Optik 125 (2014) 3127–3133

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

High accurate estimation of relative pose of cooperative space targets based on measurement of monocular vision imaging

Hui Pan [a,*], Jianyu Huang [b], Shiyin Qin [a]

[a] *School of Automation Science and Electrical Engineering Beihang University, Beijing 100191, China*
[b] *Beijing Institute of Tracking and Telecommunications Technology, Beijing 100094, China*

ARTICLE INFO

Article history:
Received 22 June 2013
Accepted 15 December 2013

Keywords:
Autonomous rendezvous and docking (ARD)
Estimation of relative pose
Cooperative space targets
Multiple targets tracking
Monocular vision imaging

ABSTRACT

Autonomous rendezvous and docking (ARD) plays a very important role in planned space programs, the success of ARD rests with the estimation accuracy and efficiency of relative pose among various spacecraft in rendezvous and docking. In this paper, a high accuracy and efficiency estimation algorithm of relative pose of cooperative space targets is presented based on monocular vision imaging, in which a modified gravity model approach and multiple targets tracking methods are employed to improve the accuracy of feature extraction and enhance the estimation efficiency, meanwhile the Levenberg–Marquardt method (LMM) is used to achieve a well global convergence. Moreover an experimental platform with DSP and FPGA is designed and implemented. The comprehensive experimental results demonstrate its outstanding accuracy and efficiency, the update rate achieves 16 Hz and the estimated error of depth does not exceed 2% with noise influence.

1. Introduction

Autonomous rendezvous and docking is necessary for planned space programs such as DARPA ASTRO, NASA MSR, ISS assembly and servicing, and other rendezvous and proximity operations [1]. Nowadays, RVD maneuvers in space have been performed for many years already (the first one performed by Neil Armstrong and Dave Scott manually in 1966). The ability of providing high accurate and reliable relative navigation information in real time is a key enabling technology for autonomous operations between moving platforms in close proximity [2]. As a hot topic of research and development in advanced space technology, autonomous rendezvous and docking without human interference are fully concerned. According to historical statistics, human have accomplished RVD for more than 300 times. Generally speaking, the procedure of rendezvous and docking involves two phases: the long-range and the near-range. Active sensors such as laser scanning and radars are always used in the long-range phase because they can measure the relative position up to several kilometers. For the second phase, cameras coupled with advanced algorithms become the most suitable solution to pose estimation because of its merits of non-contact, low power consumption, high accuracy and efficiency. In order to estimate the relative pose accurately, many research work have been carried out by many institutes and scholars.

Philip and Ananthasayanam presented a scheme for onboard relative position and attitude estimation and control for the final translational phase of an autonomous space rendezvous and docking system [3]. In their paper, they described a scheme of relative position control based on phase-plane control technique and relative attitude control based on relative quaternion feedback and obtained good results. Lepetit introduced a non-iterative solution to the P*n*P problem [4], which is superior in its rapidity and accuracy to the other iterative techniques. Lu regarded the relative position and attitude estimation as a minimization of the object-space collinear error and proposed a fast orthogonal iterative (OI) algorithm with good global convergence [5]. The algorithm is characterized with good convergence and usually converges in five to ten iterative steps from very general geometrical configurations. Thienel et al. devised a non-linear method to estimate the pose of spacecraft and carried out some tests of tracking controls, but its disadvantage lies in that much prior knowledge is necessary [6]. Khansari Zadeh proposed a new algorithm of estimation and navigation with vision information based on neural networks, and its performance of accuracy and robustness were validated through a complete virtual environment based on the six degrees of freedom (6-DOF) nonlinear aircraft dynamical system in an autonomous aerial refueling (AAR) mission [7,8]. Aghili and Kuryllo presented a fault-tolerant estimation method for the pose of space objects using 3-D vision data by integrating Kalman filter (KF) with an algorithm of iterative closest point (ICP) in a closed-loop configuration [9], in which the Euler–Hill equations are employed to derive a discrete-time model so as to open out the

* Corresponding author. Tel.: +86 18810924719; fax: +86 010 82314331.
E-mail address: panhui-17@163.com (H. Pan).

0030-4026/$ – see front matter © 2014 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.12.020

evolution process of the relative translational motion of a tumbling target satellite with respect to a chaser satellite. Daero Lee, Henry Pernicka presented a new approach to spacecraft relative attitude estimation and navigation based on the unscented Kalman filter which was implemented and evaluated for rendezvous and proximity operations. Simulation results showed that the unscented Kalman filter is more robust than the extended Kalman filter under realistic initial attitude and navigation conditions and also the relative navigation results were validated by the High Precision Orbit Propagator (HPOP) of Satellite Tool Kit [10]. Zhang and Zhang presented a robust solution to simultaneously recover the camera pose and the three-dimensional-to-two-dimensional line correspondences. With weak pose priors, their approach progressively verifies the pose guesses with a Kalman filter [11]. Taghirad and Atashzar analysed the stability of the EKF-based 3D pose estimators in detail and proposed a composite technique to guarantee the stability [12]. The absolute orientation problem can be solved in closed form using singular value decomposition (SVD), however, the computation expense of SVD is enormous, and it slows down the algorithms. In order to improve computation speed to satisfy the increasing require of real-time missions, Long and Zongquan proposed a new absolute orientation method inspired by the FOAM method in Wahba problem to replace SVD computation. Using this new method they proposed an iterative algorithm to solve the pose estimation problem with high accuracy, noise-resistance and speed [13]. Zhang and Han proposed a method to recovering the 3D positions of a known target and an amended method for error correction based on the line fitting [14].

