A FRAMEWORK OF RELATIVE NAVIGATION SYSTEM FOR NON-COOPERATIVE TARGET USING DUAL-CCD

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ABSTRACT:

The relative navigation of space non-cooperative target has great important practical value and vast prospect in application. The space non-cooperative target refer to some space flight objects which cannot provide effective cooperative information, which includes fault or disabled satellite, space debris, hostile spacecraft and so on. A set of stable and reliable relative navigation system is indispensable when real-time observing or monitoring the space non-cooperative target by steady and dependable tracking flight. Different from the relative navigation for cooperative target, non-cooperative target cannot provide any cooperative information so that traditional surveying method using single CCD and optical feature points cannot be used. Based on the theories in Astrodynamics and Photogrammetry, a prototype framework of relative navigation system using dual-CCD is advanced in the paper, which includes the following parts: analysis and design for relative spacecraft orbit, quick image matching based on features, 3D reconstruction and registration for non-cooperative target, real-time relative navigation solution and a test platform of numerical simulation.

1. INTRODUCTION

With the development of probing, exploiting and using outer space, space autonomous on-orbit service has gradually been a problem which needs to be solved urgently at present. The space non-cooperative target refer to some space flight objects which cannot provide effective cooperative information, which includes fault or disabled satellite, space debris, hostile spacecraft and so on. A set of stable and reliable relative navigation system is indispensable when real-time observing or monitoring the space non-cooperative target by steady and dependable tracking flight. That is to say, the relative location and attitude between non-cooperative target and the tracking spacecraft can be surveyed precisely. Especially at the final approximation stage of a task, the precision is the decisive factor to the success of the task.

Different from the relative navigation and rendezvous for cooperative target, non-cooperative target has no target identifiers (such as optical feature points) and proximity sensors, so the relative navigation for non-cooperative target is especially difficult and the traditional surveying method using single CCD cannot provide any reliable and precise relative navigation parameters. However, the problem will be solved effectively if using dual-CCD. Moreover, in the future, mini-space mobile platform need autonomous relative navigation system based on dual-CCD. The platform has rigorous limit in the volumes, weights and consumptions of relative navigation equipments because of its minitype, so some relative navigation sensors, such as microwave radar, rendezvous LIDAR, will be confined to use but dual-CCD and relevant equipments can meet the need.

The relative navigation surveying for space targets meets the need of spacecraft rendezvous and docking. On-orbit spacecraft rendezvous and docking have been practiced about 200 times in U.S.A and U.S.S.R. (Russia) since the 1960s. Usually, autonomous rendezvous and docking can select different surveying sensors according to different stages and different navigation information. On the final proximity stage, optical imaging sensor is generally as the main navigation sensor at present because it can provide relative location, relative attitude, relative velocity, relative angular velocity and other navigation information which meet the need of the guidance, navigation and control systems. Currently, there are mainly five optical imaging sensors which can be used into autonomous rendezvous and docking: Advanced Video Guidance Sensors made in U.S.A, Proximity Camera Sensors in Japan, Videometer in ESA, Optical Electronic System in Russia and CCD optical imaging sensors in China [1-3].

The above methods are used in the relative navigation for cooperative target. In U.S.A., the relevant researches on relative navigation for non-cooperative target have been carried out for a long time. As a representative achievement, XSS satellite series are jointly developed by Air Force Research Laboratory, Air Force Space and Missile System Centre, Navy Research Laboratory and other organizations [4]. The target of the research is to develop a kind of autonomous micro-satellite which can fulfil on-orbit checking, rendezvous and docking and revolving round objects on orbit. Two micro-satellites are projected in XSS satellite series which are XSS-10 and XSS-11. In two satellites, a set of 3D image surveying system, Visual Camera System, is equipped which uses dual-CCD to accomplish autonomous relative navigation surveying. However, relevant detailed materials about the project are

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difficult to obtain in public because of its great military and political significance. Also, Escort Micro-Satellite, presented by American AeroAstro Company, owns the function of on-orbit checking and proximity except XSS series. In China, many experts have researched the motion analysis and controlling for non-cooperative target toward the relative orbit deeply, but the researches about the relative navigation surveying are very few [5-11]. Based on single CCD optical camera, Zhang el al. realized the iterative algorithm on the relative location and attitude parameters surveying for non-cooperative spacecraft according to known structure model information of target spacecraft, which affords the paper a salutary lesson [12] .

