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Three-Dimensional Collision Avoidance Control Law for Aircraft Using Risk Function and Fuzzy Logic

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This paper proposes a new collision avoidance control law for aircraft. RCPA (Range of Closest Point of Approach), representing risk in the future, and TCPA (Time to CPA), representing current risk, are used as risk functions. Furthermore, fuzzy logic is introduced in order to achieve human maneuvering and to settle singular point and chattering problems that are discussed in previous studies. Avoidance strategy consists of four main phases, maintaining course, avoidance, parallel flight and recovery phase, and three transition phases. The parallel flight phase and three transition phases are introduced to achieve moderate avoidance and smooth phase transition, respectively. Simulation results show that the proposed control law settles the past problems and achieves smooth and adequate avoidance. This paper also discusses the fuzzy evaluation method.

Key Words: Guidance and Control, Collision Avoidance, Fuzzy Logic

Nomenclature

x, y, z: inertial coordinate system
ξ, η, ζ: relative coordinate system
v: aircraft velocity, m/s
ψ: direction angle, rad
γ: flight path angle, rad
θ: angle between line of sight and relative velocity, rad
ω: angular velocity, rad/s
R_r: relative range between evader and intruder, m
R_{os}: offset range from original course, m

1. Introduction

In recent years, the aviation transport of freight and passengers has been increasing and it is expected the demand will continue to grow. Therefore the increase in aviation traffic will be an unavoidable problem in the near future. In the situation of congested aviation traffic, the possibility of increased aviation accident risk, air collisions or near misses between aircraft is significant.

With the background of such aviation traffic, many researchers have studied[1–3)] collision avoidance controllers to reduce risk and developed aircraft collision avoidance systems; for example, the Traffic alert and Collision Avoidance System[4)] (TCAS). However, the results and the systems have the following problems.

(1) TCAS advises the aircraft to avoid threats (intruder) only on the vertical plane, using climbing or descending; hence, three-dimensional avoidance has not yet been developed. Three-dimensional avoidance including horizontal maneuvering is effective from the point of view on safety in collision avoidance problems of aircraft.

(2) The controllers studied in previous research sometimes give globally unsafe avoidance courses or diverge in calculation because of a singular point problem or chattering problem. The singular point problem is caused by the differentiation of risk functions that indicate the possibility of collision. The reason why the controller does not give a globally safe avoidance course is that only the present information is used. The threshold value, dividing two phases, given as a crisp value causes the chattering problem.

Collision avoidance is a significant problem not only in the field of aviation, but also in the field of ocean transport. RCPA (Range of Closest Point of Approach) and TCPA (Time to CPA), dealt as risk functions in this paper, have been discussed in maritime studies. The researchers in the field, however, defined these values as crisp values. The originality of this paper is to deal with these values as fuzzy values.

The objectives of this paper are as follows:

(1) To solve the problems presented in previous studies. Fuzzy logic[5,6)] is applied to solve a singular point problem and realize global avoidance. New phases with gradual transition are designed and introduced to suppress the chattering problem.

(2) For unrealized three-dimensional avoidance in TCAS, to confirm the effectiveness of three-dimensional avoidance using the proposed control law.

(3) To realize an avoidance control method/control law similar to human operation. Therefore fuzzy logic which makes empirical and experience rules applicable in the control law and new phases based on pilot judgments are introduced.

(4) To avoid not only collisions, but also near misses, "required separation" is introduced as a definite safety range. The requirement can be described as a fuzzy value instead

of a crisp value.

2. Collision Avoidance Model

2.1. One intruder and one evader in a three-dimensional area

Most aviation accidents that result in mid-air collisions or near misses occurs between two aircraft, and there are rarely accident involving three or more aircraft. Therefore, a model of two aircraft is defined and used in this paper. The following assumptions are used in this collision avoidance model.

(1) The flight of the intruder (course, speed and altitude) is assumed constant. Because course, speed and altitude are maintained in common flight.

(2) The velocities of the two aircraft (intruder and evader) are almost the same. Therefore a fast intruder approaching from the rear of the evader is not considered.

(3) After the evader moves off course to avoid the risk of collision temporarily, it returns to its original course.

(4) The control inputs of the evader are angular velocities for the purpose of simplification.

(5) The evader has a constant velocity. There is a fear of stalling at low speed. Therefore changing the velocity as an avoidance measure is not considered.

2.2. Definition of a coordinate

Aircraft have two objectives in this paper. One is collision avoidance, and the other is maintaining course. Two coordinate systems considering each purpose are used for control design.

(1) Inertial coordinate system (x, y, z)

The position of the aircraft is described in the inertial coordinate when "maintaining course" is the main purpose. Aircraft are required to fly on assigned courses, thus the inertial position is important.

(2) Relative coordinate system (ξ, η, ζ)

The position of the intruder is described in the relative coordinate when "collision avoidance" is the main purpose. The evader is required to keep a definite distance from the intruder, thus the relative position is important. The origin is located on the evader and x-axis is alined in the direction of the course heading of the evader. Moreover, the intruder position that the evader can obtain by radar or transponder mounted on the evader is relativity information. Therefore a relative coordinate system is required for avoidance from danger. The relation of two aircraft in a horizontal plane is shown in Fig. 1.

