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A flexible rule-based framework for pilot performance analysis in air combat simulation systems

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Abstract: Air combat simulation systems (ACSSs) are developed to train fighter pilots (trainees) in a virtual combat environment. In general, an ACSS consists of the following stages: planning the scenario, training, flight analysis, and performance evaluation. In this paper, the details of the framework, which is developed to analyze and evaluate the performance of the trainees, is introduced. First, the evaluation criteria for the pilot performance are defined. Next, a dynamic pilot performance evaluation system is developed that can be controlled and modified by experienced instructor pilots (instructors/trainers) to define the performance criteria details using predefined evaluation parameters. The evaluation of the trainees is conducted at the end of the flight and then a report related to the trainees' performance is generated. Eleven of the performance criteria are within the scope of this paper; however, the proposed system provides an extensible infrastructure to define new criteria and parameters.

Key words: Air combat, performance evaluation, performance criteria

1. Introduction

The training process imposes specific requirements where the training conditions must be as close to a real combat environment as possible. Therefore, special simulation systems called air combat simulation systems (ACSSs), which correspond to the needs of the air forces, have been developed. Such systems can be realized in 2 ways: a real combat aircraft with the integrated simulation computer or a virtual ground aircraft platform with an integrated simulation computer. An ACSS should be capable of supporting artificial air and ground forces. Moreover, various scenarios can be planned prior to the training and executed during the training, whether they are in the air or on the ground. Thus, such trainings yield improvement in teamwork/interteamwork and betterment of the tactical abilities of the trainees.

The developments in the electronics and warfare systems enable the trainers to conduct most of the training over simulation systems instead of deploying multiaircraft in a real airborne combat environment. This approach not only decreases training costs but also provides various training environments that could be dangerous in a real-world situation. Some of the constraints of the real-world trainings can be listed as:

i. Inadequate flight hours due to the limited budgets,

ii. Danger of collision of aircraft in close combat scenarios (closer than 5 nm),

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iii. Complications in conducting a planned training scenario in the combat environment (blue team/red team arrangements, geographic conditions) [1].

These issues can be addressed by ACSSs. Note that during combat, the pilots can perform plenty of different flight patterns or maneuvers, exhibit various reactive or proactive behaviors, make many decisions, and follow different tactics. These characteristics of the combat environment make the analysis of the pilot performance exceptionally complicated. However, assuming that the training data can be collected by ACSSs, such performance analysis systems depending on these capabilities can contribute to the fighter pilot training procedures. Weak and strong sides of a trainee can be understood with the assistance of the performance evaluation systems. Later on, the trainee can focus on the scenarios to improve his or her weak sides in special aspects. The main steps of developing an adaptive pilot performance analysis system (PiPAS) framework can be listed as:

i. Define parameters that can be used in criteria formulation/evaluation parameters,

ii. Define sample criteria that let instructors evaluate the skill set of the trainees based on the selected parameters/performance criteria,

iii. Provide a dynamic software environment for the instructors to formulate each criterion.

In this paper, these 3 stages of the pilot performance evaluation framework will be discussed along with some specific applications [2,3]. In addition to this, 32 evaluation parameters and 11 performance criteria are defined in this paper.

This paper is organized as follows. The following section represents the related work. Section 3 describes the definitions of the air combat terms. Section 4 explains the details of the proposed PiPAS. Section 5 shows the results of the study, and finally, Section 6 presents the conclusions of the study and discussions.

2. Related work

This section includes a summary of a research about pilot performance evaluation. However, before getting into the details of the related work, it would be helpful to mention the steps of the training with ACSSs, illustrated in Figure 1.

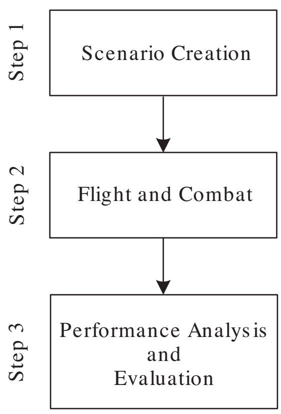

Figure 1. Steps of training with air combat simulation systems.

Step 1. Scenario creation: Scenario creation has a critical role in real air combat or the training with simulation. In this step, task definitions are formed by taking the inquiry of the enemy team and environmental conditions into account. Each scenario includes the aircraft roles, aircraft routes (steer points), and safety constraint definitions. For instance, the scenario complexity, allowed minimum and maximum altitude, and combat training area are some other parameters defined in this step.

Step 2. Flight and combat: After the scenario creation step, the pilots move to the training area and the training simulation starts in accordance with the created scenario. During the simulation, the needed data are collected in real-time for a post-review. For example, the position, orientation, and load factor of each aircraft; missile data (missile type, position, orientation, and direction), radar data; and chaff/flare data are collected during the simulation run.

