A Review on Type-2 Fuzzy Systems in Robotics and Prospects for Type-3 Fuzzy

Fevrier Valdez, Oscar Castillo, and Patricia Melin

Abstract In this article, we are offering a review of type-2 fuzzy systems and their current applications in robotics. Although, significant research work has been put forward in to showing that fuzzy systems have very good capabilities for coping with uncertainty in control applications, there is still room for improvement and this is why the interest of doing this research work. Nowadays, fuzzy logic systems are used frequently to manage uncertainty because the obtained results have been superior to traditional methods. However, when the uncertainty on the problems is high fuzzy logic is not able of manage adequately the uncertainty. For that reason, the authors are utilizing type-2 fuzzy logic to obtain better results on the control problems. In this article, we have made a review over the papers using type-1 and type-2 fuzzy systems, specifically when they are utilized in robotics. The analysis was made with several searches, for example, using nature optimization methods with type-2 fuzzy in robotics and also without the utilization of optimization methods. The collection of papers was obtained from Web of Science (WoS) and the visual tool 'connected papers'. We also briefly discuss the prospects for the utilization in the future of type-3 fuzzy systems in robotics.

Keywords Type-2 fuzzy logic · Robotics · Optimization · Type-3 fuzzy systems

1 Introduction

The main motivation of this article was performing an exhaustive review of fuzzy systems and their applications in different kinds of robotic systems. In addition,

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O. Castillo et al. (eds.), *Applied Mathematics and Computational Intelligence*,
Springer Proceedings in Mathematics & Statistics 413,
https://doi.org/10.1007/978-981-19-8194-4_17

as a natural evolution of fuzzy theory, we also discuss the possible utilization of type-3 fuzzy logic in robotics and control. Nowadays, it is very popular the use of type-2 techniques [31] to improve the performance in several areas, for instance, in [19] it was proposed a type-2 fuzzy logic controller (FLC) for the real-time control of mobile robots [25, 28, 37, 12]. The authors used the type-2 FLC to design and implement a variety of robotic behaviors on different platforms in indoor and outdoor unstructured and challenging dynamic (changing) environmental situations. According to site https://www.connectedpapers.com/ and taking as reference the work above mentioned, in Fig. 1, we found the connected papers with the reference [19], as can be seen, since 2004 the number of works in the area has been increasing steadily.

Also, in Table 1, the derivative works of the paper [19] are presented.

These are papers that cited many of the papers in the graph. This means that they are either surveys of the field or recent relevant works which were inspired by many papers in Figure 1.

Also, in [8], A New Meta-Heuristics of Optimization with Dynamic Adaptation of Parameters using Type-2 Fuzzy Logic for Trajectory Control of a Mobile Robot was proposed. Also, according to site https://www.connectedpapers.com/ and taking as reference the paper [8], in Figure 2, we found the connected papers with the reference [8], as can be seen, this work is more recent than the before analyzed work. However, the number of works is increasing in the last years. Also, Table 2 is presented the derivative works of the paper [8]. These are papers that cited many of the papers

Fig. 1 Connected papers with the paper 'A type-2 fuzzy logic controller for autonomous mobile robots' [19]

Table 1 Derivative works of the paper by Hagras in [19]

Paper	Last author	Year	Citations
Advances in type-2 fuzzy sets and systems [30]	Jerry M., Mendel	2007	344
Derivation and analysis of the analytical structures of the interval type-2 fuzzy-PI and PD controller [14]	Hao, Ying	2010	77
Adaptive type-2 fuzzy logic control of a bioreactor [18]	Bartolomeo, Cosenza	2010	9
A dynamic defuzzification method for interval type-2 fuzzy logic controllers [48]	Ibrahim, Eksin	2011	6
Systematic design of type-2 fuzzy logic systems for modeling and control with applications to modular and reconfigurable robots [6]	Mohammad, Biglarbegian	2010	2
Analysis and control of mobile robots in various environmental conditions [18]	S., Mahapatra	2012	1
Control of an ambiguous real time system using interval type 2 fuzzy logic control [50]	Deepa, Thangavelusamy	2017	1
A comparison of type-1 and Type-2 fuzzy logic controllers in robotics: a review [39]	Syed Wakil, Ah-mad	2015	0
Circumventing the fuzzy type reduction for autonomous vehicle controller [1]	Al-Rikabi	2017	0
Novel fuzzy techniques for modelling human decision making [33]	Salang, Musika	2013	0

in the graph. This means that they are either surveys of the field or recent relevant works which were inspired by many papers in Fig. 2.

