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Proportional Navigation (PN) Guidance with Nonlinear Dynamic Inversion Autopilot Controller for Surface to Air Missile (SAM)

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Abstract: *One of the important subsystems of benchmark guidance and control system of missile is nonlinear Autopilot (A/P). This paper attempts to apply Proportional navigation guidance for Surface to Air (SAM) missile to engage a maneuvering target. The problem formulation deals with a situation where the pursuer (interceptor) wishes to minimize the terminal miss whereas the evader (target) wishes to maximize it. The interceptor strategy, therefore, is determined based on the anticipated worst possible target strategy.*
In this, a nonlinear controller has been used as autopilot (A/P) to track the command. But this method required the missile parameters information. If there is uncertainty in plant parameters then, this controller will not perform well. To increase its robustness, an integrator can be used. But this will reduce the efficiency of the autopilot (A/P). So to avoid this problem a nonlinear dynamic inversion controller has been designed. Performance of nonlinear autopilot is always seen to be superior compared to linear autopilot in the presence of disturbances, aero parameter variation, gust and cross coupling.

NOMENCLATURE

- Coefficient of Lift,
- Drag coefficient,
- Pitching Moment Coefficient,
- Acceleration in X, Yand Z direction,
- Moment of Inertia in X, Y and Z direction,
- Euler angular rates

Keywords: *Proportional Navigation, Homing Guidance, Missiles, Autopilot*

1. INTRODUCTION

Homing missile guidance has been an important area of research in the past few decades. There are many advanced guidance laws have been developed using two different approaches. One approach is to use a target model in which the target is assumed to perform certain maneuver. For example, the augmented proportional navigation is derived assuming that the target acceleration vector is orthogonal to the nominal line-of-sight and its magnitude is constant. Instead of assuming the target acceleration is constant in an inertial direction, more realistic guidance laws are derived assuming that the target acceleration vector is orthogonal to the target velocity vector and its magnitude is either constant or sinusoidal. The other approach is to assume the worst possible target maneuver. That is, the target is assumed to be intelligent and tries to maximize the miss distance. In the problem formulation, the pursuer (interceptor) wishes to minimize the terminal miss whereas the evader (target) wishes to maximize it. Therefore, the interceptor strategy is determined based on the anticipated worst possible target strategy.

Classically, missile autopilots are designed using linear control approaches by either in frequency domain or by applying linear quadratic regulators. In both approach, the plant is linearized around fixed operating point, which are suitably interpolated in the sight. The basic requirement for an autopilot is fast response and minimum steady state error for better guidance performance. Finally robustness of model uncertainties and decoupling between longitudinal and lateral motion in stressing engagement scenario are important. The highly nonlinear nature of the missile dynamics due to the severe kinematic and inertial coupling of the missile airframe as well as the aerodynamics has been a challenge for an autopilot that is required to have satisfactory performance for all sight conditions in probable engagements. Modern day missile are designed with high maneuverability's to tackle highly agile and stealth target. High angle of attack operation region becomes imminent, resulting in high cross coupling of lateral and longitudinal plane. Linear autopilot (A/P) fails to address issue of cross coupling, as fundamental assumption of design of linear A/P is decoupling of longitudinal and lateral motion.

Here in this project, a nonlinear dynamic inversion controller has been used as autopilot to track the command. But this method required the missile parameters information. If there is uncertainty in plant parameters then, this controller will not perform well. To increase its robustness, integrator can be used. But this will make the autopilot slow.

2. CONCEPT OF PROPORTIONAL NAVIGATION

Many Missiles are guided to their target by “Homing guidance” laws. These laws are mathematical algorithms that are designed to guide the missile to the target in some efficient and effected ways. Perhaps most ubiquitous of the homing guidance laws is one that are usually called “Proportional Navigation” , even though is not, strictly speaking, a navigational algorithm , but the guidance algorithm.

Proportional Navigation Guidance is analogous to proportional controller. It is the basic control law, and most of the interceptors use some or the other form of this controller to guide the missile to the target. This guidance law is one of the most simple to design and implement, however its applications are restricted under certain conditions as this law doesn’t necessarily preserve the kinetic energy of the missile. For example this guidancemay turn out to be useless for a missile with no throttle, as the kinetic energy is not preserved.

The basic philosophy of the proportional navigation guidance is that two objects are in a path of collision only if their Line of Sight (LOS) doesn’t change direction. PN guidance dictates that the missile velocity vector must rotate proportionally to the rate of the LOS vector and in the same direction.

