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Particle filter-based relative rolling estimation algorithm for non-cooperative infrared spacecraft

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HIGHLIGHTS

- Geometric structure and motion pattern are uncertain.
- The uncertainties are assumed as random and time-varying variables.
- Particle filter matches feature point in a region to overcome the uncertainties.
- The rotation is estimated by solving a minimum error of feature point matching.

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ABSTRACT

The issue of feature point mismatching among infrared image sequence would bring big challenge to estimating the relative motion of non-cooperative spacecraft for it couldn't provide the prior knowledge about its geometric structure and motion pattern. The paper introduces particle filter to precisely match the feature points within a desired region predicted by a kinetic equation, and presents a least square estimation-based algorithm to measure the relative rolling motion of non-cooperative spacecraft. The state transition equation and the measurement update equation of non-cooperative spacecraft are represented by establishing its kinetic equations, and then the relative pose measurement is converted to the maximum posteriori probability estimation via assuming the uncertainties about geometric structure and motion pattern as random and time-varying variables. These uncertainties would be interpreted and even solved through continuously measuring the image feature points of the rotating non-cooperative infrared spacecraft. Subsequently, the feature point is matched within a predicted region among sequence infrared image using particle filter algorithm to overcome the position estimation noise caused by the uncertainties of geometric structure and motion pattern. Finally, the position parameters including rotation motion are estimated by means of solving the minimum error of feature point mismatching using least square estimate theory. Both simulated and real infrared image sequences are induced in the experiment to evaluate the performance of the relative rolling estimation, and the experimental data show that the rolling motion estimated by the proposed algorithm is more robust to the feature extraction noise and various rotation speed. Meanwhile, the relative rolling estimation error would increase dramatically with distance and rotation speed increasing.

1. Introduction

The space is crowded by various spacecraft, and their collision would damage and even destroy themselves [1]. It is becoming a crucial issue of space autonomous manipulation to repair the defective spacecraft and even remove the derelict man-made satellite called space debris [2]. Guidance, navigation, and control technologies for autonomous rendezvous and docking require accurate, real-time measurements and estimations of relative range, attitude and even geometric structure. The cooperative target spacecraft such as space station and man-made satellite could actively transmit their attitude information and geometric structure directly or indirectly to the chaser spacecraft. However, in addition to not offering its attitude information and geometric structure, the defective and derelict spacecraft slowly revolve around its axes of most inertia by various perturbation forces for it gradually lose energy. Meanwhile, the defective spacecraft usually tumbles as a rigid body without inertia moment and rotation shaft [3]. Furthermore, there aren't any artificial markers mounted on the non-

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cooperative spacecraft, and the chaser spacecraft can take advantage of nothing as reference to effectively estimate the flight attitude of target spacecraft. Hence, it is a key technology to accurately measure and estimate the relative pose of non-cooperative spacecraft in on-orbit maintenance and servicing plan.

The spacecraft's motion pattern could be usually estimated by means of extracting radar cross section (RCS) [4] and modulation spectrum [5] from high-range-resolution radar echo signal. However, it is a big challenge for radar to acquire enough details of the geometric structure to accurately estimate the rolling motion. As an essential payload of spacecraft, infrared optical vision owns such merit as non-contact, low power consumption and high efficiency, and it can acquire the geometric structure so as to improve the accuracy of relative pose estimation via high-resolution imaging even in poor condition [6]. The optical vision-based methods have been widely studied to enhance the relative pose estimation ability for cooperative or non-cooperative spacecraft. Optical flow algorithm was adopted to estimate the relative motion from monocular vision with the prior knowledge about the cooperative target [7]. As the markers of cylinder-shaped spacecrafts such as man-made satellite, the solar panel is usually used to estimate the relative pose of the spacecraft by means of its asymmetric feature [8]. With the aid of the angle of sight and azimuth gained by GPS/INS, the relative pose estimation accuracy could be further improved [9]. Moreover, the range detector such as laser rangefinder assists the monocular camera to enhance measurement accuracy of position and orientation of a rectangle target [10]. The stereo vision of cooperative or non-cooperative spacecraft is reconstructed by binocular cameras, and it can always achieve higher relative attitude precision than that of monocular camera [11,12]. Whereas, its effective range is restricted to the baseline length between the two cameras, and it would work as a monocular camera if the distance between chaser spacecraft and target spacecraft is longer than the baseline aircraft. Therefore, monocular camera-based infrared optical vision is the primary means to estimate the relative pose of a long-range spacecraft.

Generally, many feature points and feature lines extracted from the image are adopted to estimate the relative pose by solving linear or nonlinear iterative PNP problem [13]. Based on stereovision, iterated extended Kalman filter (IEKF) to estimate the relative pose and carried out some tests of tracking controls [14]. A fast orthogonal iterative algorithm estimated the relative pose through searching the minimization of the object-space collinear error [15]. Aghili and Kuryllo presented a fault tolerant method to estimate the relative pose by integrating Kalman filter to approach the iterative closest point in a closed-loop configuration [16]. A robust solution was proposed to simultaneously recover the camera pose and the three-dimensional-to-two-dimensional line correspondences [17]. The relative pose estimation could be simplified to some extent if the scale factor of the field depth is introduced into the imaging geometry mapping function. Lepetit presented a non-iterative solution to the PnP problem with higher accuracy than other iterative techniques [18]. However, these feature points and feature lines extracted from infrared image sequence are usually polluted by various noises, and their corresponding coordinates move randomly among continuous images to a certain extent. This undesirable noise often causes that the nonlinear iteration algorithm couldn't converge robustly [19].

