Real-time Monocular 3D Pose Tracking for Non-cooperative Spacecraft in Close Range

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Abstract—This article presents a real-time monocular vision-based algorithm to track the 3D pose of non-cooperative spacecraft for proximity operations with the 3D boundaries and 3D contour of the spacecraft as geometric features (GF). On the offline stage, the 3D boundaries are automatically extracted from the spacecraft mesh model and represented with trigonometric polynomials. At the beginning instant of pose tracking, the tracking system is initialized by a pose retrieval method. At each subsequent instant, the initial pose is first given by the error state Kalman filter (ESKF). By means of the initial pose, the 3D contour of the spacecraft is rapidly extracted from the 3D mesh model and represented by trigonometric polynomials. Then, in the input image, the 2D edge points corresponding to the 3D GFs are detected based on conditional random field (CRF). After that, the spacecraft pose is obtained in SE(3) by minimizing the distances of the projected 3D GFs to their corresponding 2D edge points with M-estimate and Newton method. The covariance matrix of the optimized pose is estimated based on the Cartesian model in the first order. With the estimated covariance matrix, the ESKF is developed based on second-order autoregression in SE(3) to produce the final pose estimate and predicts the initial pose for the tracking at the next instant. Sufficient synthetic and real trails corroborate the accuracy and efficiency of the proposed tracking method quantitatively and qualitatively.

Index Terms—Trigonometric polynomial, 3D pose tracking, non-cooperative spacecraft, geometric feature, Kalman filter

1 Introduction

…Actually, on the surface of the spacecraft there exist many 3D boundaries of arbitrary shapes. These 3D boundaries will generate salient image edges (see Fig. 1(a)). In addition, at each viewpoint, the 3D contour of the spacecraft generates the external outline of the spacecraft in image, thus always visible and easily identified (see Fig. 1(b)). Therefore, the 3D boundaries and the 3D contour are the most remarkable GFs on the spacecraft, which are much robust to the illuminance, self-occlusion, and viewpoint change, and whose projections almost contain all the 2D geometric information of the spacecraft in image (see Fig. 1(c)). Accordingly, in this paper, we propose a vision-based framework to accurately track the 6-DOF spacecraft pose in real time using arbitrary 3D boundaries and 3D contour of the spacecraft as GFs without GPU. Basically speaking, given the 3D mesh model of the spacecraft, the 3D GFs of the spacecraft are automatically extracted from the mesh model and represented by trigonometric polynomials. Then, in the input image, the 2D edge points corresponding to the 3D GFs are detected based on conditional random field (CRF). After that, the pose is rapidly determined in SE(3) by minimizing the distances of the projected 3D GFs to their corresponding edge points with M-estimate and Newton method. The novel covariance inference of pose and SE(3)-based error state Kalman filter (ESKF) guarantee the stability of the pose tracking. Sufficient trials verify that, compared to the existing methods, the proposed method has the outstanding efficiency, accuracy, and generalization. This work is the great extension of our previous work in [4], which tackles the 3D pose tracking of asteroid with its 3D contour. However, the method in [4] is incapable of dealing with the spacecraft boundaries of arbitrary shape, and sensitive to clutter background. By comparison, the methodology proposed in this paper is entirely innovative, including (I) automatic extraction and parameterization of the GFs (arbitrary 3D boundaries and contour) given the spacecraft mesh model; (II) 2D-3D correspondence based on CRF; (III) real-time pose estimation in SE(3) based on Newton method; (IV) first-order pose covariance inference based on Cartesian noise model, and (V) ESKF based on second-order autoregression (AR) in SE(3).

The rest of this paper is organized as follows. Section 2 presents the overview of our proposed method. Section 3 introduces the coordinate systems and the pose representation. Section 4 expounds the automatic extraction and representation of the 3D boundaries and 3D contour. In section 5, the spacecraft pose is determined with M-estimation. Section 6 analyzes the covariance matrix of the pose in the first order. Section 7 presents the ESKF developed from the second-order AR in SE(3), and section 8 corroborates the effectiveness of our tracking method with adequate trials. Finally, section 9 concludes the proposed method and the future research.

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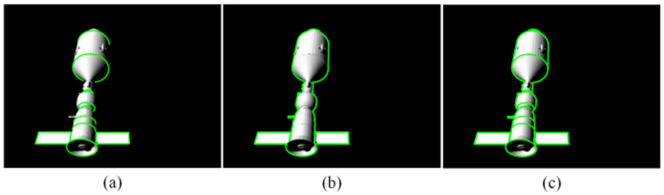

Fig. 1 Projection of 3D boundaries and contour of the spacecraft. (a) The projection of the 3D boundaries (green). (b) The projected 3D contour (green). (c) The projections of both contour and boundary.

