Adaptive Impact Time Control Via Look-Angle Shaping Under Varying Velocity

The impact time control problem can be stated as the requirement to hit the target with no other terminal constraint than achieving a specified final time. This specific terminal constraint, the impact time control problem, can be stated as the requirement to hit the target with no other terminal constraint could provide survivability against close-in weapon systems by facilitating a salvo attack capability. In addition, impact time control could be employed to force the missile pass through a certain waypoint at a specified time. With rising interest over recent years, the literature on impact time control laws has been growing rapidly. One of the earliest studies was presented in [1], which was based on proportional navigation (PN) involving the difference of the desired and estimated time-to-go values as a bias term. The same authors extended the previous work, in which the design was based on linearized kinematics, in [2] to nonlinear kinematics. Another impact time control method via biased PN was considered in [3] for cooperative attacks. The bias term was a time-varying navigation gain that was adjusted based on the time to go of the individual missile and the times to go of the cooperating missiles. As well as PN-based impact time guidance laws, there exist numerous studies based on the nonlinear control theory. A Lyapunov-based approach was considered in [4] using the same
time-to-go estimation as in [1]. The sliding mode was applied in [5], using a switching surface as a combination of the impact time error and the line-of-sight (LOS) rate. In [6], a sliding surface that was only a function of the impact time error was provided. In addition, several modifications were made to deal with the singularity of the guidance command. The common disadvantage of these guidance laws designed via the nonlinear control theory is the high acceleration demand at the beginning of the flight. As exemplified thus far, many of the impact time guidance laws in the literature require the time to go as feedback. Thus, the estimation of this quantity might turn into a source of error.

However, there are also several studies where the impact time problem is solved without relying on this information. In [7], second- and third-order polynomial guidance laws were proposed, where the guidance gain was to be calculated by solving an integral equation in order to satisfy the requirement of a zero miss distance. Also, the third-order approach is shown to produce trajectories close to optimal ones. The guidance law in [8] was derived by shaping the range as a quartic polynomial. The nonlinear design results in a closed-loop guidance law with constant coefficients, showing robustness under lagged response and seeker noise. In addition to these, guidance laws effective against moving targets were presented in [9,10]. The study in [9] adopted the vector guidance approach, directing the total acceleration to ensure the capture at the specified time. In [10], a two-phased PN guidance scheme is constructed, where the switching instant was calculated with respect to the desired impact time. Both of these guidance laws require a controlled change of missile velocity. In addition to the impact time control problem alone, simultaneous control of the impact time and angle should also be mentioned here because it can also lead to a designated impact time. In [11], the guidance command was composed of two parts, where the first part was for the impact-angle constraint with zero miss distance and the second part was for the impact time constraint. The sliding-mode control theory was used in [12] for simultaneous control of the impact time and angle. A second-order sliding-mode control law was introduced using a backstepping concept to provide robustness in the presence of uncertainties. The work in [13] provided a three-phased practical guidance law to control the impact time or/and the impact angle under look-angle and acceleration constraints. The key assumption in all of these studies is that the velocity of the missile was either constant or, on a few occasions, controllable. In contrast, the velocity is not even controllable in most missile applications. Besides, it changes under the action of drag, thrust, and the trajectory being followed. The works presented in [14,15] considered the impact time control problem under changing velocity. In [14], which devised a quadsegment polynomial method via parameterizing the trajectories in terms of the downrange, doing a preflight analysis was proposed as a first step in coping with the velocity change. In [15], on the other hand, integral sliding-mode control was performed, taking into account the rate of change of the velocity and its limits. However, a preflight analysis as in [14] might not always be feasible, and having the terminal acceleration systematically diverging away from zero as in [15] could be prohibitive. Moreover, varying velocity is assuredly a problem, not only for the impact time problem but also for the optimal guidance laws too. There are several studies that concentrated on this issue. An energy-optimized guidance law was presented in [16], where the guidance gain was varied via a time-to-go-like function. This function considered the future missile velocity and adjusted the guidance gain with respect to the predicted velocity. In [17], an extension to the previous study was presented while providing two schemes for updating the velocity and general-case cost functions for varying velocity. The study in [18] used a time-varying linear game model for an interception scenario with a known velocity profile and a lateral acceleration constraint. In addition to these studies, adaptive guidance schemes are also applied to provide robustness under varying conditions. Here, adaptation means updating the guidance gains with respect to those conditions, and no connection with the conventional adaptive control is implied. In this extent, the impact-angle control problem was studied in the literature. In [19], a nonlinear parameter adaptation scheme for impact-angle control was presented for a hypersonic gliding vehicle. The study in [20] developed two adaptive impact-angle guidance laws: one of which was based on the conventional PN guidance and the other one based on controlling the turn rate of the relative velocity vector. In both of these studies, the guidance gains were updated in a closed-loop manner; therefore, they were able to deal with varying conditions. In this study, a feasible impact time control algorithm is proposed. The guidance laws in [7] are generalized using an nth order polynomial of the look angle. Unlike [7], the linearized kinematics is used to obtain an analytical solution for the guidance gain as a function of the range, the look angle, and the duration until impact. This solution is then extended to the nonlinear domain by considering an adaptive guidance scheme. Such adaptation through periodically updating the guidance gain is not only able to overcome the unmodeled nonlinearities but it also provides robustness against disturbing factors such as autopilot lag. However, adaptation will only be sufficient as long as the velocity of the missile remains constant. As mentioned previously, the velocity is generally neither constant nor controllable. What makes the situation more problematic is...
that the velocity profile eventually depends on the trajectory, which is indeed the result of the
guidance law itself. If the future velocity profile or, equivalently, the mean value of this profile can
somehow be predicted, this information can be used to feed the adaptive guidance process. The
approach adopted in this work for predicting the mean velocity uses the analytical results extracted
from the linearized guidance loop. At each guidance step, in which the eventual objective is the
adaptation of the guidance gain, the mean velocity is predicted for the interval between the current
time and the final time using an iterative process. The prediction algorithm involves a mathematical
model of how the velocity is expected to change. In this predictive-adaptive guidance scheme, the
guidance gain is updated based on the predicted mean velocity. The outline of the Note is organized
as follows: In Sec. II, the impact time control problem is described and the general form of the
guidance command is presented. In Sec. III, the solution of the guidance gain is presented based on
linearized kinematics. Afterward, adaptive and predictive-adaptive guidance schemes for impact time
control are introduced. Last, the performance of the proposed guidance technique is demonstrated
with simulations in Sec. IV. After presenting idealized examples with constant velocity, more realistic
ground-to-ground and air-to-ground scenarios with nonconstant velocity profiles and autopilot lag are
exemplified. In addition to these simulations, which also include comparisons with optimal solutions,
a case that involves drag uncertainty is investigated.

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