Aerospace Science and Technology 42 (2015) 1–11

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Integrated guidance and control law for cooperative attack of multiple missiles

Xiaofang Wang [a,*], Yiyu Zheng [a,b], Hai Lin [a]

[a] Key Laboratory of Dynamics and Control of Flight Vehicle, Ministry of Education, Beijing Institute of Technology, Beijing 100081, People's Republic of China
[b] Deep Space Exploration Research Center, Harbin Institute of Technology, Harbin 150001, People's Republic of China

ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form 28 September 2014
Accepted 11 November 2014
Available online 8 January 2015

Keywords:
Multiple missiles
Cooperation of flight position and flight time
Integrated guidance and control law
Dynamic surface control
Control saturation
Stability and robustness

ABSTRACT

An integrated guidance and control law is developed, using the dynamic surface control theory and disturbance observation technology, for multiple missiles attacking targets cooperatively. The modeling error, aerodynamic parameters perturbation and external disturbance are regarded as system uncertainties, and then integrated guidance and control model of missile is built. Considering multiple missiles' cooperation of flight position and impact time, the constraint of maximum target look angle and the requirement of trajectory convergence, a cooperative strategy expressed by desired target look angle command is proposed. To analyze the effect of nonlinear saturation of missile control input on integrated guidance and control system, a supplementary subsystem is introduced. Three disturbance observers are designed to estimate the system uncertainties. With the signals generated by supplementary subsystem and uncertainty estimate from disturbance observers, a robust controller is designed using dynamic surface control theory to track the desired target look angle command. Based on Lyapunov stability theory and comparison principle, the stability of system under the condition of unknown uncertainties and control input saturation is proved, and the transient tracking error is also discussed. Simulation results demonstrate the effectiveness and robustness of the integrated guidance and control law.

1. Introduction

Modern warfare ships have many advanced self-defense measures against anti-ship missiles, among which the close-in weapon system (CIWS) is rather powerful. CIWS is equipped in naval ships, detects and destroys incoming anti-ship missiles at short range [9]. To break through the interception of CIWS, thus improve the survivability and hitting capability of anti-ship missiles, salvo attack of multiple missiles is an effective way, which means multiple missiles attack the target simultaneously. In the meanwhile, if missiles can approach target synchronously during the flight process, that is, the range-to-go of every missile is the same during attack process, the penetration ability of anti-ship missiles will be enhanced greatly. To realize the salvo attack and synchronous flight for multiple missiles, the guidance law with impact time constraint and flight position constraint need be explored.

In recent years, some researches have been made on the guidance law with impact time constraint for a simultaneous attack, but are rare. An impact-time-control guidance law (ITCG) based on optimal control theory for anti-ship missiles was developed in [8]. An additional term accounting for the error between the designated impact time and the estimated time-to-go was added to the proportional navigation control law to guarantee the designated impact time. Sliding mode control theory was employed to develop a guidance law with impact time constraint in [12]. To satisfy the impact time constraint, the error between the designated impact time and the estimated time-to-go was incorporated in the sliding surface. Neither in ITCG nor the guidance law in [12] there is no communication between missiles during flight, while missiles' ideal impact time was designated in advance. Assuming there is ideal communication between missiles, a two-level cooperative guidance architecture and a cooperative proportional navigation were developed in [21] and [9]. During the engagement, missiles communicate through online data link to get the time-to-go of other missiles, and then they adjust their flight to achieve the accordance of the impact time. In [3,10,13], guidance laws controlling both impact time and impact angle were proposed. The guidance law in [13] is an extension of ITCG, in which the missile jerk was used as a control input to control impact angle and an extra term about the impact time error was included in the control input to control impact time. In [10], a biased proportional navigation guidance was designed using backstepping control method. The bias consisted of such two parts as impact time error and

* Corresponding author. Tel.: +86 1068914599.
E-mail address: wangxf@bit.edu.cn (X. Wang).

http://dx.doi.org/10.1016/j.ast.2014.11.018
1270-9638/

Nomenclature

r	range-to-go	m
V	missile velocity	m/s
σ	target look angle	rad
q	line-of-sight angle	rad
θ	flight-path angle	rad
a_m	missile normal acceleration	m/s^2
P	thrust	N
X	drag force	N
Y	lift force	N
m	missile mass	kg
g	gravity acceleration	m/s^2
M_z	pitching moment	N m
J_z	the moment of inertia around the pitch axis	kg m^2
α	angle of attack	rad
δ_z	actuator deflection angle	rad
$\delta_{z\max}$	the maximum actuator deflection angle	rad
ω_z	pitch rate	rad/s
c_x	drag coefficient	
$c_y^\alpha, c_y^{\delta_z}$	lift coefficients derivatives	rad^{-1}
$m_z^\alpha, m_z^{\delta_z}, m_z^{\omega_z}, m_z^{\dot{\alpha}}, m_z^{\dot{\delta}_z}$	pitching moment coefficient derivatives	rad^{-1}
Q	dynamic pressure	Pa
S	reference area	m^2
L	reference length	m
$d_\theta, d_\alpha, d_\omega, d_n, d_\sigma$	system uncertainty	
σ^*	the desired target look angle	rad
σ_0	initial target look angle	rad
r^*	the nominal range-to-go	m
t_d	the designated impact time of multiple missiles	s
V_r	relative velocity along the line of sight	m/s

