2011 IEEE International Conference on Fuzzy Systems
June 27-30, 2011, Taipei, Taiwan

Type-2 Fuzzy Airplane Altitude Control:

A Comparative Study

Sheir Afgen Zaheer and Jong-Hwan Kim
RIT Lab, Dept. of Electrical Engineering
KAIST
Daejeon, Republic of Korea
{sheir, johkim}@rit.kaist.ac.kr

Abstract— **The standard fuzzy logic controllers, also known as type-1 fuzzy logic controllers, have often been criticized for their inability to handle uncertainties in the control processes. Therefore, a lot of attention is being focused on type-2 fuzzy logic controllers, especially, the interval type-2 fuzzy logic controllers. This paper aims at developing both type-1 and type-2 fuzzy logic controllers for an airplane altitude control problem and comparing their performances. Both the controllers have similar knowledge bases, and both of them are tested in two simulation setups, an ideally modeled setup and a setup with uncertainties. The results show that the type-2 fuzzy logic controller outperforms the type-1 fuzzy logic controller, especially, in the environment with uncertainties. Therefore, this research seems to validate the superiority of type-2 fuzzy logic control in making the controllers independent of uncertainties in intricate model details.**

Keywords — **Type-2 fuzzy logic control, altitude control, fuzzy airplane control.**

I. Introduction

The popularity of type-2 fuzzy systems has risen enormously during the past few years. Though the theoretical concepts of type-2 fuzzy sets date back to 1975 [1], the limitation of computational resources limited their practical applications. However, with the massive improvements in computational capabilities in the recent years, type-2 fuzzy systems are being widely used in various control and decision making problems.

Moreover, the type-2 fuzzy systems also answer the skepticism regarding the fuzziness of type-1 fuzzy systems. Type-1 fuzzy sets have a crisp membership value which means that each element in a set has a predefined fixed value; this violates the notion of fuzziness regarding uncertainties. A two-layered architecture to improve nonlinearity handling in type-1 fuzzy controller for the systems with dead-zones has been proposed [2]. However, the causes of nonlinearities and uncertainties in real systems are not always known. Such problems associated with uncertainties in systems or the fuzzy rules are solved in type-2 fuzzy systems by assigning a secondary membership function, to each element in the fuzzy set, rather than a crisp membership value [1], [3]. This type of type-2 fuzzy systems, known as the general type-2 fuzzy sets, are computationally very complex. Therefore, interval type-2 fuzzy systems (IT2FS) have been developed to provide a satisfactory compromise between the uncertainty handling of type-2 systems and the computational complexity [3], [4]. The IT2FS assigns a range of membership values to each element in such a way that every value in the specified range has a full secondary membership grade. Fig. 1 gives a graphical depiction of a typical triangular interval type-2 fuzzy set. The shaded region that defines the range of membership values for a particular element is called the foot of uncertainty (FoU) [3].

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0000831)

Type-2 fuzzy systems have been used in many research problems. Type-2 fuzzy logic has been widely used in mobile robot control and navigation applications [5]-[10]. A simplified real time controller for a coupled-tank liquid-level control has also been developed [11]. Moreover, type-2 fuzzy logic has also been used in medical diagnosis [12], [13]; human machine interaction [14]; traffic control systems [15], etc. Apart from the above mentioned contributions, type-2 fuzzy systems have also been used in management surveys [16] and human resource management [17]. However, there has been a very little research about the performance comparison of the type-1 and type-2 fuzzy systems developed through similar rules and membership functions, and subjected to identical testing conditions.

This paper compares the performances of the type-1 fuzzy and the interval type 2 fuzzy logic (IT2FLC) control systems for a multi-input multi-output (MIMO) airplane altitude control simulation. Type-1 fuzzy control systems have been widely used in the airplane altitude control problem. Different kinds of fuzzy altitude and/or flight controllers have been developed. Complete type-1 fuzzy flight control system has been developed [18]. Another research was aimed at developing decoupled PID controllers for speed and heading control, and a type-1 fuzzy altitude controller [19]. However, none of the

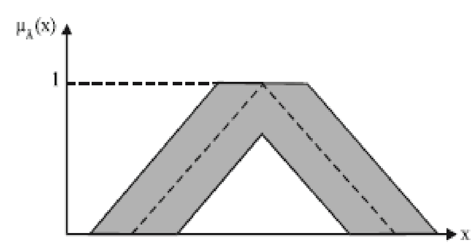

Fig. 1. Interval type-2 triangular fuzzy set.

978-1-4244-7317-5/11/$26.00 ©2011 IEEE

previous researches at flight control systems have employed type-2 fuzzy control systems.

The proposed system aims at developing a fuzzy flight control system (FFCS) with two decoupled controllers: a fuzzy heading controller (FHC) and a fuzzy altitude controller (FAC). FHC is designed as a type-1 fuzzy control system and its major functions are to control airplane's heading and lateral stability. FAC, on the other hand, is developed, first by employing a type-1 fuzzy altitude controller (T1FAC) and then by an interval type-2 fuzzy altitude controller (IT2FAC). Two sets of simulations are conducted: one with ideally modeled system and the other with a system with uncertainties. These simulations put both the T1FAC and the IT2FAC under test for each of the simulation scenarios. The resulting responses are then compared.

