*International Journal on Numerical and Analytical Methods in Engineering (IRENA), Vol. xx, n. x*

# A comparison of Type-1 and Type-2 Fuzzy Logic Controllers in Robotics: A review

Nurul Nadirah Mohd Khairi[1], S S S Ahmad[2]

**Abstract** –*Most real world applications face high levels of uncertainties that can affect the operations of such applications. Hence, there is a need to develop different approaches that can handle the available uncertainties and reduce their effects on the given application. To date, Type-1 Fuzzy Logic Controllers (FLCs) have been applied with great success to many different real world applications. The traditional type-1 FLC which uses crisp type-1 fuzzy sets cannot handle high levels of uncertainties appropriately. Nevertheless it has been shown that a type-2 FLC using type-2 fuzzy sets can handle such uncertainties better and thus produce a better performance. As such, type-2 FLCs are considered to have the potential to overcome the limitations of type-1 FLCs and produce a new generation of fuzzy controllers with improved performance for many applications which require handling high levels of uncertainty. This paper will briefly introduce the interval type-2 FLC and its benefits. We will also present briefly some of the type-2 FLC real world applications.*

***Keywords***: *Fuzzy Logic Controller, Fuzzy Type-1, Fuzzy Type-2*

## I. Introduction

Robotics is the branch of technology that deals with the design, construction, operation, and application of robots as well as computer systems for their control, sensory feedback, and information processing [1]. The concept of creating machines that can operate autonomously dates back to classical times, but research into the functionality and potential uses of robots did not grow substantially until the 20th century [2]. Throughout history, robotics has been often seen to mimic human behavior, and often manage tasks in a similar fashion. Today, robotics is a rapidly growing field, as technological advances continue; research, design, and building new robots serve various practical purposes, whether domestically, commercially, or militarily. Many robots do jobs that are hazardous to people such as defusing bombs, mines and exploring shipwrecks. In 1927 the Maschinenmensch ("machine-human") gynoid humanoid robot (also called "Parody", "Futura", "Robotrix", or the "Maria impersonator") was the first depiction of a robot ever to appear on film was played by German actress Brigitte Helm in Fritz Lang's film Metropolis. In 1942 the science fiction writer Isaac Asimov formulated his Three Laws of Robotics. In 1948 Norbert Wiener formulated the principles of cybernetics, the basis of practical robotics. Fully autonomous robots only appeared in the second half of the 20th century. The first digitally operated and programmable robot, the Unimate, was installed in 1961 to lift hot pieces of metal from a die casting machine and stack them. Commercial and industrial robots are widespread today and used to perform jobs more cheaply, or more accurately and reliably, than humans. They are also employed in jobs which are too dirty, dangerous, or dull to be suitable for humans. Robots are widely used in manufacturing, assembly, packing and packaging, transport, earth and space exploration, surgery, weaponry, laboratory research, safety, and the mass production of consumer and industrial goods [3].

Fuzzy control is regarded as the most widely used application of fuzzy logic [4]. A Fuzzy Logic Controller (FLC) is credited with being an adequate methodology for designing robust controllers that are able to deliver a satisfactory performance in the face of uncertainty and imprecision. In addition, a FLC provides a method to construct controller algorithms in a user-friendly way closer to human thinking and perception. The first FLC was developed in 1974 by Mamdani and Assilian [6] and, since then, FLCs have been applied with success to many real-world applications where the FLCs have given satisfactory performances similar (or even better) to the human operators and have successfully outperformed the traditional control systems (like PID controllers) [7].

There are many sources of uncertainty facing the FLC in dynamic real-world unstructured environments and many real-world applications; some of them are as follows:

- Uncertainties in inputs to the FLC, which translate into uncertainties in the antecedents' membership functions as the sensors measurements are affected by high noise levels from various sources. In

*Manuscript received January 2007, revised January 2007*

addition, the input sensors can be affected by the conditions of observation (i.e., their characteristics can be changed by the environmental conditions such as wind, sunshine, humidity, rain, etc.).

- Uncertainties in control outputs, which translate into uncertainties in the consequents' membership functions of the FLC. Such uncertainties can result from the change of the actuators' characteristics, which can be due to wear, tear, environmental changes, etc.
- Linguistic uncertainties as the meaning of words that are used in the antecedents' and consequents' linguistic labels can be uncertain, as words mean different things to different people [5]. In addition, experts do not always agree and they often provide different consequents for the same antecedents. A survey of experts will usually lead to a histogram of possibilities for the consequent of a rule; this histogram represents the uncertainty about the consequent of a rule [5].
- Uncertainties associated with the change in the operation conditions of the controller. Such uncertainties can translate into uncertainties in the antecedents' and/or consequents' membership functions.

