fuzzy systems. Hovewer, in our opinion, the characteristics of type-2 FLCs predispose them for that particular use.

It was presented that the time delays and packet dropouts can be handled as uncertainties of the type-2 fuzzy sets. Hence, two sets of experiments were performed where the control performance of a type-1 FLC and a type-2 FLC was compared. The first set of experiments involved variable time-delay in the network induced by a number of simultaneously transmitting nodes, whereas the second set of experiments involved packet dropouts in the wireless ZigBee network. To ensure the fairness of the comparison, the type-1 FLC was designed as a conversion of the PI controller from [2] and it was equal to the type-2 FLC without considering the uncertainties. Altough the uncertainties in the fuzzy sets of the type-2 FLC were the only difference between the two controllers used in the experiments, their regions were optimized by a genetic algorithm and the results present that the use of GA optimization to evolve the type-2 FLCs can outperform type-1 FLCs.

In addition to the graphical comparison of control performance of the FLCs, we also evaluated the performance by means of the IAE and ITAE criteria and concluded that the type-2 FLC handles the uncertainties in the NCS better than the type-1 FLC. In the future a more frequent use of type-2 fuzzy systems in the field of NCS is expected.

Table 7. Performance

	Criteria	type-1 FLC	type-2 FLC
Network delays	IAE	0.5875	0.3586
	ITAE	0.9913	0.3973
Packet dropout	IAE	0.4530	0.3361
	ITAE	0.557	0.3728

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