2.3. State differential equation

State differential equations of the aircraft (evader) in a three-dimensional area are described as follows:

$$\dot{x}_A = v_A \cos\psi_A \cos\gamma_A \quad (1)$$

$$\dot{y}_A = v_A \sin\psi_A \cos\gamma_A \quad (2)$$

$$\dot{z}_A = -v_A \sin\gamma_A \quad (3)$$

$$\dot{\psi}_A = \omega_{dA}/\cos\gamma_A = \omega_{hA} \quad (4)$$

$$\dot{\gamma}_A = \omega_{vA} \quad (5)$$

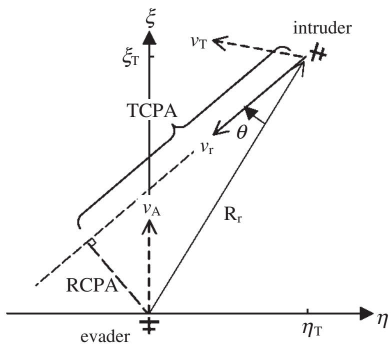


Fig. 1. Approaching relation in a horizontal plane.

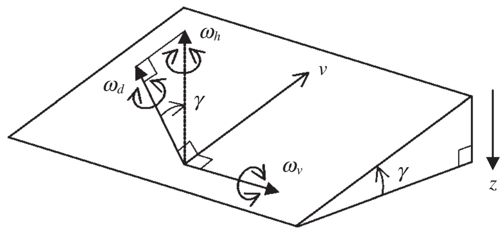


Fig. 2. Angular velocity ω_d, ω_h and ω_v.

where subscript A means the evader, and d, h and v represent a maneuvering plane, horizontal plane and vertical plane, respectively. The relation of angular velocities ω_d, ω_h and ω_v in each plane is shown in Fig. 2.

3. Avoidance Strategy

3.1. Risk function

The risk function expresses "the state of danger." A definition of the risk function cannot be decided using only one element. Various kinds of risk functions are defined in the fields of aviation/shipping. In this paper, some elements of risk functions are determined from the point of view of "what elements do humans feel as dangerous."

Humans do not solve complicated equations in their heads. It is hard to think that complex elements are used. On the other hand, if there are simple elements, humans can deal with two or three elements simultaneously. As the result of various kinds of examinations, two elements were selected for the risk functions.

One is "RCPA," the minimum relative distance between the evader and intruder in the future, and the other one is "TCPA," the required time for the intruder to fly to RCPA from its present position.

(1) RCPA; represents an element of distance and risk in the future.

(2) TCPA; represents an element of time and current risk.

3.2. Required-separation

Required-separation is the distance that the evader want to secure as a safety range. The concept of required-separation is equivalent to a protection domain of TCAS, and it is a domain deciding whether an avoidance action is necessary or not for individual security. The threshold value of a protection domain in TCAS is the crisp value. However, hu-

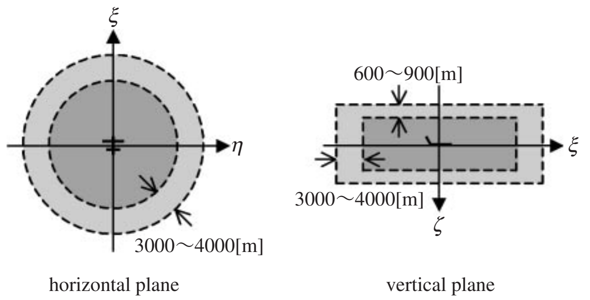


Fig. 3. Required separation.

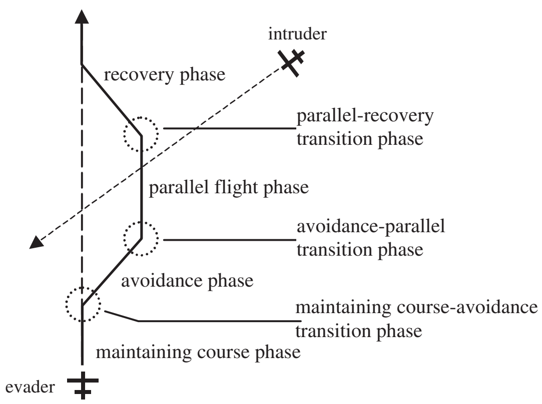


Fig. 4. Phase concept.

mans do not think the distance from the intruder as crisp when the intruder is to be avoided. Therefore, required-separation is defined with any width (gray zone). This point is different from the protection domain of TCAS/conventional collision avoidance (including ship collision avoidance).

As is shown in Fig. 3, the required-separation range for this study was 3000–4000 [m] for the horizontal plane and 600–900 [m] for the vertical plane. The evader is required to satisfy the required-separation either in the horizontal or vertical plane.

