Model Predictive Control (MPC) on Tracking Guidance and Control for High Speed Asteroid Flyby in

Daisuke Etou, Yusuke Ozawa, Seiji Yasuda and Toshio Kamiya
Space Systems Division, NEC Corporation, 1-10 Nisshin-cho, Fuchu-shi, Tokyo, 183-8501, Japan

In this paper, Model Predictive Control (MPC) for tracking guidance and control by pointing mechanism of mission camera to realize a fine pointing accuracy in DESTINY+ flyby mission is presented and demonstrated. MPC is a discrete-time multi-variable controller. At each control interval, an MPC controller uses an internal model to predict future plant behavior. An observed target direction, i.e. Phaethon direction, is calculated from the optical image captured by the mission camera and mirror angle and spacecraft attitude. Once predictive state variables are calculated from state equations, optimal control moves are calculated so as to minimize an evaluation function which is derived from the predictive state variables, weighted functions and a terminal cost function. In order to guarantee the stability, terminal cost function is applied. Comparing to the other classical control theory, advantages of the proposed method is demonstrated by numerical simulation.

Destiny+での高速フライバイにおけるモデル予測制御に基づく追尾誘導制御則

江藤大輔　小澤祐亮　保田誠司　神谷俊夫
NEC 宇宙システム事業部 183-8501 東京都府中市日新町 1-10

本論文では、DESTINY+フライバイミッションでの、ミッションカメラのポインティング機構による追尾誘導制御則として、高いポインティング精度を実現する、モデル予測制御(MPC)を紹介し、デモンストレーションを行う。MPC は、離散時間の多変数コントローラである。各制御インターバルにおいて、MPC コントローラは内部モデルを使用して、将来のプラント動作を予測する。観測量であるターゲット方向、すなわちフェートン方向は、ミッションカメラにより撮像された光学画像、ミラー角、および、探査機姿勢から算出される。状態方程式から状態変数を予測し、その予測した状態変数と、重みづけされ、終端コスト関数から算出した評価関数を最小化して、最適な制御量が計算される。安定性を保証するため、終端コスト機能を適用する。提案方法の利点を、他の古典的な制御理論と比較して、数値シミュレーションによって実証する。

1. Introduction

Now, we are developing the DESTINY+ which will be launched in 2024. DESTINY+'s mission is to flyby to the fast-moving Phaethon, take pictures of its surface and sends them to the earth. These pictures will be useful for discovering the origin of life, etc. Figure 1 shows the image of DESTINY+ during flyby to the Phaethon.

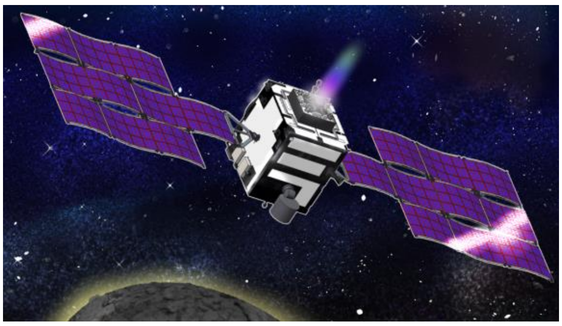

Figure 1 DESTINY+ during flyby to the Phaethon (image) (© JAXA)

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Figure 2 schematically describes the track guidance and control system of DESTINY+. Figure 2 (left) is relative position of the DESTINY+ and an asteroid position at the DESTNY+ fixed coordinate system. An asteroid passes to the B-plane with approximately constant velocity. The motor mounted on the DESTINY+ changes the Line-of-sight direction to track an image of asteroid. Figure 2 (Right) is the block diagram for tracking system. The camera takes pictures of an asteroid and sends them to the image processing system. The image processing system converts the asteroid's image to the angle of the asteroids from the center of the camera view sends it to the controller. The controller calculates motor angle along Y-axis required to track the asteroid's image using the information of attitude and orbit from bus system and drives the motor.