impact angle error. A sliding-mode-based impact time and impact angle guidance law for engaging a modern warfare ship was investigated in [3], where a combination of a line-of-sight rate shaping technique and a second-order sliding mode approach has been adopted to satisfy the constraints of impact time and impact angle. In all of above researches, the estimation of time-to-go is necessary, so the precision of time-to-go estimation has great effect on the precision of guidance law. Actually, it's very difficult to estimate time-to-go accurately, especially in the guidance law with impact time constraint, in which missile may have different maneuvering to achieve the common impact time. Ref. [20] defines a nominal range-to-go that changes to be zero when missile flight time equals to the designated impact time, and then design controller to make missile real range-to-go to track the nominal range-to-go to realize salvo attack. Estimation of time-to-go is not needed in [20], but the controller is singular and fails when the target look angle is zero, which is difficult to be avoided completely in practice. About the guidance law that can control both impact time and flight position, to author's knowledge, there is no publication so far. A new concept is developed in this paper that we realize impact time control and flight position synchronization through making missile's target look angle to track desired target look angle strategy, which not only needn't estimate time-to-go but also solves the problem of controller singular.

When designing guidance laws, it is necessary to take the dynamic characteristics of missile into accounted, because the dynamic characteristics directly determines the reaction speed of missile to the guidance command, which is especially important for impact time control guidance law. Moreover, with the structure and power constraints, missile's control input, i.e. actuator deflection angle, is limited. So with the consideration of nonlinear saturation of actuator whether the guidance command can be realized is a problem deserving of study. In addition, a homing anti-ship missile acquires target information from a seeker to implement the guidance law. In that case maintaining the seeker lock-on condition, which means the target is located in the field-of-view (FOV), is very important to realize the guidance command successfully. However, to achieve impact time control, missile trajectory may be more curving, which makes it easier for missile to miss its target within the FOV, so the seeker's target look angle must be limited within a reasonable range [16]. So far, to the authors' knowledge, there is no published work about the cooperative guidance law considering the constraints of missile dynamic characteristics, nonlinear saturation of actuator and seeker's target look angle.

Integrated guidance and control (IGC) has been a hot topic of research in recent years. It can account for the guidance command and dynamic characteristic of missile at the same time, and eliminate the time lag existing inevitably in the conventional missile guidance and control design, which separates the guidance loop from the control loop. Moreover, IGC can exploit fully the synergistic relationships among the separating subsystems. In [15], the linear–quadratic-regulator approach coupled with the feedback linearization method was used for the design of integrated controller to drive the zero-effort-miss to zero while stabilizing the airframe. In [19], a suboptimal control method, called θ–D method was employed to obtain an approximate closed-form controller. Missile guidance law and autopilot design were formulated into a single unified state space framework and the cost function was chosen to reflect both guidance and control concerns. However, the coupled guidance-control design has to account for the inherent uncertainties of the engagement problem, resulting from unknown target maneuvers, missile modeling errors, aerodynamic parameters perturbation and external disturbances. There are different methods to design the IGC controller considering the uncertainties. In [14], a game theoretic approach was employed for the design of an integrated linear autopilot-guidance controller that minimizes the interception miss and control energy of the interceptor, under the worst case of target maneuver and worst case of measurement disturbances. In recent years, such nonlinear control theory as sliding mode control (SMC) [7,11,18], backstepping control [6] and dynamic surface control (DSC) [4,5] was employed to design the robust integrated guidance-control controller. In this paper, to consider the guidance requirement and missile's dynamic characteristics simultaneously, the concept of IGC is adopted. The uncertainties are estimated through disturbance observers (DOB) and the DSC is adopted due to its advantage of avoiding the problem of 'derivative explosion' existing in SMC and backstepping control. The combination of DOB and DSC can improve the control precision and make the amplitude and the change rate of control input to be not much, which is helpful for practice.

About the nonlinear saturation characteristic of missile actuator, usually it is just considered during the later practice process rather than the design process [2,11]. The stability of the system when the saturation occurs is not analyzed rigorously. In this paper, introducing the nonlinear saturation of the actuator into design process, we analyze its effect on system stability and guidance-control precision theoretically.

In this paper, a robust IGC law including a cooperative strategy and a robust IGC controller is proposed. The cooperative strategy is developed considering the requirements of cooperation of im-