3.3. Phases

The function and phases of action used in the proposed control system to avoid an intruder causing the risk of collision/near miss are described in this section. Figure 4 shows a conceptual diagram of the phases. The proposed control law consists of four main phases and three transition phases. The transition phases operate as filler in the middle of the two main phases.

3.3.1. Main phases

Four main phases form the basis of the avoidance control law.

a. Maintaining course phase. This is the phase when the evader maintains its assigned flight course when an intruder does not exist.

b. Avoidance phase. This is the phase when the evader deviates from its assigned course when an intruder with a high risk of collision/near miss exists.

c. Parallel flight phase. This is the phase when the evader flies parallel to the original course when required RCPA (a horizontal or vertical plane) is secured. The concept of parallel flight phase has not existed in the conventional control law. It is designed and introduced as an original concept in this paper. Continuous avoidance is planned by introducing a new phase that not only includes avoidance and return, but also midway considerations.

d. Recovery phase. The displacement distance that occurs due to the avoidance measure is adjusted so that the evader returns to the original course when the risk of collision/near miss vanishes.

3.3.2. Transition phases

The following three transition phases are designed and introduced to settle the chattering problem in phase transition. Transition phases make the output ratio of previous phase decrease from 1 to 0. Simultaneously, they make the output ratio of following phase increase from 0 to 1 with arbitrary time. It is a switch that can be changed gradually. Transition phases leave possibility of one hand while controlling the other one.

a. Maintaining course-avoidance transition phase
b. Avoidance-parallel transition phase
c. Parallel-recovery transition phase

3.4. Avoidance direction

An avoidance direction is considered when the intruder's relative approach is from in front of the evader (intruder relative approach from the rear is not considered). It is assumed that the velocities of the evader and intruder are similar, and that the intruder flies on a constant course with constant velocity and altitude.

3.4.1. Horizontal plane

The approaching geometry is shown in Fig. 5. The evader is placed at the center of a coordinate and the course is taken at x-axis. From the viewpoint of the approach direction, there are three directions of front (1, 2, 3), right-hand side (4, 5, 6) and left-hand side (7, 8, 9). Moreover, from the viewpoint of crossing relation, there are four relations of collision (2, 5, 8), passing each other just to the right or left side (1, 3), forward crossing (4, 7) and rear crossing (6, 9).

Based on a civil aeronautics law providing matters about collision prevention between aircraft, the evader selects the following avoidance direction; the evader turns to pass the rear of the intruder when an intruder crosses in front of the evader (4, 7). On the other hand, the evader turns a direction away from the intruder when it crosses at the rear (6, 9) and when the evader and intruder pass each other (1, 3). Still

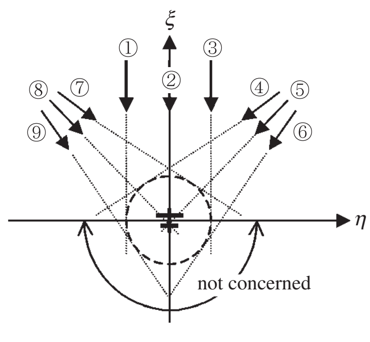


Fig. 5. Approaching geometry.

more, the evader avoids the intruder by turning to the right in the case of a collision course (2, 5, 8).

3.4.2. Vertical plane

The evader avoids the intruder by flying at a lower altitude when the intruder passes at a point relatively high to the evader. In reverse, the evader avoids the intruder by flying a higher altitude when it passes at a relatively lower altitude. However, when both aircraft fly at the same altitude, when the evader is flying an eastbound course, the evader avoids the intruder by flying at a higher altitude and when flying a westbound course, by flying at a lower altitude. (The evader on an eastbound flight is assumed in this paper.)

3.5. Measures for intruder with a similar course

For an intruder with a similar course to the evader, avoidance is considered by satisfying the required-separation mainly in the vertical plane. Therefore, the easy achievement of vertical plane avoidance is attempted by mainly using vertical avoidance angular velocity, and horizontal avoidance angular velocity is restrained.

4. Fuzzy Collision Avoidance Control Law

Fuzzy logic is applied to this control law to realize "human-like avoidance (non-crisp avoidance)." Fuzzy logic has been applied in the field of aviation (e.g., missile interception,[7–9] landing guidance[10] and maneuvering assist[11]); however, It has not been applied to avoidance problems yet. The output in an avoidance action is calculated not from the differential calculus of a risk function, but is based on an experience rule (rule base) in the fuzzy control. Therefore, a singular point problem occurring in a control law with differential calculus can be resolved.

4.1. Maintaining course/recovery phase

Aircraft are scheduled to fly according to an assigned course in maintaining course and the recovery phase. Flying off-course could become a problem in maintaining course and the recovery phase. Therefore, the same control law is used for these two phases.