Uncertainties associated with the use of noisy training data that could be used to learn, tune or optimize the FLC. All of these uncertainties translate into uncertainties about fuzzy set membership functions [5].

## II. Type 1 Fuzzy controllers

Fuzzy logic is widely used in machine control. The term "fuzzy" refers to the fact that the logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true". Although alternative approaches such as genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. Fuzzy logic was first proposed by Lotfi A. Zadeh of the University of California at Berkeley in a 1965 paper. He elaborated on his ideas in a 1973 paper that introduced the concept of "linguistic variables", which in this article equates to a variable defined as a fuzzy set. Fuzzy controllers are very simple conceptually. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensor or other inputs, such as switches, thumbwheels, and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value. Fuzzy controllers are very simple conceptually. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensor or other inputs, such as switches, thumbwheels, and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate

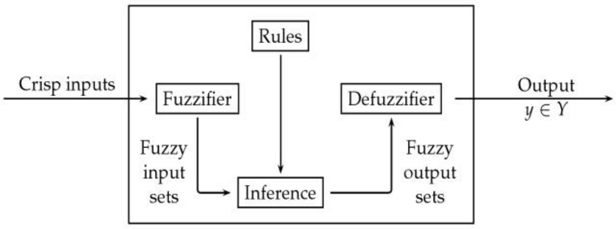

Figure 1: Fuzzy Logic Controller Block Diagram

rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value. The most common shape of membership functions is triangular, although trapezoidal and bell curves are also used, but the shape is generally less important than the number of curves and their placement. From three to seven curves are generally appropriate to cover the required range of an input value, or the "universe of discourse" in fuzzy jargon.

## III. Type 2 Fuzzy controllers

Type-2 fuzzy logic is a growing research topic—if number of publications is taken as a measure. Key researchers in the fuzzy logic community are now embracing type-2 fuzzy logic and there is much evidence of successful applications, so we can only expect this growth to continue. Other evidence of interest in type-2 fuzzy logic is that there have been special sessions at every Fuzz-IEEE since 1999 where the sessions generally consist of 20 papers or more. Figure 2: The list of reviewed articles related to Type 2 fuzzy controllers in a robotics. Type-2 fuzzy methods provide second order uncertainties allowing fuzzy systems to truly deal with real world uncertainty. In the current climate of ever faster, more powerful and more affordable hardware type-2 fuzzy methods present an exciting opportunity to explore uncertainties in real world.

The interval type-2 FLC uses interval type-2 fuzzy sets to represent the inputs and/or outputs of the FLC. The interval type-2 FLC works as follows: the crisp inputs from the input sensors are first fuzzified into input type-2 fuzzy sets; singleton fuzzification is usually used in interval type-2 FLC applications due to its simplicity and suitability for embedded processors and real-time applications. The input type-2 fuzzy sets then activate the inference engine and the rule base to produce output type-2 fuzzy sets. The type-2 FLC rules will remain the same as in type-1 FLC, but the antecedents and/or the consequents will be represented by interval type-2 fuzzy sets. The inference engine combines the fired rules and gives a mapping from input type-2 fuzzy sets to output type-2 fuzzy sets. The type-2 fuzzy outputs of the

