21st IAA SYMPOSIUM ON SPACE DEBRIS (A6)
Interactive Presentations - 21st IAA SYMPOSIUM ON SPACE DEBRIS (IPB)

Author: Prof. M. Reza Emami
University of Toronto Institute for Aerospace Studies, Canada, emami@utias.utoronto.ca

Mr. Jun Yang Li
University of Toronto Institute for Aerospace Studies, Canada, junyang.li@mail.utoronto.ca
Mr. Sean Wolfe
University of Toronto Institute for Aerospace Studies, Canada, sean.wolfe@mail.utoronto.ca

4D LIDAR-BASED SPACE DEBRIS RATE ESTIMATION

Abstract

Active Debris Removal (ADR) requires precise rendezvous and synchronization with an uncooperative object of uncertain geometry, calling for comprehensive, high performance perception suites. Cameras have been the default option for space surveillance, due to their high Technology Readiness Level (TRL). However, they are susceptible to the harsh lighting conditions of outer space. Hence, space debris competitors plan to utilize alternative optical payloads, such as Light Detection and Ranging ($LiDAR$) devices. Along with the steady rise of the LiDAR TRL, the novel frequency- modulated continuous-wave LiDAR scheme provides simultaneous velocimetry and ranging of targets in 3D, which is why these LiDARs are colloquially becoming known as *4D LiDARs*. The first Commercial-of-the-Shelf ($COTS$) 4D LiDAR was developed in 2022.

A few research has been done on the utilization of 4D LiDARs for spacecraft perception. Just recently, NASA in collaboration with Texas A&M U. researchers have explored the use of a custom-built 4D LiDAR for rate estimation in various space missions, including ADR. However, for rendezvous, synchronization and docking, in their work the estimates of the target's centre of mass are based on direction change in the measured velocities of different points on the target, which is not applicable to cases where the relative velocities are large or the target is tumbling.

This paper presents an algorithm that assumes no known geometry of the target, and decouples linear and angular velocities using a COTS 4D LiDAR to estimate the rates, position and size of a tumbling space debris, without a need for computationally expensive point-cloud registration or feature extraction algorithms. First, a box surrounding the target is estimated through principal component analysis over the range point-cloud, and the position of the target is then estimated as the box centroid. Next, vertices of the box over frames are associated with each other through minimization of the L2-norm. The angular rates of the debris are then estimated using a linear least-squares technique over the velocity point-cloud, as well as a modified Kabsch algorithm to recover the lost information about their projection along the line-of-sight. Finally, all estimates are combined in a 33-state extended Kalman filter, using the principle of conservation of angular momentum, for the estimation of the debris position, linear and angular velocities, as well as the volumetric size of the debris. The algorithm is verified through simulations, and the viability of 4D LiDAR for rendezvous and synchronization in ADR missions is demonstrated.