



Capture zone of linear strategies in interception problems with variable structure dynamics

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Received 26 June 2012; received in revised form 12 September 2013; accepted 16 September 2013

Available online 25 September 2013

Abstract

The paper considers planar interception engagements against maneuverable targets using a linearized kinematic model with constant velocities. Both the interceptor and the target have bounded controls and first-order linear dynamics. Due to the linearization, the duration of the interception is prescribed. The target dynamics is fixed, but the interceptor has variable structure dynamics, switching from one mode to another once during the engagement. For such engagements the capture zone of a given linear feedback control is constructed. Numerical examples demonstrate that proper change of the interceptor dynamic mode leads to an enlarged capture zone.

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1. Introduction

Control problems with variable structure dynamics have attracted considerable attention in the applied mathematics and control engineering communities. A rich bibliography devoted to this topic exists in the open literature (see e.g. [1–6]). The main approach in the analysis of such problems with a single controller, assuming perfect state information, has been to use the generalized Pontryagin's maximum principle (see e.g. [7] and references therein) and the dynamic programming approach [8]. A convenient and useful approach to study variable dynamics control problems either with two controllers or with unknown disturbances (playing the role of the second player) is provided by formulating these problems as two person differential games [5,6,9]. The solution of a two person differential game is a triplet consisting of the optimal control strategy, the worst-case uncertainty (disturbance) and the guaranteed value of the cost functional (the game value). Since the players do not know the actual control of each other, they should assume that the opponent uses its optimal strategy. If one player

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deviates from its optimal strategy, the cost functional will be better for the opponent. This means for each player that playing the game optimal strategy guarantees robustness with respect to all admissible opponent control options.

Modern interceptors can be equipped with two types of control systems: an aerodynamic control, to be used only in the lower atmosphere, and a thrust vector control, which can also be used in space, as well as in the atmosphere. The aerodynamic control can provide generally higher maximal lateral accelerations, but the thrust vector control has faster dynamics. If the interception takes place in the atmosphere, it is possible to switch between these two types of control systems (dynamic modes), creating a vehicle with hybrid dynamics. The objective of the interceptor is to capture the evading target, i.e. to achieve zero miss distance from the largest set of initial conditions (the capture zone) against any admissible evasive control of the target, i.e. robustly with respect to the target's behavior, while the interceptor control constraint is respected. This robust capture zone depends on the control strategy of the pursuer.

Such an interception problem with variable dynamics was solved previously [5] as a two person differential game of terminal cost and bounded controls with both players having fixed first-order dynamics. There are two conditions for the existence of a non-empty capture zone: $(*)a_{pi}^{\max} > a_e^{\max}$, $(**)a_{pi}^{\max}/\tau_{pi} \geq a_e^{\max}/\tau_e$, $i=1, 2$, where $a_{pi}^{\max}$, $i=1, 2$, and $a_e^{\max}$ are the maximal lateral accelerations, τ_{pi} , $i=1, 2$, and τ_e are the time constants of the pursuer and the evader, respectively. These conditions mean that in both control modes the pursuer is more maneuverable $(*)$ and not less agile $(**)$ than the evader. The extended optimal strategy of the hybrid pursuer in such a game consists of the optimal order of the dynamic modes, the optimal switch moment and the optimal feedback strategy. If the cost functional of the game is only the miss distance, then this optimal strategy is of the “bang–bang” type, which has the maximal capture zone. Unfortunately, the “bang–bang” strategy also yields an undesirable control chattering, which can create implementation difficulties [1,10]. In particular, it leads to an over expenditure of the control and, consequently, to an unacceptable wear of the actuators. For this reason, several studies were devoted to eliminate or at least to considerably reduce the chattering phenomenon [11–15]. One obvious candidate for chattering avoidance is the use of a linear control strategy, while respecting the maximal admissible lateral acceleration limit. In the present paper, in contrast to the classical game theoretic approach used in [5], a linear interceptor strategy is selected. Therefore, by definition, its capture zone cannot be larger than the maximal one obtained by the solution of the linear game with bounded controls. However, the advantage of this approach is that such a strategy, avoiding the inconvenient chattering, is a continuous and even smooth function of the state variables.

In the previous papers of the authors [16–20], capture zones were constructed for linear strategies in the case of players with fixed dynamics. The contribution of the present paper is to show how these results can be applied to a hybrid pursuer with two dynamic modes.

The paper is organized as follows. In the next section, the problem statement is rigorously formulated and the previously obtained results are summarized. In Section 3, the capture zone of the linear feedback control strategy is constructed and adequate numerical examples are presented. Concluding remarks are given in Section 4.

2. Problem statement and previous results

2.1. Interception problem

In this paper, an engagement between two vehicles, an interceptor (pursuer) and a target (evader), is considered. The dynamics of each vehicle is approximated by a first-order transfer

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