Chapter 2  Type 1 Fuzzy Logic and decision fusion

Four aviation scenarios are developed and simulated with the help type-1 fuzzy logic (T1FL) as a situation assessment system. To automate the system by mimicking a pilot’s mental model ability is the main objective of the implementation of the system. Some suitable modifications are incorporated in existing four aviation scenarios which have been validated using simulations.

2.1 Type 1 fuzzy logic

In real life, there are many possible conditions of certain events, apart from the two states used in the classical logic that is binary (‘0’, or ‘1’; two-valued, i.e. yes, or no); e.g. surrounding temperature might be warm, hot, very hot, cold, very cold, etc. Hence, this point conveys that uncertainties are part of the real time environment situations. Hence logic ‘0’ or logic ‘1’ or truth and falsity (0 or 1 respectively) are two end points of a continuous range of uncertainty which is expressed and modelled by fuzzy logic (FL) which is superset of crisp set theory, is multivalued logic; wherein the characteristic function, membership function is generalised to assume an infinite number of values between 0 and 1. The overall process of fuzzy inference system/process/engine (FIS) for T1FL is shown in figure 2.1.

In T1FL only the input variables are fuzzified and the membership function yields crisp values for each input value. The input variables are specified as ranges (low, medium, high, etc.). In a fuzzy...
logic, the rule ‘If $u$ is $b$, Then $v$ is $a$’; the If part is called the ancestor or premise, and Then part of the fuzzy rule is called the resultant or result part. The main process is FIS, and via fuzzy implication functions/methods (FIFs) which defines mapping between input and output fuzzy sets [3]. In case, if ancestor of a given rule has more than one part (If $u_1$ is $A_1$ AND/OR $u_2$ is $A_2$, Then $v$ is $B$), then, fuzzy logic operators (from T-norm/S-norm [1]) are used to obtain one fuzzy set value that represents the result of the ancestor or that rule. In case multiple rules fired at the same time, outputs of all rules are combined, and then the each rule that represents fuzzy sets output are aggregated into single fuzzy set. Linguistic based fuzzy rules are framed by domain expert. Finally, the fuzzified output set values (T1FL) are converted into crisp (T0FL) values using defuzzification process. The development of FLSs needs the following tasks:

i. Choose fuzzy appropriate sets and corresponding MF for fuzzification process

ii. Fuzzy rules are derived from domain expert for input and output fuzzy set mapping.

iii. Select appropriate fuzzy operator for fuzzy implication and aggregation process

iv. Choose the suitable defuzzification method.

A universe of discourse (UOD) $U$ with elements of $u$ based on fuzzy set is expressed as in equation 2.1:

$$ A = \int\{\mu_A(u)/u\} \forall u \in U $$

$$ A = \sum\{\mu_A(u)/u\} \forall u \in U $$

(2.1)

Here, $\mu_{A(u)}$ is a membership function (MF) of $u$ in set $A$ and provides the mapping of UOD in the closed interval [0, 1], figure 2.2.
The term, $\mu_A(u)$ is a measure of the degree of belongingness of u to the set A. Linguistic variable has a numeric data range value which represents a fuzzy variable. The fuzzy variables could be with different linguistic names with different fuzzy MF functions as shown in figure 2.3. Various fuzzy MF are available like Gaussian, trapezoidal, triangular, sigmoid, Z-shaped, $\Pi$- shaped and S-shaped. Suitable selection based on type and range fuzzy variable can be done. FL operators are minimum, maximum and complement corresponding to AND, OR, and NOT as in traditional crisp set theory. FIM uses various methods and aggregation uses T-norm or S-norm.

2.2 Decision Fusion in situation assessment by Fuzzy Logic Type 1 (T1FL)

Four avionic scenarios for SA: i) pair formation, ii) threat assessment, iii) flying along the airlane, and iv) attack are considered. The four models are built in MATLAB Simulink and MATLAB GUI-based tool. With the help of suitable simulation based generated data have been used to implement the final decision oriented fusion system in MATLAB/ Simulink software tool.
2.2.1 Pair formation
The model used is shown in figure 2.4 for assessment of pair formation of the two aircrafts. The data’s are obtained from sensors such as the speed, the elevation and the bearing are calculated and treated to identify that ‘if kinematics of the two aircrafts are the same’, and other inputs: ID (identity), speed and distance are used to decide ‘pair formation aspect of the two aircrafts i.e. if they fly in formation or not.’ Each input/output data is fuzzified by using Trapezoidal membership functions between 0 and 1 [1, 2]. The authors/designers’ knowledge based intuition has been utilized in setting the data range limit for all these MF functions which have used to prove the concepts. In real time situations, a domain expert provides these limits.