2. FRAMEWORK OF THE RELATIVE NAVIGATION SYSTEM

Different from the relative navigation system for cooperative target, the motion rules of the relative orbit between the non-cooperative target (called "target" for short at the following section) and tracking spacecraft must be considered in the relative navigation system for the target. And the entity model for the target can be simplified as the feature point model which can be observed by way of digital image processing utilizing the structure characters of the target. Then the task of the relative navigation will be realized using digital photogrammetry method based on "point surveying", which includes the determination for the relative location, attitude, velocity and angular velocity between the target spacecraft and the tracing spacecraft.

2.1 Analysis and Design of the Relative Orbit

Because of the randomicity of the target spacecraft's orbit, the relative motion features between the tracking spacecraft and the target can be only analyzed in a general way to obtain a relative motion equation based on general elliptical motion and solve the analytic expression of the equation owning arbitrary initial condition, which will provide theoretical basis for researching relative motion features and designing motion construction. And the relative orbit where the tracking spacecraft follows the track of the target will be analyzed and designed under integrating different constraints which include the orientation for the tracking spacecraft toward the earth and the observation scope of the satellite-borne CCD. Then the motion orbit of the tracking spacecraft will be designed based on the deep analysis of the relative motion equation to realize the tracking survey, which can provide some priori parameters and initial values for relative navigation.

Because the target orbit is an approaching circular orbit, the relative orbit motion at the proximity stage can be described by the C-W Equation which is also called as the Hill Equation [13]:

$$\left.\begin{array}{c} \ddot{x}-2\omega\dot{y}=0 \\ \ddot{y}+2\omega\dot{x}-3\omega^2 y=0 \\ \ddot{z}+\omega^2 z=0 \end{array}\right\} \tag{1}$$

where ω is the true anomaly of the target spacecraft in the equation.

If the target orbit is an elliptical orbit, the relative orbit motion will be describe by the T-H Equation [14]:

$$\left.\begin{array}{c} \ddot{x}-\left(\dot{\theta}^2+\dfrac{2\dot{\theta}^2}{1+e\cos\theta}\right)x-\ddot{\theta}y-2\dot{\theta}^2\dot{y}=0 \\ \ddot{y}+\ddot{\theta}x+2\dot{\theta}\dot{x}-\left(\dot{\theta}^2-\dfrac{\dot{\theta}^2}{1+e\cos\theta}\right)y=0 \\ \ddot{z}+\dfrac{\dot{\theta}^2}{1+e\cos\theta}z=0 \end{array}\right\} \tag{2}$$

where θ is the true anomaly of the tracking spacecraft in the equation.

According to the C-W Equation and T-H Equation, the constructions of the relative orbit will be discussed and the CCD's tracking angles, scopes and the resolution constraints of the relative navigation at every construction will be analyzed too. The process is shown in Figure 1.

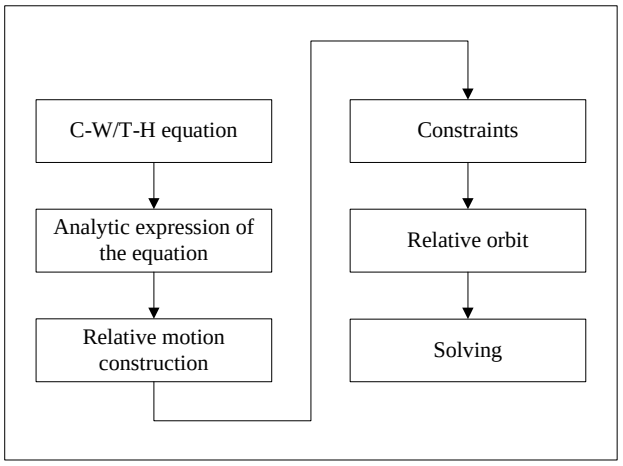

Figure 1. Analysis and design of the relative orbit

2.2 Quick Image Matching Base on Features

The image matching of spatial target will meet a greater challenge in comparison with traditional remote sensing image matching. These reasons are: 1) the speed of image matching need be raised in order to ensure the response frequency of relative navigation system. Because traditional image matching algorithm is rather time-consuming, a new matching mechanism will be adopted which will utilize the interior relevant features of sequence images fully in this paper to make the matching rate as fast as possible on the premise of keeping the matching accuracy; 2) the image of spatial target has obvious difference with geo-image of remote sensing. Under the limit of sensor's view-field and lens's field-depth, the target image will be relatively small and the textures will be rather unitary when the tracking distance is quite far. Moreover, the target background will be rather complex under the influence of space background and other space environments so as to cause a lot of trouble to the image matching. Therefore, some effective pre-processing methods need be used in order to remove pseudo image and background noise and extract useful and reliable target information to match. The process is shown in Figure 2.

