6 DoF Aircraft Simulation Model Capable of Handling Maneuver Events (WIP)

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ABSTRACT

This paper proposes an aircraft model to simulate different tactical maneuvers by handling various maneuver events in a hybrid model to develop tactic and analyze their effectiveness. The proposed model consists of a 6 degrees of freedom (DoF) model to describe high-fidelity aircraft's movement and a pilot model to effectively control the movement model. The pilot model, which includes a human factor (i.e., skills of pilot), a flight manual, and stabilizers, allows the proposed model to be more practical and effective. Through integrating a simple discrete event model to describe a tactical evasion maneuver of F-16 fighter, this paper shows the proposed model can be applied effectively in the analysis of tactics.

Author Keywords

6-DoF Aircraft Movement Model; Auto Pilot; PID Controller, Hybrid Simulation Model; Tactics Analysis

ACM Classification Keywords

I.6.5 Model Development; I.6.3 Applications; J.2.1 Aerospace;

INTRODUCTION

Air warfare takes the most important position to achieve victory in modern combat, and higher-spec aircraft and weapons are required to gain a dominant position in the air. Even if the best aircraft, such as an F-22 raptor, is used, ineffective tactics for various battle situations bring about a defeat in the war. Modeling and simulation (M&S), which has been applied in military training, analysis, acquisition and combat experiments, can be an efficient method for developing tactics and analyzing their effectiveness[1,2]. Most simulation models that are used for this purpose are a hybrid model, which is composed of a discrete event system (DES) model and a continuous time system (CTS) model[3,4,5]. The DES model, which makes a decision based on several events, is primarily used to describe tactics[6,7], whereas the CTS model, which performs a certain task such as searching, maneuvering and engagement according to the decision, is used to describe combat entities, such as aircraft, missiles, radar, etc[8,9,10]. To increase the effectiveness of analyzing various tactics with M&S, a movement model to describe the physical properties of an aircraft as well as a pilot model that controls the movement model toward the intended direction, are required.

For the movement model, a nonlinear 6 DoF model has been developed to describe the physical properties of the aircraft's movement[11]. If appropriate parameters of the model are given, it can simulate the movement of aircraft with high fidelity while considering the physical properties[19]. Several auto pilot models[12, 13, 14, 15, 16] including controllers to guide the movement model have been proposed based on the proportional-integral-derivative (PID) control theory[17]. However, the situations in which the movement model is controlled are limited to a certain situation, such as steady trim flight, horizontal or vertical direction, specific velocity and altitude, etc. Therefore, it is difficult to apply these models to develop tactics and analyze their effectiveness since the warfare situations have dynamically changed. Furthermore, they can handle limited kinds of maneuver event, which are insufficient to describe the aircraft's various tactical maneuvers.

Therefore, this paper proposes an aircraft model that can handle various maneuver events to simulate various tactical maneuvers. The proposed model consists of the 6 DoF movement model and a pilot model that includes the human factor of a pilot, the flight manual, and stabilizers to allow the analysis to become accurate and practical. Integration of the DES model with the proposed model can be effectively used to develop tactics and analyze their effectiveness.

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This paper is organized as follows: Section 2 introduces the nonlinear 6 DoF movement model, and Section 3 proposes the aircraft model for various maneuver events. Section 4 presents an example of using the model by analyzing the effectiveness of evasion tactics for an F-16 fighter. Finally, a conclusion is given in Section 5.

NONLINEAR 6 DOF MOVEMENT MODEL

The nonlinear 6 DoF aircraft movement model[11] describes movement to the x, y, z axis of the aircraft and rotation of each axis, as shown in Figure 1. u, v, w indicate the velocity in each direction of axis, and p, q, r imply an angular velocity of each axis. The movement direction of the aircraft is the x axis rotated by α degrees in the y axis and β degrees in the z axis, where VT is velocity in this direction.

