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Optimal guidance law design for guided munitions based on segmental linear functions

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ABSTRACT

To meet the requirements of the landing angle, miss distance, and control energy consumption, we study the optimal guidance law design for time-varying systems. In general, however, the optimal guidance law cannot be solved analytically. To solve the problem, we present a design method that combines the optimal control theory and segmental linear functions (SLFs). The optimal guidance law is designed using the proposed method. Ballistic simulations are conducted. Compared with the proportional navigation law, the optimal guidance law significantly increases the landing angle and decreases the miss distance. By averaging the time-varying coefficients of the optimal guidance law, we obtain a suboptimal guidance law. Simulations using the suboptimal guidance law are also made, and the results are compared with those of the optimal guidance law. The suboptimal guidance law is extremely simple and requires minimal onboard computational resources.

1. Introduction

A number of guided munitions require steep terminal trajectories that can increase the penetration capacity and damage effect. A steep trajectory can also increase the strike accuracy of global positioning system (GPS)-guided munitions, which have received considerable attention for their excellent features [1–5]. The GPS vertical measurement error is larger than its horizontal error [6,7]. To reduce the effect of this error on guidance accuracy, a near-vertical descent is required in the terminal guidance phase. We can describe the steep degree using the landing angle, which is the absolute value of the terminal flight-path angle. Volume and cost constraints limit the control capability of guided munitions. Therefore, minimal control energy consumption is expected during the flight of guided munitions. For the same reason, the landing angle is expected to approach but not equal 90°. Finally, for all guided munitions, the miss distance should be as small as possible.

All of these requirements can be achieved using a suitable guidance law. Previous guidance law research related to angle constraints may be largely divided into two categories: optimal [8–11] and not optimal. The latter is generally more likely to have advantages, such as simpler form, no range-to-target information requirement [12], no time-to-go estimation requirement [13], and robustness [14,15]. If we seek to optimize the combination of landing angle, miss distance, and control energy consumption, research on the optimal guidance law with multi-constraints is necessary.

To design the optimal guidance law, motion equations should be established first. These equations often include time-varying parameters. However, for time-varying systems, the optimal guidance law cannot generally be solved analytically. Therefore, time-varying parameters are not intended to appear in the guidance law design. When time-varying parameters are inevitable, two methods may be used to solve the problem. One method is substituting constants for time-varying parameters. This method is simple and employed by numerous studies. However, the simplification seriously decreases the effect of the designed guidance law. In fact, this method cannot be applied when the variation range of the time-varying parameters is large. The other method is combining the optimal control theory and numerical value method. However, this method has not been actively reported in the design of optimal guidance laws with multi-constraints.

In general, we obtain several discrete numerical values rather than the functional relationship between the control and state variables using numerical methods. Therefore, most numerical methods cannot be applied to the optimal guidance law design. In this paper, we present a design method of the optimal guidance law with multi-constraints based on segmental linear functions (SLFs) [16,17]. Compared with block pulse functions (BPFs), SLFs are slightly more complex, but they present better results [18].

