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Fuzzy Logic in Decision Fusion for Situation Assessment

Lakshmi Shrinivasan[1], Raol, J. R.[2]

[1]Asst. Professor, Dept. of Electronics and Communication Engg. MSRIT, and Research Scholar, Jain University, Bangalore,
[2]Prof. Emeritus, MSRIT, Bangalore.

ABSTRACT

We present results of situation assessment that: i) uses type 1 fuzzy logic (T1FL) for decision making/fusion in some aviation scenarios, ii) uses modified situation assessment (pilot's mental-) models, and iii) can have noisy inputs to the situation assessment models. The results indicate that some existing fuzzy logic implication functions in decision making/fusion work very well. This beacons to newer possibilities of applications of fuzzy logic based decision fusion and situation assessment technology to varieties of aerospace/aviation problems and other dynamic systems for intelligent decision making.

Keywords: Fuzzy logic, Fuzzy inference system, Decision fusion, Situation Assessment, Formation flight, Air lane flight, threat assessment, noisy inputs.

Nomenclature

AI	Artificial intelligence
AP	Algebraic product
ARFI	Arithmetic rule of fuzzy implication (Zadeh/Lukasiewicz)
BS	Bounded sum
COA	Centre of area
F	State transition matrix/airplane trajectory dynamics
FL	Fuzzy logic
FLDS	Fuzzy logic decision system
FIF	Fuzzy implication function/process/method
FIS	Fuzzy inference system/engine
MF	Membership function
G	Process noise gain matrix
GMP	Generalized Modus Ponens
GMT	Generalized Modus Tollens
GUI	graphical user interface
ID	Identity (of an object)
IT2FL	Interval type 2 fuzzy logic
L1OR	Level 1 – Object Refinement
L2SR	Level 2 – Situation Refinement
MORFI	Mini (-mum) operation rule of fuzzy implication (Mamdani)
MRFI	Max-min rule of fuzzy implication (Zadeh)
OA	Object assessment
PORFI	Product-operation rule of fuzzy implication (Larsen)
Q	Process noise covariance matrix
SA	Situation assessment
SI	Standard intersection
SU	Standard union
S	S-Norm
SNR	Signal to noise ratio defined as variance (signal)/variance (noise)
T	Sampling interval/T-Norm
T1FL	Type 1 fuzzy logic
w	White Gaussian process noise with covariance matrix Q

A, B	General variables (e.g. low, medium, high, etc.)
A′	Complement of A
x, y, z	x-axis, y-axis, and z- axis airplane's positions, x is state variable also
u, v	Input fuzzy variables (e.g. speed, distance, etc.)
$\mu_{A \to B}(u,v)$	Represents a membership function
RoA	The relational operator over A
*, +	'*' and + with a dot '.' over it are generalized 'product' and 'sum' operators (the specialized are AND (min) and OR (max) operators)

1. INTRODUCTION

In several engineering-science problems, we need to use available data/knowledge and information along with some logic and/or a statistical method to arrive at an appropriate decision from among many alternatives. Often decision making is coupled with the knowledge representation that is derived by inference that uses some logical process over the measured data and collected intelligent information. One objective of decision making-cum-fusion (DMF) is to take one ultimate decision and action in an entire surveillance volume, for example in a scenario of a flying aircraft, at any instant of time using outputs from different levels of data fusion: a) Level 1–Object refinement (L1OR), and ii) Level 2–Situation rrefinement (L2SR), especially in a defence system [1]. The L1OR forms object assessment (OA) by combining the information on location, parametric and identity to obtain refined representation of individual objects like emitters, platforms and weapons. In L2SR one finds a description of the relationship between objects and observed events. The aim is to obtain a total/final picture of the opponent's objective. In this paper we use T1FL to help in making decision for the three aviation scenarios: i) formation flight, ii) air lane flight, and iii) threat assessment. We briefly describe the fuzzy inference system (FIS), and the MATLAB-GUI based tool for the evaluation of the existing fuzzy implication functions for decision fusion [2-4]. The decision process is realised using MATLAB/SIMULINK toolboxes, and the results are generated using numerically simulated data. The procedure based on T1FL described here is applicable to other civilian data analysis and fusion systems also.