Input and output elements in this phase are selected based on the PD control known in the field of control. Offset distance R_{hos} (horizontal plane) and R_{vos} (vertical plane) are used as displacement quantities from the original course. $\dot{R}_{\mathrm{hos}}$ and $\dot{R}_{\mathrm{vos}}$ are used as differential calculus values of displacement quantity in usual PD control. However, instead of $\dot{R}_{\mathrm{hos}}$ and $\dot{R}_{\mathrm{vos}}$, the difference of direction angle $\Delta\psi$ (horizontal plane) and difference of flight path angle $\Delta\gamma$ (vertical plane) are used because $\dot{R}_{\mathrm{hos}}$ and $\dot{R}_{\mathrm{vos}}$ can be approximate to $\Delta\psi$ and $\Delta\gamma$, respectively, when $\Delta\psi$ and $\Delta\gamma$ are not large.

The geometry, membership function and rule base for maintaining course/recovery phase are shown in Fig. 6, Fig. 7 and Table 1, respectively. The maximum amount of the control output ω_{d} corresponds to bank angle of 30 [deg].

4.2. Avoidance phase

The avoidance phase is one of the key phases in the collision avoidance problem. Input elements in this phase are the RCPA and TCPA used as risk functions in this paper. The proposed control law outputs the appropriate ω based on a membership function and rule base as to secure the required RCPA when TCPA is less than the regulated value. The membership function and rule base in the avoidance phase are shown in Fig. 8 and Table 2, respectively.

The membership function of the control output ω_{d} is designed in accordance with the maneuvering load factor n in Japanese aviation regulations, and ω_{v} is assumed and designed so that the maximum lift L is about two times that of the aircraft weight.

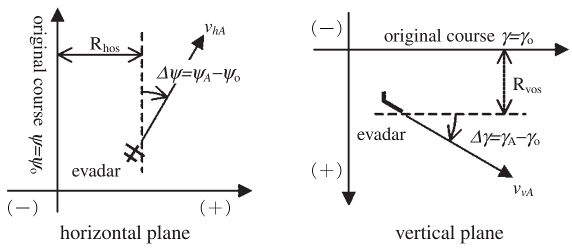


Fig. 6. Maintaining course/recovery phase geometry.

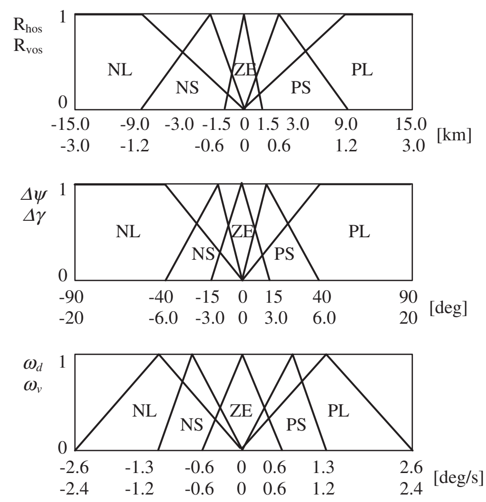


Fig. 7. Membership function in maintaining course/recovery phase.

Table 1. Rule base in maintaining course/recovery phase.

ω_{d}		$\Delta\psi$				
		NL	NS	ZE	PS	PL
R_{hos}	NL	PL	PL	PL	PS	ZE
	NS	PL	PL	PS	ZE	NS
	ZE	PL	PS	ZE	NS	NL
	PS	PS	ZE	NS	NL	NL
	PL	ZE	NS	NL	NL	NL

ω_{v}		$\Delta\gamma$				
		NL	NS	ZE	PS	PL
R_{vos}	NL	ZE	NS	NL	NL	NL
	NS	PS	ZE	NS	NL	NL
	ZE	PL	PS	ZE	NS	NL
	PS	PL	PL	PS	ZE	NS
	PL	PL	PL	PL	PS	ZE

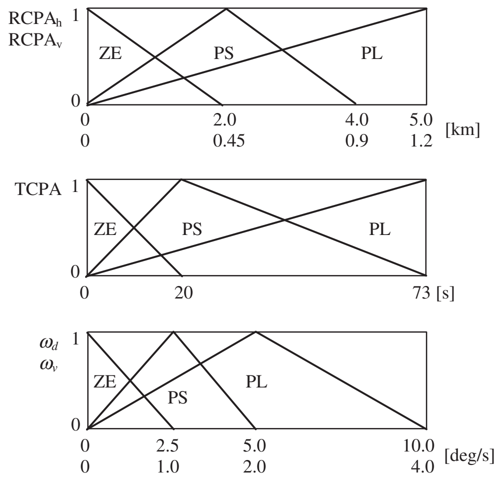


Fig. 8. Membership function in avoidance phase.

Table 2. Rule base in avoidance phase.

