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In situ space debris inspection: From observation to 3D reconstruction

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Abstract. Amidst the exponential increase in space debris, Active Debris Removal and On-Orbit Servicing missions have gained paramount importance. The success of such endeavours pivots on the comprehension of the target's geometry and dynamic conditions, highlighting the indispensable nature of target inspection. In recent times, a variety of inspection missions have employed satellites of different classes. In this context, small satellites like CubeSats have emerged as a reasonable solution, due to cost-effectiveness and rapid development capabilities. This study explores a potential inspection mission utilizing a CubeSat to evaluate a non-cooperative target, where information on relative pose are not known a priori. The aim is to retrieve essential data for executing Close Proximity Operations safely. Manoeuvring around the target, the CubeSat captures two-dimensional (2D) RGB images from multiple angles to then reconstruct its three-dimensional (3D) geometry. Optical cameras are preferred during the inspection phase due to their cost-efficiency and low power requirements, different from other technologies like laser imaging. An experimental setup is designed and built to generate a dataset of 2D images simulating in orbit conditions. Standard computer vision algorithms are employed to perform the 3D reconstruction and Artificial Intelligence used to reconstruct the scene.

Introduction

The escalating number of space debris poses a significant threat to the space industry, putting operational satellites and human space missions at risks. Notable incidents like the 2009 collision between Iridium-33 and a Russian military satellite underscore the urgency of addressing the current resident space object (RSO) situation [1, 2]. This has fuelled interest and demand for On-Orbit Servicing (OOS) missions and Active Debris Removal (ADR) applications. During the years, both manned and robotic OOS missions were carried out. For the latter, recent examples are MEV-1 and MEV-2 [3], and the future ESA mission ClearSpace-1 [4]. However, most of these missions targeted cooperative RSOs capable of controlling their attitude, ensuring safer close-proximity operations [5]. When dealing with non-cooperative targets such as tumbling debris, close-proximity operations become riskier due to uncertainties in pose, shape, and conditions. Therefore, in situ inspection of the target is critical to OOS mission success. Previous research has

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identified potential capture points and fragile components on the targets but falls short in ensuring safe trajectories during close-proximity manoeuvres. To mitigate this risk, understanding the 3D characteristics of the target is essential. Additionally, determining the target's relative pose, crucial for robotic arm capture, requires a 3D model of the target. This study investigates the feasibility of using photogrammetry to inspect an RSO. In addition, the same dataset is used to reconstruct the scene using a variation of NeRF, Neuro Radiance Fields [6]. A custom experimental setup is designed to simulate a CubeSat chaser's fly-around relative to a target RSO, CubeSats are chosen for their fast and relatively easy design process [7]. The collected data are processed to retrieve a 3D model of the target and reconstruct the scene. Preliminary results are then presented and briefly discussed.

Case study

This study focuses on Space Rider (SR), the ESA reusable spacecraft scheduled for a 2025 flight. Structurally, the spacecraft resembles a cylinder, with a diameter of approximately 2 meters and a length of 8 meters as depicted in Figure 2. Positioned near its base are two deployable solar panels, extending to around 11 meters upon deployment. These dimensions classify it as a substantial Resident Space Object (RSO) in Low Earth Orbit (LEO). Moreover, its distinct shape and colour scheme pose significant challenges for 3D model reconstruction techniques. For consistency, the spacecraft's white segment is referred to as the upper part, while the black portion is the lower part. The darker conical structure, housing the solar panels, is known as AVUM +, serving as the upper stage of the Vega-C launcher. To conduct the inspection, a circular relative orbit has been chosen. The inspector, or chaser, will maintain a constant distance of 100 meters from the target, SR.