2. DECISION-LEVEL FUSION

Decision fusion (DeF), also called symbol level fusion represents the highest level information fusion wherein the symbol represents a decision [5,6]. The decision fusion in most cases depends upon the external knowledge and/or on inference from it. In symbolic data/information the inference methods from AI can be used as computational procedures, like FL, this being so, since the fusion of symbolic information would require reasoning and inference in the presence of uncertainty. This uncertainty is modeled by FL.

The approach used in current paper is based on heuristic knowledge acquired from the domain experts (pilots/aviation experts) and hence, it is more realistic in treating the situation assessment [7] problems. It is strongly felt that the FL based decision fusion definitely would be a value addition to the performance of the decision fusion process and systems, especially because it incorporates the knowledge of the real experts. Presently, the aim is to apply T1FL and see how it performs for certain aviation scenarios considered.

3. FUZZY INFERENCE ENGINE/SYSTEM (FIS)

In T1FL only the input variables are fuzzified and the membership function yields crisp values for each input value. What this means is that the input variables are specified as ranges (low, medium, high, etc.).
In a fuzzy rule we have

'If u is A, Then v is B'

The If part is called the antecedent or premise, and Then part of the rule is called the consequent or result part. The core process is FIS/FIE that, via FIFs defines mapping from input fuzzy sets into output fuzzy sets.

If the antecedent of a given rule has more than one clause

'If u_1 is A_1 AND/OR u_2 is A_2, Then v is B'

fuzzy operators (from T-norm/S-norm [1]) are applied to obtain one value that represents the result of the antecedent for that rule. In case more rules fire at the same time, outputs of all rules are aggregated, and then the fuzzy sets that represent the output of each rule are combined into single fuzzy set.

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4. FORMATION FLIGHT

A FL based decision software/system (FLDS) residing in (its) own ship (platform) to decide whether two enemy fighter aircraft have formation flight or not is studied. The model discussed in [1,8], to assess pair formation for two aircrafts of unknown origin is also used. This conventional situation assessment (SA) model is modified by the addition of two new inputs as shown in Figure 1, and subsequently has modified rules. The inputs: ‘speed’, ‘elevation’ and ‘bearing’, are computed/processed to determine if the two aircrafts have the same kinematics. The introduction of the two new inputs: ‘altitude’ of the two aircrafts and the ‘aspect (angle)’ between them, is used with the existing model’s remaining inputs of ‘distance’, ‘ID’ and ‘speed’ to determine whether the two aircrafts are flying in a formation. Aspect angle (AA) is the number of degrees measured from the tail of an aircraft to the other aircraft [9], and it has nothing to do with bearing and its value ranges from 0 deg. to 180 deg. AA when used in addition to the distance between the two aircrafts, gives an accurate view of the lateral displacement between the two vehicles and hence, gives a more accurate representation of whether the two flights form a pair. The altitudes of both the aircrafts are checked to see if they are higher than the minimum required level and if not, then the aircrafts are considered not in a formation flight.

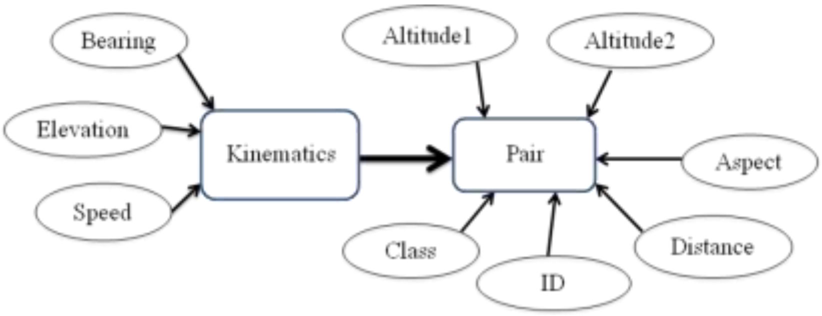

Figure 1: Modified SA model for pair formation (The old model did not have altitudes and aspect information)