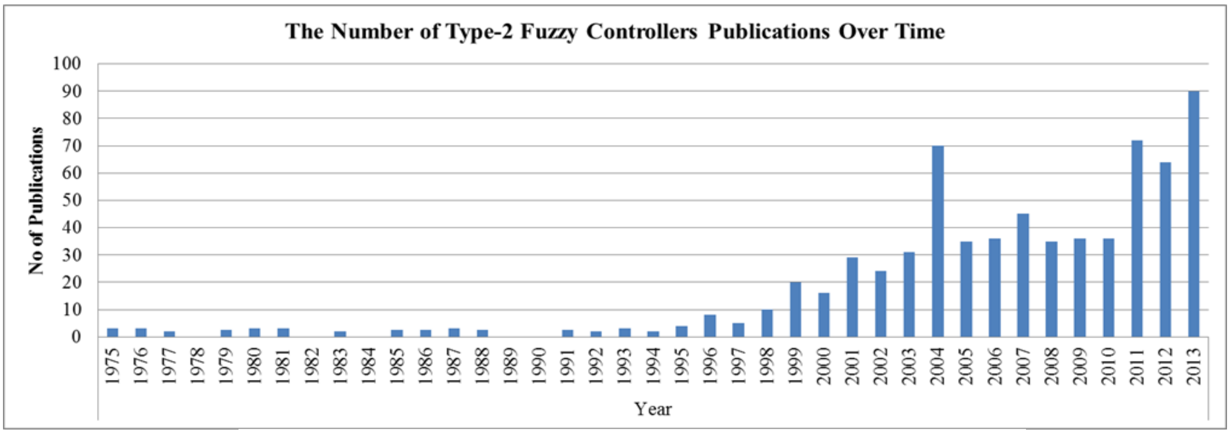


Figure 2: The list of reviewed articles related to Type-2 fuzzy controllers in a robotics

inferece engine are then processed by the type-reducer, which combines the output sets and performs a centroid calculation that leads to type-1 fuzzy sets called the type reduced sets. The interval type-2 FLCs used so far, there are two ways to perform type-reduction: using the iterative Karnik-Mendel (KM) procedure to calculate the type-reduced fuzzy sets [5] or using the Wu-Mendel uncertainty bounds method to approximate the typereduced set [8]. After the type-reduction process, the type-reduced sets (or approximate type-reduced sets) are then defuzzified (by taking the average of the typereduced/approximated type-reduced set) to obtain crisp outputs that are sent to the actuators.

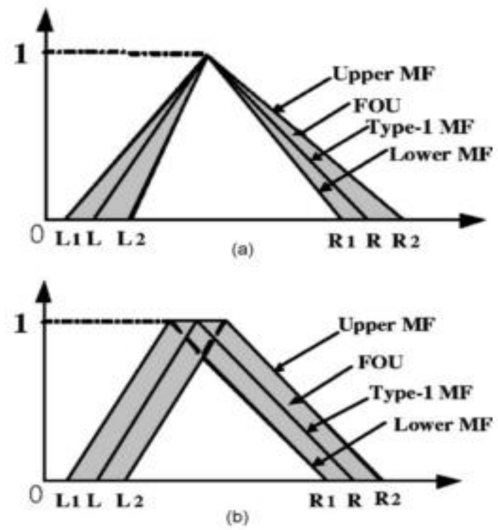


Figure 3: Examples of type-2 fuzzy sets. (a) A type-2 fuzzy set obtained by blurring the width of a triangular type-1 fuzzy set and (b) a type-2 fuzzy set obtained by blurring the apex of a triangular type-1 fuzzy set. [4]

## IV. Evaluation and Comparison

Despite having a name that has the connotation of uncertainty, researches have shown that type-1 fuzzy logic systems have difficulties in modeling and minimizing the effect of uncertainties. One reason limiting the ability of a type-1 fuzzy set to handle uncertainty is that the membership grade for a particular input is a crisp value. Recently, a new type of fuzzy set characterized by membership grades that are themselves fuzzy have been attracting interest.

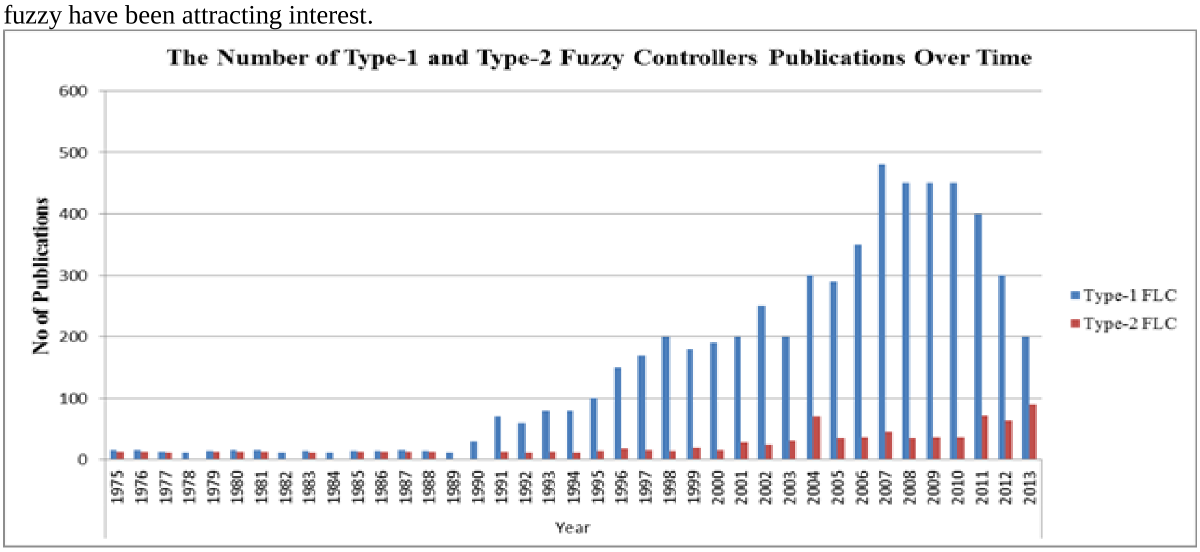


Figure 4: The Number of Type-1 and Type-2 Fuzzy Controllers Publication Over Time