![Figure 2.4 Original model of pair formation](image)

2.2.2 Threat assessment
As shown in figure 2.5, to estimate the output of the action [21] of the unidentified aircraft, the scenario considered is threat assessment, which involves the combination of the conventional inputs such as angle off, velocity, RWR sensor reading, aspect angle, class, range, ID and elevation in a methodical manner to calculate different intermediate factors like energy driven positional geometry, sensor driven positional geometry, combat geometry and situational geometry these will contribute to decision of the model.
The 3 MFs: small, med and tall represent sensor data inputs such as ‘own velocity’ and ‘closing velocity’. The 4 MFs: tall, med, low and dis Advantage, represents the speed input sensor data. The two flights having the combat geometry is assessed by using deviation and aspect angle inputs, individually having MFs small, med and tall. Negative small, Positive small and positive med are the 3 MFs for elevation input. The Illuminating and Non-Illuminating are the MFs used for input RWR (Radar Warning Receiver). The different measures possessed by an aircraft are speed, combat geometry and elevation. The kinematic and potential energy [2, 21] are a parametric measures of an aircraft. Hence energy driven positional geometry is obtained by using above mentioned parameters. EDPG and sensor driven positional geometry (SDPG) gives complete situational assessment for situational geometry. At a higher elevation levels an aircraft will be benefited by energy aspect but it faces sensor related issues. Energy and sensor both are considered by situational geometry parameter. High Adv, Adv, disadv, mutual Disadv and Neut are the five MFs for Combat Geometry, EDPG, SDPG and situational geometry. Combat, Bomb, Projectile and Trans are MFs of input class. Pal, Enemy or Unidentified are the MFs of ID. ID and class are the inputs to evaluate class of an unidentified aircraft which is based on threat system. Threat has 4 MFs: Large threat, Med threat, small threat and Begin. The own-ship and another aircraft are separated by a distance known as a range. It has 3 MFs namely Small, Med and Lengthy. Threat system outcome enables to identify the action of unknown aircraft which in turn driven by class, range and situational geometry. The unknown aircraft’s action is identified based on Threat based on Class, Range and Situational Geometry. Aggressive, Eva, Protective and Inactive are the 4 MFs used for action. Relevant rules are framed for all scenarios in each FIS system. The aggregation of
various fuzzy output sets into one fuzzy set is done using fuzzy implication method (FIM) which has PORFI and bounded sum (BS) techniques. Crisp final output is obtained by defuzzification process which uses Center of area method.

2.2.3 Flying along the airlane
The system as shown in figure 2.6 is used to decide flying formation of aircraft.

![Figure 2.6 Model for flying formation of aircraft along the air-lane](image)

The three different sensor contributions to the defined system involves are distance (the complete separation between the aircraft and airlane (the designated track path for planes), class and bearing. The inputs and outputs are fuzzified by suitable trapezoidal membership functions. Fuzzy Implication function, PORFI technique is used in the this described aviation model scenario. Aggregation is performed using BS operator of the T-conorm/S-norm, then defuzzication is done which results in crisp output via center of area (COA) method.

2.2.4 Attack
The behaviour of another approaching aircraft [2, 8] in the vicinity of own airship, i.e. whether it is friend or foe is predicted using attack model ass shown in figure 2.7. Initially the speed, aspect and distance sensor inputs are verified to see the closeness of the approaching aircraft in own airship region. Later attack prediction is done based on the identity of the aircraft and its class.

![Figure 2.7 Attack prediction aviation scenario system](image)
Small, medium and high are the three MFs are used to represent the three sensor data inputs such as, speed, distance and aspect. The in-between output closing has two membership functions: True or False. Friend, Foe or unknown are the 3 different forms and corresponding MFs of ID input sensor data. Fighter, Bomber, Transport and Missile are 4 different MFs of class input. True and False are the 2 MFs of final attack output. MORFI is FIF and standard union (SU) as aggregation method is used in fuzzy inference system and defuzzification is using centre of area (COA) is carried out.

2.3 Study of various modified situation assessment-SA models
The SA models discussed section 2.2 are modified with new inputs and new rules are incorporated and performance analysis has been done.

2.3.1 Modified pair formation model
As shown in figure 2.8 new inputs ‘altitudes’ for both the aircrafts are added along with the ‘aspect’ (angle) between them is considered.