Figure 2 depicts the flight scenario in terms of the trajectories and elevation angles of the aircrafts. In the first five seconds, the distance between the two aircrafts is small and at the end of these five seconds, their flight paths begin to diverge. In the subsequent five seconds the two aircrafts travel with a constant parallel separation. From the 15th second to the 20th second, their flight paths converge and then they fly at a constant altitude for the next five seconds. From the 25th second, both aircrafts begin descending until they reach 200m at the 30th second, remain at that altitude for five seconds and then start their ascent to 1000m, after which they fly at constant altitude. The altitudes of the two aircrafts are input separately, Figure 3. As we can see from Figures 2 and 3, at the 29th second, and also at the 9th second in the case of the second aircraft, the altitudes of the two aircrafts fall below 460m (~1500ft), which is the minimum altitude that the aircrafts should possess for formation flight.

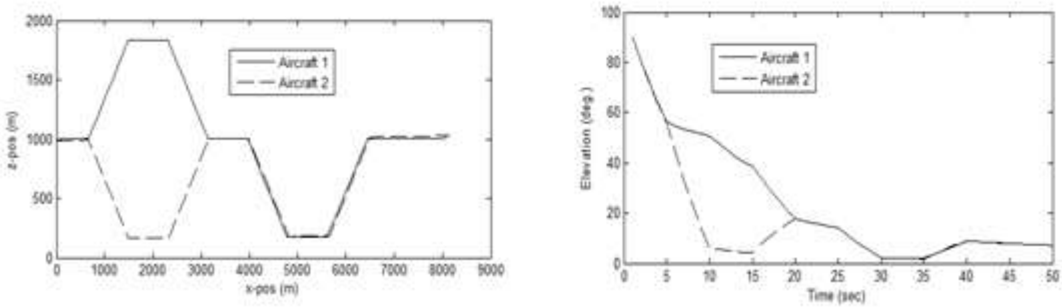

Figure 2: Simualted flight trajectories of the two aircraft: z-positons and elevations

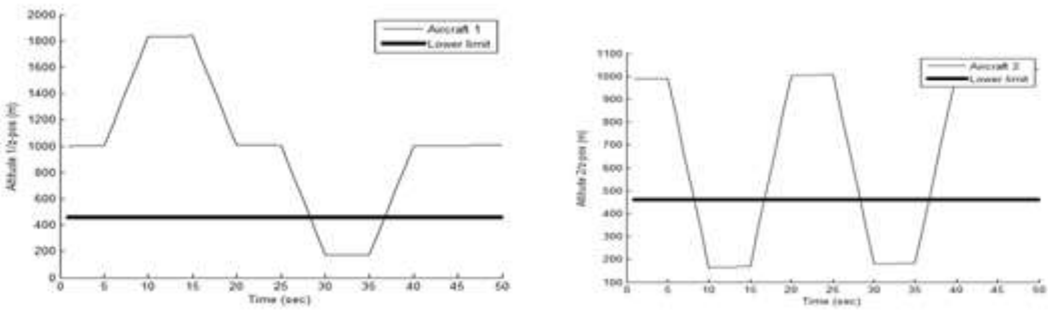

Figure 3: Altitudes of Aircraft 1 and Aircraft 2.

The AA between the two aircrafts goes below the required range (30 deg.) at the 44th second. Two important assumptions are made for this simulation, the aircrafts are: i) friendly to each other, and ii) always within the vicinity of the sensor/s. The inputs to the fuzzy logic decision system are: the numerical differences of the aircrafts' bearing, elevation, separation distance along the z-axis, speed, identity, and class. The new input, aspect, is the AA between the two aircrafts. Trapezoidal membership functions are used to fuzzify each input and output data between 0 and 1. It should be noted that the limits of these functions are provided for the sake of concept proving, based on the designers'/authors' intuition. In practice, these limits should be provided by an expert in the relevant domain. The rules used to decide whether two aircraft form a pair or not are as follows: Rule 1: If two aircrafts have the same Bearing, Elevation and Speed, then they have the same Kinematics; Rule 2: If two aircrafts have the same Kinematics, the same Identity, the same Class, and are at a short Distance from each other, then they form a pair; and Rule 3: If the Altitude of either aircraft is below 460m or Aspect lies outside of the 30 - 60 degree range, then they do not form a pair.