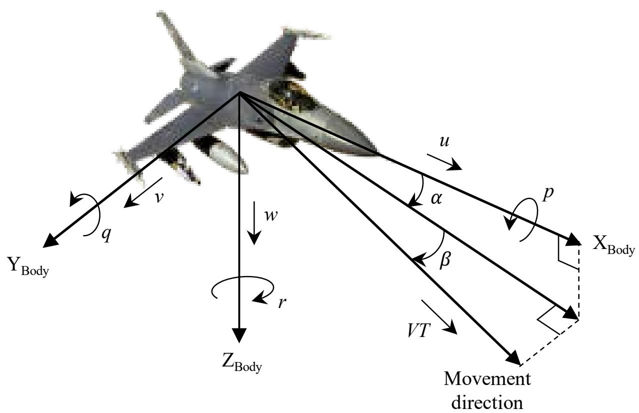


Figure 1. Parameters that describe of 6 DoF movement

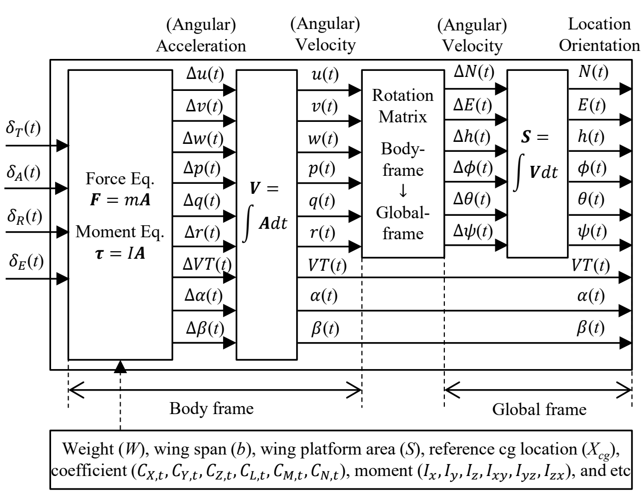


Figure 2. 6 DoF aircraft movement model

The movement model has 4 input parameters: $\delta_T(t)$ is the thrust level, $\delta_A(t)$ is the deflection degree of the aileron in a main wing, $\delta_R(t)$ is the deflection degree of the rudder of a vertical tail wing, and $\delta_E(t)$ is the deflection degree of the elevator of a tail wing. For the 4 input, the model calculates the global location (N, E, h); the Euler angle, which represents the global orientation (ϕ, θ, ψ); the attitude of the aircraft (α, β), and the velocity (VT) as outputs.

The movement model calculates 4 steps, as shown in Figure 2. In the first step, the model solves differential equations (1-6) to calculate the acceleration and angular acceleration in each axis, mainly considering 4 forces that affect the aircraft: gravity, drag, lift and thrust, and moments based on the shape of the aircraft. To correctly solve the equations, many parameters, as shown in the below of Figure 2, are required.

$$\Delta u = rv - qw - g_D s\theta + (X_A + X_T)/m \tag{1}$$

$$\Delta v = -ru + pw + g_D s\phi c\theta + (X_A + X_T)/m \tag{2}$$

$$\Delta w = qu - pv + g_D c\phi c\theta + (Z_A + Z_T)/m \tag{3}$$

$$\Delta p = 1/(I_x I_z - I_{xz}^2)\{I_{xz}(I_x - I_y + I_z)pq + [I_x(I_y - I_z) - I_{xz}^2]qr + I_{xz}N + I_z\bar{L} + I_{xz}I_z h_E q\} \tag{4}$$

$$\Delta q = (I_z - I_x)/I_y\, pr + I_{xz}/I_y\,(r^2 + p^2) + M/I_y - h_E r \tag{5}$$

$$\Delta r = 1/(I_x I_z - I_{xz}^2)\{(I_x^2 - I_x I_y + I_{xz}^2)pq + I_{xz}(I_y - I_z - I_x)qr + I_x N + I_{zz}\bar{L} + I_x I_z h_E q\} \tag{6}$$

Using the acceleration and angular acceleration, the velocity and angular velocity are integrated, then changes of the location and orientation in the global frame are transformed from the velocity based on the equations (7-12). Finally, the output is integrated with the changes. The Euler algorithm and the fourth-order RK algorithm can be used to solve the differential equations, and a fixed time sample period should be in 5 to 50 ms for accurate time-history simulation[11]. The next section will propose the whole aircraft model for various maneuver events with a pilot model to control the movement model.

