UDC 629.78

A. A. FOKOV

ANALYSIS OF THE STATE OF THE ART IN THE PROBLEM OF DETERMINING THE POSE OF ON-ORBIT SERVICE OBJECTS

Institute of Technical Mechanics
of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine
15 Leshko-Popel St., Dnipro 49005, Ukraine; e-mail: oafokov@ukr.net

Recently considerable attention has been paid to the problem of estimating the pose of an on-orbit service object. Determining the pose at a close distance still remains an open line of research, especially for non-cooperative objects (targets) of on-orbit service. The goal of this work is to overview the state of the art in the problem of determining the relative motion parameters of on-orbit service objects with emphasis on close proximity operations with non-cooperative and unknown targets. The method employed is the analysis of publications devoted to this problem over the last decade. The analysis showed the following. Determining the pose of a non-cooperative orbital object using video systems is a classical approach due to the advantages of light weight and low power consumption. Video camera based pose estimation algorithms usually require prior knowledge of the target features. The main methods of pose estimation still involve approaches based on the recognition and correspondence of image features for consecutive frames or with a target model. Another major approach to pose determination is lidar navigation, where the recognition and correspondence of features based on lidar-derived target surface point clouds are also common methods. Recently, a trend has emerged towards the development of non-feature methods for target pose determination, including unknown targets. The three-dimensional nature of lidar point cloud data is favorable for target pose estimation without any target model. As to the applicability of target pose estimation methods to an unknown target, the implementation of the obvious approach based on constructing a three-dimensional model of the target by processing a series of its images prior to estimating its spatial motion takes a lot of time, which is critical in close proximity operations. The trend in target pose estimation is the development of methods for simultaneous estimation of the pose and shape of an unknown object. In general, the case of an unknown object has not yet been fully investigated.

Keywords: *pose determination methods, on-orbit service, non-cooperative object, unknown object, methods based on object image features, non-feature methods.*

1. Wei-Jie Li, Da-Yi Cheng, Xi-Gang Liu, Yao-Bing Wang, Wen-Hua Shi, Zi-Xin Tang, Feng Gao, Fu-Min Zeng, Hong-You Chai, Wen-Bo Luo, Qiang Cong, Zhen-Liang Gao. On-orbit service (OOS) of spacecraft A review of engineering developments. Progress in Aerospace Sciences. 2019. V. 108. Pp. 32-120.
https://doi.org/10.1016/j.paerosci.2019.01.004

2. Kang G., Zhang Q., Zhang H. Pose estimation of a non-cooperative spacecraft without the detection and recognition of point cloud features. Acta Astronautica. 2021. V. 179. Pp. 569-580.
https://doi.org/10.1016/j.actaastro.2020.11.013

3. Zhao G., Xu S., Bo Y. LiDAR-Based Non-cooperative tumbling spacecraft pose tracking by fusing dept maps and point clouds. Sensors. 2018. V. 18. No. 10. Pp. 1-17.
https://doi.org/10.3390/s18103432

4. Opromolla R., Fasano G., Grass M. Uncooperative pose estimation with a LIDAR-based system. Acta Astronautica. 2015. V. 110. Pp. 287-297.
https://doi.org/10.1016/j.actaastro.2014.11.003

5. Lim T. W., Oestreich C. E. Model-free pose estimation using point cloud data. Acta Astronautica. 201 V. 165. Pp. 298-311.
https://doi.org/10.1016/j.actaastro.2019.09.007

6. Martínez H. G., Giorgi G., Eissfeller B. Pose estimation and tracking of non-cooperative rocket bodies using Time-of-Flight cameras. Acta Astronautica. 2017. V. 139. Pp. 165-175.
https://doi.org/10.1016/j.actaastro.2017.07.002

7. Barfoot T., Forbes J. R., Furgale P. T. Pose estimation using linearized rotations and quaternion algebra. Acta Astronautica. 2011. V. 68. Pp. 101-112.
https://doi.org/10.1016/j.actaastro.2010.06.049

8. He Y., Liang B., Li S. Non-cooperative spacecraft pose tracking based on point clou feature. Acta Astronautica. 2017. V. 139. Pp. 213-221.
https://doi.org/10.1016/j.actaastro.2017.06.021

9. De Jongh W. C., Jordaan H. W., Van Daalen C. E. Experiment for pose estimation uncooperative space debris using stereo vision. Acta Astronautica. 2020. V. 168. Pp. 164-173.
https://doi.org/10.1016/j.actaastro.2019.12.006

10. Sharma S., D′Amico S. Comparative assessment of techniques for initial pose estimation using monocular vision. Acta Astronautica. 2016. V. 123. Pp. 435-445.
https://doi.org/10.1016/j.actaastro.2015.12.032

11. Huang Y., Zhang Z., Zhang L., Gil-Fernández J. A low-dimensional binary-based descriptor for unknown satellite relative pose estimation. Acta Astronautica. 2021. V. 181. Pp. 427-438.
https://doi.org/10.1016/j.actaastro.2021.01.050

12. Regoli L., Ravandoor K., Schmidt M., Schilling K. On-line robust pose estimation f Rendezvous and Docking in space using photonic mixer devices. Acta Astronautica. 2014. V. 96. Pp. 159-165.
https://doi.org/10.1016/j.actaastro.2013.12.005

13. Tzschichholz T., Boge T., Schilling K. Relative pose estimation of satellites using PMD-/CCD-sensor data fusion. Acta Astronautica. 2015. V. 109. Pp. 25-33.
https://doi.org/10.1016/j.actaastro.2014.12.010