Here, PORFI implication method is used and the bounded sum (BS) operator of the T-conorm/S-norm is used in the aggregation process. The aggregated output fuzzy set is defuzzified using the centre of area (COA) method. The decision system is implemented in MATLAB/Simulink. The outputs of the previous/original and the modified/new models are compared in Figure 4.

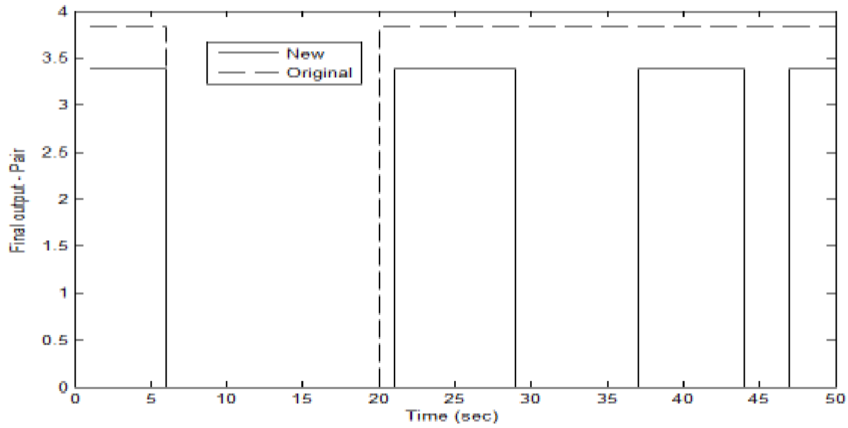

Figure 4: Outputs of the decision fusion system (DeFS) to determine formation flight for original SA model and the new SA model

We can see that system is able to correctly detect the aircrafts' pair and split periods. Table 1 illustrates the numerical comparison of the final outputs from the two models, original and new, to determine pair formation. It is observed that there is a minor change in the value of the final defuzzified output representing the decision 'Yes'. We observe that the output of the new model is different from that of the original at the 29th and 44th second as a result of the two new inputs, altitude and aspect angle, causing the third rule to be satisfied at those times.

Table 1: Results of the Formation Flight for the Two Models

Time (sec)	Original Output	New Output
1	3.7984	3.385
3	3.7984	3.385
5	3.7984	3.385
7	0	0
9	0	0
11	0	0
13	0	0
15	0	0
17	0	0
19	0	0
21	3.7984	3.385
23	3.7984	3.385
25	3.7984	3.385
27	3.7984	3.385
29	3.7984	0

31	3.7984	0
33	3.7984	0
35	3.7984	0
37	3.7984	3.385
39	3.7984	3.385
41	3.7984	3.385
43	3.7984	3.385
45	3.7984	0
47	3.7984	3.385
49	3.7984	3.385

5. THREAT ASSESSMENT

Threat Assessment builds to develop a comprehensive system. This system, as shown in Figure 5, combines the conventional inputs such as velocity, aspect angle, deviation angle (angle off), elevation, RWR sensor reading, class, ID and range in a systematic manner to compute various intermediary parameters like combat geometry, energy driven positional geometry, sensor driven positional geometry and situational geometry to determine the action of the unknown aircraft [8-10].