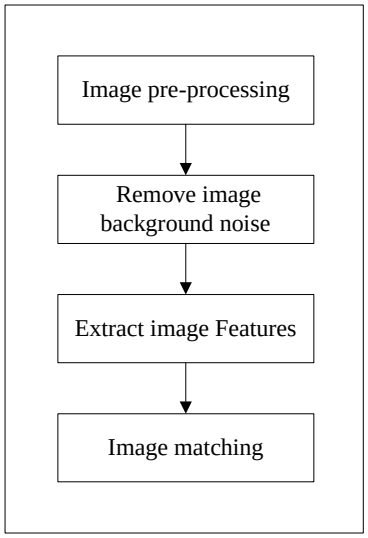

Figure 2. The process of quick image matching

2.3 3D Reconstruction and Registration for Non-cooperative Target

Image matching only can provide discrete and non-structured 3D target information. However, for the determination of relative navigation parameters and motion rules of non-cooperative target, 3D metric geometric model must be built to locate precisely the target centroid and shape. Constructive Solid Geometry (CSG) model is conveniently used to describe artificial spatial target because the artificial target has relatively regular appearance and shape. CSG uses some basic geometric entities, such as cube, cylinder and cone, to construct complex 3D entities according to some proper positive Boolean operations. Basic geometric entities can be transformed from basic condition to combined condition by way of some transformations, such as translation, rotation and scaling, and can be used to construct intermediate entities by means of some positive Boolean operations, such as intersection, union and difference. Then the intermediate entities are as basic entities to combine at a more high degree. 3D objects can be described as a CSG tree, also called as binary tree, in which basic geometric entities and its transformation parameters are leaf nodes and positive Boolean operations and transformation operations are other nodes. Basic geometric entities in CSG are mainly regular geometric entities which can be represented easily because of more simple data structure. And the model can be edited by mathematic operations such as adding, changing, modifying and deleting leaf nodes and intermediate entities to alter 3D objects conveniently. In addition, CSG can describe geometric shapes of objects precisely and strictly and construct a clearer mathematic model to query, add and delete shape data structure easily and expediently.

If 3D geometric model of non-cooperative target is known, the 3D data field must be matched with the known model to locate the target centroid and principal axis and construct quickly the body coordinate system of the tracked spacecraft. But if it is unknown, the whole 3D model of the target will be built based on long-time tracking and observing. The process is shown in Figure 3.

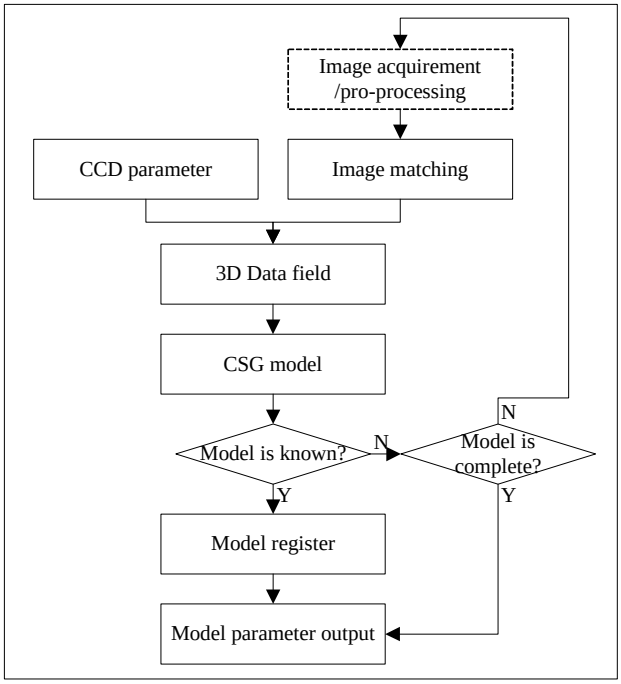

Figure 3. 3D Reconstruction and Registration for Non-cooperative Target

2.4 Real-time Solution for Relative Navigation

The relative navigation parameters between targets, such as relative location, relative attitude, can be obtained by CSG model of non-cooperative target, and then the relative velocity and angular velocity can also be acquired using time relation of sequence images. In the algorithm, the above process is integrated closely into image matching and 3D reconstructing and the combined adjustment algorithm will be adopted to solve jointly the parameters for image matching, 3D reconstruction and navigation and at the same time Extended Kalman Filtering is used to realize real-time relative navigation.

