

Type-2 Fuzzy Airplane Altitude Control: A Comparative Study

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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].

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

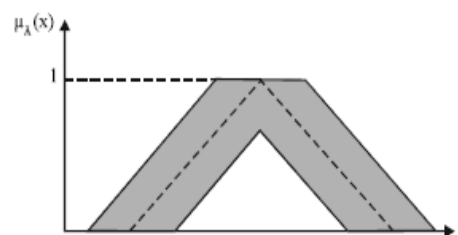


Fig. 1. Interval type-2 triangular fuzzy set.

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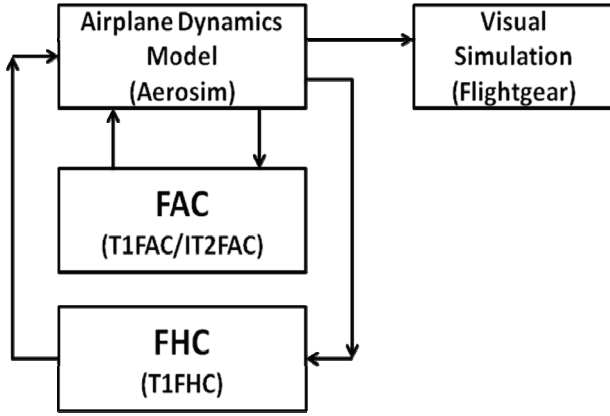


Fig. 4. Overall FFCS architecture.

values once they are achieved. The desired altitude and heading are calculated using the three desired position coordinates 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-1 and 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:

$$Aileron = (0.55\pi / 180) * BankAngle. \quad (1)$$

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

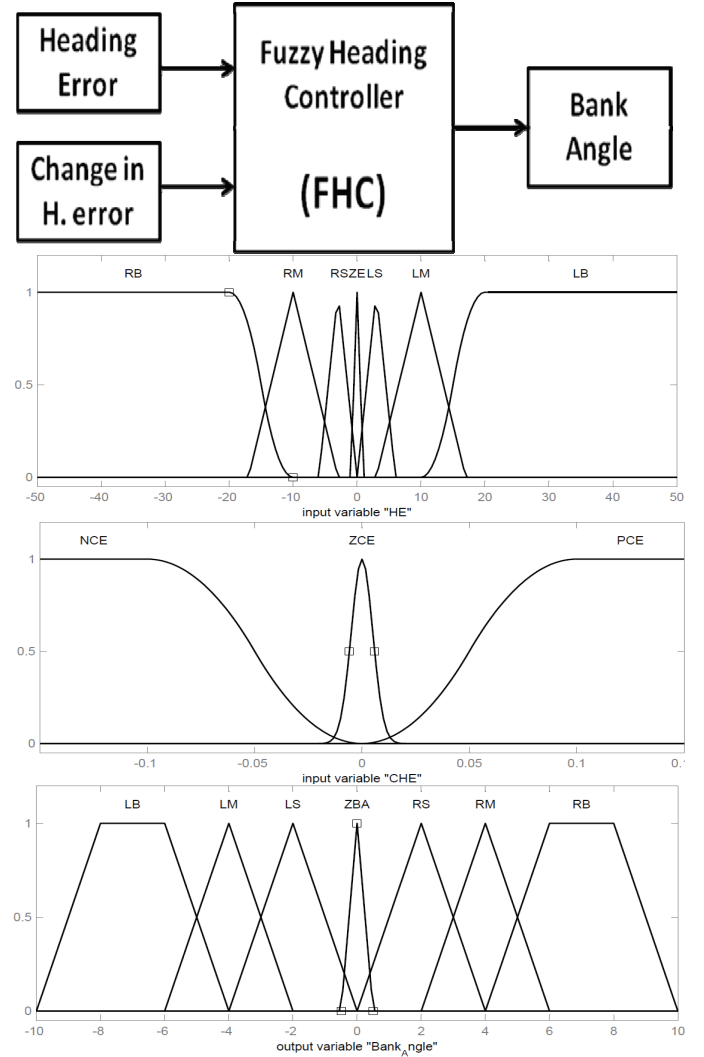


Fig. 5. (Top to Bottom) The schematics of FHC, and the membership functions of inputs and output respectively.

and outputs for the T1FAC and the IT2FAC are discussed in the following subsections.