Step 3. Performance analysis and evaluation: After the training simulation, a complete analysis of the shots, maneuvers, and reactions of the pilot are produced. The analysis process can be accomplished with the help of 3-dimensional (3D) debriefing systems under the instruction of one of the trainers. However, note that the performance analysis of the trainees based on visual inspection, which depends only on the aid of the debriefing system, can lead to some deceiving results. For instance, in such cases, it is not possible to exactly estimate the data ranges, aspect angle, or some of the other parametric data depending on the 3D visualizations. These incomplete data affect the judgment of the instructors during the evaluation process. Obviously, developing a performance evaluation system is a complex task, since there is a wide range of movements and behaviors carried out by pilots due to the complexity of the air combat environment. In the past, only some of the parameters were calculated after the training. These were simple statistical data such as the kill ratio and missile-hit ratio, which gave only a little information on the pilot and the team performance [4]. Later on, the research on the positional advantage of the aircraft was initiated with [5] and followed with [6]. As a result, the all-aspect maneuvering index (AAMI), which describes how pilots are performing their maneuvers within the weapon engagement zone (WEZ), is introduced. The AAMI outputs kill/no kill ratios, probabilities of occurrences of some airborne events, and information on the trainees' combat engagement capabilities [6–8].

On the other hand, there is still a need for computer-based systems that automatically analyze the performance of the trainees. Therefore, the PiPAS, which represents an infrastructure for the instructors to analyze and evaluate the performance of the trainees, is proposed.

3. Air combat terms

Before giving the details of the proposed system, commonly used terms are given in this section. Note that each term that is discussed here is of vital importance for the performance of the trainees. All of these terms below are used in the evaluation parameters and performance criteria, which will be explained in Section 4.

1. *Heading*: It shows the nose direction of the aircraft in angles. The angle is calculated by taking a reference point as $0°$. The heading value changes between $-180°$ and $+180°$.

2. *Angle off:* This is also called the heading cross angle. It is the difference of the heading values of 2 aircraft. If both aircraft are heading in the same direction, then the angle off is $0°$. At a $90°$ angle off, one aircraft is perpendicular to the other [9].

3. *Aspect angle:* The aspect angle is the number of degrees, measured from the tail of one aircraft to the foe aircraft. It indicates the aircraft's relative position to the foe's 6 o'clock position. It is determined from the tail of the opposing aircraft. The tail, 6 o'clock position, is $0°$. The nose of the foe is $180°$. If the

aircraft is on the right side of the foe, that is right aspect. If the aircraft is on the left side, that is left aspect [9].

4. *Load factor (G):* The load factor is the ratio of the total load supported by the airplane's wing to the total weight of the airplane. It results in a pressure on the pilot, especially in maneuvers. The harder the turn, the more fatigue effect on the pilot. This is because the G-force blockades the blood flow to the brain. After some time under high G-force, the pilot may become faint. This situation is called 'tunnel vision'. To summarize, the effect of the G-force on the pilot depends on 2 variables [10]:

   i. G-force value.

   ii. G-force duration (how long the pilot is subjected to G).

   A negative G-force may exert a 'redout' effect on the pilot. This effect occurs if the blood flow increases more than usual. Because of aircraft dynamics, it is not very common to be subjected to a negative G-force for a long time [10].

   One of the most important terms in the G-awareness of the pilot is the G-induced loss of consciousness (GLOC). The GLOC is defined as the loss of cognitive brain functions [11]. The GLOC has 2 serious traits. First, it is more dangerous than other pilot stresses since it is not possible for a pilot to accurately and reliably know how close he or she is to the GLOC threshold. Second, since amnesia (of the incident) is a characteristic of the GLOC, the pilot may never know that he or she has ever lost consciousness and may not be cognizant of any close calls. The best solution to the GLOC problem is pilot awareness [12].

5. *Weapon envelope:* The weapon envelope shows the effective distances of a particular weapon over the enemy aircraft. It takes into account the weapons' maximum and minimum ranges, weapon capabilities, aspect angle, speed, angle off, relative headings, and so on. The basic shape of a weapon envelope is egg-shaped, as shown in Figure 2 [9].

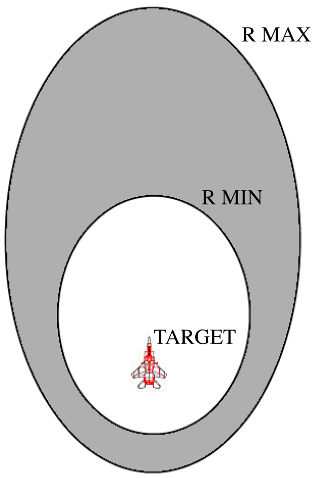

Figure 2. Weapon envelope [9].

In Figure 2, RMAX is the maximum effective range and RMIN is the minimum effective range of a particular weapon.

During the training, the situation of staying in the enemy aircraft's weapon envelope and taking the enemy to his or her weapon envelope shows the pilots' defensive and offensive performances, respectively. In that case, air combat is converted to a game [13]. This game represents a highly simplified version of air combat, yet it is sufficiently complex so as to exhibit a rich variety of combat phenomena. In this game, if one player ignores the opponent's weapon envelope when choosing his or her strategy, then he or she is playing offensively. Or, if the player ignores his or her own weapon envelope when deciding his or her strategy, then he or she is playing defensively.

6. *Chaff*: One of the earliest forms of electronic counter measures is the chaff, which is generally large quantities of radar-reflective material (often small lengths of foil or wire and also possibly gases) released into the air to produce false targets or large clouds of clutter, like a noise. The chaff is used as a jammer in air combat. The chaff can deceive Doppler radars in the beam aspect (right and left aspect), while it can deceive a missile in all of the aspect values [14].

