Aerospace Science and Technology 53 (2016) 169–187

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Three dimensional impact angle constrained integrated guidance and control for missiles with input saturation and actuator failure

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ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form 17 March 2016
Accepted 21 March 2016
Available online 29 March 2016

Keywords:
Integrated guidance and control
Input saturation
Impact angle constraint
Actuator failure
Dynamic surface control
Extended state observer

ABSTRACT

A three dimensional integrated guidance and control law with impact angle constraint is developed, using the dynamic surface control and extended state observer techniques, for the bank to turn (BTT) missile attacking a ground fixed target in the presence of input saturation and actuator failure. Firstly, a novel three dimensional integrated guidance and control model based on Coriolis theorem is built without assuming the angle between line of sight and missile velocity is small or almost constant. Then, to analyze the effect of input saturation on missile's integrated guidance and control system, a smooth tangent function, a Nussbaum function, and an auxiliary system are introduced. The actuator failure, modeling error, and aerodynamic parameters perturbation are viewed as the lumped system uncertainty. Three extended state observers are designed to estimate uncertainty. With the signal generated by the auxiliary system and uncertainty estimate from extended state observer, a robust controller is designed using dynamic surface control technique to track the desired impact angle. The stability of system is proved using Lyapunov theory. Numerical simulations are implemented to demonstrate the effectiveness and robustness of the integrated guidance and control law.

1. Introduction

The classical design approach of the missile guidance and control system is to design the guidance and control subsystems separately and then integrate them. This design approach ignores the coupling between the guidance and control subsystems. As a result, guidance and control subsystems fail to work synergistically, and the performance of overall missile system is not fully exploited [1–3]. To eliminate these shortcomings, a new design idea called integrated guidance and control (IGC) was put forward for the first time in [4]. The IGC views the guidance subsystem and control subsystem as a whole and directly generates the fin deflection commands according to the states of the missile and the target relative to the missile to drive the missile to intercept the target [3]. The IGC can fully exploit the synergistic relationship between the separated subsystems to optimize the performance of the overall system. Up to now, various control methods such as game theory [5], subspace stabilization [6], small gain theorem [7], L_1 adaptive control [8], linear quadratic regulator (LQR) [9,10], active disturbance rejection control (ADRC) [11], feedback linearization [3,12], state dependent Riccati equation (SDRE) [13], θ-D approach [14], model predictive static programming (MPSP) [15], dynamic inversion [16], backstepping [17–19], sliding mode control [2,20–31], and dynamic surface control [32–34] are employed to design IGC law.

Many of the above works, however, were concentrated on two dimensional (2D) IGC design; for example, [5–7,9,11,17–30]. In order to fully exploit the cooperative relationship among the pitch, yaw, and roll channels, three dimensional (3D) IGC laws were also proposed in the literature. By combining the nonlinear missile dynamics with the nonlinear dynamics describing the pursuit situation of a missile and a target in the three dimensional space, a fully 3D IGC model was established in [33]. Then, a novel simple adaptive block dynamic surface control algorithm was proposed to design a 3D IGC law. Based on the IGC model in [33], the L_1 adaptive control and the block backstepping sliding mode schemes were respectively used to design 3D IGC controllers in [8] and [34].

In order to enhance the lethality of missile's warhead [48,49], some attempts have been made on the design of IGC law with impact angle constraint. Considering the linearized missile longitudinal dynamics, a 2D impact angle constrained IGC law was developed using the LQR method in [9]. In [11], the ADRC based

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http://dx.doi.org/10.1016/j.ast.2016.03.015