![Figure 2.8 Modified pair formation model](image)

Aspect angle is expressed in degrees off the tail of a reference aircraft to the heading aircraft [22]. This in conjunction with the distance input helps in providing an accurate view of the sideways movement between the two aircrafts and enhances the accuracy in decision of the two aircrafts whether they form a pair or not. Also another sensor input data i.e. flight level or altitude was used. For both the flights this level was checked and if it was above the minimum altitude level then it adds on the correctness of the pair formation decision else they are not in pair formation. New altitude level information makes more accurate and robust decision result.
2.3.2 Comparison of decision output with original and modified new pair formation model
MATLAB simulation tool is used to generate the required Kinematic data for the 2 flights. The complete simulation is carried out for fifty seconds. Figures 2.9 and 2.10 represent the flight levels of aircraft 1 and 2 respectively.

![Flight level of Aircraft 1](image1)
![Flight level of Aircraft 2](image2)

Figure 2.9 Flight level of Aircraft 1
Figure 2.10 Flight level of Aircraft 2

![Comparison of outputs](image3)

Figure 2.11 A comparative analysis of outputs of existing and modified model decision fusion system to decide flight’s pair formation

It is observed from results, that, the space among the 2 flights is very less at the beginning of first 5 seconds of simulation. The last 5 seconds these flights routes start to deviate. In the next successive 5 seconds the two flights move away with a fixed similar separation. The flight routes starts to join from fifteen to twentieth seconds and for next five seconds they fly with fixed flight levels. The flights keep moving downward from 25th second onwards, till they touch 200m. They remain at same flight level from 30th second and subsequent next 5 seconds. Later they start to fly upwards up to 1000m, after that fixed flight level is maintained. As can be seen from figures 2.9,
and 2.10, the least flight level is to be maintained by flights is 460m (1500ft). At 29\textsuperscript{th} time second the flight level of the 1\textsuperscript{st} aircraft falls below 460m (1500ft), and at the 9\textsuperscript{th} time stamp the other aircraft follows the same. At the 44\textsuperscript{th} simulation time the aspect angle which is the least flight level that the aircrafts must possess for pair formation of flight, by the 29\textsuperscript{th} second, and also by the 9\textsuperscript{th} second in the situation of the other aircraft. Further, the aspect angle amongst the two aircrafts falls further down the necessary range (30°). By observing the figure 2.11 and Table 2.1 it has been observed that decision fusion system is able to properly identify the aircrafts’ pair formation and splitting time zones.

2.3.2.1 Threat assessment model
Referring figure. 2.4, in MATLAB, a promising aviation scenario is simulated for 20 time second duration to realize the correct functioning of the system, the typical initial condition of an opponent bomber airship is considered at a great distance from own-ship, with a little elevation, speed and aspect angle. The deviance angle is medium at this time of stamp. The flights has stirred very nearer for next 10 seconds and then moving with a very great speed. This results in large aspect angle and very small deviance angle. During entire simulation time period the velocity of own-ship is a fixed value and small, also the RWR is continuously lightened. figure. 2.12 shows simulated output of threat assessment aviation scenario decision results which is accurately predicting the threat the output result in the form of crisp decision produced by the system for the current situation.

![Figure 2.12 Threat aviation scenario decision result](image-url)
Table 2.1 Comparison of existing and modified system results pair formation of flight

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Existing system output result</th>
<th>Modified system output result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>3.79</td>
<td>3.38</td>
</tr>
<tr>
<td>3.</td>
<td>3.79</td>
<td>3.38</td>
</tr>
<tr>
<td>5.</td>
<td>3.79</td>
<td>3.38</td>
</tr>
<tr>
<td>7.</td>
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<td>0</td>
</tr>
<tr>
<td>9.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17.</td>
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<td>0</td>
</tr>
<tr>
<td>19.</td>
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<td>0</td>
</tr>
<tr>
<td>21.</td>
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<td>3.38</td>
</tr>
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</tr>
<tr>
<td>49.</td>
<td>3.79</td>
<td>3.38</td>
</tr>
</tbody>
</table>
2.3.2.2 Flying along the airlane model

Referring to figure 2.5, the model uses the simulated data for this scenario generated using MATLAB for 30 seconds. Fig. 2.13 shows the aircraft with airlane positions in the yaw plane and figure 2.14 shows the bearings of the flights with corresponding flight path route with suitable different data arguments as observed from the source point (0, 0). For the simulation purpose a civilian flight is assumed.