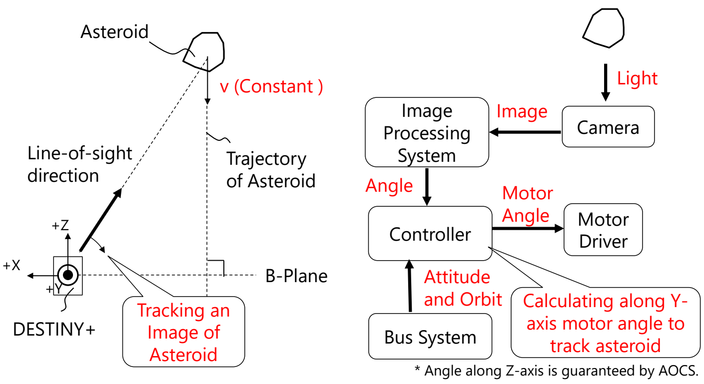

Figure 2 The track guidance and control system of DESTINY+

As a classical control system to drive such a motor, a Feedback (FB) system, a Feedforward (FF) system and a combination of FB and FF are often adopted. But both control system have some problems as the DESTINY+'s track guidance and control system. In the Feedback system, the angle toward an asteroid is sent to the controller to calculate driving angle of the motor, but the accuracy deteriorates due to the delay caused by communication time, calculation time and an image update time. In the Feedforward system, the asteroid's orbit estimated in advance is used to calculate driving angle of the motor, but the accuracy also deteriorates due to estimation error. So another control system is required for the DESTINY's track guidance and control system.

2. Model Predictive Control System (MPC)

(1) Overview

We proposed the Model Predictive Control System (MPC) for the DESTINY's track guidance and control system. The MPC has been proposed in various literatures [1]-[4]. The MPC is discrete-time multi-variable controller. The process of MPC consists of predicting future state by state equation based on the inner model and calculating control quantities by minimizing an evaluation function including the predicted future state. Because these predicting and calculating process are executed in real time, high accuracy can be expected.

On the other hand, another similar control system called Predictive Control System (PFC) has been proposed [5]. The difference between the PFC and the MPC is in the calculating process. In the PFC, control quantities are calculated by a linear polynomial function approximation including the predicted future state, so the PFC is inferior in accuracy to the MPC.

Next we will discuss the control stability. Conventional Nyquist stability is no applicable to the MPC, because the MPC is discrete-time controller. There are two methods for design of stability on discrete-time domain. One is "Lyapunof function method" the other is "Terminal cost method". "Lyapunov function method" selects Lyapunov function as an evaluation function converging over infinite time. Since "Lyapunov function method" is required to design for infinite time, it is complex design. On the other hand,

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“Terminal cost method” replaces the last weighted function Q of the evaluation function with different function P which is a solution of Riccati equation avoiding the infinite complexity. Although “Terminal cost method” is simpler than “Lyapunov function method”, the reference [1] and [4] show that both method is essentially the same.

(2) State equation for the DESTNY+

First, we will formulate state equation for the DESTNY+. Figure 3 shows Asteroid’s moving model from time k to k+1 at the DESTINY+ fixed coordinate system.

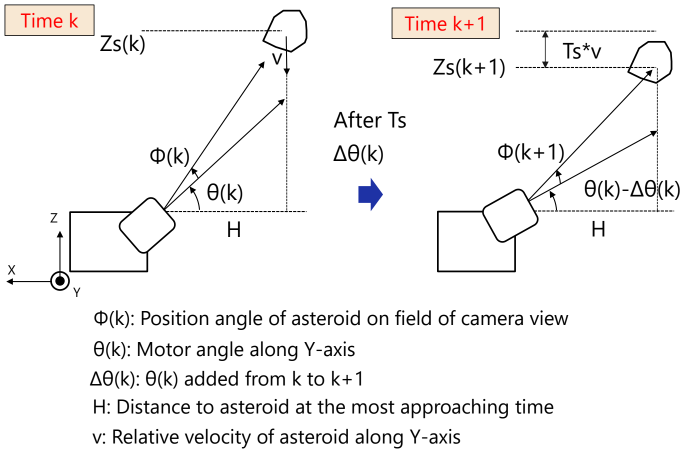

Figure 3　Asteroid’s moving model from time k to k+1 (DESTNY+ fixed coordinate system)

(Eq.1) is the state equation from k to k+1. It includes the change of angle by the asteroid’s movement from k to k+1 and the motor angle added from k to k+1.