$$\Delta N = uc\theta c\psi + v(-c\phi s\psi + s\phi s\theta c\psi) + w(s\phi s\psi + c\phi s\theta c\psi) \tag{7}$$

$$\Delta E = uc\theta s\psi + v(c\phi c\psi + s\phi s\theta s\psi) + w(-s\phi c\psi + c\phi s\theta s\psi) \tag{8}$$

$$\Delta h = us\theta - vs\phi c\theta - wc\phi c\theta \tag{9}$$

$$\Delta \phi = p + t\theta(qs\phi + rc\phi) \tag{10}$$

$$\Delta \theta = qc\phi - rs\phi \tag{11}$$

$$\Delta h = (qs\phi + rc\phi)/c\theta \tag{12}$$

PROPOSED AIRCRAFT MODEL

The proposed aircraft model for various maneuver events consists of a analyzer which interprets the maneuver events, the 6 DoF movement model[11], a control augmentation system (CAS), and a pilot model to control the movement model to accomplish the given event, as shown in Figure 3. The input and output of the proposed model is an event that allows a tactical DES model to utilize it easily. Table 1 shows the maneuver events that the proposed model can handle, and the model makes an output event when it completes the given

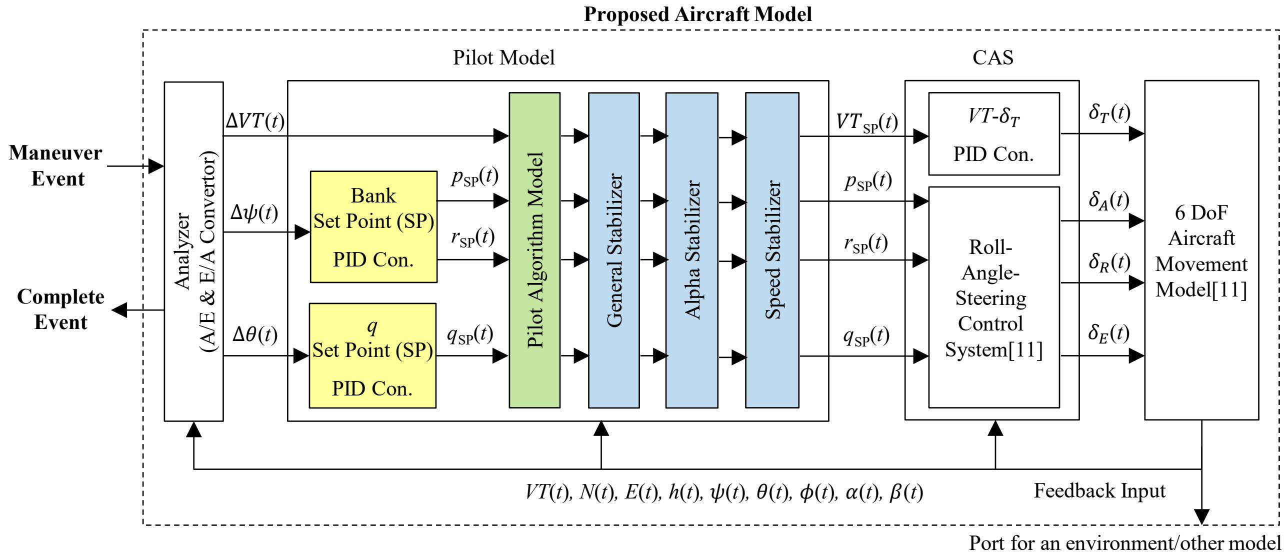


Figure 3. Overall structure of the proposed aircraft model for various maneuver events

event. These diverse events and their combinations allow the aircraft to perform various tactical maneuvers, and this leads to efficient analysis of tactical effectiveness.

When an maneuver event is given, the analyzer interprets the event and transforms it to change the amount of horizontal direction ($\Delta\psi$), vertical direction ($\Delta\theta$) and velocity (ΔVT) from the current direction and velocity. Also, usage of the feedback input from the movement model checks to determine whether or not the given event is accomplished, and the analyzer creates an output event in case of completion. Based on HDEVS formalism[18], the analyzer functions as a converter that transforms an event to an analog signal and vice versa.

Event	Description/Set Parameters
Take-off	- Take off with keeping the velocity and angle until reaching the desired altitude. - velocity (VT), rise angle (θ_{rise}), desired altitude (h_{rise})
Landing	- Land on the landing location - landing location (N, E, h)
Waypoint	- Move to the waypoint while keeping the velocity and using the bank angle within the maximum bank. - waypoint (N, E, h), velocity (VT), max bank (ϕ_{max})
Direction	- Change direction to the desired direction while keeping the velocity and using the bank angle within the maximum bank. - desired direction ($\Delta\psi$, $\Delta\theta$), velocity (VT), max bank (ϕ_{max})
Tracking	- Chase the moving target by using proportional navigation. - target location (N, E, h): required updating with a radar.
Keeping	- Maintain the pitch, bank, and velocity. - pitch (θ), bank (ϕ),velocity (VT)
Predefined	- Perform the predefined tactical maneuvers e.g. turning flight, barrel turn, screw rolls, loop, etc.

