Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

An optimal one-way cooperative strategy for two defenders against an attacking missile

Qilong Sun, Naiming Qi, Zheyao Xu, Yanfang Liu *, Yong Zhang

Department of Aerospace Engineering, Harbin Institute of Technology, Harbin 150001, China

Received 18 September 2016; revised 7 November 2016; accepted 21 January 2017

KEYWORDS

Cooperative strategy;
Interception;
Increased survivability;
Navigation gain;
One-way cooperation system

Abstract This paper investigates a cooperative strategy for protecting an aerial target. The problem is solved as a game among four players (a target, two defenders, and a missile). In this scenario, the target launches two defenders (defender-1 and defender-2) simultaneously, to establish a one-way cooperation system (OCS) against an attacking missile. A new optimal evasion strategy for the target is also derived. During the engagement, the target takes into account the reaction of the attacking missile, and guides defender-1 to the interception point by receiving information from defender-1. Depending on the control effort of the target, defender-2 can choose appropriate launch conditions and use very limited maneuvering capability to intercept the missile. For adversaries with first-order dynamics, simulation results show that the OCS allows two defenders to intercept the missile. During the engagement, even if one defender or communication channel is broken, the OCS still allows an interception to be made, thus increasing the target's survivability.

1. Introduction

With the rapid development of interception technology, threats to aircraft are growing. Thus, aircraft need to establish a defense system to protect themselves. The problem of an aircraft defense system involves multiple agents, including an aircraft, an attacking missile, and a defending missile. In this scenario, the aircraft, the attacking missile, and the defending missile are referred to as the target, the attacker, and the defender, respectively. The interception problem conventionally involves a single missile pursuing a target. Over the years, a variety of guidance laws have been proposed to describe such one-on-one engagements while assuming perfect information.[1,2]

In recent years, various pursuit-evasion scenarios involving multiple agents have been developed. A pursuit-evasion scenario in which several pursuers try to capture a single evader has been described.[3–6] A game including two pursuers and one evader was investigated.[7–9] In this game, the two pursuers attempted to minimize their distances from the evader, while the evader attempted to maximize its distances from the two pursuers. The game was investigated using differential theories. Rusnak[10] proposed a differential game for three persons, namely, a lady, a bandit, and a bodyguard. In order to solve

* Corresponding author.
E-mail address: liuyanfang_hit@163.com (Y. Liu).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.06.007
1000-9361 © 2017 Production and hosting by Elsevier Ltd. on behalf of Chinese Society of Aeronautics and Astronautics.

the differential game, an approach based on multiple-objective optimization theory was presented, and the required conditions for the solution were discussed. Ratnoo and Shima[11] proposed an approach for protecting the target in the case where the defender used the line-of-sight guidance law to pursue the attacker at a speed at least as fast as that of the attacker. A different approach was used by Yamasaki et al.[12,13] to address a scenario in which the target protected itself by launching a defender that used a new line-of-sight guidance law. Ratnoo and Yamasaki proposed a similar method, wherein the purpose was to command the defender to be in the line of sight between the attacker and the target at all times. This approach performs better than the one where the defender pursues the attacker using a linear guidance law. Rubinsky and Gutman[14–16] investigated an approach wherein the attacker could evade the defender and continue pursuing the target in a scenario in which the target and the defender were independent and provided no help to each other. Further, Gutman and Rubinsky[17,18], in order to reduce the time error, used a new method to calculate the interception time and proposed a three-dimensional nonlinear vector guidance strategy. Ratnoo and Shima[19] analyzed a three-player problem in which the attacker and the defender used different guidance laws.