$$\phi(k+1) + \mathrm{atan}\left(\frac{Zs(k+1)}{H}\right) = \phi(k) + \mathrm{atan}\left(\frac{Z_s(k)}{H}\right) - \Delta\theta(k) \qquad \text{(Eq.1)}$$

(Eq.2) is the linear state equation from k to k+1.

$$\varphi(\mathrm{k}+1) = \varphi(\mathrm{k}) - \Delta\theta(k) \qquad \text{(Eq.2)}$$

$$\text{where} \quad \tau(\mathrm{k}) = \mathrm{atan}\left(\frac{Zs(k)}{H}\right) \qquad \varphi(\mathrm{k}) = \phi(\mathrm{k}) + \tau(k)$$

(3) Evaluation function

Next, we will formulate the evaluation function for the DESTNY+. Figure 4 shows timeline processing for the DESTINY+. At t_0 the camera mounted on the motor gets image of an asteroid. Ts is sampling time of controller. Hw is delay time by image processing, calculation and communication. Hp is end time of control using the image of asteroid taken at t_0. The time to control using the image of asteroid taken at t_0 is from Hw to Hp.

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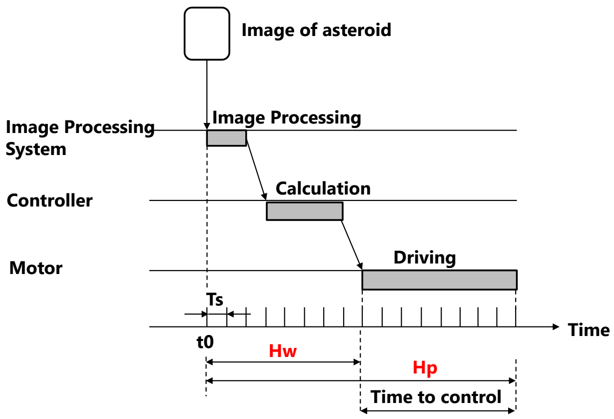

Hw: Delay by Image Processing, Calculation and Communication

Hp: End time of control using the image of asteroid taken at t0

Figure 4　Timeline Processing for DESTINY+

We will construct evaluation function with the target bringing the image of an asteroid to the center of camera view from Hw+1 to Hp. $\phi(k)$ is position angle of an asteroid on field view of camera, so the evaluation function is as (Eq.3). (Q, R) is weighted function determined by controllability.

$$\mathrm{J}(t_0) = \frac{1}{2}\left\{\sum_{i=Hw+1}^{Hp} \phi(i+t_0)Q\phi(i+t_0) + \Delta\theta(i+t_0)R\Delta\theta(i+t_0)\right\} \quad \text{(Eq.3)}$$

Using $\varphi(\mathrm{k})$ determined in (Eq.2), (Eq.3) is transferred to (Eq.4).

$$\mathrm{J}(t_0) = \frac{1}{2}\left\{\sum_{i=Hw+1}^{Hp}\{\varphi(i+t_0) - \tau(i+t_0)\}Q\{\varphi(i+t_0) - \tau(i+t_0)\}\right) + \Delta\theta(i+t_0)R\Delta\theta(i+t_0)\right\} \quad \text{(Eq.4)}$$

Next, we will introduce terminal cost for stability. We replace the last weighted function Q with different function P which is a solution of Riccati equation including Q and R. The final evaluation function is as (Eq.5).

$$\mathrm{J}(t_0) = \frac{1}{2}\left\{\sum_{i=Hw+1}^{Hp-1}\{\varphi(i+t_0) - \tau(i+t_0)\}Q\{\varphi(i+t_0) - \tau(i+t_0)\}\right) + \Delta\theta(i+t_0)R\Delta\theta(i+t_0)\right\}$$

$$+\frac{1}{2}\varphi(Hp+t_0)P\varphi(Hp+t_0) \quad \text{(Eq.5)}$$

(4) Calculation of motor angle Δθ

Last, we will calculate motor angle $\Delta\theta$ using the state equation (Eq.2) and the evaluation function (Eq.5). The calculation process is as follow.