The paper is organized as follows: Section II describes the airplane model. Section III gives an overview of the overall control scheme and the FHC, and section IV explains the two altitude controllers, T1FAC and IT2FAC. Section V describes the results of T1FAC and IT2FAC. Finally the discussions and conclusion follow in section VI.

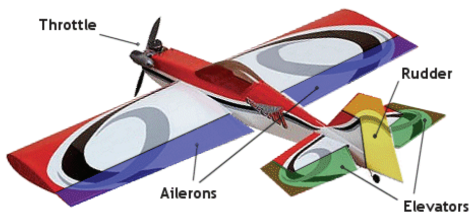

Fig. 2. Basic airplane controls.

II. The Airplane Model

In order to assess the performances of the developed controllers, an airplane model is required. A propulsion based RC airplane is modeled. The control surfaces for a typical RC airplane are shown in Fig. 2. The throttle is used to regulate the speed of the airplane by varying the rotational speed of the propeller, the elevator is used to control the airplane's ascent and descent, the ailerons are used for airplane's lateral stabilization and mid air turning, and the rudder is used for the on-ground taxiing of the airplane. The specific RC model used as a control problem in this research is the Kadet MK-II RC airplane model. The aerodynamic parameters for MK-II RC airplane used are the same as in the previous research [19].

Aerosim Blockset in Simulink environment is a simulation tool for modeling and control of airplanes [20]. The Aereosim Blockset is configured for the Kadet MK-II RC airplane by using the aerodynamic configuration file consisting of aerodynamic coefficients and parameters for the Kadet MK-II RC airplane [19]. A snapshot of the Simulink control model is shown in Fig. 3. As evident from Fig. 3, any airplane can be modeled by plugging in the corresponding airplane parameters to each block.

III. The Fuzzy Flight Control System

The fuzzy flight control system (FFCS) consists of two decoupled controllers: A fuzzy heading controller (FHC) and a fuzzy altitude controller (FAC). The goal of FFCS, schematically shown in Fig. 4, is to autonomously track the desired altitude and the heading, and then maintain the desired

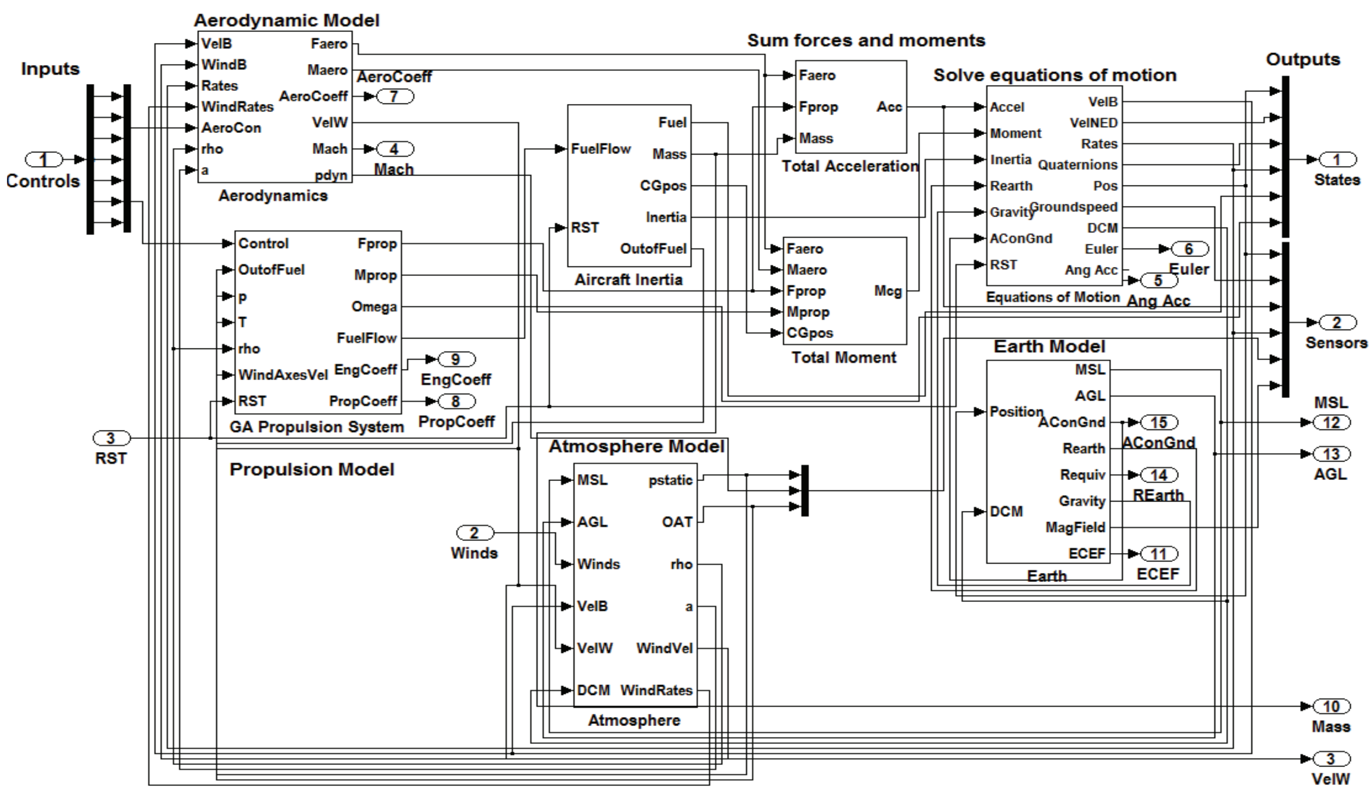

Fig. 3. The block diagram of Simulink based airplane model.

