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A dimensionless relative trajectory estimation algorithm for autonomous imaging of a small astronomical body in a close distance flyby

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Abstract

The world's first micro-spacecraft, "Proximate Object Close flYby with Optical Navigation" (PROCYON) has the advanced mission to approach an asteroid in dozen km (a one-order closer imaging distance compared with previous probes). In such a close distance encounter, the estimation of the relative trajectory of the target is necessary to perform autonomous imaging. However, the estimation is difficult owing to rapid changes of the line-of-sight direction of the target body. To overcome this problem, a novel dimensionless or direction only relative trajectory estimation algorithm, which uses a least square method, is proposed. The evaluation function for the least square method coincides with the error property of picture information to enable all of its calculations to be recursive and linear. It is suited for the implementation on the limited on-board computer. Numerical simulation results indicate that the proposed algorithm should enable the one-order closer flyby observation.

Keywords: Interplanetary flyby; Optical navigation; Small spacecraft

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1. Introduction

In recent years, the field of nano- and micro-satellites is one of the most flourishing areas of space engineering studies. With the success of the development and launch of the world's first 1-kg-class CubeSat in 2003, a lot of universities have begun the utilization of small satellites (Nakasuka et al., 2010). Purposes of utilization include demonstrations of advanced technologies and cheaper satellites using COTS (commercial off the shelf) components. Moreover, there are several start-up companies making small satellites for practical usage (Nakasuka, 2011). For more than ten years, small satellites have been jammed together only in low Earth orbit missions. To bring down this barrier, the 50-kg-class micro-spacecraft, "Proximate Object Close flYby with Optical Navigation" (PROCYON) was developed and launched into an interplanetary orbit. The purpose of PROCYON is to demonstrate necessary technologies for interplanetary micro-spacecraft with actual scientific missions (Funase et al., 2014). These technologies include attitude control (Ikari et al., 2015; Ito et al., 2015), temperature control (Yoshino et al., 2015), and deep-space communication (Kobayashi et al., 2015). After its launch, most of these technologies have been validated (Funase et al., 2015). PROCYON has several advanced engineering and scientific missions. One of them is a close distance flyby adjacent to a near Earth asteroid. Although the mission involves the risk of collision, high-resolution images of the asteroid could be obtained with

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Nomenclature

$\left(\frac{r}{\vert r\vert}\right)_k = (l, m, n)^T$	line-of-sight vector of the target body direction observed from the spacecraft
$\boldsymbol{\omega_k} = (\omega_x, \omega_y, \omega_z)^T$	angular velocity of the line-of-sight direction vector of the target body observed from the spacecraft
k	observation index (from 1 to N)
X, Y	pixel position on the imager coordinate (see Fig. 1)
$P(X, Y)$	luminance value of a pixel located at (X, Y)
a	height of the image
b	width of the image
dx, dy	extracted position of the target on the imager coordinate
$\boldsymbol{R}$	relative position vector of the target body with respect to the inertia frame (see Fig. 5)
$\dot{\boldsymbol{R}}$	relative velocity vector of the target body with respect to the inertia frame (see Fig. 5)
$\boldsymbol{R_0} = (x_0, 0, 0)^T$	initial relative position vector of the target body ($t = 0$) with respect to the inertia frame (see Fig. 5)
$\boldsymbol{r}$	non-dimensionalized vector of $\boldsymbol{R}$
$\dot{\boldsymbol{r}} = (\dot{x}, \dot{y}, \dot{z})^T$	non-dimensionalized vector of $\dot{\boldsymbol{R}}$
$\boldsymbol{r_0}$	non-dimensionalized vector of $\boldsymbol{R_0}$
t	time
J	evaluation function for the least square method
w_k	weighting coefficient of the least square method
θ	separation angle between the observed direction and the x axis
t (subscript)	true value
η	noise on an angle observation
α	angle between the line-of-sight vector and the relative velocity vector
h_0	non-dimensionalized closest approach distance
$+$ (superscript)	following observation
$-$ (superscript)	previous observation
POS	pixel on the sky [rad/pixel], angular resolution by a single pixel of the image
Δt	time difference between the previous observation and the following observation
$\Delta\theta$	separation angle between the previous observation and the following observation
$\boldsymbol{C}$	rotation matrix from the imager fixed coordinate to the inertia coordinate
ϕ	mirror rotation angle (see Fig. 1)
S	$\sqrt{\frac{1}{\sin^2 \alpha_t} - 1}$
$N(0, \sigma^2)$	normal distribution with mean 0 and variance σ^2
$\mathbf{A}, \mathbf{B}$	3×3 and 3×1 matrix to represent the coefficients of the simultaneous equations of the least square method
$\hat{\boldsymbol{x}} = (\hat{\dot{x}}, \hat{\dot{y}}, \hat{\dot{z}})^{\mathrm{T}}$	estimator vector
$closest$ (subscript)	value at the time of the closest approach
$\epsilon_{\dot{r}}, \epsilon_\theta, and \epsilon_{\theta,closest}$	metrics to observe the estimation accuracies (see Eqs. (28)–(30))

this close approach. The attitude control system of PROCYON is a three-axis stabilization using four reaction wheels. To capture images of the asteroid during the whole sequence from the initial phase to the proximity phase of the flyby, PROCYON is equipped with a single axis rotatable, light weight telescope (Hosonuma et al., 2013). Using a 45 deg inclined mirror, the line-of-sight direction of the telescope can be changed agilely and safely compared with the attitude maneuvering of the whole spacecraft. This concept was originally introduced for the Stardust imaging camera (Newburn et al., 2003).

The system is described in Figs. 1 and 2, and its configurations are summarized in Table 1. This telescope has another role which is to perform relative orbit determination using faint star images of the asteroid. This determination is performed for several days before the closest approach.

Referring to past examples, several in-flight flybys of small bodies such as asteroids and comets have been performed. STARDUST (Bhaskaran et al., 2004; Veverka et al., 2013), a probe of NASA performed flybys of the asteroid Annefrank in 2002, the comet 81P/Wild in 2004, and the comet Tempel 1 in 2011. The minimum distances of these flybys were over 150 km. STARDUST was equipped with a rotatable telescope to track target bodies. Deep Impact also planned the flyby of Tempel 1 with a minimum distance of about 500 km (Mastrodemos et al., 2005; Frauenholz et al., 2008), and performed tracking of its nucleus autonomously (Kubitschek et al., 2006). Deep Space1 (Buratti et al., 2014), which was also an interplanetary probe of NASA, made a flyby of the comet 19P/Borrelly at a minimum distance of about 2171 km. Chang'e-2 (Huang et al., 2013), the Chinese unmanned lunar probe, made a close flyby of a near Earth asteroid at a quite small minimum distance of about 1.6 km in 2012 and captured some images of the asteroid Toutatis (Bu et al., 2014). As Chang'e-2 did not change the line-of-sight direction of its telescope during the approach, the images in the vicinity of the closest approach were not recorded. On the contrary, PROCYON had a plan to make a close distance flyby of the asteroid and to capture the images even in the vicinity of the closest approach of the target body using the rotatable mirror. During the flyby, target pointing control should be processed on-board, since there is a significant