To reduce the uncertainty derived from these polluted feature points and feature lines, this paper introduces particle filter to precisely match the feature points to improve the performance of relative rolling estimation. The relative pose measurement is converted to maximum posteriori probability estimation via assuming the uncertainties about geometric structure and motion pattern as random variables. The feature points are matched based on particle filter within a predicted region among infrared sequence image, and the rolling motion is estimated by solving the minimum error of feature point mismatching using least square estimate theory.

The remainder of the paper is organized as follows. The motion model of non-cooperative spacecraft is presented in Section 2. The uncertainty of relative pose estimation is analyzed and the particle filter-based relative pose measurement algorithm is derived in Section 3. Some experiments are included in Section 4 to evaluate the performance of the proposed algorithm. Conclusions are drawn in Section 5.

2. Motion model of non-cooperative spacecraft

The derelict spacecraft ultimately revolve around its axes of most inertia by various perturbation forces for it gradually lose energy. Furthermore, the non-cooperative spacecraft is an uncontrolled rigid body without prior information such as mass and geometric structure, and it rolls disorderly without relevant moving parameter including inertia moment and rotation shaft. Meanwhile, there aren't any artificial markers mounted on the non-cooperative spacecraft, and the chaser spacecraft can take advantage of nothing as reference to effectively estimate the flight attitude of target spacecraft.

2.1. State transition equation

The rolling motion of non-cooperative spacecraft can be decomposed into rotation motion and translation motion, and the vector $\mathbf{A}_t = [\boldsymbol{\Omega}_t\ \boldsymbol{\omega}_t\ \mathbf{p}_t\ \mathbf{v}_t]$ is adopted to describe the motion at any moment t, where $\boldsymbol{\Omega}_t = [\phi\ \theta\ \varphi]$ and $\boldsymbol{\omega}_t = [\omega_\phi\ \omega_\theta\ \omega_\varphi]$ denote the rotation Euler angle and rotation speed between spacecraft coordinate system and camera coordinate system, respectively, and $\mathbf{p}_t = [\mathbf{p}_x\ \mathbf{p}_y\ \mathbf{p}_z]$ and $\mathbf{v}_t = [v_x\ v_y\ v_z]$ represent the position and the velocity about translation motion, respectively. Therefore, the relative kinematics equation of the non-cooperative spacecraft would be described as [20]

$$\begin{cases} \frac{(\boldsymbol{\Omega}_t - \boldsymbol{\Omega}_{t-1})}{\Delta t} = \mathbf{M}(\boldsymbol{\Omega}_{t-1})\boldsymbol{\omega}_{t-1} \\ \frac{(\boldsymbol{\omega}_t - \boldsymbol{\omega}_{t-1})}{\Delta t} = \mathbf{J}^{-1}\mathbf{T} \\ \frac{(\mathbf{p}_t - \mathbf{p}_{t-1})}{\Delta t} = \mathbf{v}_{t-1} \\ \frac{(\mathbf{v}_t - \mathbf{v}_{t-1})}{\Delta t} = \mathbf{F}/m + (\mathbf{J}^{-1}\mathbf{T})^{*}\mathbf{r}_t + \boldsymbol{\omega}^{*}_{t-1}(\boldsymbol{\omega}^{*}_{t-1}\mathbf{r}_t) \end{cases} \tag{1}$$

where m and $\mathbf{J}$ denote the mass and the inertia moment of target spacecraft, respectively; $\mathbf{r}_t$ is the radius vector of the target spacecraft at moment t; $\mathbf{T}$ and $\mathbf{F}$ represent the total outside torque and the total outside force, respectively; * denotes the antisymmetric matrix, and Δt is time interval between two continuous images.

The rotation Euler angle $\mathbf{M}(\boldsymbol{\Omega}_t)$ is the transformation matrix from $\boldsymbol{\omega}_t$ to $\boldsymbol{\Omega}_t$, and it is defined as

$$\mathbf{M}(\boldsymbol{\Omega}_{t-1}) = \begin{bmatrix} 1 & \tan\theta_{t-1}\sin\phi_{t-1} & \tan\theta_{t-1}\cos\phi_{t-1} \\ 0 & \cos\phi_{t-1} & -\sin\phi_{t-1} \\ 0 & \sin\phi_{t-1}/\cos\theta_{t-1} & \cos\phi_{t-1}/\cos\theta_{t-1} \end{bmatrix}\mathbf{R}_{c\to b,t} \tag{2}$$

where $R_{c\to b,t}$ is the rotation matrix from camera coordinate system to spacecraft coordinate system.

In practice, many unknown factors of non-cooperative spacecraft couldn't be included into the relative kinematics equation, and the movement has a strong uncertainty. These factors could be classified as two categories, namely, internal factors and external factors. The mass, geometric structure, inertia moment and rotation shaft are the internal factor. The various forces acting on the spacecraft and linear acceleration are the external factors, and they are time-varying. Therefore, the relative motion of spacecraft would be uncertain term, and it could be described as random