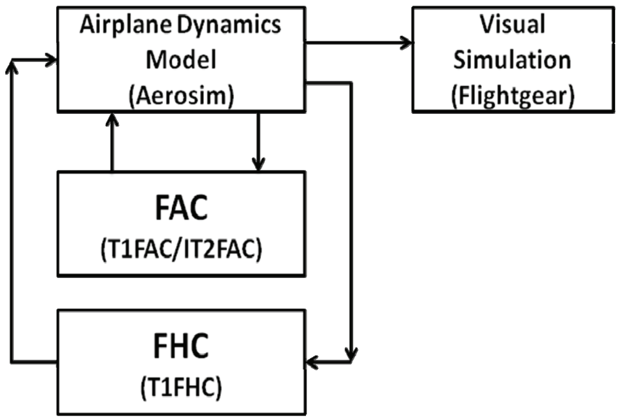

Fig. 4. Overall FFCS architecture.

values once they are achieved. The desired altitude and heading are calculated using the three desired position co-ordinates specified by the user. The overall system is also linked with Flightgear for the visual simulation of the airplane behavior.

A. *The Fuzzy Heading Controller*

Though this research is aimed at the performance comparison of type-1and type-2 fuzzy systems in altitude control, designing a heading controller is imperative because of the following two reasons:

- The heading controller is in charge of the ailerons, thus providing the in-flight lateral stability essential for the airplane to track the desired altitude.
- The airplane, while ascending, descending or maintaining altitude, also experiences some horizontal displacement; the heading controller ensures that the horizontal displacement is in the required direction.

The heading controller employed in this research is a FHC. The FHC is a type-1 fuzzy controller; the schematics along with the membership functions are shown in Fig. 5. The bank angle calculated by FHC is then transformed to the control surface level command to the ailerons by using the following proportional compensator:

$$Aeleron = (0.55\pi / 180) * BankAngle. \qquad (1)$$

IV. The Fuzzy Altitude Controllers

The FACs have been widely implemented by researchers for controlling the altitude of both manned and unmanned aerial vehicles. The altitude controller is a multi-input and multi-output (MIMO) system, generally developed by considering altitude error, change in altitude error and airspeed as the controller's inputs while elevator/angle of attack and throttle level are the controller's output. The throttle is linked with the FAC because throttle regulates the amount of thrust required by an ascending or descending airplane.

The similar control schematics are considered in this paper. The rule base for the controller is developed using the expert knowledge based on literature review and personal experiences with RC airplane control [19]. The fuzzy set representation and the membership functions for the inputs and outputs for the T1FAC and the IT2FAC are discussed in the following subsections.

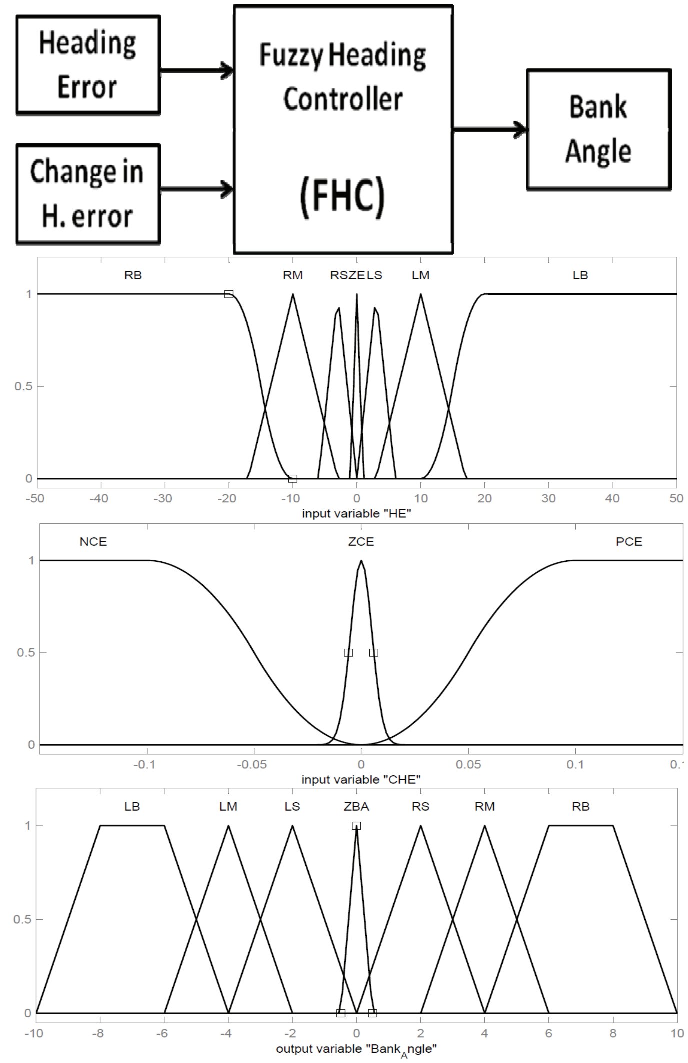

Fig. 5. (Top to Bottom) The schematics of FHC, and the membership functions of inputs and output respectively.