Table 1. Diverse maneuver events for the proposed aircraft model

The pilot model calculates the set point of VT and the angular velocity of each axis as the 4 inputs of the CAS by using the amount of change. It consists of several sub models: 2 PID controllers, which represent the skill and ability of a pilot, a pilot algorithm model to apply a flight manual, and 3 stabilizers for maintaining aircraft stability. To increase the effectiveness of the tactical analysis with M&S, this model utilizes human the factors of a pilot and a flight manual, as well as proper controllers for the movement model.

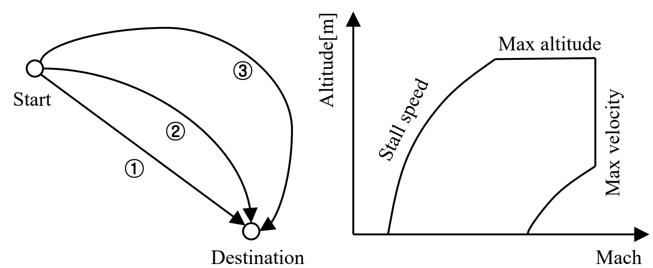


Figure 4. Different flight paths based on the setting of the bank PID controller(left), and a flight envelope for the stabilizer(right)

The 2 controllers: the bank controller and the q controller are the key point to apply the human factors. The bank controller calculates the bank degree of the aircraft to decrease $\Delta\psi$ as 0 in the horizontal direction and makes outputs p and r to accomplish that bank. Meanwhile, the q controller calculates q to decrease $\Delta\theta$ as 0 in the vertical direction. Both controllers use PID control theory; thus, their coefficients of each term (i.e., K_p, K_i, and K_d) have a great influence on the result of the controller. Namely, a flight path of the proposed aircraft model depends on the setting of these parameters, as shown on the left side in Figure 4. Therefore, the human factors, such as the pilot's skill and ability, can be applied to the proposed model through the appropriate setting of the parameters. This allows the proposed model to effectively simulate the tactics.

The flight manual is embedded in the pilot algorithm model, and this helps to facilitate a stable flight for the movement model and prevents its flight to be distant from the real flight.

Also, it calculates the set point of VT to decrease ΔVT as 0 in the movement direction. Several items in the flight manual of South Korea Air Force are detailed below.

- Increasing or decreasing of the bank angle and load factor simultaneously is impossible.
- When the bank angle is more than 30 degrees, decrease it below than 30 degrees and manipulate the pitch in the ascending or descending direction.
- Change rate of the bank angle should be set to 90 degrees per second.

Several stabilizers beyond the algorithm model tune these set points to keep the movement model stable in a variety of situations. To prevent the movement model from falling into a stall condition, they mainly control the velocity and angle of attack (α) based on the flight envelope, as shown on the right side of Figure 4. Each of them contains stabilizing algorithms and PID controllers. Since situations are dynamically changed in the combat field for simulating tactics, these stabilizers bring value to the aircraft model by maintaining the stability of the movement model.

The CAS is included in the proposed model as a middle stage to effectively control the movement model, and it transforms the outputs of the pilot model to the inputs of the movement model. It consists of 2 controllers: VT-δ_T controller and the roll-angle-steering control system[11]. The former generates δ_T to accomplish VT_{SP}, and the latter generates δ_T, δ_T, and δ_T to maintain the angular velocities of each axis p_{SP}, q_{SP}, and r_{SP}.

In summary, the proposed aircraft model has various maneuver events to analyze the effectiveness of tactics through integration with the DES model. Various tactical maneuvers can be expressed with these events. The human factors, the flight manual, and stabilizers foster accuracy and practicality within the analysis. The next section shows a simple example of using the proposed model for an F-16's tactical evasion maneuver.