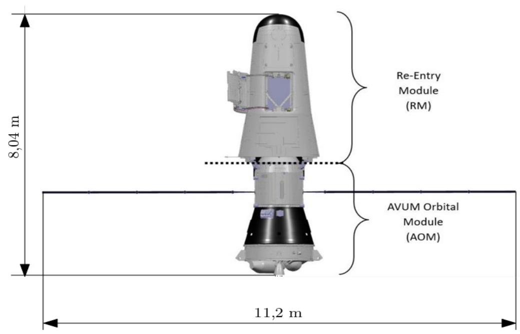


Figure 2: Space Rider dimensions [9]

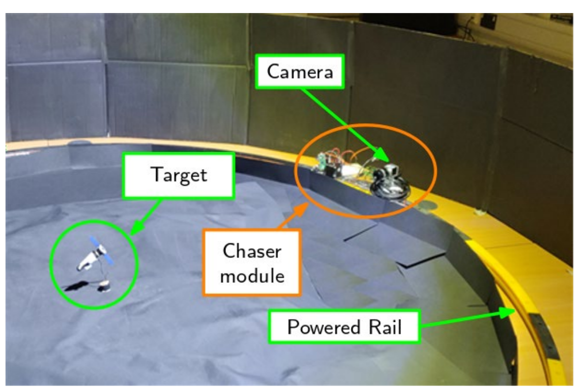


Figure 1: Experimental setup. The chaser is free to move along the rail maintaining a constant distance from the target.

Experimental setup

To replicate the case study in a laboratory setting, a scaled-down setup was designed and built as in Figure 2. Primarily constructed through 3D printing, this setup aims to modularity and ease of reproduction in any laboratory environment. The monorail approach was chosen to provide power to the chaser module. The circular rail has a diameter of 2 meters and beneath it, a gear facilitates the movement of the chaser module. The base of the chaser module mirrors the dimensions of a 3U CubeSat, measuring approximately 300mm × 100mm. Equipped with a machine vision camera featuring a 16mm lens, the chaser is controlled by an onboard Raspberry Pi 4, overseeing both the camera and the rail's motion via a stepper motor. To simulate orbital lighting conditions, the room is obscured and the setup enveloped with matte black panels. The sole source of illumination directed towards the target is a Sun Simulator, emitting a nominal luminous flux of 9000 lumens. The target comprises a 3D-printed, scaled-down 1:100 model of SR.

3D reconstruction techniques

3D scanning techniques are utilized to capture information about an object's shape or other attributes. These techniques find extensive application across various fields in the industry. For instance, they are employed in industrial settings for quality control along production lines and in the entertainment industry to digitally recreate actors and props. Several approaches exist to achieve the desired outcomes, with the most prevalent ones used in space being photogrammetry and LiDAR. The decision for this study leaned towards photogrammetry due to its simplicity and minimal requirements. Unlike LiDAR, photogrammetry does not necessitate specialized instruments, relying solely on a camera and adequate lighting, while also imposing a relatively low computational load. The algorithm employed in this work is the industry-standard Structure from Motion, which, based on features extracted from each image, is capable of determining the relative pose of the cameras.

For reconstructing the scene, Instant-NGP, Neural Graphics Primitives, is chosen as the most viable option. Instant-NGP is a modified version of NeRF created to obtain a faster and less computational heavy network. These characteristics are critical for a future implementation on board of a satellite.

Data processing and results

The pictures are acquired by the chaser during a full lap around the target. In each round, a total of 37 pictures is taken, spaced evenly at 10-degree intervals, with the first and last images overlapping. The camera's position is then estimated using COLMAP, a general-purpose Structure-from-Motion pipeline [8]. The pipeline's general workflow is depicted in Figure 3. Initially, the camera's position is determined, locating them in 3D space. Following this, a sparse point cloud is generated. These initial tasks can be executed using CPU power alone, enabling direct onboard processing using the Raspberry Pi. The last step is the retrieval of the dense point cloud, that can be then used to create the mesh. The final step involves generating a dense point cloud, which can then be used to construct a mesh. To assess the accuracy of the reconstruction, the point cloud is compared to the original CAD model using Cloud Compare, a 3D point cloud processing software. The distance between each element of the point cloud and the nearest point on the mesh is calculated to gauge the quality of the acquired 3D information. The results indicate