A. *The Type-1 Fuzzy Altitude Controller*

The first controller developed for altitude control is T1FAC. T1FAC was developed as a Mamdani type-1 fuzzy logic controller. This 3-input 2-output controller was tuned via simulations. Fig. 6 shows the architecture of the T1FAC along with the membership functions for inputs and outputs, respectively. The t-Norm and s-Norm operators used are "min" and "max", respectively, with "min" implication and "max" aggregation. The centroid method is employed for defuzzification.

B. *The Interval Type-2 Fuzzy Altiude Control*

The layout of the IT2FAC and the membership functions for inputs and outputs, respectively are shown in Fig. 7. The interval type-2 fuzzy sets are defined using a principal membership function (similar to T1FAC) with a certain footprint of uncertainty (FoU). The principal membership function and FoU are transformed into the left and right membership functions (LMF and RMF) according to the following membership definitions for triangular membership functions:

$$LMF = triangular\ MF\ [A\text{-}FoU*N,\ B\text{-}FoU*N,\ C\text{-}FoU*N]$$

$$RMF = triangular\ MF\ [A+FoU*N,\ B+FoU*N,\ C+FoU*N] \quad (2)$$

where A, B, and C are the three index parameters for the primary triangular member ship functions. N is the normalization factor given as:

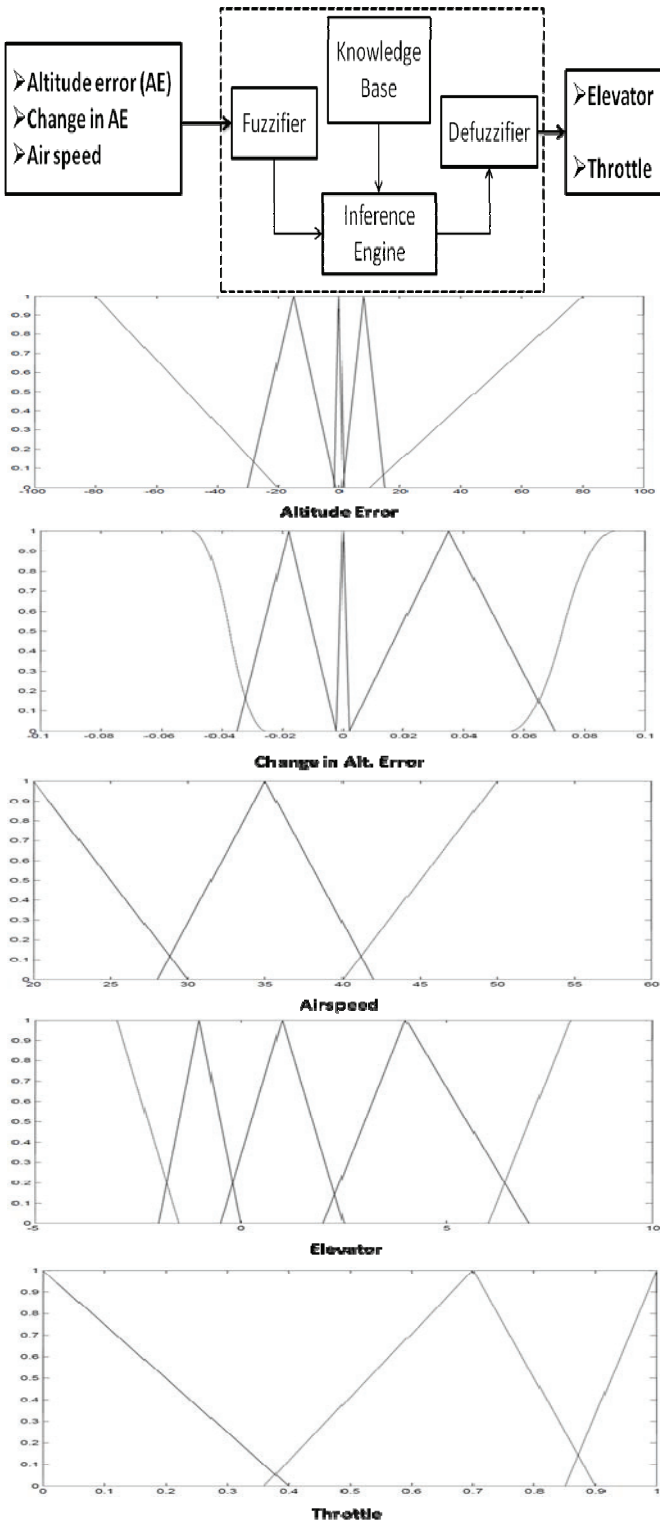

Fig. 6. (Top to Bottom) The schematics of T1FAC, and the membership functions of inputs and outputs respectively.

