Online Supervised Training of Spaceborne Vision during Proximity Operations using Adaptive Kalman Filtering

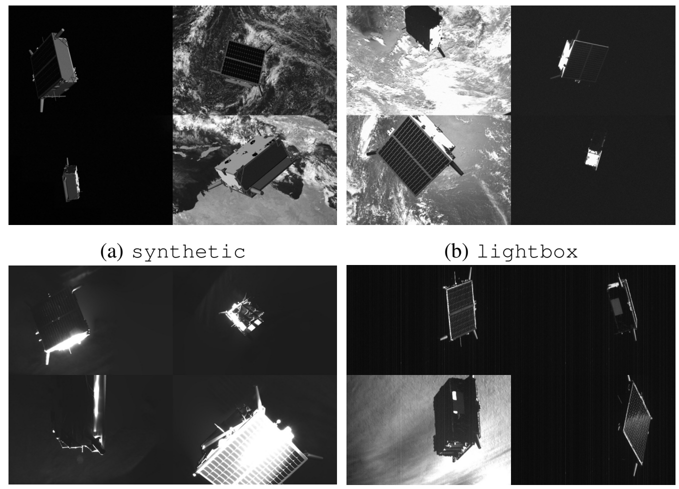
Tae Ha Park Simone D'Amico

This work presents an Online Supervised Training (OST) method to enable robust vision-based navigation about a non-cooperative spacecraft. Spaceborne Neural Networks (NN) are susceptible to domain gap as they are primarily trained with synthetic images due to the inaccessibility of space. OST aims to close this gap by training a pose estimation NN online using incoming flight images during Rendezvous and Proximity Operations (RPO). The pseudo-labels are provided by an adaptive unscented Kalman filter where the NN is used in the loop as a measurement module. Specifically, the filter tracks the target's relative orbital and attitude motion, and its accuracy is ensured by robust on-ground training of the NN using only synthetic data. The experiments on real hardware-in-the-loop trajectory images show that OST can improve the NN performance on the target image domain given that OST is performed on images of the target viewed from a diverse set of directions during RPO.

I. Introduction

In space robotics, one of the most sought-after capabilities is autonomous Guidance, Navigation and Control (GN&C) with respect to non-cooperative objects such as satellites and debris. This requires estimating the pose (i.e., position and orientation) of the target relative to the servicer, which enables various future missions for on-orbit servicing [1] and debris removal [2]. Performing pose estimation using a single monocular camera is particularly attractive due to its low mass and power requirements suitable for on-board satellite avionics.

Machine Learning (ML) and Neural Networks (NN) have recently emerged as prevailing methods for pose estimation especially for known targets [3]–[9]. This is a scenario suitable for space missions with a priori information on the client's target spacecraft. However, unlike in terrestrial applications such as autonomous driving, spaceborne NNs must address several challenges unique to space environments. First, the computational resource is scarce on-board the satellite with no or minimal GPU support. Second, access to space is severely restricted, even more so beyond Low Earth Orbit (LEO), which implies a lack of annotated flight images of the target spacecraft for training and validation of NNs. Therefore, spaceborne NNs must instead be trained on synthetic imagery rendered with computer graphics which lack visual characteristics typical of the space imagery. It also implies a lack of representative images for *on-ground* performance validation which is crucial for ensuring the success of costly and safety-critical space missions.



(a) `synthetic` (b) `lightbox` (c) `sunlamp` (d) `prisma25`

Fig. 1: Various image domains of the Tango spacecraft from the SPEED+ dataset [10] (a, b, c) and actual space flight (d).

As flight images do not become available until close-range rendezvous in space, one key strategy is to instead create high-fidelity surrogate images on-ground that can be used to evaluate the robustness of NN models trained on synthetic images across domain gap (also known as sim2real gap) on flight images. These so-called Hardware-In-the-Loop (HIL) images can be created along with high-accuracy pose labels using a satellite mockup model in a robotic testbed capable of emulating high-fidelity space illumination conditions [11]. For instance, Fig. 1 shows examples of HIL image domains of the SPEED+ dataset [10], `lightbox` and `sunlamp`, which comprise images of the mockup model of the Tango spacecraft from the PRISMA mission [12], [13] illuminated with albedo light boxes and a sun lamp, respectively. Captured with an actual camera inside a realistic space-like environment, these HIL images can be used for comprehensive evaluation of NN robustness on otherwise unavailable flight images. However, while HIL images can significantly reduce the visual gap between the synthetic and spaceborne images, there are still remaining gaps largely due to the fact that HIL domains create images of an inexpensive mockup model that fails to capture the real satellite's material and surface properties.

In order to completely close the domain gap, this work proposes to perform Online Supervised Training (OST) using incoming flight images in space during Rendezvous and Proximity Operations (RPO). As shown in Fig. 2, the pose

The authors are with the Space Rendezvous Laboratory (SLAB), Department of Aeronautics & Astronautics, Stanford University, Stanford, CA 94305. Email: {`tpark94, damicos`}`@stanford.edu`.

For visualization of various datasets and results, please see the project website: `https://taehajeffpark.com/ost/`.

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