Recently, different types of models of cooperation between the target and the defender against the attacker have been presented. Perelman et al.[20] reported a cooperative target-defender guidance law with unbounded controls based on a two-team linear quadratic differential game against a homing missile. In this scenario, the target assists the defender in intercepting the missile. Meanwhile, the target also performs evasive maneuvers. Shaferman and Shima[21] analyzed a multiple-model adaptive control scheme to propose a possible homing-missile guidance law. Further, Shima proposed two-way linear quadratic strategies for optimal cooperation between the target and the defender against a homing missile. The missile used a known linear guidance law, but the defender had limited maneuverability to intercept the attacker.[22] However, it has been shown that two-way cooperation between the defender and the target requires installation of additional equipment on the defender, which may often be unavailable.[23] In the same study, a one-way cooperation strategy was presented wherein only one defender protected the target. In this strategy, the defender sends information independently to the target, which lures the missile in a manner to assist the defender to intercept it. The target sends a message to the defender that allows it to turn toward the predicted intercept point. However, the navigation gains and launch conditions of the defender were not analyzed. A differential cooperative game wherein the target and the defender cooperate against the attacker was reported by Garcia et al.[24,25] These studies provided optimal strategies for each one of the players and performed additional analyses of the target escape regions for a given target/attacker speed ratio.

However, in these studies, the defense system only had one defender and the navigation gains of the players were not analyzed. Thus, if the defender or communication channel was to break, the interception would fail. Meanwhile, because the navigation gains of the players were not analyzed, the control effort of the defender would be easily saturated, as it would not be able to select a reasonable navigation gain. In this paper, we set an aircraft's protection as the background when the aircraft faces an interceptor's threat. In order to increase the level of the aircraft's protection and survivability, we design a system with two defenders to protect the aircraft. The defenders and the aircraft exhibit one-way cooperation, and communication between the aircraft and the two defenders is complementary. Thus, even if one of the defenders or communication channels is broken, the system can still intercept the missile. The navigation gain of the defenders is analyzed, and one can select a reasonable navigation gain for the defenders while avoiding the need for control efforts larger than the defenders' maximum control ability.

2. Problem formulation

2.1. Problem description

The endgame scenario and problem flow chart are displayed in Fig. 1. The problem consists of four entities: an attacking missile (M), an aircraft described as a target (T), and two defenders (D_1 and D_2). It is assumed that defender-1 uses a linear guidance strategy to intercept the attacking missile while sending information to the target, and that defender-2 receives the control effort information from the target regarding the predicted intercept point. The target launches the defenders to form an OCS to protect itself. It is assumed that the missile attacks the target using a linear guidance strategy that is known to the target. The ranges between the target and the missile, the missile and defender-1, and the missile and defender-2 are denoted by R_{MT}, R_{MD_1}, and R_{MD_2}, respectively. Further, V_M, V_T, V_{D_1}, and V_{D_2} are the velocities of the missile, the target, defender-1, and defender-2, respectively. Their lateral accelerations are denoted as a_M, a_T, a_{D_1}, and a_{D_2}, respectively. The lines of sight between the target and the missile,

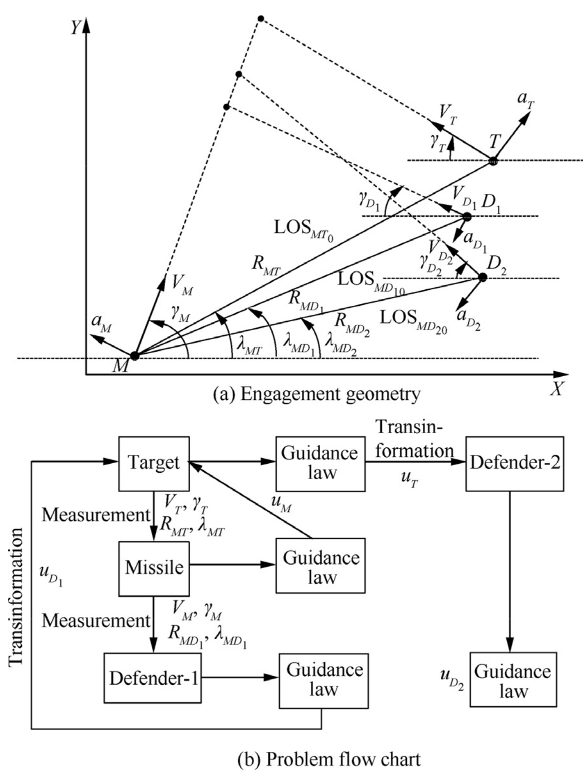

Fig. 1 Engagement geometry and problem flow chart.

Please cite this article in press as: Sun Q et al. An optimal one-way cooperative strategy for two defenders against an attacking missile, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.06.007