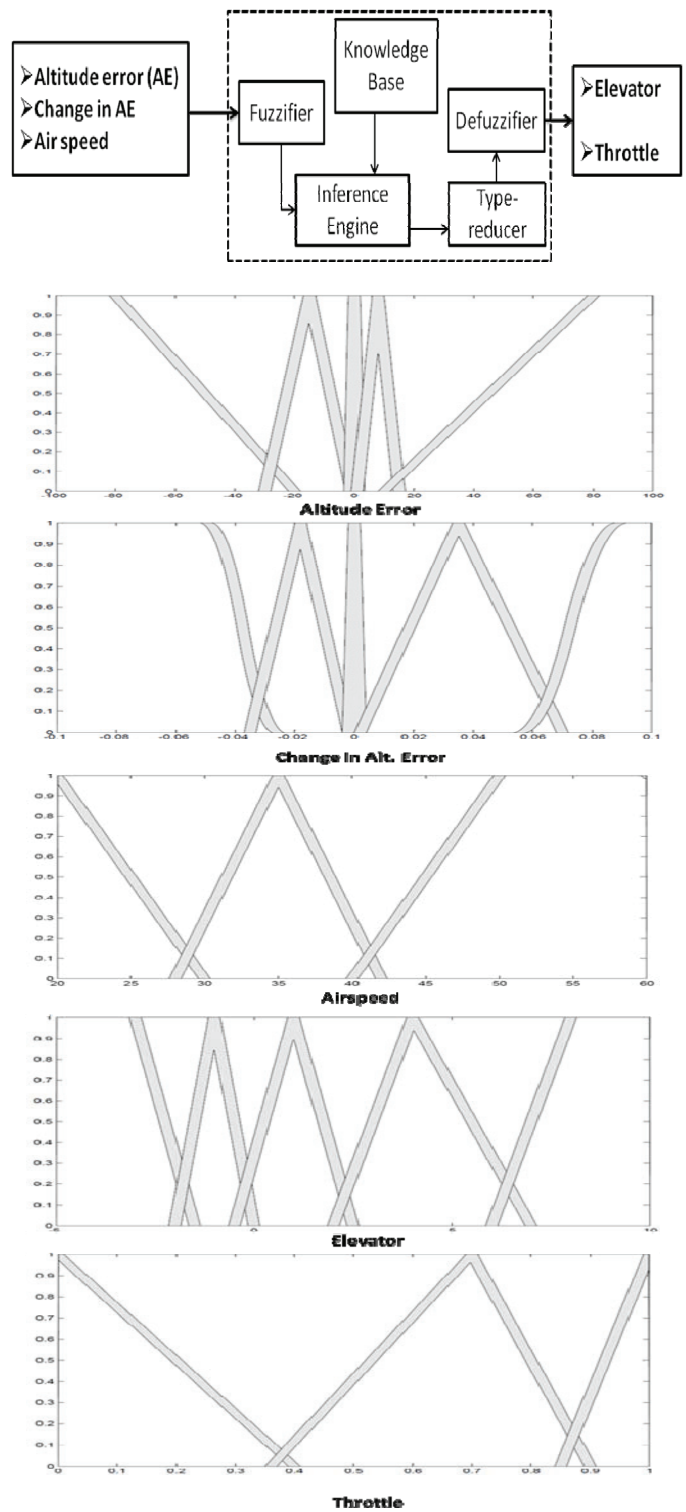

Fig. 7. (Top to Bottom) The schematics of IT2FAC, and the membership functions of inputs and outputs respectively.

$$N = (UoD_{max} - UoD_{min})/200 \quad (3)$$

where UoD_{max} and UoD_{min} are the maximum and minimum values, respectively, of the universe of discourse (UoD). Whereas, for Gaussian membership functions, the FoU defined is used to convert the membership functions to a pair of LMFs and RMFs with same variance but variable means. The conversion is defined by the following equations:

$$LMF = gauss\ MF\ [\sigma,\ \mu - FoU*N]$$
$$RMF = gauss\ MF\ [\sigma,\ \mu + FoU*N] \quad (4)$$

where σ and μ are the variance and the mean of the primary membership functions, respectively. The fuzzy operations used are similar to those used in T1FAC but with an addition of "KM type reduction" [3], [21].

V. Simulations and Results

Two types of simulations were conducted to gauge the performances of both the controllers. The first simulation setup was conducted under an ideal environment with no noises and uncertainties. However, the second setup had a level of random noise associated with both the actuator model and the sensory model. The introduction of this noise made the airplane model uncertain, i.e., the system no longer was exactly the same for which the altitude controller was designed. The performances in both the simulation setups were evaluated by their success in tracking the reference altitudes. In the particular scenario discussed here, the airplane, initially at an altitude of 500m, was required to ascend to a height of 700m. Once a steady state was achieved the airplane was then required to descend to an altitude of 300m. Additionally, simulations to observe the response of the developed IT2FAC under the ramp reference input were also conducted. The setup for this simulation scenario is explained in section V-D The simulation setup was also linked with a visual simulator to observe the airplane response in a 3D simulated environment. Flightgear was used as a visual simulator. Flightgear is an open-source flight simulator development project licensed under the GNU General Public Liscence. A snapshot of the visual simulation is shown in Fig. 8.