Nomenclature

V	missile velocity	m/s
θ	flight path angle	rad
ϕ_c	heading angle	rad
q_1	elevation angle of the line of sight	rad
q_2	azimuth angle of the line of sight	rad
θ_M	elevation angle of the missile velocity with respect to the line of sight	rad
ϕ_M	azimuth angle of the missile velocity with respect to the line of sight	rad
R	missile target range	m
V_{Rx}, V_{Ry}, V_{Rz}	components of the velocity of target with respect to missile in the line of sight frame	m/s
a_{x4}, a_{y4}, a_{z4}	components of missile acceleration in the line of sight frame	m/s^2
V_x, V_y, V_z	components of missile velocity in the inertial frame	m/s
V_{x4}, V_{y4}, V_{z4}	components of missile velocity in the line of sight frame	m/s
$\mathbf{R}$	the vector of missile target relative range	m
$\mathbf{\Omega}$	the vector of angular velocity of the line of sight frame with respect to the inertial frame	rad/s
$\mathbf{V_R}$	the vector of the velocity of target with respect to missile	m/s
$\mathbf{a_R}$	the vector of the acceleration of target with respect to missile	m/s^2
X, Y, Z	drag, lift and side forces	N
m	mass of the missile	kg
γ_v	velocity bank angle	rad
θ_f	the desired flight path angle	rad
C_{X0}	zero-lift drag coefficient	
$C_X^{\delta_x}, C_X^{\delta_y}, C_X^{\delta_z}$	partial derivatives of drag force coefficient with respect to δ_x, δ_y, and δ_z	
g	gravity acceleration	m/s^2
α	angle of attack	rad
β	angle of sideslip	rad
$\omega_{x_1}, \omega_{y_1}, \omega_{z_1}$	body axis roll, yaw and pitch rates	rad/s
$J_{x_1}, J_{y_1}, J_{z_1}$	roll, yaw and pitch moments of inertia	kg/m^2
$M_{x_1}, M_{y_1}, M_{z_1}$	roll, yaw, and pitch moments	N·m
M, T	missile and target, respectively	
$q = 0.5\rho V^2$	dynamic pressure	Pa
ρ	air density	kg/m^3
S	reference area	m^2
L	reference length	m
$C_Y^\alpha, C_Y^\beta, C_Y^{\delta_z}$	partial derivatives of lift force coefficient with respect to α, β, and δ_z	
$C_Z^\alpha, C_Z^\beta, C_Z^{\delta_y}$	partial derivatives of side force coefficient with respect to α, β, and δ_y	
$m_{x_1}^\alpha, m_{x_1}^\beta, m_{x_1}^{\delta_x}$	partial derivatives of rolling moment coefficient with respect to α, β, and δ_x	
$m_{y_1}^\beta, m_{y_1}^{\delta_y}$	partial derivatives of yawing moment coefficient with respect to α, β and δ_y	
$m_{z_1}^\alpha, m_{z_1}^{\delta_z}$	partial derivatives of pitching moment coefficient with respect to α and δ_z	
$\delta_x, \delta_y, \delta_z$	aileron, rudder, and elevator deflections	rad/s
$\delta_{mx}, \delta_{my}, \delta_{mz}$	the bounds of aileron, rudder, and elevator deflections	rad/s
τ_x, τ_y, τ_z	the effectiveness factors of δ_x, δ_y, and δ_z	
ϕ_{cf}	the desired heading angle	rad
C_X^α, C_X^β	partial derivatives of drag force coefficient with respect to α and β	
$C_X^{\alpha\beta}$	second partial derivative of drag force coefficient with respect to α and β	

2D IGC law was proposed to make the LOS angle near the desired value. The nonlinear uncertainty caused by target maneuver and interceptor dynamics was estimated and compensated for in real time. In [19], the integrated backstepping design with disturbance observer was developed for 2D IGC law with impact angle constraint. In [28,29], the impact angle constrained IGC designs for homing missiles against ground fixed targets in the pitch plane were derived using an adaptive SMC algorithm and an adaptive nonlinear control law, respectively. In [30], novel finite time convergent sliding-mode control laws were proposed for a class of uncertain nonlinear systems. Then, these new SMC schemes were employed to design a chattering-free impact angle constrained IGC law in the 2D plane. To the best knowledge of the authors, however, little attention has been paid to the design of 3D impact angle constrained IGC law. Supposing the pitch, yaw, and roll channels were decoupled with each other, a 3D impact angle constrained IGC law was built using adaptive multiple sliding surface control algorithm in [31]. In [2], a fully 3D IGC controller that accurately satisfied terminal impact angle constraints in both azimuth and elevation was proposed utilizing an adaptive Multiple Input Multiple Output sliding mode control theory.

In practice, nonlinear saturation is often encountered in the control system. Physical input saturation on hardware implies that the magnitude of the control signal is always constrained. The existence of input saturation constraint often severely limits system performance, giving rise to undesirable inaccuracy or leading instability [35,36]. Therefore, it is of significance to explicitly take the input saturation into consideration in the design of IGC law. In [37], a 2D IGC law for multiple missiles attacking targets cooperatively was developed using the dynamic surface control theory and disturbance observation technique, where an auxiliary system was introduced to cope with the problem of input saturation. Assuming the pitch, yaw, and roll channels are decoupled, an adaptive dynamic surface control based 3D IGC controller with input saturation for homing missiles was proposed in [38]. An auxiliary system was first introduced into the IGC model in the pitch plane. Then, a smooth tangent function and a Nussbaum type function were employed to deal with the problem of input saturation. A similar control scheme was further applied to the yaw channel and roll channel.

Another important problem encountered for IGC system is the control failures, such as partial loss of effectiveness or thrust failure. Control failure can also degrade system performance, and lead to instability or even catastrophic accidents. In [39], a fault tolerant 2D IGC law was proposed based on backstepping and input to state stability. An adaptive law was designed to estimate the unknown effectiveness factor.

As discussed above, great progress has been made on the research of IGC law design over the past thirty years. However, there are still some open problems in the design of IGC law. First, all the 2D IGC models in [22,24] and the 3D IGC model in [33] were built with the assumption that the angle between the line of sight (LOS) and missile velocity was small or almost constant. However, it was pointed out in [7,18] that this assumption might not be valid in practice. Therefore, how to build a reasonable 3D IGC model still remains unsolved. Second, the problem of input saturation in the design of 3D IGC law was solved by assuming the pitch, yaw, and roll channels were decoupled. To the best of the authors'