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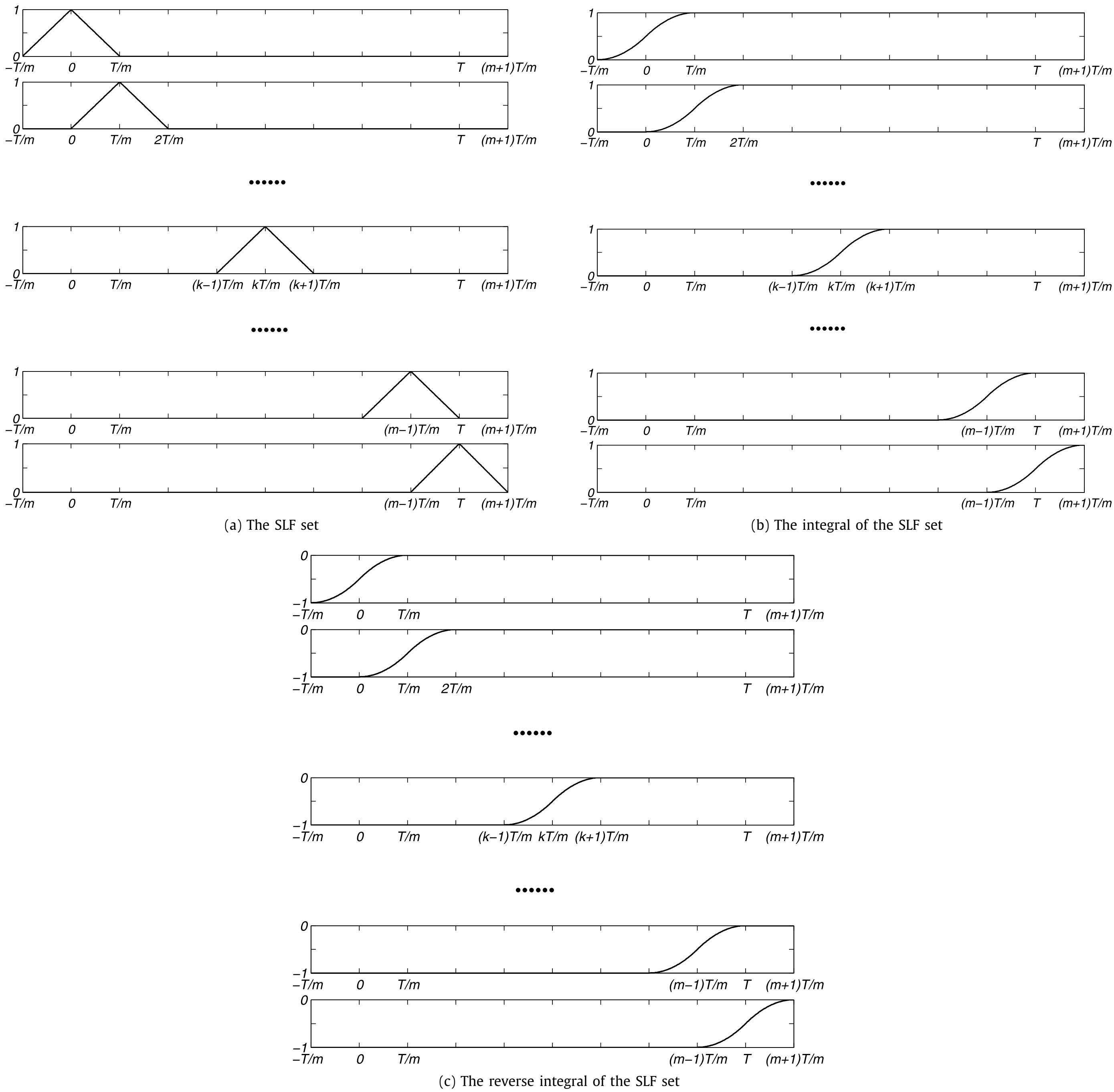

(a) The SLF set

(b) The integral of the SLF set

(c) The reverse integral of the SLF set

Fig. 1. The SLF set, its integral, and its reverse integral.

2. Definition of SLFs and their some elementary properties

A SLF set $\phi_k(t)$ $(k = 0, 1, 2, \cdots, m)$ can be defined in the interval $[0, T]$ as follows:

$$\phi_k(t) = \begin{cases} (1-k) + mt/T, & (k-1)T/m \le t \le kT/m \\ (1+k) - mt/T, & kT/m \le t \le (k+1)T/m \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Based on Fig. 1(a), the product of two SLF is presented as follows:

$$\phi_k(t)\phi_j(t) = \begin{cases} \phi_k^2(t), & k = j \\ \phi_k(t)\phi_j(t), & k = j \pm 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Therefore, the SLFs are not disjoined with each other in the interval $t \in [0, T]$. When $(k-1)T/m \le t \le kT/m$, for any $f(t)$, we have the following:

$$\sum_{k=0}^{m} f(t)\phi_k(t) = f(t)\big((1+k-1) - mt/T\big) + f(t)\big((1-k) + mt/T\big) = f(t) \tag{3}$$

An arbitrary integrable function $f(t)$ in $[0, T]$ can be expanded into the SLF series as follows:

$$f(t) \cong \sum_{k=0}^{m} f_k\phi_k(t) = \boldsymbol{\Phi}^{\mathrm{T}}(t)\boldsymbol{F} \tag{4}$$