ω_d ω_v		RCPA$_h$, RCPA$_v$				
		NL	NS	ZE	PS	PL
TCPA	ZE	PL	PS	ZE	NS	NL
	PS	PS	ZE	NS	NL	NL
	PL	ZE	NS	NL	NL	NL

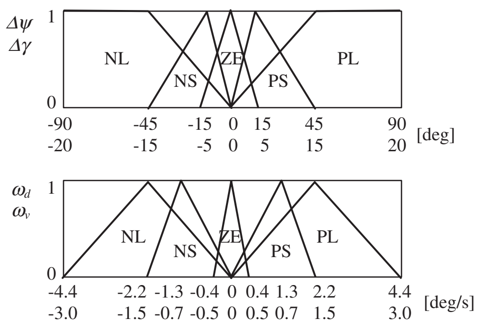


Fig. 9. Membership function in parallel flight phase.

Table 3. Rule base in parallel flight phase.

ω_d ω_v	$\Delta\psi$, $\Delta\gamma$				
	NL	NS	ZE	PS	PL
	PL	PS	ZE	NS	NL

4.3. Parallel flight phase

An aircraft flies parallel to the provided course in the parallel flight phase. Therefore only the displacement of the direction and flight path angle are required. Input elements are $\Delta\psi$ and $\Delta\gamma$ for the horizontal plane and vertical plane, respectively.

The membership function and rule base of the parallel flight phase are shown in Fig. 9 and Table 3, respectively. The control output ω_d is designed as a bank angle of less than 45 [deg] in order to prevent excessive avoidance. The maximum amount of ω_v in the parallel flight phase is designed as 75% of ω_v in the avoidance phase.

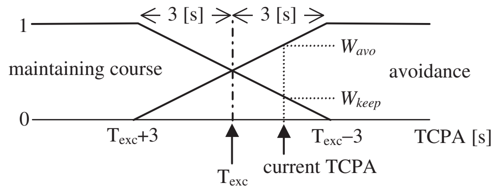


Fig. 10. Maintaining course-avoidance transition phase.

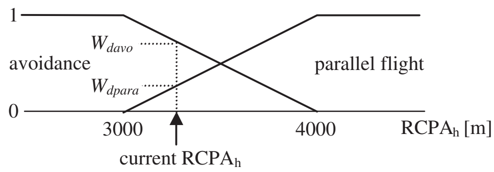


Fig. 11. Avoidance-parallel transition phase.

4.4. Maintaining course keeping-avoidance transition phase

Maintaining course-avoidance transition phase is the transition phase shifting from the maintaining course phase to the avoidance phase.

As shown in Fig. 10, a weight coefficient for each output of maintaining course and avoidance are determined from the current TCPA. In this paper, $T_{\mathrm{exc}} \pm 3$ [s] (T_{exc}; execute TCPA) of an extent is set as the transition domain. Therefore, while a phase transition is about 6 [s], the phase can be shifted gradually. The output angular velocity of this phase is expressed in the following equations:

$$\omega_{\mathrm{h}} = (W_{\mathrm{keep}}\omega_{\mathrm{dkeep}} + W_{\mathrm{avo}}\omega_{\mathrm{davo}})/\cos\gamma \tag{6}$$

$$\omega_{\mathrm{v}} = W_{\mathrm{keep}}\omega_{\mathrm{vkeep}} + W_{\mathrm{avo}}\omega_{\mathrm{vavo}} \tag{7}$$

where, ω_{keep} and ω_{avo} are the output by maintaining course and avoidance logic, respectively, and W_{keep} and W_{avo} are weight coefficients for ω_{keep} and ω_{avo}. Additionally, subscript h and v of ω represent the horizontal plane and vertical plane, respectively.

4.5. Avoidance-parallel transition phase

Avoidance-parallel transition phase is the transition phase shifting from the avoidance phase to the parallel flight phase.

As shown in Fig. 11, a weight coefficient for each output of avoidance and parallel flight is determined from the current RCPA. Then the range of required-separation is regarded as the transition domain. The output angular velocity of this phase is expressed in the following equations:

$$\omega_{\mathrm{h}} = (W_{\mathrm{avo}}\omega_{\mathrm{davo}} + W_{\mathrm{para}}\omega_{\mathrm{dpara}})/\cos\gamma \tag{8}$$

$$\omega_{\mathrm{v}} = W_{\mathrm{avo}}\omega_{\mathrm{vavo}} + W_{\mathrm{para}}\omega_{\mathrm{vpara}} \tag{9}$$

where, ω_{para} is the output by parallel flight logic and W_{para} is the weight coefficient for ω_{para}.

Using this technique, the evader is continuously clear of the intruder, and stable avoidance is provided. When a phase in the horizontal plane changes to the avoidance-parallel transition phase earlier than the vertical plane, the output in the vertical plane becomes parallel flight phase ($W_{\mathrm{vpara}} = 1$, $W_{\mathrm{vavo}} = 0$). On the other hand, when a phase

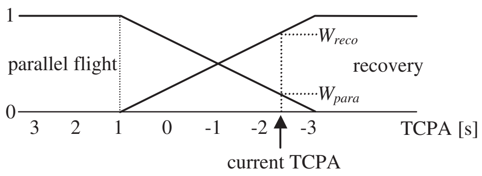


Fig. 12. Parallel-recovery transition phase.