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 Altitude 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:

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

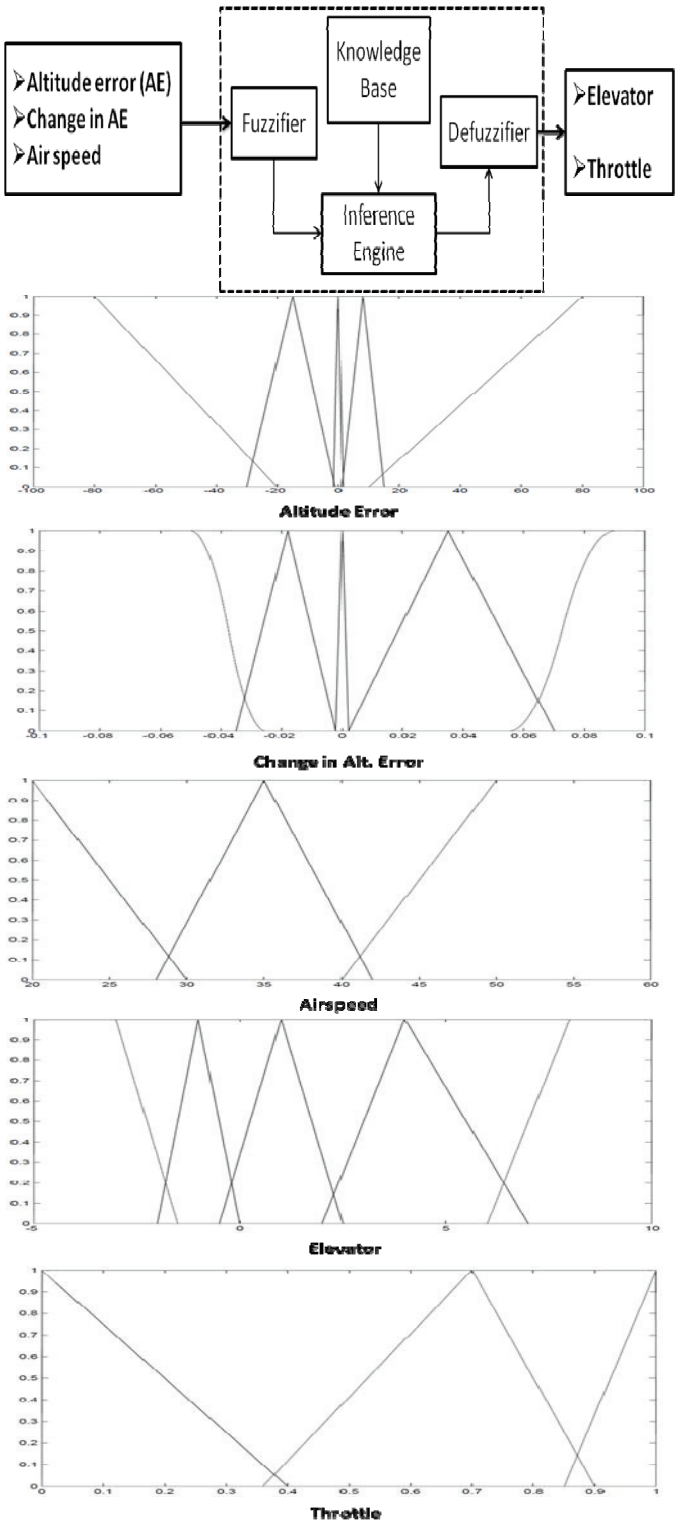


Fig. 6. (Top to Bottom) The schematics of T1FAC, and the membership functions of inputs and outputs respectively.

