Pose measurement and ground validation Based on lidar in-orbit

TingTing Lin\textsuperscript{1,a}, Ronghua Li\textsuperscript{2,a,h}, Youqing Yang\textsuperscript{3,h}, Heng Li\textsuperscript{4,a}

\textsuperscript{a}Dept. Mechanical Engineering, Dalian Jiaotong University, Dalian 116028, China
\textsuperscript{b}Shanghai Institute of Aerospace Systems, Shanghai 201109, China

1 E-mail: tingtingwin@163.com \textsuperscript{2}E-mail: lironghua705@163.com \textsuperscript{3}E-mail: 1169360115@qq.com \textsuperscript{4}E-mail: 1308083136@qq.com

Abstract: An effective ground validation method is proposed to solve the difficult problem of non-cooperative target position measurement in-orbit verification. First of all, this paper highlights the effectiveness of a light fuzzy target point cloud model visible part judgment method to search. Secondly, laser reflection intensity is used to realize the point cloud registration process, not only the influencing factors of the space radiation source to the image, but also the incident angle imaging quantitative analysis. Finally, points cloud precise registration is achieved according to the iterative algorithm. This method realizes the ground verification work of the robustness, real-time performance of the position, attitude measurement algorithm, and shortens the study cycle of the future on-orbit control task.

1. Introduction

The research on space in orbit is a process of huge investment and a long return cycle. The non-cooperative target position measurement based on laser radar, as the key link of space orbit manipulation technology, has been highly valued by the related fields in various countries\textsuperscript{11}.

Volpe Renato\textsuperscript{2} deals with on-orbit relative pose and shape estimation with the use of a monocular camera and a distance sensor. Pan Wang \textsuperscript{3} a method based on multi-sensor to measure the pose of a 3D (three-dimensional) object is proposed. Huang Jianming of Shanghai Aerospace Engineering Research Institute judged the visibility of face nodes by area method. Because the area method was built through the finite element system, the model surface formed by the four corners was inconsistent with the real target model\textsuperscript{4}. T. Zhang \textsuperscript{5} A radar spatial registration method is proposed to overcome the problem of bias registration with uncorrelated multiple targets. Holz D\textsuperscript{6} search for matching points based on various local shape feature descriptors, and provide initial values for the iterative neighbor registration algorithm; The traditional ICP algorithm needs better initial value and low efficiency\textsuperscript{7,8}. A point cloud automatic registration method based on laser reflection intensity is proposed in this paper, to realize the initial registration of ICP accurately\textsuperscript{9}.

This paper highlights the effectiveness of light fuzzy target point cloud model visible part judgment method to search; secondly, using laser reflection intensity to realize point cloud registration process, not only analyzes the influencing factors of the space radiation source to image, but also to the incident angle imaging quantitative analysis; finally, according to the iterative algorithm to achieve near point cloud precise registration and give ground test examples. This method realizes the first ground verification work of the robustness and real-time performance.
2. The judgment of point cloud visibility

According to the model point cloud density setting threshold, the points around the same ray direction are classified into one class, and the point with the smallest mode is selected as the reference point in the class; Comparing again the direction of the vector formed by the points in the same class and the reference point with the directivity of the vector formed by the reference point and the viewpoint; Finally, remove the blind point near the vector direction.

2.1 Fuzzy search based on light

As shown in Figure 1, if the light is extended along the direction of propagation, all target points on the line except the nearest point are not measurable and should be removed. However, because the target cloud is usually a discrete point cloud, there is no strict two-point in the same line when the ray propagation path is simulated. The light fuzzy search method is used to appropriately relax the conditions that satisfy the point in the same light to resolve this problem.

2.2 Delete non-measurable point cloud

As shown in Figure 2, First of all, the nearest point of the internal range radar coordinate system is obtained in the last step to use as a benchmark. Secondly, the benchmark constitutes a vector with all the other points in the class and contrasts with the reference point vector. Finally, the invisible points can be removed, and the same point of the face can be retained as a base point in the next class.

3. Point cloud coarse registration

First, the local point cloud in the overlap area of the point cloud is determined by using the nearest point of the horizontal line of sight and its certain range. Secondly, using the orthographic projection method of point cloud projection onto a plane and generate laser reflection intensity image, and then
use the SIFT algorithm for image matching.

In this paper, the noise equivalent power model is presented for the influence of speckle effect and receiver noise in lidar imaging quality.

\[ P_{r,speck} = P_{r} + N(0, E_t^2) \]  
\[ E_t = \frac{4KB}{R_L\Psi_i} \]  
\[ S_r = \text{intensity of speckle noise}; \quad P_r = \text{echo power in an ideal state.} \]  
\[ f(S_r) = \left[ \frac{M^W}{S_r} S_r e^{-\frac{M^W}{S_r}} \right]^{I(M)} \]  
\[ k = \text{Boltzmann constant}; \quad T = \text{absolute temperature}; \quad B = \text{receiver bandwidth}; \quad N = \text{noise factor}; \quad R_L = \text{load resistance}; \quad \Psi_i = \text{for the current response of the detector.} \]

3.1. Automatic registration based on laser reflection intensity

According to the position of measurement angle precision index (<1°), the model point cloud is generated from the 360°360 direction of the laser reflection intensity image, respectively. Match with the reflection intensity image of the measuring point cloud in turn. The 2D homonym index obtains the 3D points of the laser point cloud data. The calculation of the initial registration model is carried out by the 3D points in each direction. The point cloud is unified into one coordinate system by the initial registration model.