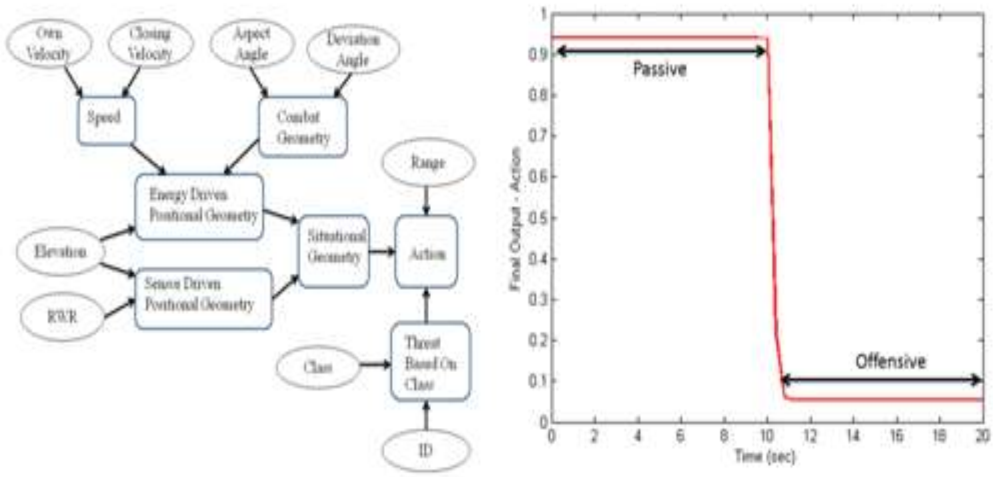

Figure 5: SA Model for threat assessment and Output of the DeFS to predict action

The inputs Own Velocity and Closing Velocity have three MFs: Low, Medium and High. Speed has four MFs: High Advantage, Medium Advantage, Low Advantage and Disadvantage. Aspect Angle and Deviation Angle, each with the MFs Low, Medium and High, are combined in order to assess the Combat Geometry of the two aircrafts. Elevation represents the elevation of the other aircraft with respect to own-ship and has three MFs: Negative Low, Positive Low and Positive Medium. The input RWR has two MFs: Illuminating and Non-Illuminating. Speed, Combat Geometry and Elevation are used to compute the Energy Driven Positional Geometry (EDPG) [11]. EDPG is a measure of the advantage possessed by an aircraft from a kinetic and potential energy point of view [10]. Sensor Driven Positional Geometry (SDPG) is a measure of the sensor advantage that the aircraft's elevation and RWR puts it under. Situational Geometry represents the overall situation based on 'Energy Driven Positional Geometry' and 'Sensor Driven Positional Geometry'. An aircraft at a higher elevation might be at an energy advantage but at a sensor disadvantage. Situational Geometry is a parameter which takes both into consideration. Combat Geometry, EDPG, SDPG and Situational Geometry have five MFs: High Advantage, Advantage, Disadvantage, Mutual Disadvantage and Neutral. Class represents the type of aircraft and has four MFs: Fighter, Bomber, Missile and Transport. ID and has three MFs: Friend, Foe or Unknown. Class and ID of the unknown aircraft are taken into consideration to compute the Threat based on Class.

It has four MFs: High Threat, Medium Threat, Low Threat and Benign. Range represents the distance between own-ship and the other aircraft and has three MFs: Short, Medium and Long. Threat based on Class, Range and Situational Geometry is used to predict the unknown aircraft's actions. The output, Action, has four MFs: Offensive, Evasive, Defensive and Passive. Appropriate rules are defined in each FIS, taking all possible scenarios into consideration. The implication method used is PORFI and bounded sum (BS) is used for aggregation. Center of area (COA) method is used to defuzzify the output. To verify the proper working of the system, a possible situation is simulated using

MATLAB for 20 seconds. In this scenario, an enemy bomber is considered. Initially, the bomber is at a large distance from own-ship, with a low elevation, speed and aspect angle. During this time, the deviation angle is medium. After ten seconds, the aircraft has moved closer and is now travelling with a high speed. It has moved higher up and turned such that it has a high aspect angle and low deviation angle (facing own-ship head-on). The velocity of own-ship is a constant low for the entire simulation period and the RWR is always illuminated. Figure 5 shows the decision given by the system for this scenario. The system is able to correctly identify the threat posed by the enemy aircraft.

6. STUDY OF EFFECT OF NOISE ON FL BASED DECISION FUSION SYSTEMS

In practical situations the inputs sourced from the sensors are often contaminated with noise and hence, it is necessary to test the decision fusion systems' performance in the presence of noise. In order to test the systems, most inputs to the system are exposed to noise and the performance evaluated. The amount of noise added to the inputs is varied by trial and error and the minimum SNR of the inputs for which the system produces the expected performance is determined [12].

a) Threat Assessment: Various inputs have been contaminated with random input signal, and only one input is shown in Figure 6. A comparison between the outputs of the system with and without the addition of noise is also shown in Figure 6. From trial and error, it was found that the decision system could produce accurate results for or above SNR of 20dB with reasonable tolerance levels.