According to our experiments, we found that the primary factors that affect the estimate accuracy lie in the accuracy of feature points localization and the estimate algorithm. In order to improve the estimation accuracy, a modified Gaussian weighting gravity model approach is adopted. Moreover, in order to improve the robustness, the efficiency LM (Levenberg–Marquardt) iterative estimation algorithm is used in the scheme. On the other hand, the multiple targets tracking method is employed to decrease computing time. In addition, a simple and effective method is utilized to match feature points.

The paper is organized as follows: in Section 2, performance requirement and challengeable issues of ARD are stated. In Section 3, a series of related algorithms are presented here. The experiment results and discussion are presented in Sections 4 and 5, respectively.

2. Performance requirement and challengeable issues

Autonomous rendezvous and docking (ARD) without interference of human is a complex and dangerous mission. The platform should capture good images of the targets successfully and estimate the relative pose accurately in real time. Any mistake, for example, failure of capturing images or the algorithm cannot exact feature points precisely may result in failure even disaster. So, a good scheme should be characterized with accuracy, efficiency and robustness. On this account, a dedicated reliable onboard system and high efficient estimating algorithm is presented in this paper.

Firstly, what is most important for the hardware platform is reliability, accidents should be avoided as far as possible during ARD. Power off and failure of capturing images are most likely to happen, so backups are necessary. Given this consideration, a dedicated parallel platform is designed with two DSPs and two FPGAs. A testbed is idle when the other one works well and it will play its role when the other is abnormal. For both of them, DSPs take charge of computation and FPGAs are in charge of capturing images, respectively, the sketch map of hardware platform is shown in Fig. 1. The choice depends on several factors including sampling frequency, computational requirements, parallelism of implementing algorithm, programmability, low power consumption and maintenance costs [15,16]. TMS320DM642GDKA720 is a fixed-point 600 MHz clocked processor is capable of providing up to 4800 million instructions per second. The central processing unit (CPU) fetches very-long instruction words (256 bits wide) to supply up to eight 32-bit instructions to the eight functional units during every clock cycle. The CPU features two sets of functional units. Each set contains four units and 32 32-bit registers [17]. DM642 has three video ports (VP0, VP1 and VP2) which make it appropriate solution for video application. FPGA EP2C20Q240C8 manufactured by Altera was chosen as another CPU to take charge of capturing images.

Secondly, the algorithm must be capable of estimating relative pose accurately with high efficiency. The whole procedure can be partitioned into four sections: image acquisition, feature points localization, matching and estimation. According to experiments, the first two parts consume most of the time consumption. The initial scheme is a serial procedure that every part is executed in turn and then go to the next round. Obviously, the time consumed is the sum of every part. In this scheme, DSP is idle during image acquisition. Given the character of the platform and the separability of the algorithm, the parallel scheme is a better choice, which means that after completing one image acquisition, FPGA launches the next round immediately and meanwhile DSP executes the left computation procedures, the sketch map is shown in Fig. 2. This parallel scheme makes full use of the platform and the total time consumed decreases from 98 ms to 63 ms.

3. Implementing algorithms and integrative optimizing result

3.1. High precision locating algorithm

Ameliorating the precision of localization plays a key role in improving estimation. Given the shape of flares, gravity model approach is a good choice, some other approaches can also be applied, for example, Edleblute and Agili adopted least-square ellipse fitting method to find the exact location of the centroids [18]. In their research, they captured two images with LEDs turning on and off respectively, then subtracted the second image from the first one, thus resulting with the LEDs and some weak background noise, then used least-square ellipse fitting method to locate the centroids of the spots. However, this method needs the camera and target to keep relative static during the two images acquisition, which is unpractical for ARD.

As mentioned in literature [18], image can be conceived as the superposition of targets and background>better locating precision can be obtained when subtracts the background, therefore, a modified Gaussian weighting gravity model approach with threshold is presented here. The centroid coordinate extracted with the modified approach is shown below

$$\begin{cases} x_c = \dfrac{\sum_{x=1}^{n}\sum_{y=1}^{m} I(x,y)x}{\sum_{x=1}^{n}\sum_{y=1}^{m} I(x,y)} \\ y_c = \dfrac{\sum_{x=1}^{n}\sum_{y=1}^{m} I(x,y)y}{\sum_{x=1}^{n}\sum_{y=1}^{m} I(x,y)} \end{cases} \quad (1)$$