・Substituting the state equation (Eq.2) into the evaluation function (Eq.5)

・Differentiating the evaluation function by $\Delta\theta$ to be minimized

(Eq.6) shows calculation result $\Delta\theta(k)$ (motor angle added from t_0 + Hw to t_0 + Hp)

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$$\begin{pmatrix} \Delta\theta(t_0+Hw) \\ \Delta\theta(t_0+Hw+1) \\ \cdots \\ \Delta\theta(t_0+Hp) \end{pmatrix} = -G^{-1}\cdot W \quad \text{(Eq.6)}$$

where

$$\mathrm{G} = M^T\widetilde{Q'}M + \widetilde{R'} \qquad \mathrm{W} = (\psi(t_0+Hw)L^T - \boldsymbol{T}(t_0)^T)\tilde{Q}M$$

$$M = \begin{pmatrix} -1 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot \\ -1 & -1 & -1 & -1 \end{pmatrix} \qquad \tilde{Q}' \equiv \begin{pmatrix} Q & 0 & \cdots & \cdots & 0 \\ 0 & Q & \cdots & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \cdots & P \end{pmatrix}$$

$$\tilde{R}' \equiv \begin{pmatrix} R & 0 & \cdots & \cdots & 0 \\ 0 & R & \cdots & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \cdots & 0 \end{pmatrix} \qquad L = \begin{pmatrix} 1 \\ 1 \\ \cdots \\ 1 \end{pmatrix} \qquad \mathbf{T}(t_0) = \begin{pmatrix} \tau(t_0+Hw) \\ \tau(t_0+Hw+1) \\ \cdots \\ \tau(t_0+Hp) \end{pmatrix}$$

3. Demonstration

We analyzed position angle error during flyby compared with the conventional control using a conventional control simulation tool. Table 1 shows the condition of analysis.

Table 1 The condition of analysis

Distance to asteroid on the most approaching time		510 km
Relative velocity of asteroid		35km/s
Distance Error at the most approaching time		-10km
Time Error during flyby		3s
Time	Delay by Image analysis	0.15s
	Delay by communication	0.05s
	Delay by calculation for control	0.5s
	Delay by update time-interval	1.0s (MAX)
	Sampling time (Ts)	1/32 s
	Time to control (Hw-Hp)	32 step or 160 step
Other	Random error of asteroid area's center	0.003 deg (3 σ)
	Bias error of asteroid area's center	Input shadow movement during Flyby (Referring from ITOKAWA's real data)

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Figure 5 shows the result of analysis. Figure 5(left) indicates that position angle error of MPC is much smaller than that of FB or FB+FF control. Figure 5(Right) indicate that expanding calculation range does not improve the accuracy, only to increase calculation time.

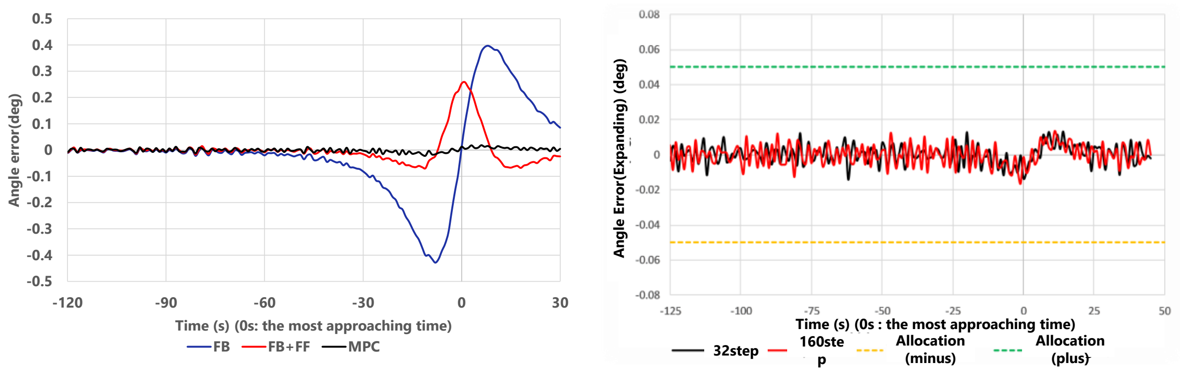

Figure 5　The results of analysis

4.　Conclusion

We propose model predictive control (MPC) for DESTINY+ flyby mission. We have formulated the MPC model according to the DESTINY+ mission and analyzed position error angle during flyby. Positon angle error during flyby of MPC is much smaller than that of conventional classical control.

[Reference]

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