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

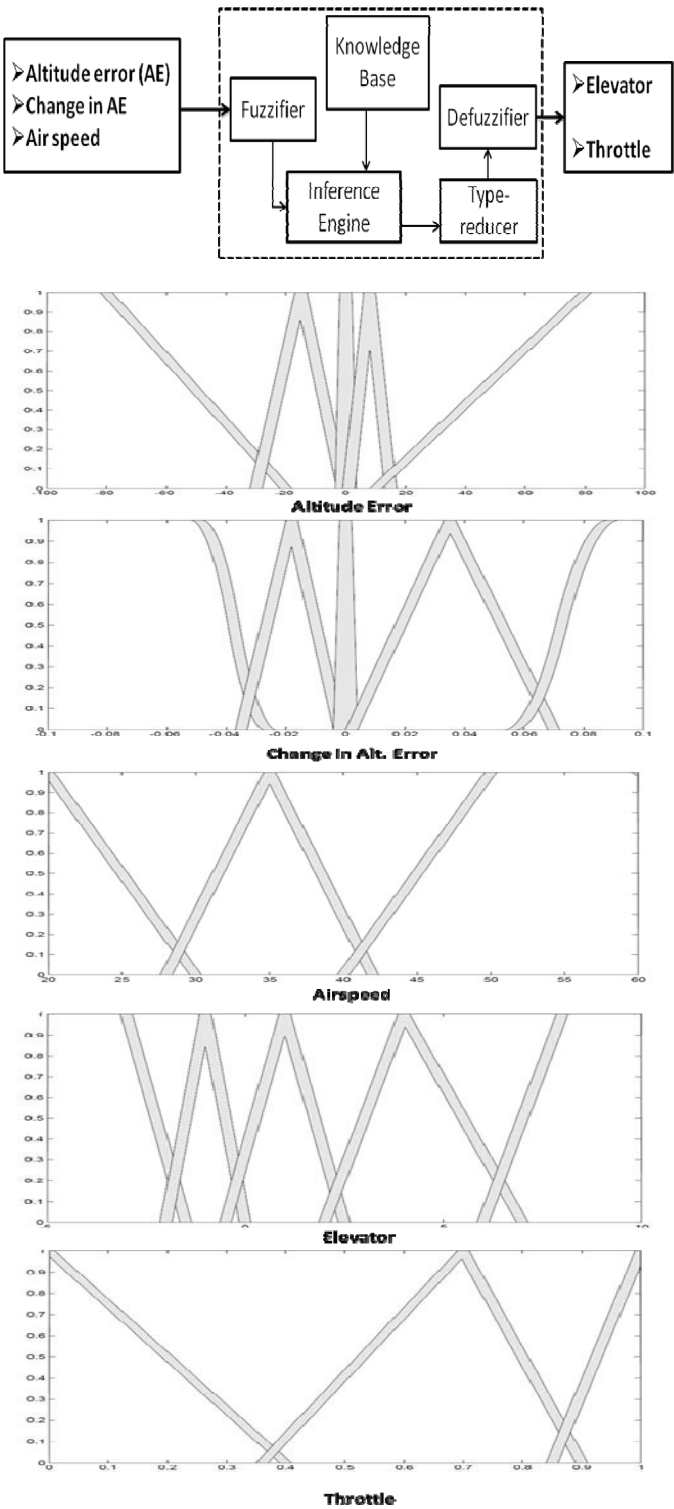


Fig. 7. (Top to Bottom) The schematics of IT2FAC, and the membership functions of inputs and outputs respectively.

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

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:

$$\begin{aligned} LMF &= \text{gauss MF} [\sigma, \mu - FoU*N] \\ RMF &= \text{gauss MF} [\sigma, \mu + FoU*N] \end{aligned} \quad (4)$$

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 Licence. A snapshot of the visual simulation is shown in Fig. 8.



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

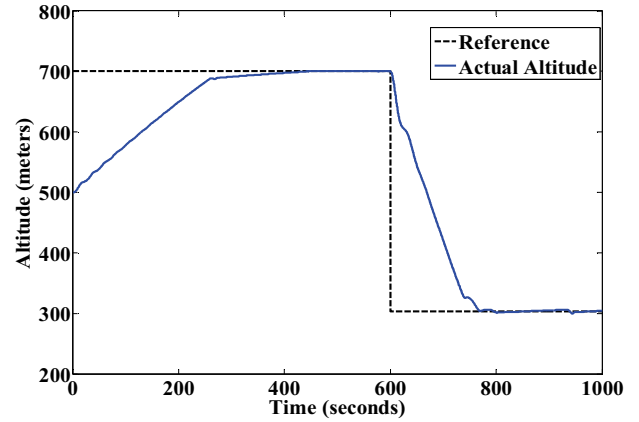


Fig. 9(a). Results of T1FAC in the ideal simulation setup.

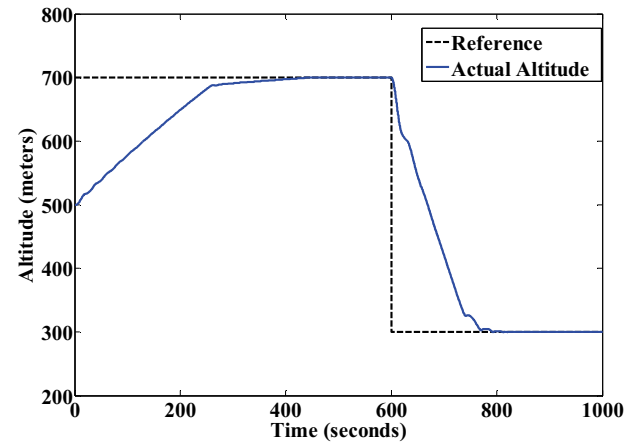


Fig. 9(b). Results of IT2FAC in the ideal simulation setup.