The remaining sections of this article are formed in the following fashion. In Section 2, a sample of papers from the review of the literature is offered. In Section 3, the review of Type-2 fuzzy logic in robotic applications is shown, and Section 4 outlines the review with Type-1 fuzzy logic in robotics. Lastly, in Section 5, the conclusions are outlined.

2 Literature Review

In this section, we briefly describe a sample of the papers that have utilized type-2 fuzzy in robotic applications. These papers offer an idea of the kind of works that have been done in this area.

In [36], controlling a robotic manipulator was intended under significant external perturbations and parametric uncertainties. The authors decided to use Type-2 fuzzy logic as an adequate choice to cope with the uncertainty of dynamic environments,

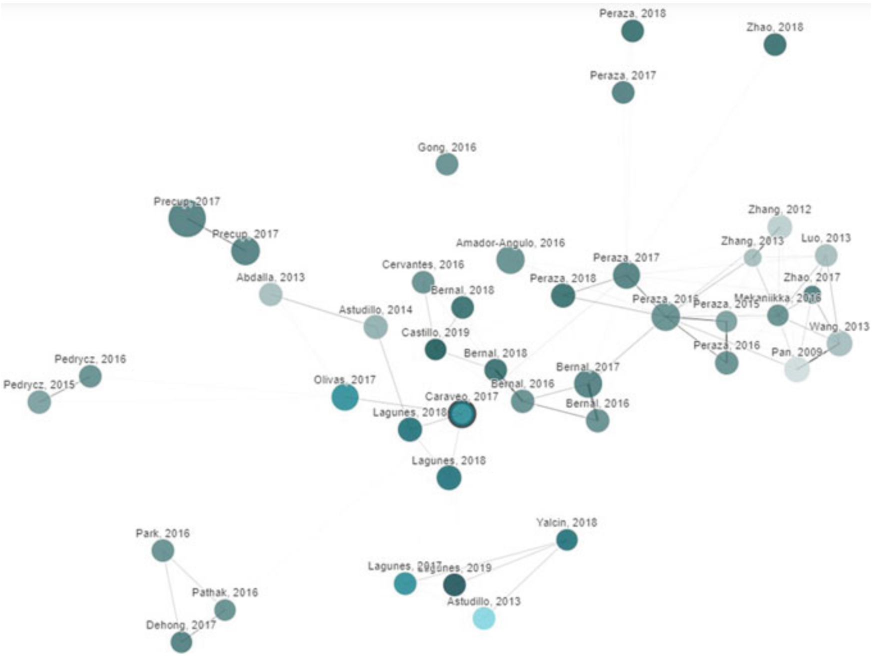

Fig. 2 Connected papers with the paper 'a new meta-Heuristics of optimization with dynamic adaptation of parameters using type-2 fuzzy logic for Trajectory control of a mobile robot' [8]

for example, the utilization of membership functions with fuzzy values. Also, they used a neural network to achieve additional robustness behavior. In this case, the initial rules are based on a sliding surface of a controller, and in this way, it can improve the system's performance.

In [44], a review of recent type-2 fuzzy controller applications was described. The authors made a survey about the applications of controllers, encompassing areas such as robotics, manufacturing systems, electrical systems, and aircraft control. The most promissory ones have been found to be in the robotics and automotive areas, where type-2 FLCs have exhibited to perform better than their type-1 fuzzy counterparts and also with respect to traditional controllers.

In [40] an alternative systematic methodology to explicitly derive membership functions for both type-1 FLC and interval type-2 FLC was presented. The proposed approach to obtain a closed-form relationship between inputs and output offers information on their impact on the footprint of uncertainty parameters. Also, in [23], a novel application of genetic algorithms (GA) optimization approach to optimize the scaling factors of interval type-2 fuzzy proportional derivative plus integral controllers is proposed for 5-degrees of freedom redundant robot manipulator for trajectory tracking task.