As illustrated in Figure 3, a type-2 fuzzy set may be obtained by starting with a type-1 membership function (MF) and then blurring it. The blurred area, referred to as the Footprint of Uncertainty (FOU), is bounded by upper and lower membership functions. Points within the "blurred area" have membership grades given by type-1 membership functions. The FOU provides an extra mathematical dimension, thereby enabling the uncertainties in the shape and position of the type-1 fuzzy set to be represented. Figure 4 show the list of reviewed articles related to Type-1 and Type-2 fuzzy controllers in a robotics.

Type-1 FLCs cannot fully handle or accommodate the linguistic and numerical uncertainties associated with dynamic unstructured environments as they use precise type-1 fuzzy sets. Type-1 fuzzy sets handle the uncertainties associated with the FLC inputs and outputs by using precise and crisp membership functions that the user believes capture the uncertainties. Once the type-1 membership functions have been chosen, all the uncertainty disappears because type-1 membership functions are totally precise [5].

The linguistic and numerical uncertainties associated with dynamic unstructured environments cause problems in determining the exact and precise antecedents' and consequents' membership functions during the FLC design. Moreover, the designed type-1 fuzzy sets can be sub-optimal under specific environment and operation conditions; however, because of the environment changes and the associated uncertainties, the chosen type-1 fuzzy sets might not be appropriate anymore. This can cause degradation in the FLC performance, which can result in poor control and inefficiency and we might end up wasting time in frequently redesigning or tuning the type-1 FLC so that it can deal with the various uncertainties.

It has been argued that using interval type-2 fuzzy sets to represent the inputs and/or outputs of FLC has many advantages when compared to the type-1 fuzzy sets.

- As the type-2 fuzzy sets membership functions are fuzzy and contain a footprint of uncertainty, then they can model and handle the linguistic and numerical uncertainties associated with the inputs and outputs of the FLC. Therefore, FLCs that are based on type-2 fuzzy sets will have the potential to produce a better performance than the type-1 FLCs when dealing with uncertainties [9].
- Using type-2 fuzzy sets to represent the FLC inputs and outputs will result in the reduction of the FLC rule base when compared to using type-1 fuzzy sets, as the uncertainty represented in the footprint of uncertainty in type-2 fuzzy sets lets us cover the same range as type-1 fuzzy sets with a smaller number of labels and the rule reduction will be greater when the number of the FLC inputs increases [5].
- Each input and output will be represented by a large number of type-1 fuzzy sets, which are embedded in the type-2 fuzzy sets [5], [10]. The use of such a large number of type-1 fuzzy sets to describe the input and output variables allows for a detailed description of the analytical control surface as the addition of the extra levels of classification give a much smoother control surface and response. In addition, according to Karnik and Mendel [11], the type-2 FLC can be thought of as a collection of many different embedded type-1 FLCs.
- It has been shown in [12] that the extra degrees of freedom provided by the footprint of uncertainty enables a type-2 FLS to produce outputs that cannot be achieved by type-1 FLSs with the same number of membership functions. It has been shown that a type-2 fuzzy set may give rise to an equivalent type-1 membership grade that is negative or larger than unity. Thus, a type-2 FLC is able to model more complex input-output relationships than its type-1 counterpart and, thus, can give better control response.

Table 1: The list of reviewed articles related to comparison of Type-1 and Type-2 Fuzzy Controllers in Robotics

| Ref. No | Domain of the problem |
|---|---|
| [13] | The design of control systems to handle uncertainties |
| [14] | DC motor model in a closed loop simulation |
| [15] | Analysis of interval T2 and T1 in the context of learning behaviours. |
| [16] | Problem-driven design of uncertainty-robust. |
| [17] | Tracking problem of the dynamic model of a unicycle mobile robot. |

Table1 provides a list of the articles, which clearly focused on the comparison of Type-1 and Type-2 Fuzzy Controllers that can be considered in robotics application.