7. *Flare:* A flare is used to deceive infrared systems. When expelled by a target, it presents a source point of infrared energy, generally more intense than that of the target, which tends to attract a heat-seeking missile [14].

8. *Positional geometry:* The range, aspect angle, and angle-off are used to describe the angular relationship between 2 aircraft, as shown in Figure 3. These 3 factors show the aircraft's positional advantage [12].

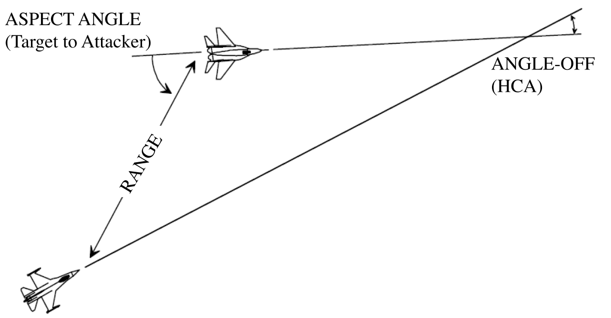

Figure 3. Positional geometry [12].

4. The details of the proposed PiPAS

The proposed PiPAS gives a flexible infrastructure to the instructor to analyze and evaluate the performance of the trainee from different aspects. The component diagram of the proposed system is shown in Figure 4. It includes 2 subsystems: the criteria formulation system and performance analysis system.

One of the purposes of this paper is to define the constant parameters, evaluation parameters, and performance criteria. Now, we will illustrate these parameters and criteria and then continue with the illustrations of the criteria formulation system and the performance analysis system.

4.1. Constant parameters

In order to create formulations for the pilot performance, some constant values are defined by the instructor pilot. Some constants used in the PiPAS are explained below:

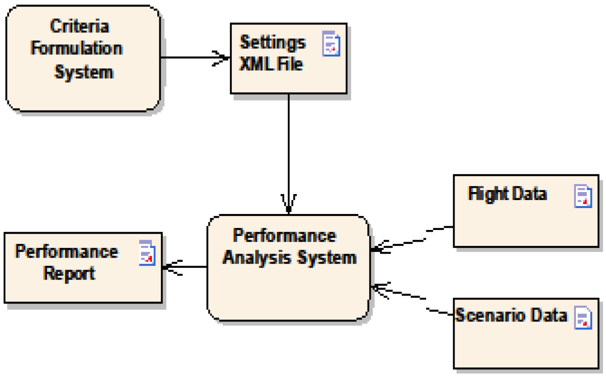

Figure 4. Component diagram of the PiPAS.

1. *Bubble*: This value indicates the safety range between 2 friendly aircraft. A dangerous (undesired) situation occurs when one aircraft is inside of another friendly aircraft's bubble, which might cause a crash.

2. *Min/max G value*: These values show the allowable G-force values during the training. Min and max G-force values change according to the scenario (task) and aircraft specifications.

3. *Minimum abort range (MAR) values:* The MAR shows the effective range values of an aircraft missile. These values change according to the aspect angle, missile type, and altitude of the aircraft [15]. For each aircraft missile, these values are entered by the instructor. A sample screenshot from the PiPAS for entering the MAR values is shown in Figure 5.

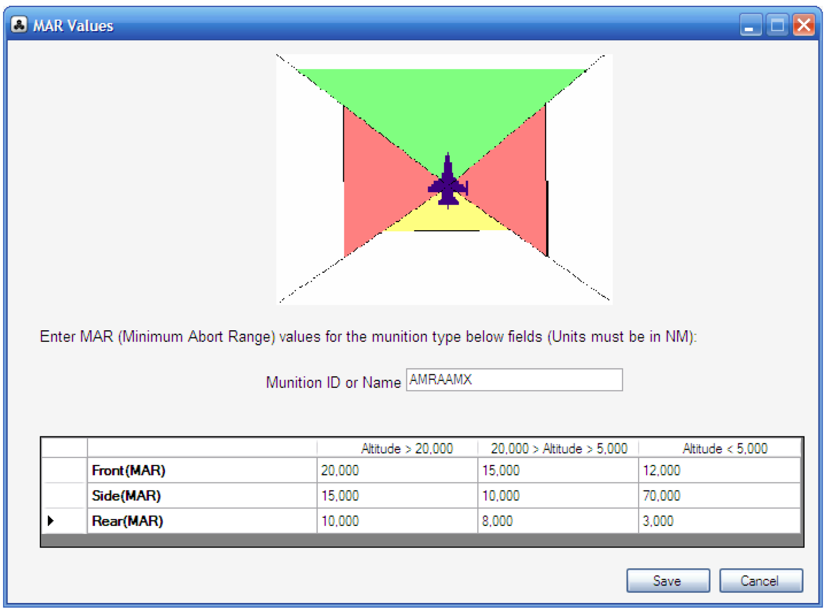

Figure 5. MAR input screen.

4. *N-pole values*: The N-pole shows the most effective range values of an aircraft missile. In this range, the pilot has less probability of escaping than with the MAR range [15].

4.2. Evaluation parameters

These parameters are also used in the formulation of the performance criteria. Each parameter can be taken directly from the scenario creation phase or derived from raw data collected during the simulation. There are 41 evaluation parameters used in the PiPAS, but only the more important ones are explained below:

1. *Scenario complexity*: This is set by the instructor during the scenario creation phase. It has values of 0, 1, and 2 that correspond to easy, moderate, and hard scenarios, respectively.