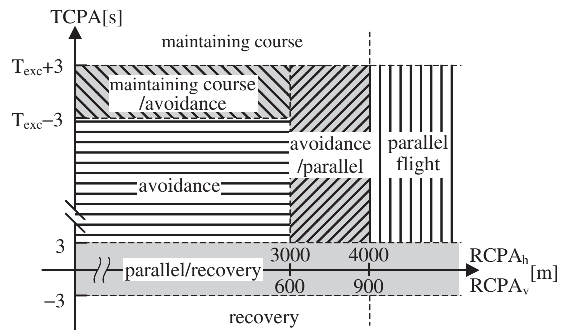


Fig. 13. Phase definition domain.

in the vertical plane changes to the avoidance-parallel transition phase earlier, the output in the horizontal plane becomes parallel flight phase ($W_{\mathrm{hpara}} = 1$, $W_{\mathrm{havo}} = 0$). In other words, when either the horizontal plane or vertical plane shifts to the avoidance-parallel transition phase, the other plane becomes parallel flight phase.

4.6. Parallel-recovery transition phase

Parallel-recovery transition phase is the transition phase when shifting from the parallel flight phase to the recovery phase.

As shown in Fig. 12, this phase is defined for TCPA $\pm$ 3 seconds. Two seconds are assigned to the parallel flight phase at the beginning of the parallel-recovery transition phase because the phase acting before this phase may not always be the parallel flight phase. The phase shifts from parallel flight phase to recovery phase gradually during the following four seconds. The output of this phase is expressed in the following equations:

$$\omega_{\mathrm{h}} = (W_{\mathrm{para}}\omega_{\mathrm{dpara}} + W_{\mathrm{reco}}\omega_{\mathrm{dreco}})/\cos\gamma \tag{10}$$

$$\omega_{\mathrm{v}} = W_{\mathrm{para}}\omega_{\mathrm{vpara}} + W_{\mathrm{reco}}\omega_{\mathrm{vreco}} \tag{11}$$

where, ω_{reco} is the output of recovery logic and W_{reco} is the weight coefficient for ω_{reco}.

A defined domain assigned for each phase is shown in Fig. 13. Defined domains are assigned temporarily, and modification of the design is comparatively easy since the upper limit and lower limit of the membership function of each phase is only rewritten.

5. Simulation

5.1. Simulation conditions

Simulation conditions are shown in Fig. 14. The conditions assume collision and near-miss courses in the horizontal and vertical planes.

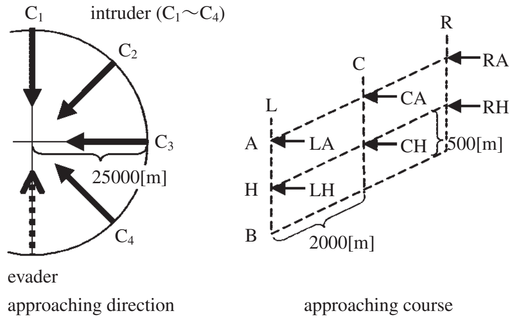


Fig. 14. Simulation cases.

5.1.1. Approach direction

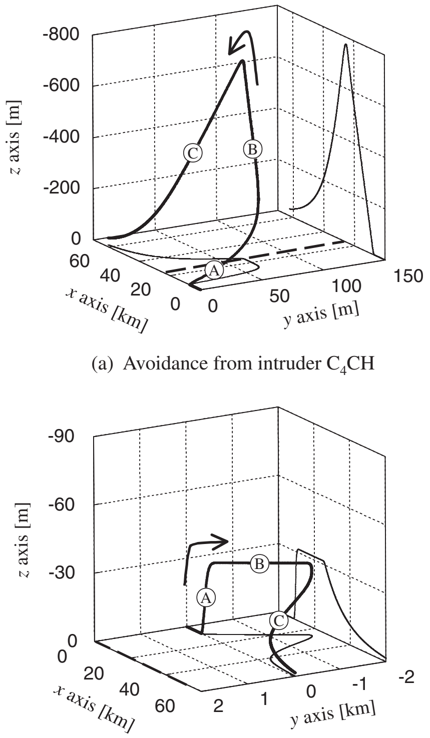
Approach direction represents the approach relation between the evader and intruder in the horizontal plane. The evader with course 000 [deg] is assumed. For the intruder, four basic courses of 180, 225, 270 and 315 [deg] are assumed as collision courses ($C_1 \sim C_4$). The initial position of the intruder is assumed at a distance of 25000 [m] to the collision point for each course.

5.1.2. Approach course

Right and left courses from the collision course with offsets of 2000 [m] are assumed as near-miss courses at the same altitude. Two horizontal near-miss courses of the right side (R) and left side (L) are assumed for one collision course (C). Moreover, for the three courses of R, C and L at the same altitude (H), three courses of 500 [m] above (A) from the same altitude (H) are assumed as vertical near-miss courses. Calculation results for courses of 500 [m] below (B) could be the same as the results of 500 [m] above (A) because these are symmetrical with the same altitude (H). Therefore, calculations of below (B) can be omitted. Consequently, six courses are assumed for each basic course. Additionally, the velocity of both aircraft is assumed to be 250 [m/s] (equivalent to a jet passenger plane).