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.

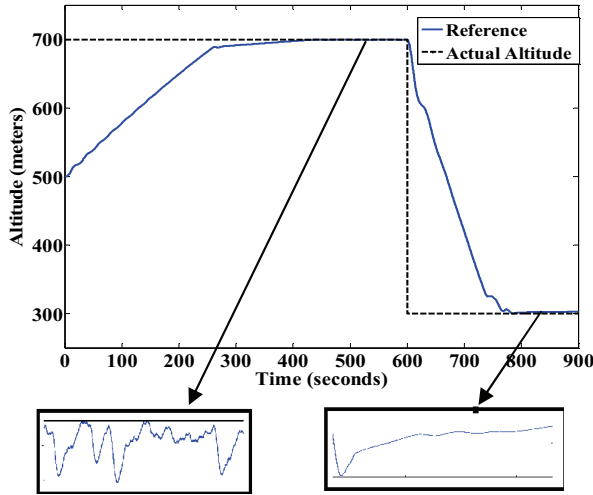


Fig. 10(a). Results of T1FAC in the simulation setup with uncertainties (Bottom blocks are the magnified steady state responses, (RMSE = 3.58 m)).

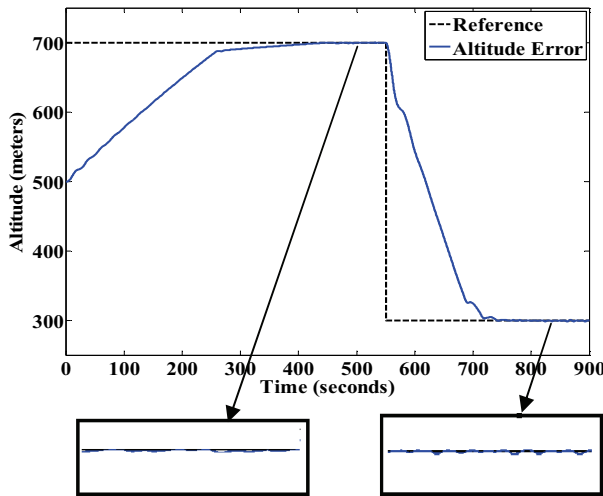


Fig. 10(b). Results of IT2FAC in the simulation setup with uncertainties (Bottom blocks are the magnified steady state responses (RMSE = 0.43 m)).

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 FoUs in the previous simulations, on the steady 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

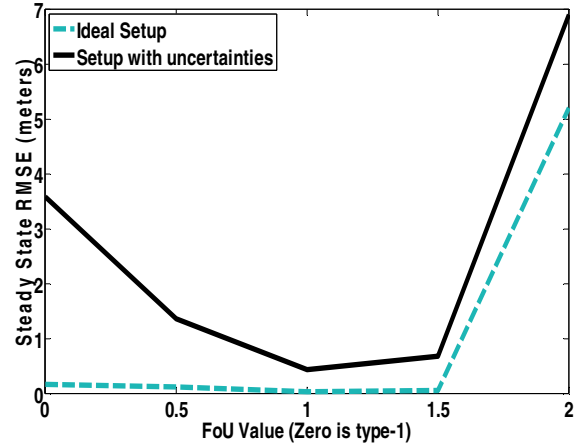


Fig. 11. Steady state RMSE as the result of simulations with different values of FoUs

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

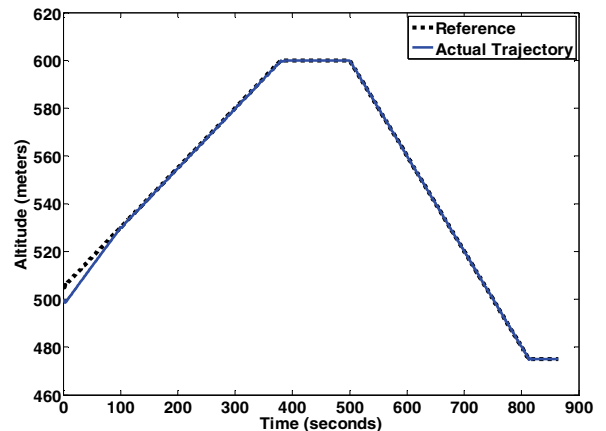


Fig. 12. Tracking response of IT2FAC to a ramp input

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.

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