![Figure 2.13 Location of airlane and aircraft](image)

**Figure 2.13 Location of airlane and aircraft**

![Figure 2.14 Aircraft and considered airlane bearing relation results](image)

**Figure 2.14 Aircraft and considered airlane bearing relation results**

2.3.2.3 Modified attack prediction model

Figure 2.15 depicts, the upgraded version of existing attack aviation scenario system model. This system considers the velocity of the own aircraft and that of the new flight objectives are not known. To find out the speed benefit of own aircraft over the new aircraft, the two velocities are compared. Also, the RWR sensor data information is pulled in. The main intention of including RWR sensor data is to give a alert warning signal, when a threat signal is issued from the radar,
that might be emitted from the opponent aircraft posing a threat signal to own aircraft. The fusion of this data with other available source of information helps in judging the purposes of the other aircraft. The upgraded model has, the new inputs such as own velocity and closing Velocity with 3 membership functions namely, small, med and large. The remaining inputs, outputs, attack and their corresponding MFs are same.

The updated new model is implemented using fuzzy logic toolbox in MATLAB/Simulink environment, the output decision result is, as depicted in figure 2.16. To validate the model, the required data is generated using simulation for time period of twenty seconds. The assumed initial conditions are that, it is a fighter opponent aircraft which would be at a far distance with respect to own airship and having a moderate aspect angle. When 10 seconds time lapsed, the aircraft has come nearer and the aspect angle became huge. During the complete simulation time period, the velocity of the own aircraft is very small, on the counterpart the opponent’s is very large. The initial first 15 seconds the RWR data is illuminated whereas for remaining time period it is not-illuminated. By observing the results as shown in figure 2.16, the modified new model is able to accurately predict the act of the aircrafts as attacking or non-attacking.
2.4 Study with different If..Then.. rules
In T1FL system, the mapping of input variables to output is done and fuzzy output sets are obtained, this is assisted by the linguistic rules framed by domain human experts. Rules are very important as they guide the final fuzzified output.

2.4.1 Pair formation model
The two aircrafts pair formation [2] act is decided by the following rules.

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.

Rule 3: 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.

The new addition of rule 3 would enhance decision results in terms of pair formation or not of two aircrafts. The comparative results of pair formation or not is as described in section 2.3.2, as shown in figure 2.11 and table 2.1. Rules are very important as they guide the final fuzzified output.

2.4.2 Flying along the airlane
The aircraft whether flying along the designated path or route or airlane or not is guided by specific rules which are mentioned below.

Rule 1: If the aircraft has the same bearing as the airlane and if it is close to the airlane, then the aircraft is flying along the airlane.

Rule 2: If the aircraft is civilian, then there is a high possibility that the aircraft is flying along the airlane.

As explained in section 2.3.2.2 these rules helps to identify the typical aircraft whether it is flying along the airlane or not which is shown in figures 2.13 and 2.14.

2.4.3 Attack model
The guidelines provided in making decision about the attack [8] intension of the other aircraft is given by rules which are described below.

Rule 1: If an aircraft has high speed advantage, has a close distance to another aircraft and is heading towards it (high aspect), then the aircraft is trying to close in on the other.

Rule 2: 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 output results obtained using above domain expert guided rules able to better predict of attack by other aircraft which is described in section 2.3.2.3 and figure 2.16.

2.5 Effect of noise on SA models

Most of the times, avionics situations, in which the real time sensor input data are noisy in nature. Hence, it is extremely important to check and validate decision fusion system model for various parametric performance metric in the presence of uncertainties. To carry out the testing the inputs are added with noises and then the reliability and robustness of the system has been validated. Certain number of iteration with different amount of noises had been carried .Then the least SNR of the noise has been identified to be added to the data inputs. Based on this quantity level of SNR, the performance of the system is evaluated.

2.5.1 Threat assessment

Real time sensor data are always affected by noisy random signals. To prove concept of robustness in decision output results, one sample signal with random signal is considered which is as shown in figure 2.17 (a). Decision fusion result outputs comparison is carried out with and without addition of uncertainties (noise signal) and is depicted as shown in figure 2.17 (b) With certain number of iteration, it is identified that the system could generate the precise and accurate results for noise levels of 20dB and above with efficient accurate tolerance levels.

Figure 2.17 (a) Range input with noise of DeFS for threat assessment and (b) Output of DeFS with and without noise for threat assessment
2.5.2 Flying along airlane
In complete decision fusion system, the noisy data environment in various avionics situation, is simulated by addition of certain levels of noise in the sensor input data. One of the situation is identification of the two aircrafts whether they are flying along the airlane or not. This decision is dependent upon the two main sensor inputs i.e. distance and bearing. figure 2.18 shows the noise added distance and bearing input signal plots. With suitable number of iterations, it is proved from the results that system is efficiently handles the noisy signals and produces accurate decision results for SNR of 20dB and above as depicted in figure 2.18. This Fig also gives a complete picture of comparison of output results of the system model based upon uncertainties with and without consideration.

Figure 2.18 Distance and Bearing differences between aircraft and air lane and the final outputs of the DeFS for airlane with and without noise.