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Designing a closed-loop guidance system to increase the accuracy of satellite-carrier boosters' landing point

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A B S T R A C T

A novel closed loop guidance method is provided in this paper to increase the accuracy of satellite-carrier boosters' landing point. The proposed method can be used in the first stage of flight vehicles that fly in atmosphere. In this case, solid motor propelled boosters would be able to more accurately land on the desired point. Moreover, in sub-optimal technique, the closed-loop guidance system would produce commands after booster separation, which guide second stage of satellite-carrier from initial conditions to the desired condition of orbit injection. In this method, sub-optimal integrated solution of control and guidance in closed-loop is developed. This sub-optimal technique named as Model Predictive Static Programming (MPSP) that is based on nonlinear optimal control theory and derived from combined philosophies of Model Predictive Control and Approximate Dynamic Programming; solves a class of finite horizon optimal control problems with terminal constraints. Furthermore because sensitivity matrices that are necessary for obtaining this solution can be computed recursively, this technique is computationally efficient and is appropriate for online implementation. In this paper, the dynamic equations of system are modeled in the presence of aerodynamic loading and the servo-mechanism dynamic. Moreover, by considering integrated guidance and control loops, a solution of the guidance and control system is proposed by three-degree of freedom spherical earth simulation model in atmosphere. Result show that proposed closed-loop guidance not only is able to remove aerodynamic and thrust modeling errors in first stage by flight data update that caused to more accurate of boosters' landing point, but also would still be able to guide second stage of satellite-carrier to the desired condition of placement in the orbit.

1. Introduction

In the first phase of the flight satellite-carrier systems, using open-loop guidance method is convenient. But when the system is outside the atmosphere and the aerodynamic loading are no longer there, implicit closed-loop algorithms are employed to guide the system towards the appropriate path. Using this guidance method, along with the use of solid motor propelled boosters, cause a large error in the predicted landing point of the first phase boosters. Although due to the simplicity of implementing the algorithm in the flight computer, these methods eliminate the need for high-speed computers in the system, they require a tremendous load of computations before the flight and in case of significant disturbances in flight time, huge control commands are produced and possibly lead to a large final error in flight path.

In this study, a closed-loop guidance method is proposed for the satellite-carrier system in order to increase the accuracy of boosters' landing point. This method is recommended to guide and control all flight stages of a satellite-carrier system, including the first stage of flight in the atmosphere, to the final stages of satellite injection in the orbit.

Using this method, flight path errors in the first stage due to environmental factors and errors in estimate of the aerodynamic coefficient and solid motor burnout time will be reduced, and after separating, solid motor boosters will be able to more accurately land on the desired point. In the subsequent phases of flight, this method is able to generate commands using the sub-optimal technique to guide the system from the initial condition after separation to the desired final condition for satellite injection in the orbit.

It is worth mentioning that common methods of trajectory optimization-based guidance, which is known as explicit guidance, using nonlinear optimal control theory, simultaneously with the optimization of a performance index, in addition to satisfying

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the terminal constraints, can also cover the constraints defined in the path. However, in the most of the applied guidance methods, optimal guidance methods are not used, due to the impossibility of solving in real time due to computational intensity [1].

On the other hand the combination of the model predictive control (MPC) [2] and approximate dynamic programming (ADP) [3] has created an innovative efficiency technique to solve finite horizon optimal control problems with terminal constraints. This method was first introduced by Padhi in 2009, was called Model Predictive Static Programming (MPSP) [4].

This method is a suboptimal designing technique which is based on non-linear optimal control theory and considering its recursive closed-loop nature, it benefits from a highly efficient computation process. Therefore, its computations can be performed through an internal computer in the system in real time. Accordingly, this method is known as a closed-loop real time solution technique in optimal control.

Innovations of this method compared to two-point boundary value problem in optimal control, is that in order to update the control history, it merely uses one static costate vector with same dimension of the state vector. In this method, there is no need for the direct computation of the costate vector and the required sensitivity matrices for updating this vector are computed recursively. Since sensitivity matrices computation is a recursive process, the computation load for updating the control history is very low and the proposed method is computationally very efficient. This allows the MPSP method to be employed in online implementation [5]. In recent years, the MPSP technique has been developed in the various applications for guiding the aerospace systems, particularly, trajectory optimization, and promising results have been published.