3. DESIGN OF CONTROLLER

In this approach the state q is identified as faster dynamic response, while α, and is characterized as slow state variable. The angular rate q; strongly depends upon the fin deflection. Thus to start with, a fast state controller for q; is designed. Having designed afast-state controller, a separate, approximate inversion procedure was carried out to design the slow state controller for alpha. It may be noted that, such a model reduction method was possible as there was significant difference in the time scale between the fast and slow state in the open loop dynamics of missile.

As stated earlier the design of this controller depends on two time-scale separation. The outer loop is slow dynamics and the inner loop is fast dynamics. The outer loop controller takes the commanded acceleration and current acceleration as input and generates the rate command which works as an input to the inner loop (fast dynamics) which generates fin deflection. [1]

In this approach, the design of the controller has been divided in two parts, the pitch body rate, ‘q’ has been identified as the faster dynamic response and the angle of attack α is identified as the slow rate variables. The angular rate is highly dependent on the fin deflection for a tail controlled missile.

3.1. Design of Slow Dynamics (Outer Loop)

In a controller the desired dynamics are imposed on the controller so as to obtain the required results. In the slow rate dynamics, the acceleration and current dynamics of the missile is given as an input to the autopilot from the guidance law. This acceleration is inverted to the desired angle of attack by the following equation:

Having determined the $\dot{\alpha}$, from the slow rate dynamics, it is inverted to get the commended pitch body rate command as

Where is the controller gain which is taken as 10.

3.2. Design of Fast Dynamics (Inner Loop)

The rate command from the outer loop is used to evaluate the desired dynamics. Here the second order dynamics is considered

Once the $\dot{qd}$ is found out, it can be inverted into the required fin deflection by the following relation:

In inner loop, the robustness study [2] [3] is carried out where the states and output are pitch body rates. The objective as explained before is to come up with a nominal controller, which will meet the goals of nominal system i.e. the nominal states $[q^*]$ as $t\to\infty$ and hence the adaptive control will meet the goals of the actual system.The technique used for designing nominal controller is Dynamic inversion.

3.3. Simulation

For the simulation purpose the 3 DOF pitch dynamic of missile has been used as given below.

4. RESULTS AND DISCUSSION

To show the capability of a PN guidance system with a non-linear dynamic inversion controller, we have depicted 3 cases. In case 1, the target is static at an altitude of 3000 meters and at a distance of 5000 meters from the origin. In case 2 the target is moving at a constant velocity. Case 3 discusses the interception of a ballistic target moving at a constant forward velocity and falling freely towards the ground. For each case the trajectory of the missile as well as the target has been shown. Also various other parameters are plotted as well which depict the effectiveness of the autopilot design.

4.1. Case 1 (Static Target)

As stated above in case I the target is static at an altitude of 3000 meters from the ground. The missile is launched at right angle to the ground. The following figures show the various parameters with respect to time until the missile intercepts the target.

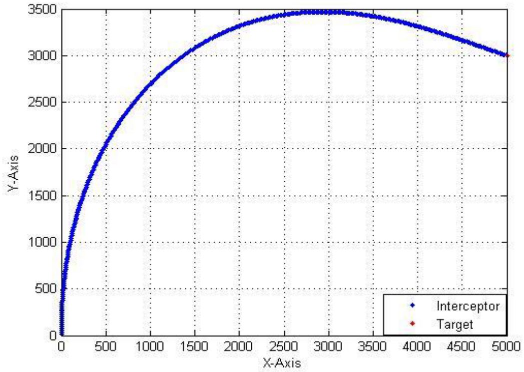

Fig. 1: The trajectory of missile and target

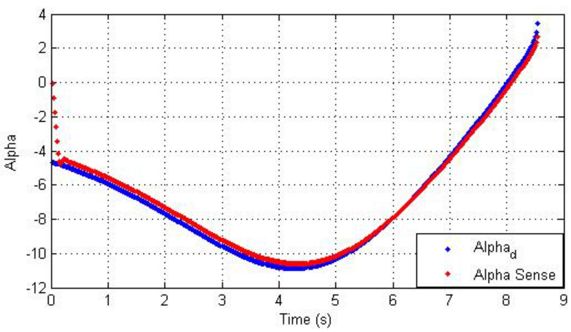

Fig. 2: The Variation of angle of attack(with respect to time4.2. Case 2 (Constant Velocity Target)