EXPERIMENTS

The tactical evasion maneuver can either be conducted vertically or horizontally. In the case of vertical evasion, the aircraft descends while maintaining a leading angle when it detects a missile 20 km ahead. If the missile approaches the predefined distance that is termed the evasion distance, the aircraft radically ascends by using the maximum G factor. Then, the missile overshoots and misses the aircraft because its velocity is too fast for it to radically ascend. The numbers in Figure 5 represent this vertical evasion process. Horizontal evasion has a similar process to that of vertical evasion. In the case of horizontal evasion, the aircraft turns right, keeping the leading angle when it detects the missile 30 km ahead. If the missile approaches within the evasion distance, the aircraft radically turn left by using the maximum turn-G factor. Similar to the result in vertical evasion, the missile overshoots due to its velocity.

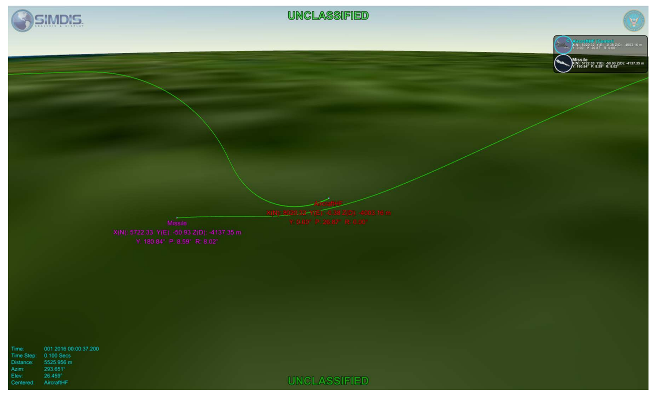


Figure 6. Screen shot of the simulation using the proposed aircraft model in the experiment

This experiment analyzes for the effectiveness of an F-16's tactical evasion maneuver by using the proposed aircraft model and a simple DES model, as shown in Figure 6. The DES model gives a maneuver command to the aircraft model when an event is detected. For example, the DES model sends the "Direction" event in Table 1 with a specific leading degree to the aircraft model when the missile is detected from 20 km ahead. The effectiveness of the tactic is expressed as "Evasion Success Rate", and it is estimated according to various leading degrees and evasion distances. The simulation result is shown in Figure 7. From the result, when the leading degree is too small or when the evasion distance

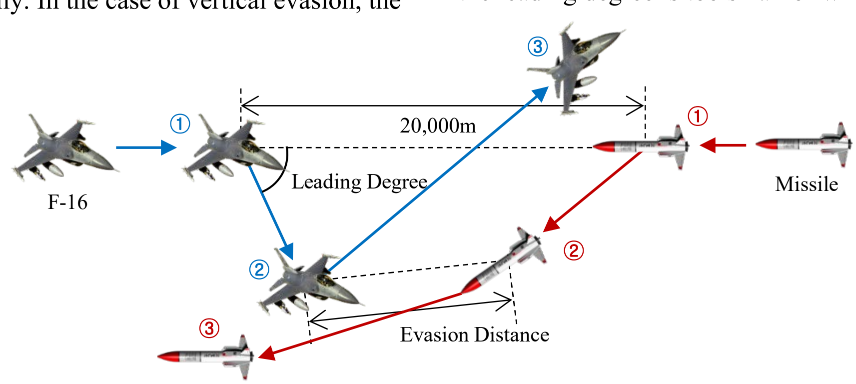
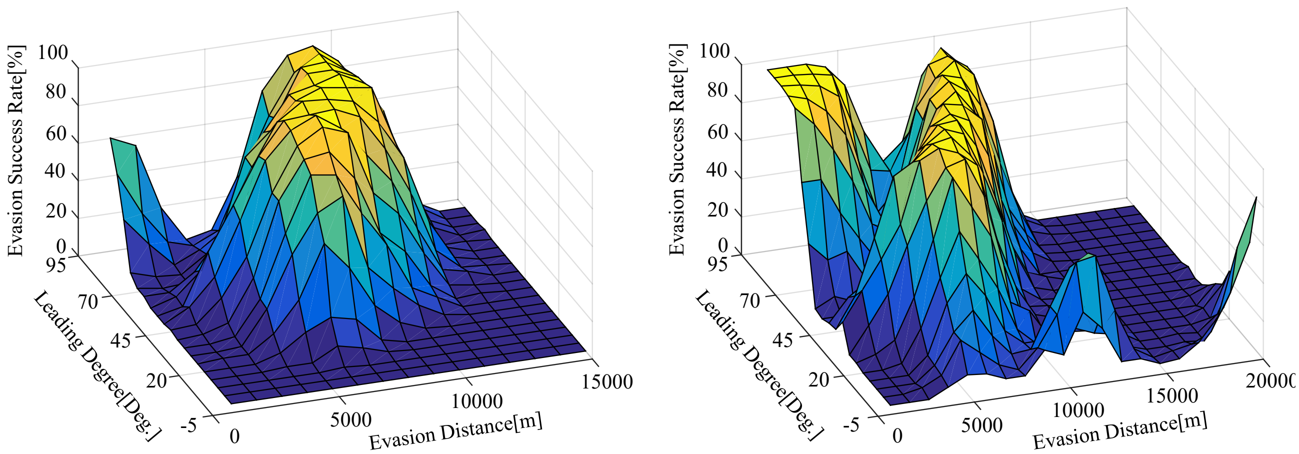


