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Pose and motion estimation of unknown tumbling spacecraft using stereoscopic vision

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Abstract

This paper develops a method to estimate the relative pose, motion, and center of mass of an unknown tumbling target using stereoscopic vision. First, the positions and velocities of detected feature points on the spacecraft are tracked and estimated by the measurements of optical flow and photogrammetry. Random observation noises are included in the process. Second, the angular velocity and attitude of the target are estimated by the least square method and q-method, respectively. Finally, the position and velocity of the center of mass of the spacecraft are recovered based on the relative kinematics of the target by successive images over a predefined observation period. Numerical simulations are conducted to demonstrate the effectiveness and precision of the proposed method.

Keywords: Pose and motion estimation; Unknown spacecraft; Stereoscopic vision; 3D reconstruction; Least square; Q-method

1. Introduction

Relative pose (position and orientation) and motion estimation of a spacecraft (target) is one of the critical tasks in the autonomous proximity operation missions, such as spacecraft rescuing, repairing, refueling, and capturing (Stoll et al., 2009; Barnhart et al., 1998; Wang et al., 2015; Chen and Wen, 2018; Flores-Abad et al., 2014). Among these missions, most targets are considered cooperative. For instance, there are some prior knowledge about the targets' geometrical properties or fiducial markers, or there is information exchange between the target and the service spacecraft (chaser). The state of a cooperative target can be measured by differential GPS receivers (Jing et al., 2016; D'Amico et al., 2013) or a vision-based navigation system with some position-sensing diodes (Kim et al., 2007; Jia and Xin, 2013) located at known positions on the target.

However, in the mission of active debris removal, the debris (targets) are usually non-cooperative (Opromolla et al., 2017), which leads to the algorithms for cooperative targets inapplicable. To address this challenge, vision-based approaches are appealing to estimate the state of a non-cooperative target due to the advances of the passive nature of visual sensors (Zhang et al., 2010, 2015; Yu et al., 2014). Many vision-based methods have been proposed in the past with limited applications for unknown targets in space (D'Amico et al., 2014; Pesce et al., 2017; Ma et al., 2017; Segal et al., 2014; Aghili, 2012). Model matching methods were used to estimate the state of targets with known geometrical shape (Terui et al., 2006; Opromolla et al., 2015). Dehann et al. (2013) adopted the stereo vision to approximate the center of mass (CM) of the target by measuring its center of geometry. Du et al. (2011) determined the pose of a large non-cooperative

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target by two collaborative cameras. Dong and Zhu (2016a, 2016b) estimated the pose and motion of an non-cooperative target with a monocular camera, where the optical flow was used to track feature points with known configuration. Lichter and Dubowsky (2004) presented a method to estimate the state using 3D point cloud obtained from several cooperative 3D sensors. Tweddle (2013) proposed a Simultaneous Localization and Mapping (SLAM) solution to estimate the full state of a spinning non-cooperative target, which can only be implemented offline due to its high computation complexity. Segal and Gurfil (2009) approximated the CM of the target by averaging several feature points based on stereo vision and a Kalman filter was designed to improve the estimation accuracy. Biondi et al. (2017a, 2017b) proposed a method to estimate the CM of a large non-cooperative spacecraft subject to low translation and fast rotation motion using the kinematic registration method.

The motivation of this work is to develop an innovative stereo vision-based algorithm to estimate the pose, motion, and CM of an unknown tumbling target. First, the positions and velocities of the detected feature points on the target are estimated. Then, the estimates of relative pose, motion, and CM are obtained by least square (LS) method and q-method based on the measurements of consecutive image sequences. The main advantages of the newly developed method are: (i) the CM of the target and the constellation of feature points are estimated simultaneously without prior knowledge about the geometrical shape of the target; (ii) the knowledge of noise distribution is not required.

2. Observation model

As depicted in Fig. 1, assume that two cameras are identical with parallel image planes. The cameras are separated by a baseline b, which is the distance between the right camera's center of projection $\mathrm{COP_R}$ and the left camera's center of projection $\mathrm{COP_L}$. The target is in the field of view (FOV) of both cameras. Two coordinate frames are used to describe the relative pose and motion of the unknown target. The first is the target body frame $\mathcal{T}$, which is a Cartesian frame fixed to the target with its origin at the CM and coincident with the principal axes of inertia of the target. The second is the camera frame $\mathcal{C}$. It is a Cartesian frame, with its origin attached to $\mathrm{COP_R}$, with $\hat{\boldsymbol{x}}_\mathcal{C}$ and $\hat{\boldsymbol{z}}_\mathcal{C}$ axes parallel to the image plane and $\hat{\boldsymbol{y}}_\mathcal{C}$ axis pointing towards to the target. The position and attitude of the target are defined by the vector $\boldsymbol{\rho}_0$ directing from $\mathrm{COP_R}$ to the CM of the target expressed in the frame $\mathcal{C}$ and the direction cosine matrix $\boldsymbol{R}_c^t$ rotating vectors from the frame $\mathcal{C}$ to the frame $\mathcal{T}$, respectively. The corresponding translational and rotational velocities of the target are denoted as $\dot{\boldsymbol{\rho}}_0$ and $\boldsymbol{\omega}_{tc}^c$, respectively.