In the resolution process, the key to the problem is to describe the rotation relation between two coordinate systems effectively and reliably. There are many parameters to describe the rotation relation in mathematics, which include Euler-angle, Gibbs vector, Cayley-Klein parameters, Paul spin matrices, orthogonal rotation matrix, the coordinate axes and angles, orthogonal matrix, Hamilton quaternions and others. In Photogrammetry, Euler-angle and orthogonal rotation matrix are commonly used but the latter cannot be used widely because it needs six constraints. The primary researches present the quaternions have clear superiority in resolution. They have an efficient algorithm because it does not execute the operation of trigonometric functions and they are calculated easily because they need only a constraint. And they can describe the rotation axis and the rotation angle directly because they have obvious geometric sense. At the same time, the quaternions are not singular and they are steady to describe the transformation between two coordinate systems. Therefore, the quaternions and dual-quaternions can be adopted to describe relevant transformation relation between the coordinate systems entirely [15-16].

3. EXPERIMENT PROPOSAL

Numerical simulation is as the test program to test the soundness, reliability and stability of the algorithm. If the condition ripens, the simulation for the semi-entities will be designed and tested.

3.1 Numerical Simulation

The simulation of numerical simulation, which is composed of mathematic models, simulation software and computers to complete relevant computer simulation and graphic and image simulation, researches the real system only by way of building the mathematic model of the system and needn't any parts of real system. Building mathematic model and developing professional simulation module are the keys to the program, such as simulation generating and processing of CCD image symbols, astrodynamics and orbit model of relative motion between the target and the tracking spacecraft, resolution for relative navigation and so on.

Based on Matlab/Simulink, which have high efficiency and great advantage in modeling in comparison with other general developing programs, the test platform of numerical simulation provides not only linear system modeling but also non-linear system modeling. In addition, the platform is a open simulation system which can be used to develop special simulation modules in order to realize special simulation tasks. The constitution of the platform is shown in Figure 4.

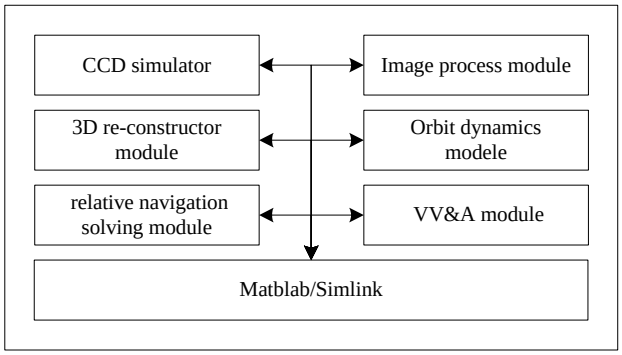

Figure 4. The constitution of the numerical simulation test platform of relative navigation system

3.2 Hard-in-loop Simulation

After the above numerical simulation, only the test for real system can further judge whether the functions and capabilities meet the design demands, in which hard-in-loop simulation is the best method. In the hard-in-loop simulation, non-cooperative target is equipped in a platform owning 6 degrees of freedom, whose motion follows the pre-planned relative orbit and attitude-dynamics model designed by computers. Dual-CCD are controlled by the professional image-collection board and high-performance DSP module computer to complete the relevant image acquisition, target recognition, feature extraction, image matching and so on. Finally, all data will be conveyed in the master-control DSP module computer to realize the solution of relative navigation. The following hardware modules for simulation are indispensable: 6-DOF platform, CCD, parallel-image-collection board, DSP developing board, also called as module computer, D/A and A/D interfaces. The platform structure is shown in Figure 5.

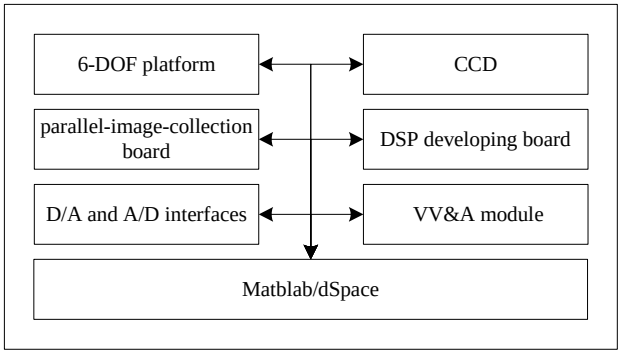

Figure 5. The constitution of the semi-entity simulation platform of relative navigation system

4. CONCLUSION

Relative navigation for space non-cooperative target has important practical value and wide practical prospect. Based on the relevant theories and methods in Digital Photogrammetry and Astrodynamics, the framework of relative navigation system rebuilds 3D geometric model of the target by way of the image matching algorithm based on features and the CSG method under analyzing the relative motion rules between space targets and researching the preprocessing methods for 3D sequence images of space targets deeply. And then the real-time solution for relative navigation is carried out by means of the photogrammetric location theory and Extended Kalman Filtering. Finally, the soundness, reliability and stability of the theory and algorithm for the relative navigation are tested by numerical and semi-entity simulation methods entirely.

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