Table 2 Derivative works of the paper [8]

Paper	Last author	Year	Citations
Optimization of membership function parameters for FLCs of an autonomous mobile robot using the flower pollination algorithm [38]	José, Soria	2018	3
Path Finding for a Mobile Robot Using Fuzzy and Genetic Algorithms [26]	Arbnor, Pajaziti	2017	2
Comparative Study in FLC Optimization using Bee Colony, Differential Evolution, and Harmony Search Algorithms [9]	Cinthia, Peraza	2019	2
Optimization of FLCs Using Galactic Swarm Optimization with Type-2Fuzzy Dynamic Parameter Adjustment [4]	Fevrier, Valdez	2019	2
Comparative Study of the Conventional Mathematical and FLC for Velocity Regulation [49]	Cinthia, Peraza	2019	1
Shadowed Type-2 Fuzzy Systems for Dynamic Parameter Adaptation in Harmony Search and Differential Evolution Algorithms (Castillo et al. 2019b)	Patricia, Ochoa	2019	1
Intelligent Information and Database Systems [35]	Bogdan, Trawin ski	2019	0
Interval Type-2 fuzzy logic for dynamic parameter adjustment in the imperialist competitive algorithm [5]	Fevrier, Valdez	2019	0
On Characterizations of Directional Derivatives and Sub differentials of [51]	Dong, Qiu	2017	0

In [11], a type-2 fuzzy logic controller (FLC) is proposed, in their work for robot manipulators with joint elasticity and structured and unstructured dynamical uncertainties, a controller is based on a sliding mode control strategy. To enhance the real-time functioning of the controller, the simpler interval type-2 fuzzy sets were used. On the other hand, in [22], a novel concept of an interval type-2 fractional-order fuzzy PID (IT2FO-FPID) controller, which requires fractional-order integrator and fractional-order differentiator, is proposed. The incorporation of Takagi–Sugeno-Kang (TSK) type interval type-2 fuzzy logic controller (IT2FLC) with fractional controller of PID-type is investigated for time response measure due to both unit step response and unit load disturbance. Also, in [16], a computationally efficient systematic procedure to design an optimal type-2 fuzzy logic controller was proposed. The most important idea was to optimally find the controller gains using the particle swarm algorithm, and then optimally find the membership function parameters utilizing a more basic genetic algorithm.

In [32], an H-infinity output feedback controller is developed for a class of time-delayed MIMO nonlinear systems, containing backlash as an input nonlinearity. More specifically, a state observer is put forward to estimate non-measurable states. The control strategy was segmented into two modules: a type-2 fuzzy module that approximates the uncertainty in the model, and an H-infinity-based controller module that reduces the effects of external perturbations.

In [2], a stable robust adaptive interval type-2 fuzzy H-2/H-infinity, controller (RAIT2FH(2)H(infinity)C) for a class of uncertain nonlinear systems was proposed, which aims to address the above concerns through its hybrid robust/adaptive structure. More specifically, the H-2 energy and tracking function is optimized with respect to a H-infinity, perturbation attenuation constraint, while the interval fuzzy system manages the uncertainty in the approximation of the unknown system dynamics. In [13], an interval type-2 fuzzy logic controller is designed for under actuated truss-like robotic finger to accomplish the goal of stabilization in its equilibrium point. In addition, the behaviors of the controller are compared with respect to the type-1 fuzzy case to highlight the advantages of the type-2 approach.

In [10], a method for finding the optimal value of n in type-n fuzzy systems is presented. Also, in this work, the author proposed the utilization of bio-inspired optimization algorithms with fuzzy dynamic parameter adaptation for obtaining the optimal n value. The proposed approach may be utilizable in optimally designing type-3 (or higher type) fuzzy controllers in robotics, which could potentially (in the near future) achieve higher performance than type-2 fuzzy control. More in the long-term future, it is possible that type-4 fuzzy or even higher type-n could be applicable to real problems in diverse areas, such as control, pattern recognition, medical diagnosis, and time series prediction.

An optimal interval type-2 fuzzy logic control-based closed-loop drug administration to regulate the mean arterial blood pressure is presented in [42] which consisting of an interval type-2 fuzzy controller, which acts as pre-compensator to the traditional PID controller is presented, to regulate the mean arterial blood pressure of a patient by administering the drug sodium nitroprusside in a controlled manner. An effective nature-inspired optimization technique, which is called the cuckoo search algorithm, is utilized for finding the optimal method parameters.