2. *Number of blue forces*: The number of friendly aircraft taking part in the training simulation.

3. *Number of red forces*: The number of enemy aircraft taking part in the training simulation.

4. *Number of destroyed red forces*: The number of enemy aircraft destroyed by the trainee.

5. *Number of destroyed blue forces*: The number of friendly aircraft destroyed by the trainee (accidentally).

6. *Percentage of successful shots*: It is calculated using the collected data via Eq. (1).

   $$\textit{Percentage of successful shots} = \textit{number of successful shots / total shots} \times \textit{100} \quad (1)$$

7. *Missile fired to red forces*: The total number of shots fired at the enemy aircraft by the trainee.

8. *Dataset at shooting time*: A dataset including the data for the evaluated pilot and for the shooting aircraft at the time of a missile shot. The dataset includes the heading, speed, altitude, and load factor of both aircraft at the time of the missile shot.

9. *Range at shooting time:* It is calculated via Eq. (2), where *alt* is the altitude, *lon* is the longitude, *lat* is the latitude, and suffixes R and B for each variable correspond to the shooting aircraft and evaluated trainee aircraft, respectively.

   $$Range = \sqrt{(altR^2 - altB^2) + (lonR^2 - lonB^2) + (latR^2 - latB^2)} \quad (2)$$

   Range could be calculated more precisely by taking the ellipsoidal shape of the earth into account [16] but this is not within the scope of this paper.

10. *Angle off at shooting time*: The angle off value between the evaluated pilot's aircraft and the shooting aircraft is formulated as in Eq. (3), where *hR* is the heading of the shooting aircraft and *hB* is the heading of the evaluated pilot's aircraft.

    $$AngleOff = hR - hB \quad (3)$$

11. *Missile miss distance:* It is the nearest distance between the missile and the enemy aircraft, if the shot misses.

12. *Dead/alive after training*: It shows whether the trainee that completes the training simulation is dead or alive.

13. *Number of training area violations*: The training area is defined during the scenario creation. This parameter shows how many times a pilot violated this area (went outside of the area). The training area is created by a set of steer points (latitude and longitude). Consequent steer points create a line. When calculating whether an aircraft is outside of the training area at a simulation time, the following steps are used:

i. A virtual line is drawn from the aircraft to a virtual steer point that is known for sure to be outside of the training area.

ii. The number of intersection points between this virtual line and the training area lines are calculated. The intersection algorithm of the object-oriented graphics rendering engine is used in the PiPAS [17].

iii. If the number of intersection points is odd, then the aircraft is inside of the training area (Figure 6a); otherwise, it is outside of the training area (Figure 6b).

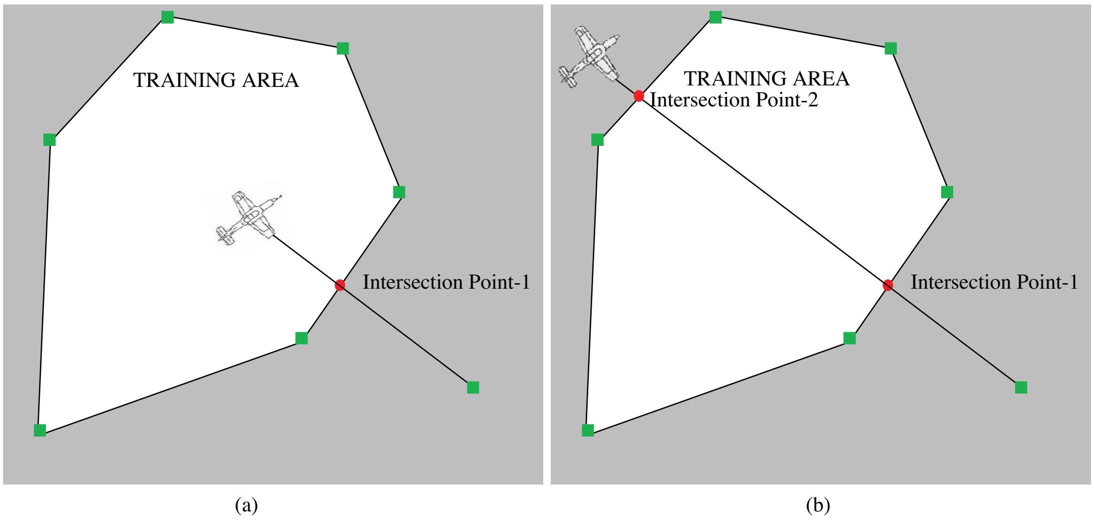

Figure 6. a) Aircraft is inside of the training area and b) aircraft is outside of the training area.

14. *Number of altitude block violations*: Altitude blocks (allowable minimum and maximum altitudes) are defined during the scenario creation step. This parameter shows how many times the trainee violated these constraint values.

15. *Number of bubble violations*: This shows how many times the trainee is inside of the bubble zone of another friendly aircraft.

16. *Number of max G violations*: The number of times that the trainee exceeded the allowable max G-force (the allowable maximum and minimum G-force values are defined by the instructor during the scenario creation step).

17. *Number of min G violations*: The number of times that the pilot was subjected to a G-force below the allowable minimum level.

18. *Average G*: This parameter shows the average value of the G-force that the pilot is subjected to during the entire training.