4. Precise registration and position measurement

\[ \{P_i, i=1,2,3,...,N\} \] represent the first set of points in space.

\[ f(R,t) = \sum_{i=1}^{N} ||Q_i - (RP_i + T)||^2 \rightarrow \min \]  

The purpose of the ICP algorithm is to find the rotation \( R \) and translation \( T \) transformation between the target point set and the reference point so that the two matching data meet the optimal matching under a certain degree of measurement. It is assumed that the coordinates of the target set \( P \) are \( \{P_i, i=1,2,3,...,N\} \). The coordinates of the reference point set are \( \{Q_i, i=1,2,3,...,N\} \). In the Kth iteration, the corresponding point coordinate with \( P \) is \( \{Q^k, i=1,2,3,...,N\} \). Calculating the transform matrix between \( P \) and \( Q^k \) and the original transform is updated until the data is the average distance between less than a given value, which satisfies (5) minimum. Specific steps: Take a set of points \( P_i \in P \) in the target point set \( P \).

\[ ||Q_i^k - P_i^k|| \rightarrow \min \]  
\[ \sum_{i=1}^{N} ||R^k P_i^k + T^k - Q_i^k||^2 = \min \]  
\[ P_i^{k+1} = \left\{ P_i^{k+1} = R^k P_i^k + T^k, P_i \in P \right\} \]  
\[ d^{k+1} = \frac{1}{n} \sum_{i=1}^{N} ||P_i^{k+1} - Q_i^k||^2 \]  

Returning to (5) if \( d^{k+1} \) more than the \( \tau \) until \( d^{k+1} \) or the number of iterations is greater than the preset maximum number of iterations.

5. Example of ground verification

5.1. Acquisition and preprocessing of target point cloud data

Target point cloud and reconstruction effect as shown in Figure 3:
5.2. Judgment of point cloud visibility
Using the vs2013 software programming to determine the visual location of the target point cloud, as shown in figure 4:

![Fig. 4 Judgment of point cloud visibility](image)

5.3. Coarse registration
Using the vs2013 software programming to determine the visual location of the target point cloud, and coarse registration, as shown in Figure 5-6:

![Fig. 5 The registration effect of SIFT operator](image)

![Fig. 6 Coarse registration](image)

5.4. Precise registration and position calculation
The precision registration and pose measurement results are shown in the following table.

| Parameters   | $X$/m | $Y$/m | $Z$/m | $\theta$/m | $\varphi$/m | $\psi$/m |
|--------------|-------|-------|-------|------------|-------------|---------|
| True data    | 127.16| 99.370| 27.983| 0.6724     | 4.1395      | 7.6272  |
| Measuring data| 127.12| 99.492| 27.963| 0.2843     | 4.0413      | 7.6266  |
| Error        | 0.040 | -0.122| 0.020 | 0.3881     | 0.0982      | 0.0006  |
| True data    | 146.87| 81.276| 31.357| 8.0145     | 33.763      | 18.760  |
| Measuring data| 146.89| 81.260| 31.316| 7.5799     | 33.932      | 18.489  |
| Error        | -0.016| 0.0152| 0.0411| 0.4346     | 0.169       | 0.271   |
| True data    | 3.5329| 1.9379| 130.17| 19.714     | 25.579      | -7.892  |
| Measuring data| 3.5618| 1.9728| 130.17| 20.142     | 25.478      | -8.050  |
| Error        | 0.0289| 0.0349| -0.000| -0.428     | 0.101       | 0.158   |
Acknowledgments
This work has been supported by National key R & D plan (2018YFB1107805); the Liaoning Provincial Natural Science Foundation Project (20180520015); and the Dalian Support for High-Level Talent Innovation and Entrepreneurship Project (2017RQ134)

References
[1] Wu Bin, Ye Dong, Zhang Xin, et al. Embedded algorithm for relative pose measurement between non-cooperative targets. Optics and Precision Engineering, 2016;24(11):2804-2813.
[2] Renato V, Marco S, Palmerini G B. Pose and Shape Reconstruction of a Noncooperative Spacecraft Using Camera and Range Measurements [J]. International Journal of Aerospace Engineering, 2017, 2017:1-13.
[3] Pan Wang, Zhu Feng, Hao Yingming. Pose Measurement Method of Three-Dimensional Object Based on Multi-Sensor [J]. Acta Optica Sinica, 2019, 39(2):0212007.
[4] Huang JM, Liu Yu. Simulation of lidar imaging for space target. Infrared and Laser Engineering, 2016;45(9): 45-51.
[5] T. Zhang, H. Li, R.-B. Wu. Radar spatial registration with multiple targets based on probability hypothesis density filter[J]. Control & Decision, 2018, 33(8):1429-1435.
[6] Holz D, Ichim AE, Tombari F, et al. Registration with the Point Cloud Library: A Modular Framework for Aligning in 3-D [J]. IEEE Robotics & Automation Magazine, 2015, 22(4): 110-124.
[7] Zhou L, Bai S, Li Y. Energy Optimal Trajectories in Human Arm Motion Aiming for Assistive Robots. Identification and Control, 2017;38(1):11–19.
[8] Du Y, Li R, Li D, Bai S. An ankle rehabilitation robot based on 3-RRS spherical parallel mechanism. Advances in Mechanical Engineering, 2017;9(8):1-8.
[9] Bai S, Angeles J. Coupler-curve synthesis of four-bar linkages via a novel formulation. Mechanism and Machine Theory 2015;94(2):177-187.