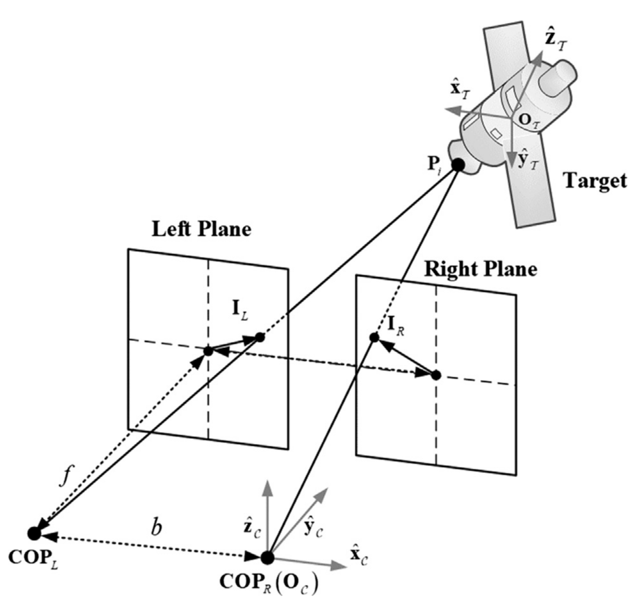

Fig. 1. Stereo vision measurement system.

Assuming a set of N feature points on the target are detected and tracked by a stereo vision measurement system. For an arbitrary point P_i, $i = 1, \ldots N$, on the target with a 3D coordinates $\boldsymbol{\rho}_i = [\rho_{ix} \quad \rho_{iy} \quad \rho_{iz}]^T$ in the frame $\mathcal{C}$, its projection on the image planes of the right and left cameras can be expressed as $\boldsymbol{I}_R = [u_{iR} \quad v_{iR}]^T$ and $\boldsymbol{I}_L = [u_{iL} \quad v_{iL}]^T$ in the image frames, respectively. Here, the image frame is a 2-D coordinate system in the image plane with its origin at the center of the image plane.

For an ideal pinhole camera model, the perspective projection transforms the feature point P_i from the 3-D space onto the 2-D image plan ($\mathbb{R}^3 \rightarrow \mathbb{R}^2$), such that

$$\boldsymbol{\eta}_i = \begin{bmatrix} u_{iR} \\ v_{iR} \\ u_{iL} \\ v_{iL} \end{bmatrix} = \begin{bmatrix} f\frac{\rho_{ix}}{\rho_{iy}} \\ f\frac{\rho_{iz}}{\rho_{iy}} \\ f\frac{\rho_{ix}+b}{\rho_{iy}} \\ f\frac{\rho_{iz}}{\rho_{iy}} \end{bmatrix} \tag{1}$$

where f is the focal length.

Define the disparity as

$$d_i \triangleq u_{iL} - u_{iR} \tag{2}$$

The position of the feature point P_i can be recovered from Eq. (1) as

$$\boldsymbol{\rho}_i = \begin{bmatrix} \rho_{ix} \\ \rho_{iy} \\ \rho_{iz} \end{bmatrix} = \begin{bmatrix} \frac{bu_{iL}}{d_i} - b \\ \frac{bf}{d_i} \\ \frac{bv_{iL}}{d_i} \end{bmatrix} = \begin{bmatrix} \frac{bu_{iR}}{d_i} \\ \frac{bf}{d_i} \\ \frac{bv_{iR}}{d_i} \end{bmatrix} \tag{3}$$

The image velocity of a feature point is defined as the time derivative of its image coordinates (Heeger and Jepson, 1992),

$$\begin{bmatrix} \dot{u}_{iR} \\ \dot{v}_{iR} \\ \dot{u}_{iL} \\ \dot{v}_{iL} \end{bmatrix} = \frac{1}{\rho_{iy}} \begin{bmatrix} f & -u_{iR} & 0 \\ 0 & -v_{iR} & f \\ f & -u_{iL} & 0 \\ 0 & -v_{iL} & f \end{bmatrix} \dot{\boldsymbol{\rho}}_i \tag{4}$$

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