P.Melin et al. [13] present the study of the controllers' design for non-linear control system using type-1 and type-2 fuzzy logic. They stated that by using type-2 FLC, the lower overshoots errors and the best settling times were obtained. They conclude that, the best results were obtained using type-2 fuzzy systems because type-2 fuzzy systems can handle uncertainties and provide them with more parameters and more design degrees of freedom.

In J.Garibaldi et al. [14] study shows that the type-1 and type-2 controllers cannot be statistically distinguished from each other. In simulation of a micro robot DC motor, seven and five term controllers of type-1 without appreciable loss of control. The three term membership functions can either be all trapezoidal or the central membership functions triangular. The results show that the three term controllers are as stable as the seven and five term controllers when a step change or load is applied. When noise is applied the three term controllers perform equally with the seven and five term controllers. In this study, type-1 controllers performance is over the type-2 controllers performance because the inertia change case, is that the level of noise applied was too low.

In 2010 M.Manic et al. [15] present a comparative analysis of type-1 and interval type-2 FLCs in context of learning behaviors for mobile robotics. The controllers were trained to autonomously perform a wall-following behavior for a sonar equipped mobile robot. It was experimentally demonstrated that the smoothing of the interval type-2 control output reduces the ability of the controller to quickly react to sudden and abrupt changes in the input signal. An interval type-2 fuzzy controller also outperforms the type-1 fuzzy controllers near the set point of the controller when coping with dynamic uncertainties.

M.manic et al. [16] use Interval Type-2 Fuzzy Controllers to allow for partially dependent of the problem domain. Sensory noise and the uncertain system parameters have been considered as a two primary sources of the system uncertainty. It was conclude that the Interval Type-2 Fuzzy Controllers provides improvements in terms of both performance and robustness compared to Interval Type-1 Fuzzy Controllers.

O.Castillo et al. [17] presented simulation results from an optimization method that mimics chemical reactions applied to the problem of tracking control. Both of type-1 and type-2 fuzzy controllers were able to perform better to reach smaller error values in less time than genetic algorithms and under the presence of disturbance.

## V. Conclusion

In this review paper, we presented the comparison between type-1 FLC and type-2 FLC in robotics. Through the review of the Fuzzy Logic Controllers applications in robotics, it has been shown that as the level of imprecision and uncertainty increases, the type-2 FLC will provide a powerful paradigm to handle the high level of uncertainties present in real-world environments. It has been also shown in various applications that the type-2 FLCs have given very good and smooth responses that have always outperformed their type-1 counterparts. Thus, using a type-2 FLC in real-world applications can be a better choice than type-1 FLCs since the amount of uncertainty in real systems most of the time is difficult to estimate [28]. The type-2 FLC had the problem that it was envisaged as a computability expensive system due to the computational overhead associated with type-reduction and the use of the iterative KM procedure.

However, it has been shown that the Wu-Mendel uncertainty bounds method can give a very good approximation to the type-reduced sets and, thus, the computational bottleneck of the type-2 FLC has been eliminated, thus paving the way for the use of embedded type-2 FLCs for various industrial processes as has been shown in [19], [21]. Although the interval type-2 FLC has explored some of the potential of the type-2 FLCs, more advantages can be gained through the generalized type-2 FLC whose potential is to be explored [3]. From the above discussion, it has been shown that the type-2 FLC overcomes the limitations of type-1 FLCs and will present a way forward to fuzzy control and especially in highly uncertain environments, which includes most of the real-world applications. It is envisaged to see a wide spread of type-2 FLCs in many real-world application in the next decade.

## Acknowledgements

This research was supported by Universiti Teknikal Malaysia Melaka and Ministry of Education Malaysia under grant no FRGS/2013/FTMK/ICT02/02/1/F00161.

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## Authors' information

**Nurul Nadirah Binti Mohd Khairi** received her B.Sc degrees in Computer Science (Artificial Intelligence) from University of Technical Malaysia Malacca in 2013. She is currently a research student of Information Technology at the University of Technical Malaysia Malacca. Her interests are: Soft Computing, Fuzzy Logic Controllers, Granular Computing, and Robotics

**Sharifah Sakinah Syed Ahmad** is a Senior Lecturer of Industrial Computing, Faculty of Information Technology and Communication, Universiti Teknikal Malaysia Melaka. Her first degree was in BSc in Applied Mathematics (Computer Modeling), then completed her master in Mathematics from University Science of Malaysia in 2001 and 2002, respectively. She received her Ph.D in Software Engineering and Intelligent System from University of Alberta, Canada. Her current research interests lie in fuzzy modeling, intelligent system, and granular computing.