In [17], the authors designing an interval type-2 fuzzy pre-compensated PID controller applied to two-DOF robotic manipulator with variable payload. Also, (Nodeh, Ghasemi, and Daniali 2019b) were proposed a method based on tuning of the higher-order sliding mode controller parameters by the interval type-2 fuzzy logic. In this case, the usual chattering effect of the traditional sliding mode is vanished by using higher-order sliding mode control and a saturation function that produces higher robustness when compared to the traditional method.

In [24], a novel application of artificial bee colony (ABC) algorithm to optimize the fractional-order operators and scaling factors of interval type-2 fractional-order fuzzy proportional integral derivative controller was proposed for redundant robotic system for trajectory track controller structure is also implemented for benchmark fractional-order plants and uncertain inverted pendulum system.

A robot with the leader–follower approach has a disadvantage in the case of failure in formation if the leader robot fails. To overcome such problem, in [47], the authors proposed the formation control using interval type-2 fuzzy logic controller (IT2FLC). In this case, to validate the appropriateness of the controller, several simulations were undertaken under different environmental situations with several different parameters.

In [3] were proposed a stable indirect adaptive robust mixed H-2/H-infinity control approach to an alpha-plane representation of a general type-2 fuzzy framework. The model is shown to be both efficient and very useful for performing a theoretical analysis. In [20], an improved nonstationary fuzzy system approach versus type-2 fuzzy system for the lifting motion control with human in the loop simulation was presented.

Finally, in [29], proposal of a novel application of biogeography-based optimization (BBO) to optimize a controller in order to achieve high performance estimation of states. The type-2 fuzzy approach is utilized to eliminate the chattering problem in the sliding mode control. The Lyapunov theorem is used to establish a proof of stability for the controller. The novel control approach is validated utilizing a computational simulation of a two-link robot arm problem with very good results.

The previous works can be viewed as a representative sample of the research that has been done in recent years in the area of fuzzy logic for robotics.

3 Review of Type-2 Fuzzy Logic in Robotics

In this section, we are offering a review of recent works utilizing type-2 fuzzy logic in robotics with the goal of improving the understanding of this area, as well as envisioning its possible evolution. In the literature review, we presented several articles in a general way using type-2 fuzzy for robotics. Based on the search that was done in Web of Science "Type-2 fuzzy logic systems in Robotic", we encountered 19 works mentioned above. In Figs. 3 and 4, we can observe as in recent years the use of type-2 fuzzy in robotics is increasing. According to data collected in WoS and using the software VOSviewer [15], the network is shown in different views in Figs. 5 and 6 obtaining only six connected authors, the type of analysis to create the map was made by co-authorship and the unit of analysis is by authors.

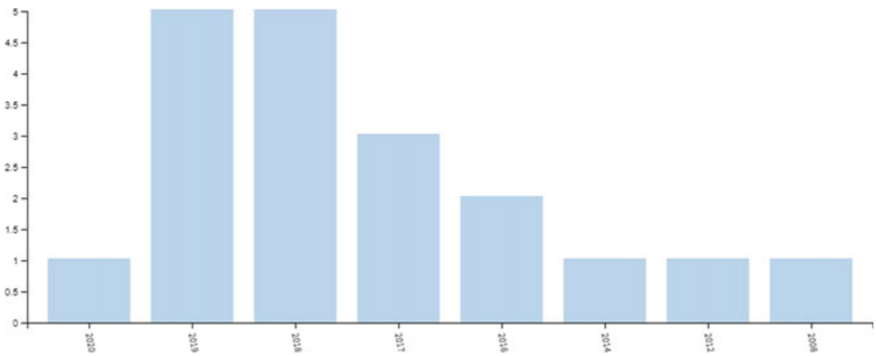

Fig. 3 Showing 19 records with number of papers by year for the TOPIC: (Type-2 fuzzy logic systems in robotic)