Fig. 8. A snapshot of the visual simulation in Flightgear.

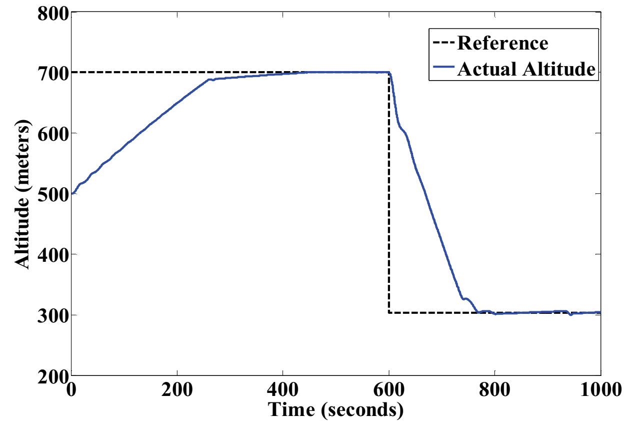

Fig. 9(a). Results of T1FAC in the ideal simulation setup.

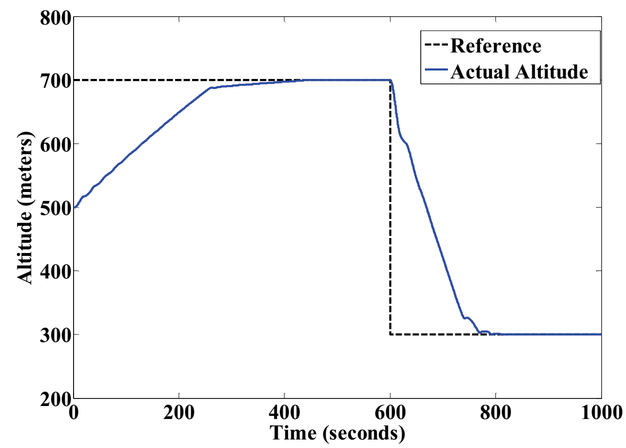

Fig. 9(b). Results of IT2FAC in the ideal simulation setup.

A. *The Ideal Simulation Environment*

The simulation results are shown in Fig. 9 (9(a) for T1FAC and 9(b) for IT2FAC). As evident from the figure, both the controllers were able to perform the job at the hand. However, when analyzed in detail, the steady state response under T1FAC had a slight measure of unwanted oscillations. Moreover, the mean steady state error over a number of simulations, in case of T1FAC, was up to 0.17 meter; while in case of IT2FAC, the steady state error was under 0.03 meter.

B. *The Uncertain Simulation Environment*

In this setup, a level of uncertainty was introduced in the plant model. This uncertainty was introduced to slightly perturb the airplane model and to propagate uncertainty to the actuator and sensor modules. This arrangement provided a system whose behavior differed from the actual model for which the controller was designed and tuned. Moreover, it also provided with the opportunity to validate the often advocated hypothesis about the superiority of the interval type-2 fuzzy logic controllers, as compared to the type-1 fuzzy logic controllers, in handling uncertainties. The results of these simulations are summarized graphically in Fig. 10 (10(a) for T1FAC and 10(b) for IT2FAC). It can be seen that the steady state response generated by T1FAC is not satisfactory.

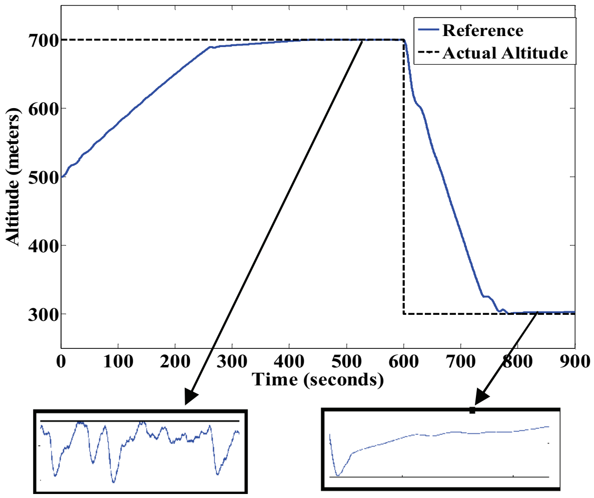

Fig. 10(a). Results of T1FAC in the simulation setup with uncertainties (Bottom blocks are the magnified steady state responses, (RMSE = 3.58 m)).

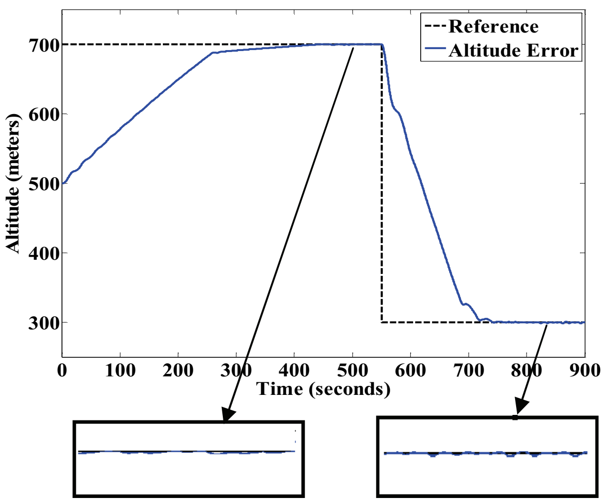

Fig. 10(b). Results of IT2FAC in the simulation setup with uncertainties (Bottom blocks are the magnified steady state responses (RMSE = 0.43 m)).