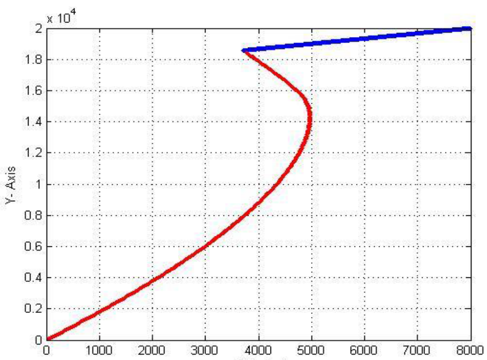

Fig. 3: The trajectory of missile and target

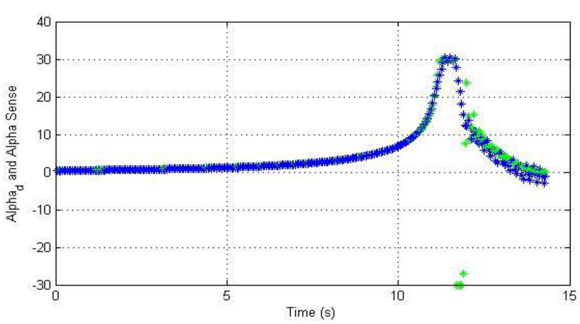

Fig. 4: The Variation of angle of attack (α) with respect to time

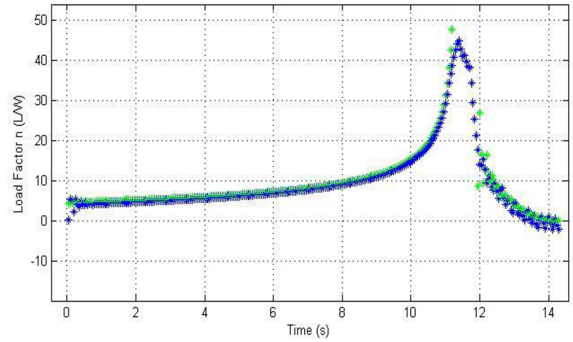

Fig. 5: The Variation of load factor with respect to time

In this case the target is moving at a constant velocity of 200 ms-1 along the x-axis and 50 ms-1 along the y-axis. The missile is launched at an angle of 60o to the ground. The following graphs show the variation of various parameters with respect to time to show the effectiveness of the PN guidance with a dynamic inversion autopilot.

4.3. Case 3 (Ballistic Target)

In this case the target has a constant initial velocity of 100 ms-1 along the x-axis and is proceeding the ground under the force of gravity. The target is moving towards the ground with a constant acceleration of 9.8 ms-2 along the y-axis. The missile islaunched at angle of with respect to the ground. The following figures show the variation of various parameters with respect to time.

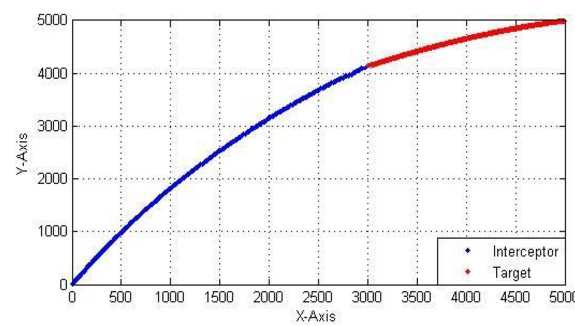

Fig. 6: The trajectory of missile and target

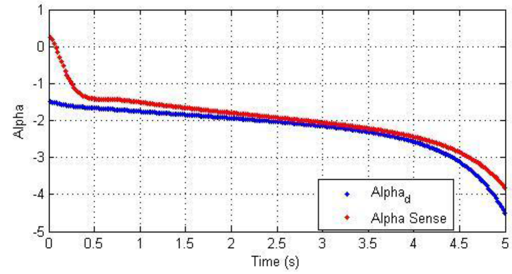

Fig. 7: The Variation of angle of attack (α) with respect to time

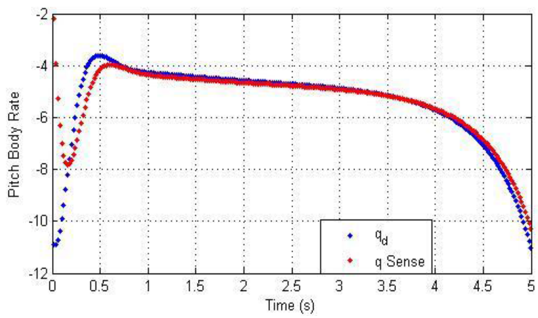

Fig. 8: The Variation of pitch body rate with respect to time for the missile

5. CONCLUSION

With the above stated results we would like to conclude that the aim of the project (To design an autopilot for an interceptor) has been successfully achieved. The results clearly state that the interceptor has proven its robustness in successfully intercepting the target, be it a stationary, ballistic or a maneuvering target. With this we would also like to conclude the robustness of the Nonlinear Dynamic Inversion Autopilot as it has been able to achieve the requisite pitch body rates in the fast response.

This is a wide field of research with a huge scope of future improvements. The autopilot can be coupled with better and smart guidance systems such as the 'Game Theory Guidance' to provide better results.

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