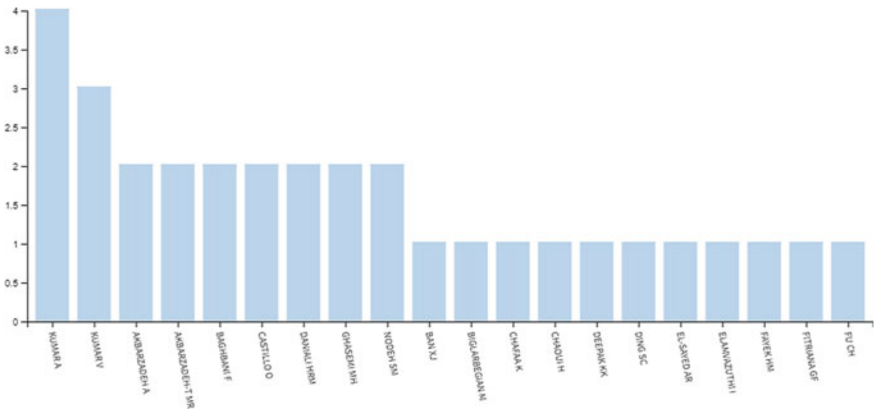

Fig. 4 Showing 19 records with the main authors and their papers for the TOPIC: (Type-2 fuzzy logic systems in robotic)

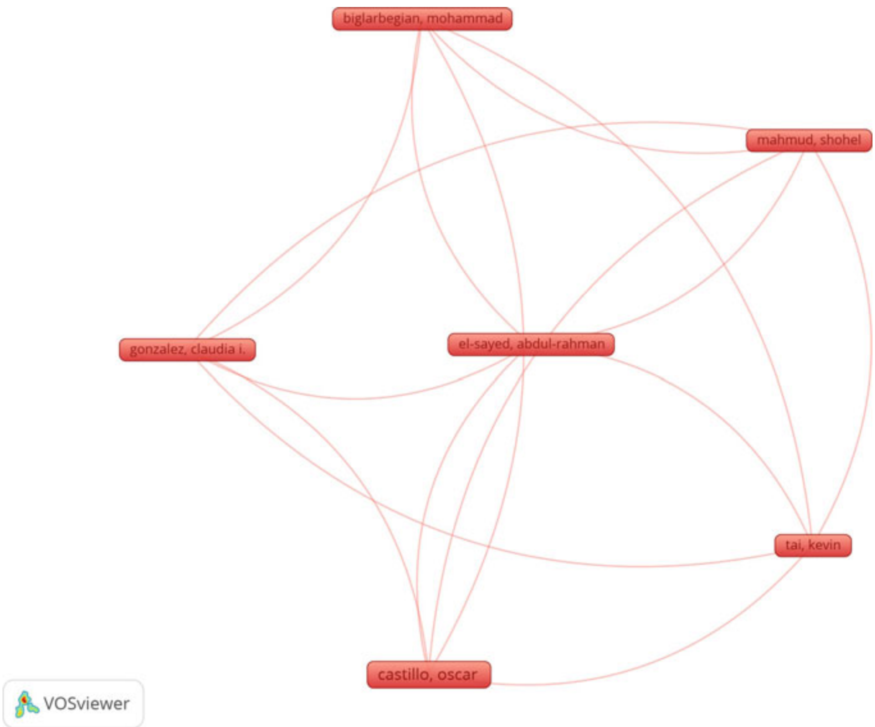

Fig. 5 Network visualization by connected authors with the topic type-2 fuzzy logic systems in robotic of WoS