C. *Effects of Different Values for Footprint of Uncertainties*

The IT2FAC had an additional parameter that required tuning; this parameter was the footprint of uncertainty (FoU), given in (2). An appropriate value for FoU was thus needed. The optimization of FoU is out of the scope of this paper. However, the effects of different values of FoU, in the neighborhood of the FoU*s* in the previous simulations, on the steady state performance were studied. The study state performances, for different FoU values, in terms of steady state root mean squared errors (RMSE) are summarized in Fig. 11. In each of the cases in Fig. 11, the FoU was assumed to be the same for all the fuzzy membership functions. It is evident from these simulation results that a balanced level of FoU value is essential for the desired performance of the system. Therefore, the value of the FoU should not be too large to

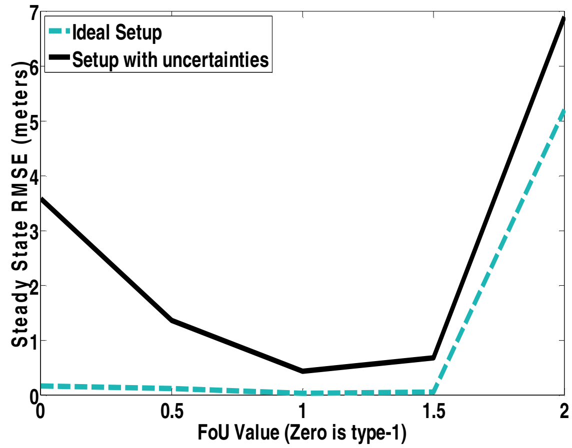

Fig. 11. Steady state RMSE as the result of simulations with different values of FoUs

vanquish the minimum level of preciseness required for the distinctive identifications of the fuzzy sets.

D. *Ramp response of the IT2FAC*

All the results and analysis in the previous subsections were based on the step response of the developed IT2FAC. This subsection deals with the response of the IT2FAC when subjected to a reference input with a ramp (sloped) profile. The results of the simulation, with ramp as a reference input, are shown in Fig. 12. In this setup, the airplane was made to track the reference altitude trajectory that linearly ascended to an altitude of 600 meters, then stayed there for a while, and finally, descended linearly to the altitude of 475 meters. As evident from the figure, a successful tracking response was observed.

VI. Discussions and Conclusion

The purpose of this paper was to compare the performances of the T1FAC and the IT2FAC in an airplane altitude control problem. In the ideal simulation environment, both the controllers were able to track the desired altitude. However in the second simulation environment that had some modeling uncertainties, IT2FAC was the clear winner because

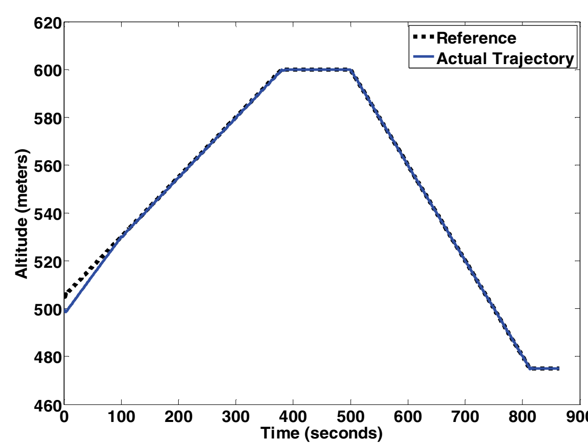

Fig. 12. Tracking response of IT2FAC to a ramp input

the system with T1FAC showed oscillatory behavior around the reference altitude set-points.

This success of IT2FAC can be attributed to its non-crisp membership functions. These non-crisp membership values make IT2FAC more robust than its simpler counterpart with crisp membership values, i.e., T1FAC. The control problem in this study, however, emphasized only on stability and steady state response. Therefore, the control problems and studies emphasizing transient response characteristics like rise time, settling time, etc., might limit the extent to which these results can be generalized. However, considering the current problem, it can be safely deduced that interval type-2 fuzzy logic controller outperforms type-1 fuzzy controller, especially, in handling uncertainties. This finding also seems to be consistent with most of the research done on type-2 fuzzy logic controllers.

The IT2FAC can be further improved by optimizing the controller for desired transient and steady state responses, such as rise time and settling time, etc. Moreover, the FHC can also be upgraded to type-2 fuzzy control for a complete type-2 fuzzy flight control system.

REFERENCES

[1] L. A. Zadeh, “The Concept of a Linguistic Variable and Its Application to Approximate Reasoning–1,” *Information Sciences*, vol. 8, pp. 199-249, 1975.