In the reference [6], the authors, using the inverse dynamics approach [10], solved the problem of uncertainty in the time of the final boundary conditions caused by the uncertainty of a solid motor burnout time in launch vehicle. Then, by solving this problem, MPSP method is implemented for guided the solid motor propelled launch vehicle outside the atmosphere.

MPSP method is also used in reference [7] to implement middle phase guidance. In this reference, the problem of not knowing accurately from the time of flight in the middle phase has been resolved by changing the time variable to the final position of the middle phase guidance.

The new G-MPSP method is presented in the references [8, 9]. In this method, the requirement for the discretization of the equations is eliminated, and the algorithm can implement the closed loop guidance as a continuous time. In these references, this method has been implemented for the air-to-ground system with a limitation of the angle of collision course in the three-dimensional space.

On the other hand, usually during trajectory optimization in explicit and implicit guidance methods, the dynamic effect of the control system is neglected. Though the dynamic effect of the control system is low outside the atmosphere, but during the flight through atmosphere, particularly when there are no exact calculations for the aerodynamic coefficients and in the presence of atmospheric disturbances, the dynamic effect of the control system cannot be ignored in trajectory optimization.

Therefore, in this paper, it has been tried to provide a simultaneous solution algorithm for effective dynamic equations in the flight trajectory in the presence of control system equations.

In the following, at first, the theory supporting this technique is introduced and then its implementation on motion equations for a flight vehicle system in the presence of aerodynamic loads will be discussed. Next, by adding control system equations, an integrated solution to the control and guidance system for a flight vehicle system using this technique is presented.

2. The theory behind MPSP

In this method, a discrete non-linear system is considered based on the state variables and its output dynamic equations as follows.

$$X_{k+1} = F_k(X_k, U_k) \tag{1}$$

$$Y_k = h(X_k) \tag{2}$$

In equation (1) $X \in \Re^n, U \in \Re^m, Y \in \Re^p$ and $k = 1, 2, \ldots, N$ are the time steps. It is worth mentioning that the main objective is to calculate a trend of alterations for the input control history U_k, $k = 1, 2, \ldots, N-1$, in a way that in the intended time period, the output vector Y_N reaches the desired value Y_N^* at the final time; that is, $Y_N \to Y_N^*$. Moreover, in order to realize this objective, the changes in the control command are calculated based on the minimum control effort.

In the technique proposed here, it is required to start from a proper guess history in the selected time period. In this method, in each stage of solving the equations, the error of the control command in any moment is calculated based on its value from the previous phase and it is subtracted from previous values. This process will continue until the values of the output vector in the final moment reaches the desired output values.

The mathematical details of the new MPSP technique are presented in reference [5]. According to the results of these reference, updated control variable, with the assumption that the control effort is lower, as follows.

$$U_k = U_k^0 - dU_k = U_k^0 - R_k^{-1} B_k^T A_\lambda^{-1} dY_N \tag{3}$$

Here R_k is the weight function and is positive definite matrix and A_λ is defined as follows:

$$A_\lambda \triangleq \sum_{k=1}^{N-1} B_k R_k^{-1} B_k^T \tag{4}$$

As well as we calculate the coefficient of B_k recursively. In order to do this, first, B_{N-1}^0 and B_{N-1} are defined as follows:

$$B_{N-1} = \left[\frac{\partial Y_N}{\partial X_N}\right]\left[\frac{\partial F_{N-1}}{\partial U_{N-1}}\right] \tag{5}$$

$$B_{N-1}^0 = \left[\frac{\partial Y_N}{\partial X_N}\right] \tag{6}$$

The sensitivity matrix B_k, $k = (N-2), (N-3), \ldots, 1$ are also calculated as follows:

$$B_k^0 = B_{k+1}^0\left[\frac{\partial F_{K+1}}{\partial X_{K+1}}\right] \tag{7}$$

$$B_k = B_k^0\left[\frac{\partial F_k}{\partial U_k}\right] \tag{8}$$

It is clear from (3) that the updated control history solution is a closed form solution, which is perfectly suitable for real-time calculations.

Here it's expected, only one update can be performed at a time step and the next improvement can be carried at the next time step, but since that the small error approximation has been used in deriving the closed form control update, if the non-linearity of the system is high, this approximation may not show good performance in general. Hence the process needs to be repeated in an iterative manner before one arrives at the converged solution.

It is worth mentioning that the number of discretization points, N, plays an important role in convergence and the ability of the computer to perform real time computations, i.e., if low number of discretization points is selected, the algorithm will not converge