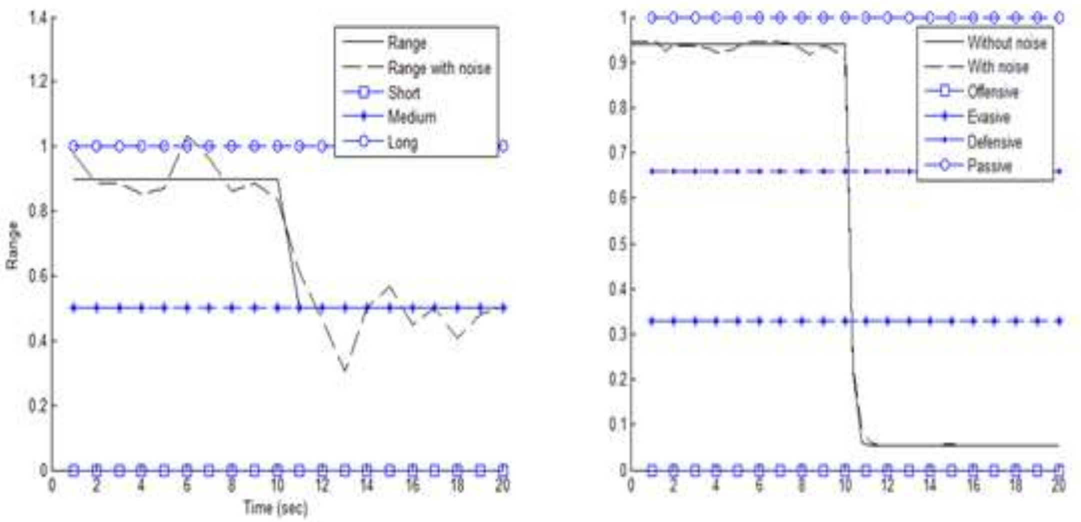

Figure 6: Range input with noise and Output of DeFS for threat assement with noisy inputs

b) Flying along air-lane: Now, we describe a system that is used to decide if a particular aircraft is flying along the air lane. A sensitivity study is carried out to check the performance of system in the presence of noise. The inputs to the system are distance (the absolute separation between the aircraft and the air lane along the y-axis), the absolute value of bearing difference between them, and the class of the aircraft. Trapezoidal MFs are used to fuzzify the inputs and outputs. The rules used to decide whether a particular aircraft flies along an air lane or not are as follows [4]: Rule 1: If the aircraft has the same bearing as the air lane and if it is close to the air lane, then the aircraft is flying along the air lane; Rule 2: If the aircraft is civil, then there is a high possibility that the aircraft is flying along the air lane.

PORFI is used as the implication method, and bounded sum (BS) operator of the T-conorm/S-norm is used in the aggregation process. The aggregated output fuzzy set is defuzzified using the centre of area (COA) method. The Simulink model to determine if an aircraft is following the air lane uses the FL Toolbox for the inference system [11]. The trajectory of the aircraft and its relative motion with respect to the air lane is simulated. The bearings of the aircraft as well as that of the air lane are also generated. Noise is added to the system's inputs to simulate the presence of noise in various sensors that might be interfaced with the decision system. The two primary inputs processed to decide if the aircraft is following the air lane are distance and bearing. Upon the addition of noise to the distance between the aircraft and air lane, the input becomes as shown in Figure 7. The bearing difference is also exposed to noise and the subsequent plot is also shown in Figure 7. From trial and error, it was found that the system could produce accurate results for or above an SNR of 16dB with reasonable tolerance levels. A comparison between the outputs of the system with and without the addition of noise is shown in Figure 7.