14. Volpe R., Palmerini G. B., Sabatini M. A passive camera based determination of a non-cooperative and unknown satellite's pose and shape. Acta Astronautica. 2018. V. 151. Pp. 805-817.
https://doi.org/10.1016/j.actaastro.2018.06.061

15. Piatti D. Time-of-Flight cameras: tests, calibration and multi-frame registration for automatic 3D object reconstruction. Ph.D. Thesis. Politecnico Di Torino. Doctoral Sch of Environment and Territory. 2011. URL: https://www.academia.edu/500056/Time_of- _Flight_cameras_tests_calibration_and_multi_frame_registration_for_automatic_3D_o ect_reconstruction?email_work_card=view-paper (Last accessed on September 22, 2022).

16. ASC's 3D Flash LIDAR camera selected for OSIRIS-REx asteroid mission. NASASpaceFlight.com. URL: https://www.nasaspaceflight.com/2012/05/ascs-lidar-camera-osiris-rex-asteroid-mission/ ((Last accessed on September 22, 2022).

17. Tzschichholz T., Ma L., Schilling K. Model-based spacecraft pose estimation and motion prediction using a photonic mixer device camera. Acta Astronautica. 2011. V. 6 Iss. 7-8. Pp. 1156-1167.
https://doi.org/10.1016/j.actaastro.2010.10.003

18. Lim T. W., Toombs A. J. Pose estimation using a flash lidar. AIAA Guidance, Navigation, and Control Conference. American Institute of Aeronautics and Astronautic - National Harbor, Maryland. 13-17 January 2014. AIAA 2014-0089. doi:10.2514/6.201 0089.
https://doi.org/10.2514/6.2014-0089

19. Lim T. W. Point cloud modeling using the homogeneous transformation for non-cooperative pose estimation. Acta Astronautica. 2015. V. 111. Pp. 61-76.
https://doi.org/10.1016/j.actaastro.2015.02.002

20. English C., Okouneva G., Choudhuri A. Shape-based pose estimation evaluation using expectivity index artifacts. PerMIS'12: Performance Metrics for Intelligent Syster College Park Maryland. 20-22 March 2012. doi: 10.1145/2393091.2393105
https://doi.org/10.1145/2393091.2393105

21. Woods J. O., Christian J. A. LIDAR-based relative navigation with respect to non-cooperative objects. Acta Astronautica. 2016. V. 126. Pp. 298-311.
https://doi.org/10.1016/j.actaastro.2016.05.007

22. Aldoma A., Tombari F., Rusu R. B., Vincze M. OUR-CVFH - Oriented, unique and repeatable clustered viewpoint feature histogram for object recognition and 6DOF pos estimation. Pattern Recognition - 2012. Lecture Notes in Computer Science. V. 7476. Conference proceedings. Berlin, Heidelberg: Springer, 2012. Pp. 113-122
https://doi.org/10.1007/978-3-642-32717-9_12

23. Zhu W., She Y., Hu J., Wang B., Mu J., Li S. A hybrid relative navigation algorithm for a large-scale free tumbling non-cooperative target. Acta Astronautica. 2022. V. 194. Pp.114-125.
https://doi.org/10.1016/j.actaastro.2022.01.028

24. Capuano V., Kim K., Chung S. J. Monocular-based pose determination of uncooperative space objects. Acta Astronautica. 2020. V. 166. Pp. 493-506.
https://doi.org/10.1016/j.actaastro.2019.09.027

25. Goncharenko M. O. Comparative analysis of image descriptor formation method in the context of the video flow segmentation problem. Bionics of Intelligence. 2015. V. 85 No. 2. Pp. 90-94. (in Russian).

26. Pesce V., Haydar M. F., Lavagna M., Lovera M. Comparison of filtering techniques for relative attitude estimation of uncooperative space objects. Aerospace Science and Technology. 2019. V. 84. Pp. 318-328.
https://doi.org/10.1016/j.ast.2018.10.031

27. Pesce V., Opromolla R., Grassi M. Autonomous relative navigation around uncooperative spacecraft based on a single camera. Aerospace Science and Technology. 2019. V. 84. Pp. 1070-1080.
https://doi.org/10.1016/j.ast.2018.11.042

28. Gubarev V. F., Salnikov N. N., Melnychuk S. V. Ellipsoidal pose estimation of an uncooperative spacecraft from video image data. In: Control Systems: Theory and Applications. River Publishers. 2018. Pp. 169-195.
https://doi.org/10.1201/9781003337706-9

29. Li Y., Xie Y. Relative state estimation of model-unknown spinning noncooperative target using stereo EKF-SLAM. 2017. 36th Chinese Control Conference (CCC), Dalian, China. 2017. Pp. 5893-5898.
https://doi.org/10.23919/ChiCC.2017.8028291

30. Cavenago F., Lizia P. D., Wittig A. On-board spacecraft relative pose estimation wit high-order extended Kalman filter. Acta Astronautica. 2019. V. 158. Pp. 55-67.
https://doi.org/10.1016/j.actaastro.2018.11.020

31. Guthrie B., Kim M., Urrutxua H., Hare J. Image-based attitude determination of co-orbiting satellites using deep learning technologies. Aerospace Science and Technolog 2022. V. 120. 107232.
https://doi.org/10.1016/j.ast.2021.107232

Received on March 3, 2023,
in final form on March 27, 2023