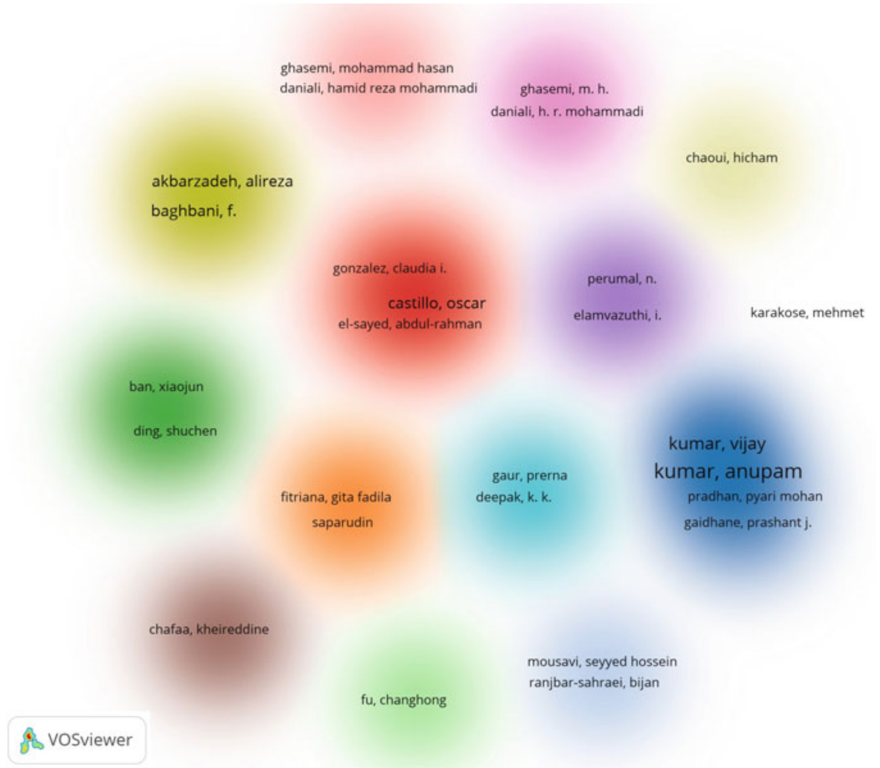

Fig. 6 Cluster density for all authors with the topic'type-2 fuzzy logic systems in robotic' of WoS

4 Review of Type-1 Fuzzy Logic in Robotics

In this section, we are offering a summary of the recent works using type-1 fuzzy logic in robotics with the goal of improving the understanding of this area. Based on the search that was done in Web of Science "Fuzzy logic systems in Robotics", we encountered 422 works. However, the first eight papers are cited in this review but the complete list can be consulted in WoS with the topic above mentioned ([7, 27, 21, 34, 41, 45, 43, 46]). In Fig. 7, we can observe as in the last years the use of type-1 fuzzy logic in robotic is relatively greater than type-2 fuzzy systems, but expect in the future that type-2 and type-3 will increase at a greater rate.

5 Conclusions

After finalizing the review, we can note that a plethora of articles utilizing fuzzy systems in robotics have been put forward with the goal of improving the navigation

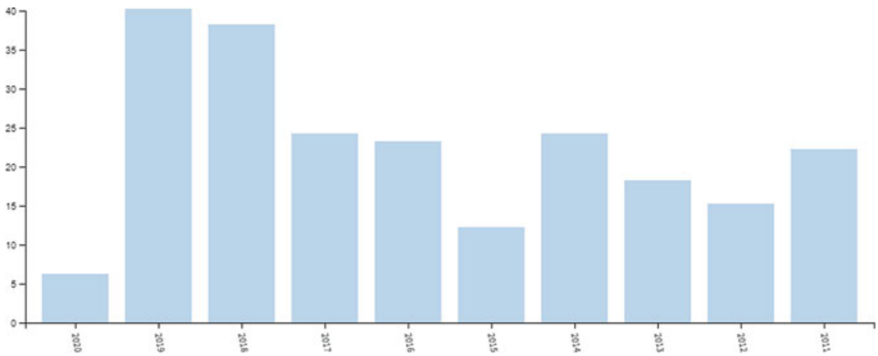

Fig. 7 Showing 422 records for TOPIC: (Fuzzy logic systems in robotics)

results of the robots. The relevance of fuzzy logic in real robotic problems has been established. Nowadays, the controllers are becoming increasingly complex, and a learning process for parameters is required, and it is a challenging task to the users to perform trial and error each time they execute the system. Therefore, the utilization of fuzzy systems is a good choice to enhance the results with a relatively small computational cost. Also, with this survey, we can realize the increasing utilization of type-1 and type-2 fuzzy systems, which are becoming more popular. With the results obtained from WoS, and the visual tool 'connected papers', we have observed how the tendency is to use fuzzy systems in robotics every day because the researchers have been achieving good results utilizing this methodology on the problems. Also, nowadays, we can find in the state-of-the-art hybrid methods to enhance the results. Also, as a future work, we can explore more combinations, for example, optimization methods using fuzzy logic for parameter adaptation could be included in the survey of hybrid methods with parameter adaptation using type-1 or type-2 fuzzy logic for comparison among the methods. Another advantage of elaborating this type of review paper is the encouragement offered to the authors to utilize techniques to improve the performance achieving the best possible results with these techniques. Finally, we can mention that a more recent related area that has been receiving increasing attention is the use of type-3 fuzzy logic, and at the moment, there are only a few papers on type-3 fuzzy control and robotics, but believe that this new area will gain more popularity in the near future. More in the long-term future, it would be possible to talk of type-4 fuzzy logic or even higher types of fuzzy applied to intelligent control and robotics.

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