19. *Number of shots at the pilot*: The total number of missile shots at the trainee from the enemy forces.

20. *Number of shots evaded by the pilot*: The number of shots that the trainee evaded or that missed the trainee's aircraft.

21. *Number of the enemy's MAR entrances*: The total number of times that the pilot entered the MAR zone of any enemy aircraft. The MAR values of a particular weapon are entered by the instructor as constants. The pseudocode for calculating the number of entrances into the enemy's MAR is shown in Figure 7. In the pseudocode, the *Constant1*, *Constant2*, and *Constant3* values are created during the scenario creation step according to altitude and aspect angle of the aircraft.

```
if aspect angle > 120
    if angle - off between +45  and  - 45 //front aspect
        Range < Constant1(with altitude comparison)
            if Not inside MAR
                MAR = MAR+1
    if angle - off between +135  and +45 //side aspect
        Range < Constant2(with altitude comparison)
            if Not inside MAR
                MAR = MAR+1
    if angle - off between  - 135  and  - 45 // side aspect
        Range < Constant2(with altitude comparison)
            if Not inside MAR
                MAR = MAR+1
    if angle - off between  - 135 and  - 180 OR between +135 and +180 //rear aspect
        Range < Constant3(with altitude comparison)
            if Not inside MAR
                MAR = MAR + 1
```

Figure 7. Calculation of the number of entrances into the enemyğs MAR.

22. *Total time of the enemy's MAR entrances*: The total time spent in seconds by the trainee inside of any enemy aircraft's MAR zone.

23. *Number of the enemy's N-pole entrances*: The total number of times that the trainee entered the N-pole zone of any enemy aircraft. The N-pole values of a particular weapon are entered by the instructor as constants.

24. *Total time of the enemy's N-pole entrances*: The total time spent in seconds by the trainee inside any enemy aircraft's N-pole zone.

25. *Number of the pilot's MAR entrances by the enemy*: This shows how many times the pilot was in the situation of taking an enemy aircraft into his or her MAR zone.

26. *Total time of pilot's MAR entrance by the enemy*: The total time spent in seconds by the enemy aircraft inside of the trainee's aircraft's MAR zone.

27. *Number of pilot's N-pole entrance by the enemy*: This shows how many times the pilot was in the situation of taking an enemy aircraft into his or her N-pole zone.

28. *Total time of pilot's N-pole entrance by enemy*: The total time spent in seconds by the enemy aircraft inside of the N-pole zone of the trainee's aircraft. The N-pole and MAR zones of the evaluated pilot's aircraft from different views are shown in Figure 8 [15].

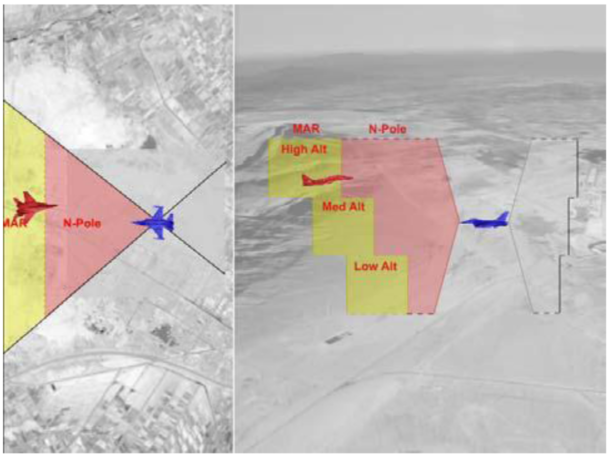

Figure 8. N-pole and MAR zones of the pilot [15].

29. *Number of chaffs released:* The total number of chaffs released by the trainee during the training.

30. *Number of shots deviated by chaff*: The total number of shots from enemy aircraft deviated by the trainee by releasing a chaff.

31. *Number of flares released*: The total number of flares released by the trainee during the training.

32. *Number of shots deviated by flare*: The total number of shots from enemy aircraft deviated by the trainee by releasing a flare.

4.3. Performance criteria

Each performance criterion represents a different characteristic of the trainee. In this paper, 11 performance criteria have been defined. Aviation institutes or air forces laboratory reports and air combat terms are also taken as references through the criteria definition. One of the reports includes some performance metrics, such as preventing enemies from reaching the target, F-16 fighter jet mortalities, striker kills, and successful shots to be destroyed by enemy shots [15]. After a 5-day simulator training, it was indicated that the performance of the trainee for each criterion was improved. Also note that expert pilots took part in the creation of these criteria. Another report includes the target kill percentage and maneuver index, which is an algorithm calculating positional advantage of an aircraft [18]. Eleven performance criteria of the PiPAS are listed and explained below:

1. *Shooting success*: This criterion evaluates the shooting capability of the trainee.

2. *WEZ management*: The WEZ shows the effective range of munitions. When the trainee tries to achieve his or her goal, he or she should also show good performance in the WEZ management. This criterion evaluates being inside the effective range of enemy aircraft's munitions or taking the enemy to his or her effective range. The WEZ management success of the trainee depends on the MAR and N-pole parameters [15]. Ideally, what is expected from the trainee is to minimize the duration of being inside of the enemy aircraft's MAR and N-pole zones, and to maximize the duration of taking the enemy aircraft into his or her MAR and N-pole zone.