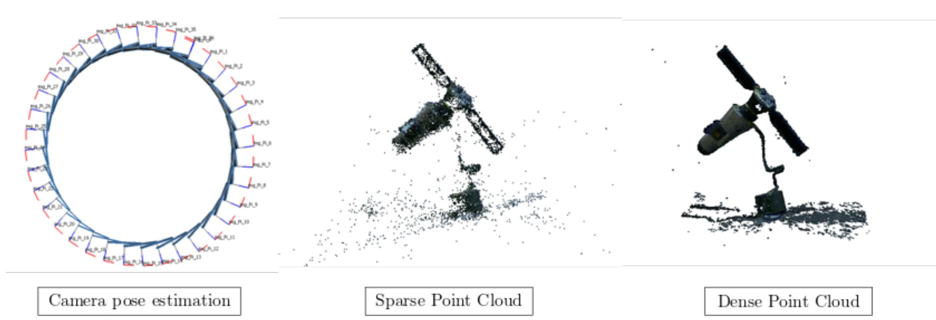
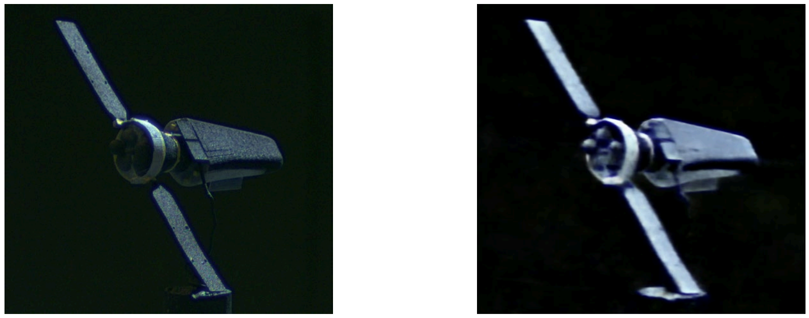


Figure 3: 3D reconstruction pipeline.

that the mean distance between points was 0.02 mm, with a standard deviation of 0.08 mm, demonstrating the precision of the reconstruction.



(A) (B)

Figure 4: On the left (A) the original image, on the right (B) an image from the reconstructed scene.

Regarding Instant-NGP, first the pictures are fed to COLMAP which is used only for the first step retrieving the camera pose. When finished, the dataset and the camera pose file are fed into the neural network which is able to fully reconstruct the scene in less than 2 minutes. For this study an Nvidia RTX 4080 gpu is used. The results show a PSNR of 18.3, a comparison between the original image and the reconstructed one is shown in Figure 4.

Conclusions

In this paper, a preliminary study on the inspection of a Resident Space Object to retrieve its 3D model is presented. The target taken in consideration is Space Rider, an ESA spacecraft designated for operations in Low Earth Orbit (LEO). The goal of the study is to create a 3D model of SR using standard photogrammetry algorithm. Opting for photogrammetry implies that the equipment needed on board on the inspector satellite, specifically a CubeSat in this case, is limited to a camera, a visible RGB for these tests. A custom setup was designed built to simulate the in-orbit conditions. It includes a self-sufficient module, approximately the size of a 3U CubeSat, that orbits the target in a circular path at a fixed distance of 1 meter. The module's camera captures images at regular intervals. The target is a 3D-printed model of ESA Space Rider at a 1:100 scale. After collecting the images COLMAP is used to retrieve the camera pose and generate a point cloud of the environment. This point cloud is then compared to the original CAD model of the target, revealing an average distance of around 0.02 millimetres between the points and the original model. The same camera pose used to then recreate the point cloud is also used as input to a Neural Network, Instant-NGP, to reconstruct the scene. While the findings are still in their early stages, they suggest that this method is suitable for creating a detailed 3D model of the target. Such data could be invaluable for informing the design of future On-Orbit Servicing (OOS) or Active Debris Removal (ADR) missions.

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