2 Algorithm Overview

The pipeline of the pose tracking system is demonstrated in Fig. 2, where k denotes the time instant; I_k and $\boldsymbol{p}_k$ are the spacecraft image taken by a calibrated camera and the estimated pose at time instant of k respectively. Given the 3D mesh model of the spacecraft, the 3D boundaries are automatically extracted from the mesh model and represented by trigonometric polynomials in the offline phrase (the brown box). At each instant k of tracking, the tracking system is initialized by ESKF when k>0 or a pose retrieval method at k=0 (the orange box). The pose retrieval method first segment the spacecraft from the input image I_0 by the network SISnet [5], and then estimate the pose by the method in [2]. This paper is dedicated to the real-time 6-DOF pose tracking, so the pose initialization strategy exceeds the research scope of this paper. It should be noticed that there exist other methods available for the initialization at k=0 [1][2][3]. With the initial pose, the instantaneous 3D contour of the spacecraft is rapidly extracted from the spacecraft mesh model and represented by trigonometric polynomials (the red box). Subsequently, the system searches in I_k the 2D edge points corresponding to the extracted GFs (boundary and contour) by CRF, and then calculate the spacecraft pose in real time by minimizing the distances between the projections of the extracted GFs and the corresponding 2D edge points with M-estimate and Newton method (the blue box). After that, the covariance matrix of the optimized pose is calculated in the first order based on Cartesian model (the green box). Eventually, by means of this covariance matrix, the ESKF developed on second-order AR in SE(3) is performed to generate the final unbiased pose estimate $\boldsymbol{p}_k$, and give the initial pose for the next instant k+1 (the dash line box). In the following, we will clarify our tracking method according to this pipeline.

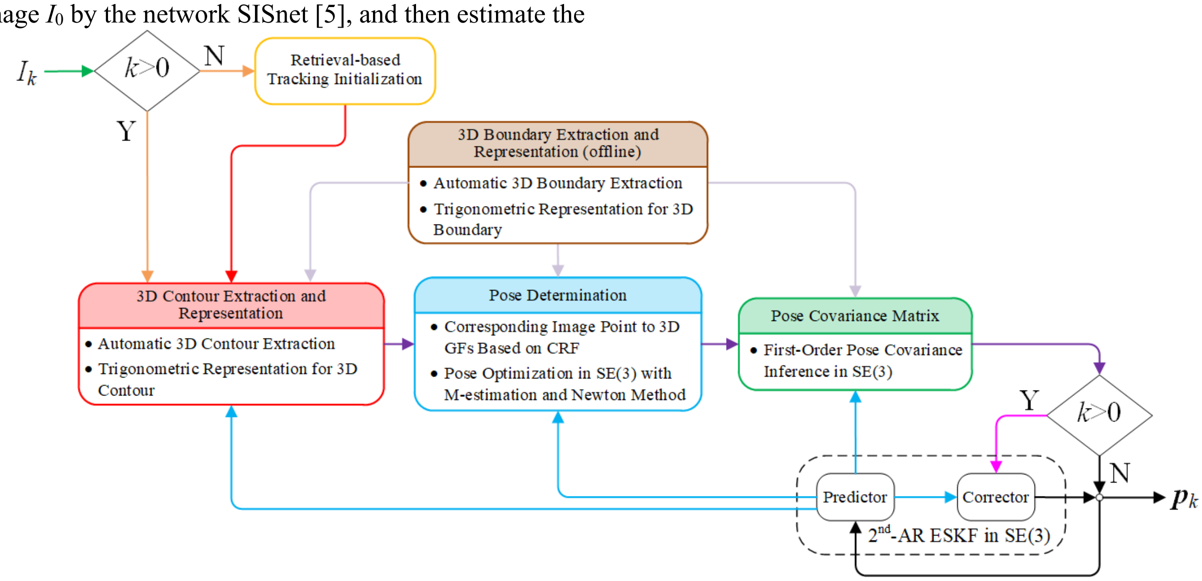

Fig. 2 Pipeline of our proposed tracking algorithm.

3 Coordinate Systems and Relative Motion

4 Extraction and Representation for 3D Boundary and Contour

4.1 3D Boundary Extraction

4.2 Redundant Boundary Elimination

4.3 Representation for 3D Boundary

4.4 3D Contour Extraction and Representation

5 Real-time Pose Determination

5.1 Data Correspondence

5.2 Pose Optimization

6 Covariance Analysis of Pose

7 Error State Kalman Filter

8 Experiments

8.1 Synthetic Trial

8.1.1 Robustness to Dark Space

8.1.2 Robustness to Cluster Background

8.1.3 Robustness to Distance

8.1.4 Robustness to Noise

8.2 Real Trial

…the magenta number at each frame is the time instant, and the GFs are projected onto the image as the red lines via the estimated pose.…Video 1 and Video 2 show the whole tracking of the two spacecrafts.

9 Conclusion and Future Work

Reference

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