The Estimator is the Key Element in Interception Endgames

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Extended abstract

In an earlier study, presented at the 3rd EUCASS [1], an innovative guidance strategy was outlined by integrating the design of a multiple model adaptive estimator and a differential game based guidance law. Such strategy indicated two potential breakthroughs in the interception of randomly maneuvering targets in Ballistic Missile Defense. Further studies indicated that while the differential game based guidance law is a robust solution for a large family of practical scenarios [2], the estimation process associated with it still needs improvement.

The homing guidance of an interceptor missile is a stochastic optimal control problem with the objective to minimize, using a sequence of noise corrupted measurements, the expected value of the miss distance. For using these measurements as a basis of a feedback control, the noisy signals have to be filtered. Eventual target maneuvers are considered as unknown bounded disturbances. Classical guidance laws, like Proportional Navigation did not required exact knowledge of the target maneuvers. Satisfactory homing performance, i. e. small miss distances, could be achieved by a rather large maneuverability advantage (more than 3) over the target. In modern guidance laws the knowledge of the actual target acceleration is necessary for achieving small miss distances with a reasonably modest maneuverability advantage. Unfortunately, the acceleration of another object cannot be measured from a moving platform. In the ideal case, where all measurements are noise free and the dynamic model is perfectly known, the unmeasured variable can be reconstructed by an observer. In reality, such reconstruction has to be made, using the available noise corrupted measurements, by an estimator. Thus, in an interceptor guidance system the estimator is an indispensable element, performing a dual role, the role of a filter and the role of an observer. The homing performance of an interceptor missile is limited by the estimation accuracy. The objective of this paper is to present an overview of the different error sources involved in the necessary estimation process in an interception endgame and to indicate directions for further investigations.

The estimation error consists of two components. The first one is dynamic in nature and expressed by the delay occurring during the convergence of the estimated state variables. The second component is of stochastic nature and expressed by the variance of the converged estimate. In order to satisfy the requirement for a small miss distance in interception endgames, the estimation process has to minimize both the estimation delay and the variance of the converged estimation error. Due to the different nature of the error components, no clear unique definition of an *optimal* estimator for short term control problems can be found in the literature.

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The design of a Kalman filter minimizes only the second error component. This fact has been very convenient, because most control processes are of long duration and abrupt variations of the state variables are not expected. In such cases the estimation delay is not critical. In an interception endgame the situation is different. Such an endgame is of short duration and the estimation errors occurring near the final time are crucial. Therefore, the estimation process has to become faster as the final time of the endgame is approaching. For effective terminal guidance, the time-to-go, which is available in most guidance systems, has to be considered in the estimator design.

Although the validity of the *separation* and *certainty equivalence* properties has never been proven for realistic interception problems, in the 50 years long history of guided missiles it has been of common practice to design the estimators and missile guidance laws independently. Such non optimal design approach has been very comfortable and was adopted, because it succeeded to satisfy the performance requirements, due to the substantial maneuverability advantage of guided missiles over their manned aircraft targets.

Simulations of a planar interception endgame scenario [3] demonstrated the problem caused by the noise corrupted measurements requiring the presence of an estimator. These simulations used a guidance law and a set of parameters that guarantee, in the ideal case of perfect information and without an estimator in the guidance loop, zero miss distances against all admissible bounded target maneuvers. In Fig. 1 the average miss distance of 100 Monte Carlo runs is shown as the function of the disturbance occurrence time-to-go. In this figure one can observe the *critical* time-to-go, $(t_{go})_{cr}$; which is the boundary between the regions of small and large miss distances as well as the almost constant average miss distance for large values of time-to-go. The *critical* time-to-go is composed of the *delay* due to the convergence of the estimated state variables (including also the maneuver detection) and the reaction time of the interceptor autopilot. The simulation results showed that small miss distance can be achieved only if a disturbance, such as target acceleration, starts in the early part of the endgame. In this case, the state estimation converges, leaving sufficient time the closest approach. If the disturbance occurs later, the combination of the same estimator with the same guidance law fails to provide satisfactory results because of the estimation delay.

Not being able to rely on the unproven *separation* and *certainty equivalence* properties, for stressing scenarios (e.g. in Ballistic Missile Defense), an engineering approach of an *integrated* estimation and guidance algorithm was introduced [3] and presented in detail in [1]. The *integrated* estimation and guidance algorithm in [3] had different estimation strategies before and after the *critical* time-to-go and also included some modifications in the original (perfect information) guidance law. This "logic based" *integrated* algorithm, developed for a planar scenario, showed encouraging results and was validated also in 3D interception endgames [4].

In spite of this success, further investigations are still needed for developing effective robust estimation/guidance guidance strategy against randomly maneuvering targets in more general realistic, noise corrupted scenarios. Since the robustness of the differential game based guidance law has been already demonstrated [2], the new directions consider mainly the estimation aspect, such as establishing a criterion for a suitable estimator performance for short range interception endgames against randomly maneuvering targets and the development of an innovative estimator design that explicitly considers the time-to-go in the estimation process of randomly maneuvering target acceleration. Based on the insight gained from [3] the criterion of *suitable* estimator performance for short range interception endgames against randomly maneuvering targets can be formulated in the following form: *The convergence time of a suitable estimator for short range interception endgames against randomly maneuvering targets has to be shorter than the time-to-go less the delay due to the autopilot dynamics.*

Based on the criterion of suitability a new approach for estimation design had to be developed. This approach is based on two elements:

1, decreasing the value of the *critical* time-to-go, subject to an acceptable level of the average miss distance for large time-to-go ;

2, designing a small number (as few as possible) *tuned* estimators that cover the entire range of short time-to-go (less than the critical one) and guarantee a robust acceptable level of miss distances. For the short time-to-go region terminal guidance law modifications may also be necessary, as in [3]. Naturally, such design can be very much dependent on the relevant parameters of the scenario. In the proposed presentation some tentative estimator designs will be presented

References

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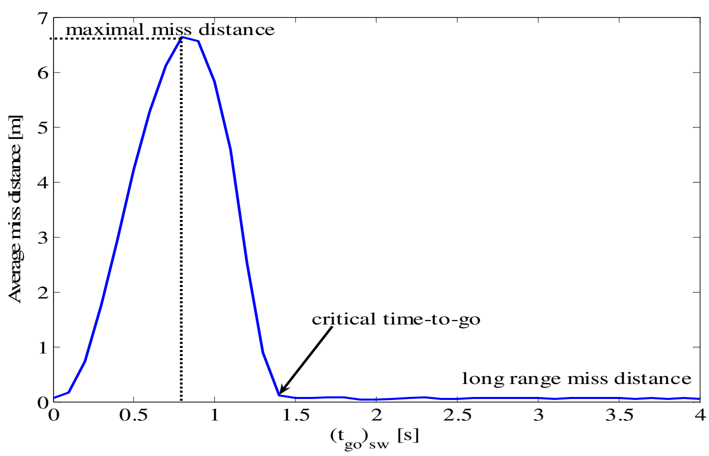

Fig. 1. Homing performance against random disturbances in short duration endgames