[2] J.-H. Kim, J.-H. Park, S.-W. Lee and Edwin K.P.Chong, "A Two-Layered Fuzzy Logic Controller for Systems with Deadzones," IEEE Trans. on Industrial Electronics, vol. 41, no. 2, pp. 155-162, Apr. 1994.

[3] J. M. Mendel, Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions, Prentice-Hall, Upper-Saddle River, NJ, 2001.

[4] J. M. Mendel, R. I. John and F. Liu, “Interval type-2 fuzzy logic systems made simple,” *IEEE Trans. on Fuzzy Systems*, vol. 14, pp. 808-821, December 2006.

[5] N. Baklouti and A. M. Alimi, “Motion Planning in Dynamic and Unknown Environment Using an Interval Type-2 TSK Fuzzy Logic Controller,” *Proc. IEEE FUZZ Conference*, pp. 1848-1853, London, UK, July 2007

[6] J. Figueroa, J. Posada, J. Soriano, M. Melgarejo and S. Rojas, “A Type-2 Fuzzy Controller for Tracking Mobile Objects in the Context of Robotic Soccer Games,” *Proc. IEEE FUZZ Conference*, pp. 359-364, Reno, NV, May 2005.

[7] H. Hagras, “A Type-2 Fuzzy Logic Controller For Autonomous Mobile Robots,” *Proc. IEEE FUZZ Conference*, Budapest, Hungary, July 2004.

[8] H. Astudillo, O. Castillo, L. T. Aguilar and R. Martinez, “Hybrid control for an autonomous wheeled mobile robot under perturbed torques,” in Foundations of Fuzzy Logic and Soft Computing (P. Melin et al, Eds.), *Proc. of IFSA 2007*, Cancun, Mexico, June 2007, Springer-Verlag, Berlin, Heidelberg, pp. 594-603.

[9] Yuan-Shiu Chen and L. Yao, "Robust Type-2 Fuzzy Control of an Automatic Guided Vehicle for Wall-Following," *Soft Computing and Pattern Recognition, 2009. SOCPAR '09. International Conference of* , vol., no., pp.172-177, 4-7 Dec. 2009.

[10] R. Martínez, O. Castillo and L. T. Aguilar, “Optimization with Genetic Algorithms of Interval Type-2 Fuzzy Logic Controllers for an Autonomous Wheeled Mobile Robot Using Genetic Algorithms,” *Studies in Computational Intelligence*, 2008, Volume 154/2008, pp. 3-18

[11] Dongrui Wu Woei Wan Tan, “A simplified type-2 fuzzy logic controller for real-time control,” *ISA Transactions*, Volume 45, Issue 4, October 2006, pp. 503-516, ISSN 0019-0578.

[12] P.R. Innocent and R. I. John, “Type-2 Fuzzy Medical Diagnosis.” *Proc. IEEE FUZZ Conference*, pp. 1326-1331, 2002

[13] L. Di Lascio, A. Gisolfi and A. Nappi, “Medical Differential Diagnosis Through Type-2 Fuzzy Sets,” *Proc. IEEE FUZZ Conference*, pp. 371-376, Reno, NV, May 2005.

[14] P. Herman, G. Prasad and T.M. McGinnity, "Designing a robust type-2 fuzzy logic classifier for non-stationary systems with application in brain-computer interfacing," *Systems, Man and Cybernetics, 2008. SMC 2008. IEEE International Conference on* , vol., no., pp.1343-1349, 12-15 Oct. 2008

[15] P.G. Balaji and D. Srinivasan, “Type-2 fuzzy logic based urban traffic management,” *Engineering Applications of Artificial Intelligence*, Volume 24, Issue 1, February 2011, pp. 12-22, ISSN 0952-1976.

[16] S. Auephanwiriyakul, A. Adrian and J. M. Keller, “Type-2 Fuzzy Set Analysis in Management Surveys,” *Proc. IEEE FUZZ Conference*, Honolulu, HI, May 2002, pp. 1321-1325.

[17] F. Doctor, H. Hagras, D. Roberts and V. Callaghan, “A Type-2 Fuzzy Based System for Handling the Uncertainties in Group Decisions for Ranking Job Applicants within Human Resources Systems,” *Proc. IEEE FUZZ Conference*, Hong Kong, China, June 2008.

[18] L. Doitsidis, K.P. Valavanis, N.C. Tsourveloudis and M. Kontitsis, "A framework for fuzzy logic based UAV navigation and control," *Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on* , vol.4, no., pp. 4041- 4046 Vol.4, April 26-May 1, 2004.

[19] A. Awan, S. A. Zaheer, N. Ahsan, A. Mushtaq, M. Qasim, U. Mushtaq, A. Ijaz, J. Iqbal and K. Munawwar, "Autonomous control for a Kadet MKII RC airplane,"*Emerging Technologies, 2008. ICET 2008. 4th International Conference on* , vol., no., pp.50-55, 18-19 Oct. 2008.

[20] Aerosim, Aeronautical Simulation Blockset v1.2, Users Guide.

[21] N. N. Karnik and J. M. Mendel, “Centroid of a type-2 fuzzy set,” *Information Sciences*, vol. 132, pp. 195-220, 2001.