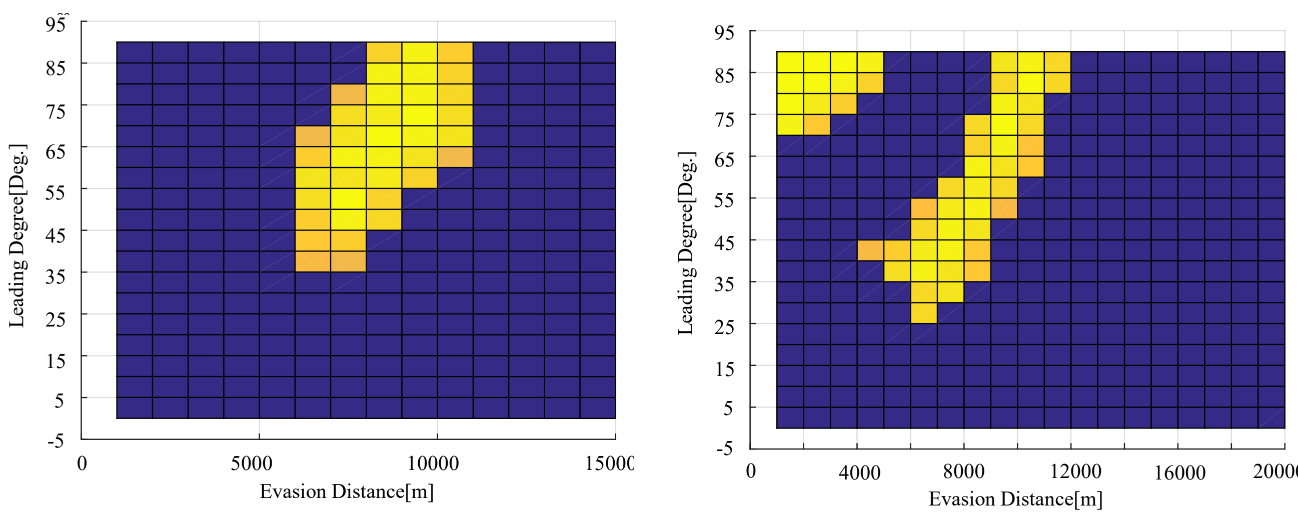
Figure 5. Tactical evasion maneuver of an F-16 fighter in the vertical direction



(a) Vertical evasion

(b) Horizontal evasion

Figure 7. Simulation result of tactical evasion in vertical (a) and horizontal (b) directions by using the proposed aircraft model



(a) Vertical evasion

(b) Horizontal evasion

Figure 8. Regions where the success rate is more than 80% in vertical (a) and horizontal (b) directions

is too short or too long, the missile chases the aircraft and hits it. In other words, effective tactical evasion requires a larger leading degree and proper evasion distance, as shown in Figure 8. As in these experiments, the proposed aircraft model can be used effectively to develop tactics and analyze their effectiveness by integrating a tactical DES model.

CONCLUSION

This paper proposes an aircraft simulation model for handling various events to simulate an array of tactical maneuvers. The model uses a 6 DoF movement model to describe the physical properties of the aircraft's flight motion. It also includes a pilot model that contains the human factors of a pilot, the flight manual and stabilizers to maintain the stability of the aircraft in various warfare situations, further enhancing the accuracy and practicality of the aircraft model. Through integration with a tactical DES model, the proposed model can be effectively applied for the development of tactics and analysis of their effectiveness, as shown in the experiments in Section 4. Further research will improve the proposed model and develop the other CTS models such as a radar, network, command and control, etc. The final objective of this work is to integrate these models to simulate an air engagement between 20 F-16 fighters and 20 Mig-29 fighters.

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