3. *Friendly fire*: This evaluates the situation of the shots fired at friendly aircraft, since it is possible due to the dynamic situation of an air combat environment. This situation can be avoided by using the radar effectively and being in close communication with team members.

4. *Defensive success*: This criterion evaluates the defensive side of the trainee. The trainee should use suitable maneuver tactics to deviate the shots fired by the enemy. The best defense is not being inside of the effective range of the enemy. This is possible when the defensive aircraft has greater speed than the attacker's. The defensive aircraft has to perform 3 actions [14]:

   i. Preclude the attacker to shoot,

   ii. Preclude the attacker not to take the best position to shoot,

   iii. Shoot the attacker, even in bad positions.

5. *Offensive success*: This criterion evaluates the attack side of the trainee. The attacking maneuvers and shooting success can be included in this criterion. The main goal of an offensive success is to destroy the enemy aircraft.

6. *Mission success*: This evaluates the performance of the tasks assigned to the trainee during the scenario creation. Succeeding in a task is important, but being alive after a mission is the main goal of a pilot. The most important goal is vitality [12].

7. *Bubble success*: This criterion evaluates whether the trainee is obeying the bubble zone values when close to a friendly aircraft. There can be accidental crash situations in close formation tactics and obeying the bubble zone ranges prevents such accidents [12].

8. *Chaff/flare success:* This evaluates efficient usage of chaff and flares by the trainee. Generally, chaff and flares are used with defensive maneuvers. Maneuvers can be done effectively while the missile is puzzled by the chaff or flare.

9. *Obeying altitude limits*: This evaluates if the trainee obeys the minimum and maximum altitude limits. During the scenario creation, the minimum and maximum altitudes are defined by taking the geographic situation of the training area or taking the tactical reasons into account. The trainee should fly within these limits. The importance of this criterion was also emphasized in [19].

10. *Obeying training area*: This criterion evaluates if the trainee obeys the training area points. The trainee should fly inside of this area for safety reasons.

11. *G control success*: This criterion evaluates the management of the G by the trainee.

These 11 performance criteria are only some examples that can be formulated by the PiPAS and it also provides the ability to define new criteria using its dynamic infrastructure.

4.4. Criteria formulation system

The criteria formulation system allows the instructor to formulate the *performance criteria* using the defined *constants* and *evaluation parameters* obtained from the collected raw data. Each performance criterion evaluates the trainee from a different view. In the criteria formulation step, the instructor defines the rules and formulations for each performance criterion. The flowchart of the constructed performance criterion is shown in Figure 9. In addition to the air combat related *constants* and *evaluation parameters*, *mathematical operators* are also included in the score definition and level definition rules.

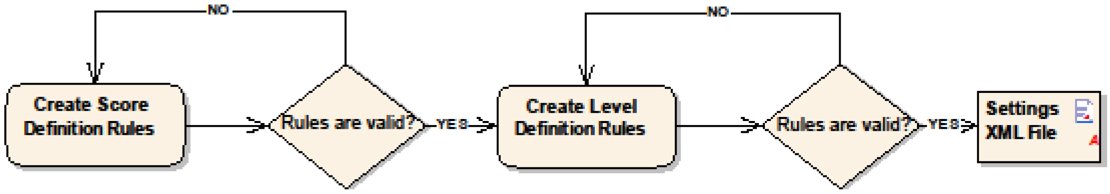

Figure 9. The flowchart of the constructed performance criterion.

4.4.1. Score definition rules

Score definition rules are used to define a score for the related performance criteria. In other words, a score is calculated by interpreting the created rules. The relationship between the definition rules and the score is shown in Figure 10. The definition rules are created using the *evaluation parameters*, *mathematical operators*, and *constant parameters.*

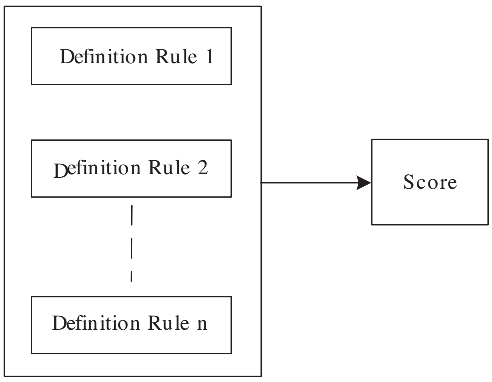

Figure 10. Relation between the score and definition rules.

The evaluation parameters and constant parameters have been explained in detail in the previous section. The following mathematical operators can be used to define the rules: + , − , * , / , % , &(and) , |(or) , !(not) , ==(equals) , !=(not equal) , > , >= , < , <= , and (,). The floating point or decimal numbers can also be used in the rules.

There are 3 keywords that can be used inside of a rule:

i. *IF*

ii. *SCORE*

iii. *ENDIF*

IF is used to define a condition. It is used in the following format:

IF(condition)

SCORE is used to assign a score. It is used in the following format:

$$Score\ =\ Formulation$$

The result of the created formulation is calculated and added to the score value. If the score already has a value, then the new value is added to the old value.

ENDIF shows the end of an *IF*. Every *IF* must finish with an *ENDIF*.