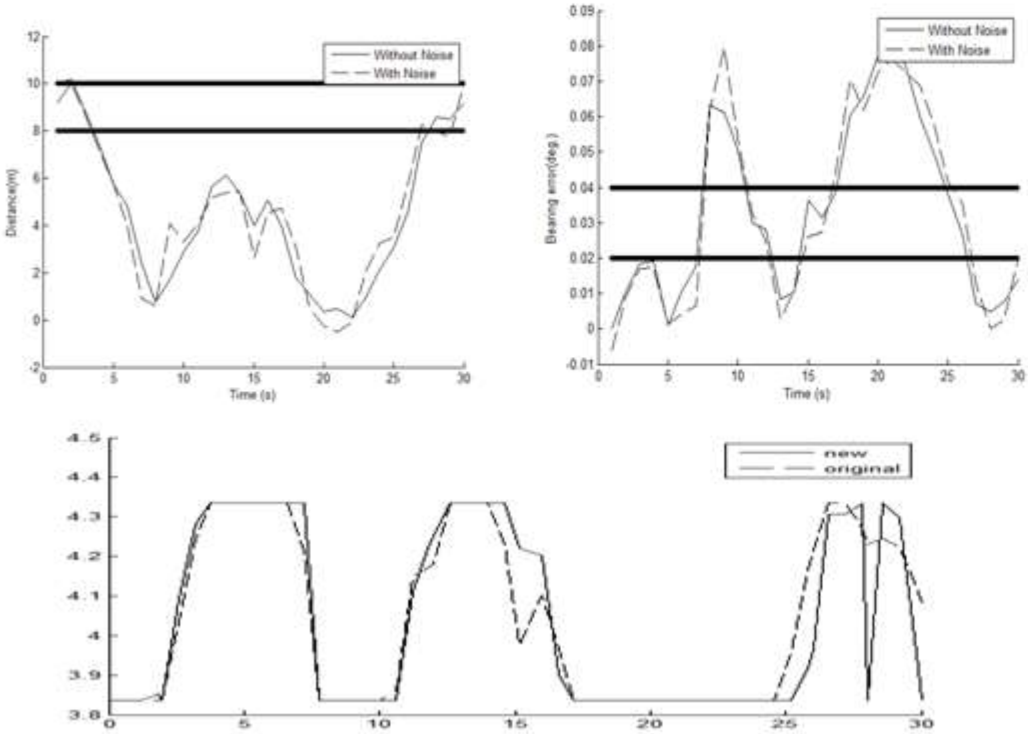

Figure 7: Distance and Bearing differences between aircraft and air lane and the final outputs of the DeFS for air lane with and without noise.

7. DISCUSSIONS OF THE RESULTS

The main aim of this work has been to illustrate the use and application of fuzzy logic type 1- T1FL to the three aviation scenarios in decision making/fusion using situation assessment models. The decision making has been incorporated in the rules: i) if two aircraft have the same kinematics, identity, class and are at a short distance from each other then they form a pair' - (a decision here), ii) if the altitude of either aircraft is below 1500ft (460m) or aspect lies outside of the 30 - 60 degree range, then they do not form a pair, iii) if an aircraft is closing in on another, has a different ID and is a fighter aircraft, then the aircraft is attacking the other, and iv) if an aircraft is closing in on another, has a different ID, is a fighter aircraft and RWR is illuminated, then the aircraft is attacking the other. The results of this work are qualitative as well as quantitative and are presented in Table 1 and Figures 4, 5, and 7. Also, these decision systems have been tested extensively in the presence of noise (in several inputs) to simulate the noise associated with the sensors in the actual environment. The systems proved to be stable with the presence of noise. It was found that the threat assessment system provided accurate outputs above a minimum SNR of 20dB, and the along air lane system provided accurate results above a minimum of 16dB SNR. Thus, the FIF-evaluation tools as applied to the existing FIFs have been proved to be working satisfactorily for the situation assessment in the aviation scenarios presented in this paper.

CONCLUDING REMARKS

We have briefly discussed the FIS and decision fusion paradigms and considered three aviation applications, viz. formation flight, air lane and threat assessment. The results indicate that some existing fuzzy implication functions work well for the examples considered. While the results are very encouraging, some more studies can be made to evaluate these FIFs and their applicability in general control systems as well as in aerospace data fusion and decision fusion systems. This definitely opens up several novel possibilities of applications of decision fusion based on fuzzy logic to varieties of aerospace and aviation problems in decision making.

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