5.2. Simulation results

Avoidance trajectories from intruder C_4CH and C_1LH are shown in Fig. 15. Figure 15 (a) and (b) are examples showing that avoidance is achieved by satisfying the required-separation in the vertical plane and horizontal plane, respectively. A, B and C in Fig. 15 express the avoidance, avoidance-parallel transition and recovery phase, respectively. In the early stage of avoidance, the required RCPA is kept by three-dimensional avoidance (A). Afterwards, adequate avoidance that is stable and not excessive using only two-dimensional maneuvering in the horizontal plane or vertical plane (B) is followed. Finally, the evader returns (C) to its original course immediately by three-dimensional maneuvering after the avoidance. It is confirmed that an adequate avoidance series is achieved from these results, as clearly expressed by projection to the horizontal (*x*–*y*) plane and vertical (*y*–*z*) plane. For (B), the required-separation of either the vertical plane or horizontal plane is satisfied. Then the control output in the other plane becomes the parallel flight phase. Therefore, the evader can avoid the only using



(a) Avoidance from intruder C_4CH

(b) Avoidance from intruder C_1LH

Fig. 15. Avoidance trajectory (bold solid line).
Thin lines and dashed line represent avoidance trajectory projections (horizontal and vertical plane) and intruder's trajectory, respectively.

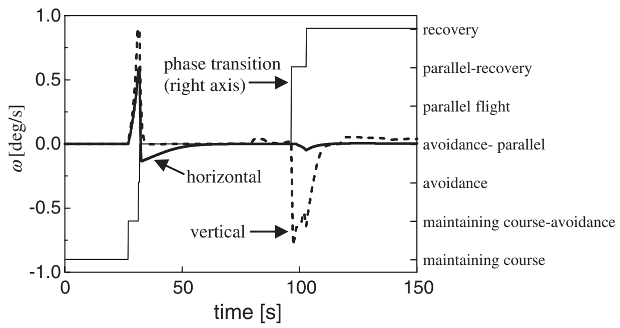


Fig. 16. Angular velocity and phase transition in avoidance from C_4CH.

the vertical or horizontal plane, without three-dimensional maneuvering.

The angular velocity variation and phase transition are shown in Fig. 16. The thin line represents the phase transition, bold solid line and dashed line show the angular velocity used in the horizontal and vertical planes to avoid intruder C_4CH. Smooth angular velocity variation restraining a sudden control input and disappearance of phase chattering is confirmed because of introducing the transition phases. In particular, avoidance using stable flight maintaining an angular velocity of about 0 [deg/s] is achieved in the avoidance-parallel transition phase.

6. Evaluation

6.1. Evaluation method

The simulation results are evaluated using an original method applying fuzzy logic. Evaluation parameters, consisting of main and sub-elements, are used for evaluation.

Selected evaluation parameters are classified, and their membership functions are defined. Simulation results are evaluated by membership function grades of upper-class (main elements). Membership function grades of lower-class (sub-elements) are referred to when upper-class grades are equal. When there are several evaluation parameters in the same class, the product of those grades is regarded as the grade of the class.

6.2. Evaluation parameter

6.2.1. Main element

The relative distance from the intruder is a key item from the point of view of safety in collision avoidance problems. Therefore, either of the following elements is selected when required-separation in the horizontal plane or vertical plane is satisfied.

a. The minimum relative distance in the horizontal plane ($R_{\rm rhmin}$)

b. The minimum relative distance in the vertical plane ($R_{\rm rvmin}$)

Membership functions of $R_{\rm rhmin}$ and $R_{\rm rvmin}$ are defined as shown in Fig. 17, based on the assumed required-separation.

6.2.2. Sub element

The following three sub-elements are selected from the point of view of comfortable flight and moderate (not excessive) avoidance. These membership functions are shown in Fig. 18.

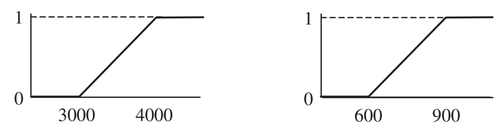
a. The maximum angular velocity ($|\omega|_{\rm max}$)

b. The maximum offset range in the horizontal plane ($|R_{\rm hos}|_{\rm max}$)

c. The maximum offset range in the vertical plane ($|R_{\rm vos}|_{\rm max}$)

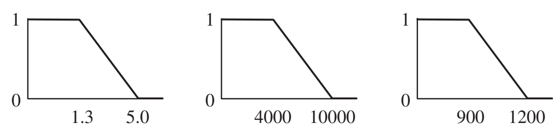
6.3. Evaluation results

Evaluation results are shown in Fig. 19. Two horizontal axes represent simulation cases, approaching direction and courses, and the vertical axis represents the evaluation



(a) $R_{\rm rhmin}$ [m] (b) $R_{\rm rvmin}$ [m]

Fig. 17. Membership function for evaluation main element.