A simple example rule set that includes *IF*, *SCORE*, and *ENDIF* is shown in Figure 11. There are 2 rule definitions in this rule set. Line 1 through line 3 is the 1st rule; and line 4 through line 6 is the 2nd rule.

```
IF (DeadOrAlive == 1 & DestroyedEnemyACs >= 5)
    SCORE  = 75
ENDIF
IF (DeadOrAlive == 0)
    SCORE   = 0
ENDIF
```

Figure 11. An example score definition rule set.

In the next stage, a validation of score definition rules should be executed. If 1 of the following 3 conditions is realized, then the validation of the rules would fail:

i. *IF* that does not finish with an *ENDIF*.

ii. The condition part of *IF* and formulation part of *SCORE* is mathematically incorrect.

iii. The condition and formulation part of *IF* and *SCORE* are blank.

4.4.2. Level definition rules

The score value for a performance criterion is generated with the score definition rules. The level definition of a trainee for each performance criterion is defined after the scoring. The level indicates the amount of capability of the trainee. The level is defined by a set of level definition rules. The relationship between the definition rules and the level is shown in Figure 12.

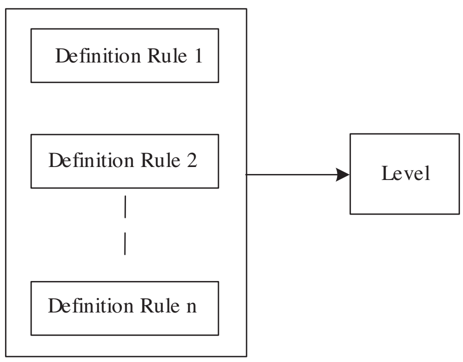

Figure 12. Relation between the level and definition rules.

Definition rules are created using the *level values*, *mathematical operators*, and *numeric values*. The level types are shown in Table. These values are also used in the United States Air Force [2].

Table. Level types.

Level	Description
QUALIFIED+	Performance is at very good level.
QUALIFIED	Performance is at an adequate level.
NOT QUALIFIED	Performance is not adequate (lack of capability).

There are 2 main differences between the level definition rules and the score definition rules:

i. Instead of the *SCORE* keyword, the *LEVEL* keyword is used. The *LEVEL* keyword starts with 'Level = ' and ends with '*QUALIFIED+*', '*QUALIFIED*', or '*NOT QUALIFIED*'.

ii. Evaluation parameters and constant parameters are not used.

A simple example rule set that includes *IF*, *LEVEL*, and *ENDIF* is shown in Figure 13. There are 3 rule definitions in this rule set. Line 1 through line 3 is the 1st rule, line 4 through line 6 is the 2nd rule, and line 7 through line 9 is the 3rd rule.

```
IF (Score  <= 50)
    Level = NOT QUALIFIED
ENDIF
IF (Score  > 50 | Score  <= 75)
    Level = QUALIFIED
ENDIF
IF (Score  > 75)
    Level = QUALIFIED+
ENDIF
```

Figure 13. An example level definition rule set.

In the next stage, a validation of the level definition rules should be executed. If 1 of the following 5 conditions is realized, then the validation of the rules would fail:

i. *IF* that does not finish with an *ENDIF*.

ii. The condition part of *IF* is mathematically incorrect.

iii. *LEVEL* does not end with '*QUALIFIED+*', '*QUALIFIED*', or '*NOT QUALIFIED*'.

iv. The condition and formulation part of *IF* and *LEVEL* are blank.

v. Any decimal value between 0 and 100 is not assigned to any level type.

4.5. Performance analysis system

After the criteria formulation system, the score and level definition rules created by the instructor are saved in XML file format. After the flight simulation, the performance analysis system is activated. This system takes the flight data, scenario data, and rules XML file, which is generated from the criteria formulation system, as inputs. Finally, a performance report that includes the score and level values for each performance criterion is generated.

The raw data collected from the training are used for the interpreting process to generate the score and level. The interpreter starts with calculating each evaluation parameter from the collected raw data. The score is then calculated using the score definition rules. Finally, the level is generated using the level definition rules.

Logically, the interpreter can be divided into 2 parts: the *rule parse* and *mathematical parse*. In the *rule parse*, the rules are processed from begin to end and in the *mathematical parse*, mathematical formulations or statements inside of the rules are parsed and a numeric value is generated. The parsing algorithm pseudocode for the score definition rules is shown in Figure 14.

```
Begin
double  Score;
-   For each rule line
    i f   keyword type  =  SCORE
        Score += mathematical parse result of formulation part of the rule
    i f   keyword  type = IF
        if     mathematical parse result of condition part of the rule > 0
                do nothing
        if mathematical parse result of condition part of the rule   =< 0
            while  keyword  type != ENDIF
                next rule line
-   next rule  line
End
```

Figure 14. Parsing process of the score definition rules.

The C# software library (MTParser) is used for the mathematical parse [20]. The same parsing process is also used for the level definitions and a level is generated. After the interpreter process is executed, the performance report is generated.

5. Results

In order to show the results of the PiPAS, a sample criteria set is defined. For every 11 criteria, the score and the level definition rules are created. The score definition rules for the shooting success criterion are shown in Figure 15.

In the next stage, the level rules are defined. A sample level definition rule set for this criterion is shown in Figure 16.

For the remaining 10 criteria, sample rules are also defined. Note that these rules are only sample rules showing the flexibility of the PiPAS. The creation of the rules should be carried out by experienced instructors.

```
SCORE = DestroyedRedForces * 10 - DestroyedBlueForces * 50
IF ( DeadOrAlive == 0)
    SCORE = - 70
ENDIF
IF ( DeadOrAlive == 1 )
    SCORE = 30
ENDIF
IF ( range > 30 && range < 50 )
    SCORE = 20
ENDIF
IF ( SpeedAtShootingTimeShooter > SpeedAtShootingTimeTarget )
    SCORE = 7
ENDIF
IF ( AltAtShootingTimeShooter > AltAtShootingTimeTarget )
    SCORE = 6
ENDIF
```

Figure 15. Sample score definition rules for the shooting success criterion.

```
IF ( SCORE >= 75)
    LEVEL = QUALIFIED+
ENDIF
IF( SCORE >= 50 & SCORE < 75)
    LEVEL = QUALIFIED
ENDIF
IF( SCORE < 50)
    LEVEL = NOT QUALIFIED
ENDIF
```

Figure 16. Sample level definition rules for the shooting success criterion.

In order to interpret the rules, the raw data collected should be used. In this paper, the raw data of a simulation flight are used and the PiPAS is utilized in the evaluation of a trainee.

For the sample score and level rules, the performance report output of the PiPAS is given in Figure 17. It can be seen in Figure 17 that the trainee has a 'QUALIFIED' level in shooting success, WEZ management, and defensive success criteria, and a 'QUALIFIED+' level in the friendly fire, mission success, bubble success, obeying altitude limits, obeying training area, and G control success. However, the offensive success and chaff/flare success of the trainee are in the 'NOT QUALIFIED' level.

The raw data used in the above example include the following information:

Aircraft (AC) general info: AC ID and force ID (0: neutral, 1: blue, and 2: red).

Aircraft continuous info: AC ID, dead or alive, latitude, longitude, altitude, speed (x, y, z direction), heading, G force, and simulation time.

PERFORMANCE REPORT

CRITERIA	SCORE	LEVEL
Shooting Success	63	QUALIFIED
WEZ Management	60	QUALIFIED
Friendly Fire	100	QUALIFIED+
Defensive Success	75	QUALIFIED
Offensive Success	54	NOT QUALIFIED
Mission Success	80	QUALIFIED+
Bubble Success	100	QUALIFIED+
Chaff/Flare Success	35	NOT QUALIFIED
Obeying Altitude Limits	100	QUALIFIED+
Obeying Training Area	100	QUALIFIED+
G Control Success	100	QUALIFIED+
AVARAGE	79	QUALIFIED

Figure 17. Performance report output of the PiPAS.

Missile continuous info: Missile ID, latitude, longitude, altitude, speed (x, y, z direction), state (–3: target hit, –2: target missed, and –1: deviated by chaff), shooting AC ID, target AC ID, and simulation time.

Chaff continuous info: Chaff ID, latitude, longitude, altitude, simulation time.

Four training flights, for a given pilot, are analyzed using the PiPAS. After each training session, the results of the PiPAS are shared with the pilot. Figure 18 shows the results curve of the pilot for the defensive and offensive success criteria.

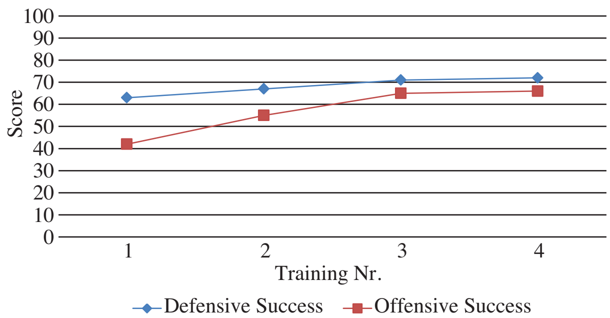

Figure 18. Results curve for defensive and offensive success criteria.

As seen from Figure 18, sharing the results with the pilot contributed to his or her performance and the scores of the defensive and offensive success criteria were increased. The PiPAS raised the performance awareness of the pilot.

6. Discussion and conclusion

There has not been much research in the development of aircraft simulation systems. Generally, the performance assessment of trainees is performed with discussions among the pilots with the help of 3D visualization. The performance evaluation system (PES) is a system that proposes a solution for choosing pilot candidates [21].

The PES is developed through the contributions of flight instructors, senior fighter pilots, and psychologists. It includes some basic tasks about aircraft control and shooting, and then evaluates the pilot candidate. Another study was done in the statistical analysis of 137 simulated air-to-air missile shots [22].

A pilot performance evaluation system, such as the proposed the PiPAS, provides important training advantages to air forces all around the world. The combat pilots' strong and weak sides can be determined with the aid of software systems. Such dynamic pilot performance evaluation systems enable the instructors to create scenarios based on their own experiences and also define important performance evaluation criteria. Moreover, the pilots' performances can be tracked with such systems. The learning curve for each criterion can be generated from past flight scores.

This system has also been demonstrated to air forces pilots and they have expressed that the usage of such systems would contribute to their training processes.

As a future work, the number of parameters employed can be extended to a level that will lead to the development of criteria that can measure some other features, such as fatigue and situation awareness.

Author statement

The views expressed in this paper are those of the authors and do not reflect any official policy or position of the Air Forces or Department of Defense of the Republic of Turkey or of any other country.

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