(a) $|\omega|_{\rm max}$ [deg/s] (b) $|R_{\rm hos}|_{\rm max}$ [m] (c) $|R_{\rm vos}|_{\rm max}$ [m]

Fig. 18. Membership function for evaluation sub-element.

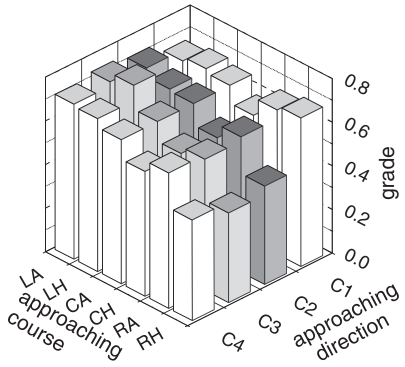


Fig. 19. Evaluation results.

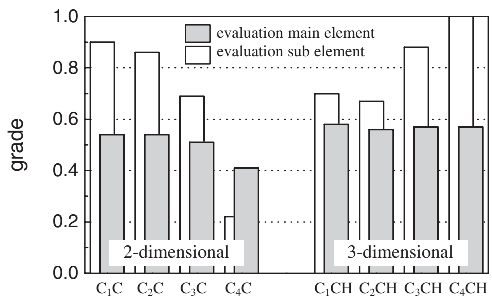


Fig. 20. Comparison with evaluation results in two dimensions.

grade. The following evaluation order is confirmed from Fig. 19: LA (1st); LH; CA; RA; CH; RH (6th). This order can be arranged into three groups. The first group is the L group (LA and LH), the initial position of each intruder is left 2000 [m]; the next group is the A group (CA and RA), the initial position of each intruder is 500 [m] above; and the last group is the H group (CH and RH), the initial position of each intruder is the same altitude as the evader.

The L group is rear-crossing preparation. In this case, avoidance is comparatively easy since the evader takes an avoidance course that is directed away from the intruder. As a result, a better evaluation result is provided for the L group. In the A group, the evader avoids the intruder by traveling 500 [m] in a vertical direction. This group is based on the condition that required-separation in a vertical direction (600–900 [m]) is easy to be satisfied. On the other hand, the conditions of the H group are severe compared to the A group. It is considered that good or bad tendencies in evaluation results appear for such reason.

As shown in Fig. 20, the evaluation results for the two-dimensional (horizontal plane) model has an inclination depending on an intruder approaching direction. Evaluation deteriorates as the intruder's initial position nears similar course geometry (C_4) from opposite course geometry (C_1).

In contrast, the grade of evaluation main element is almost uniform in the proposed three-dimensional model, and the degrade tendency does not appear. It shows that avoidance for an intruder with a similar course is improved more appropriately by modifying the three-dimensional.

7. Conclusion

The following conclusion was derived from simulation and evaluation results.

(1) Resolution of singular point and unrealizable global avoidance problem

A singular point problem can occur at the point where the differential coefficient of risk function becomes 0. Differential calculus in a control process was eliminated in the proposed control law by applying fuzzy logic; therefore, the singular point problem was resolved. Moreover, the proposed control law does not depend on reducing the direction of risk function; therefore, it is possible to realize global avoidance.

(2) Resolution of chattering problem

If the threshold value of the phase is set by as a crisp value, chattering can occur because the phase shifts instantly. A transition phase that makes a gradual phase shift was designed and introduced in this proposed control law; therefore, chattering problem was resolved.

(3) A design on the basis of experience is possible

A rule base, as an experience law (If-Then rule), is used in the control process of the proposed control law; therefore, a design on the basis of experience is possible. Moreover, design ideas are easy to understand and the design itself is comparatively simple.

(4) Setting of required-separation is possible

Conventional studies do not mention relative distance with an intruder when considering avoidance. However, relative distance is a significant parameter in an avoidance problem. Required-separation is designed using a rough value with a gray zone in this paper. Modification of this value in the designing stage is easy. Because required-separation depends on a value set by RCPA in the avoidance-parallel transition phase, therefore only the upper and lower limits of the membership function of this phase need to be modified (and phases next to each other corresponding to it).

(5) Realization of stable avoidance

The parallel flight phase is introduced for the purpose of realizing stable avoidance. A stable flight (avoidance), turning or climbing/descending angular velocity of about 0 [deg/s] in an avoidance-parallel transition phase was realized by introducing a parallel flight phase and its insertion to the transition phase. Therefore, the expected purpose of introducing the parallel flight phase was achieved.

(6) Appropriate avoidance and prevention of excessive avoidance

The parallel flight phase has the purpose of restraining excessive avoidance and achieving moderate avoidance as a form of human operation. This was realized using the avoidance-parallel transition phase for either the horizontal or vertical plane in the proposed three-dimensional model. Applying this control law, it was confirmed that the evader can perform adequate avoidance without extreme action.

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