National Aeronautics and Space Administration

Robust Data-driven Vision-based multi-Spacecraft (RDVS) Guidance and Control

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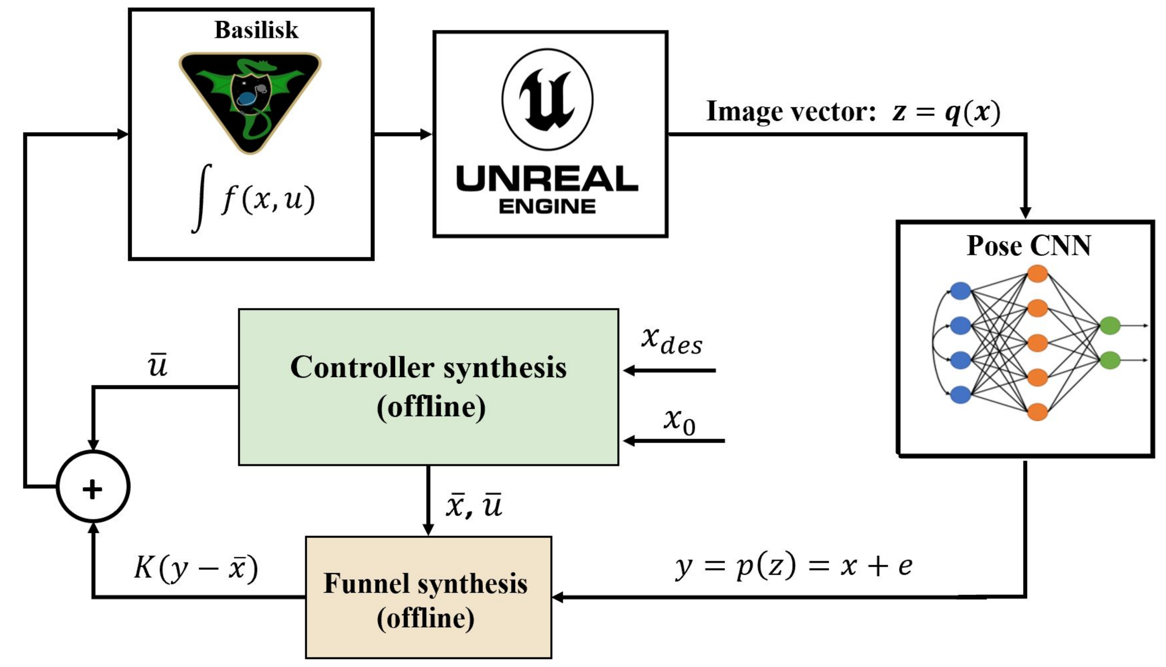
Objectives

RDVS is a framework for multi-spacecraft motion-planning assuming camera images along with machine learning algorithms are the main metrology system for relative navigation.

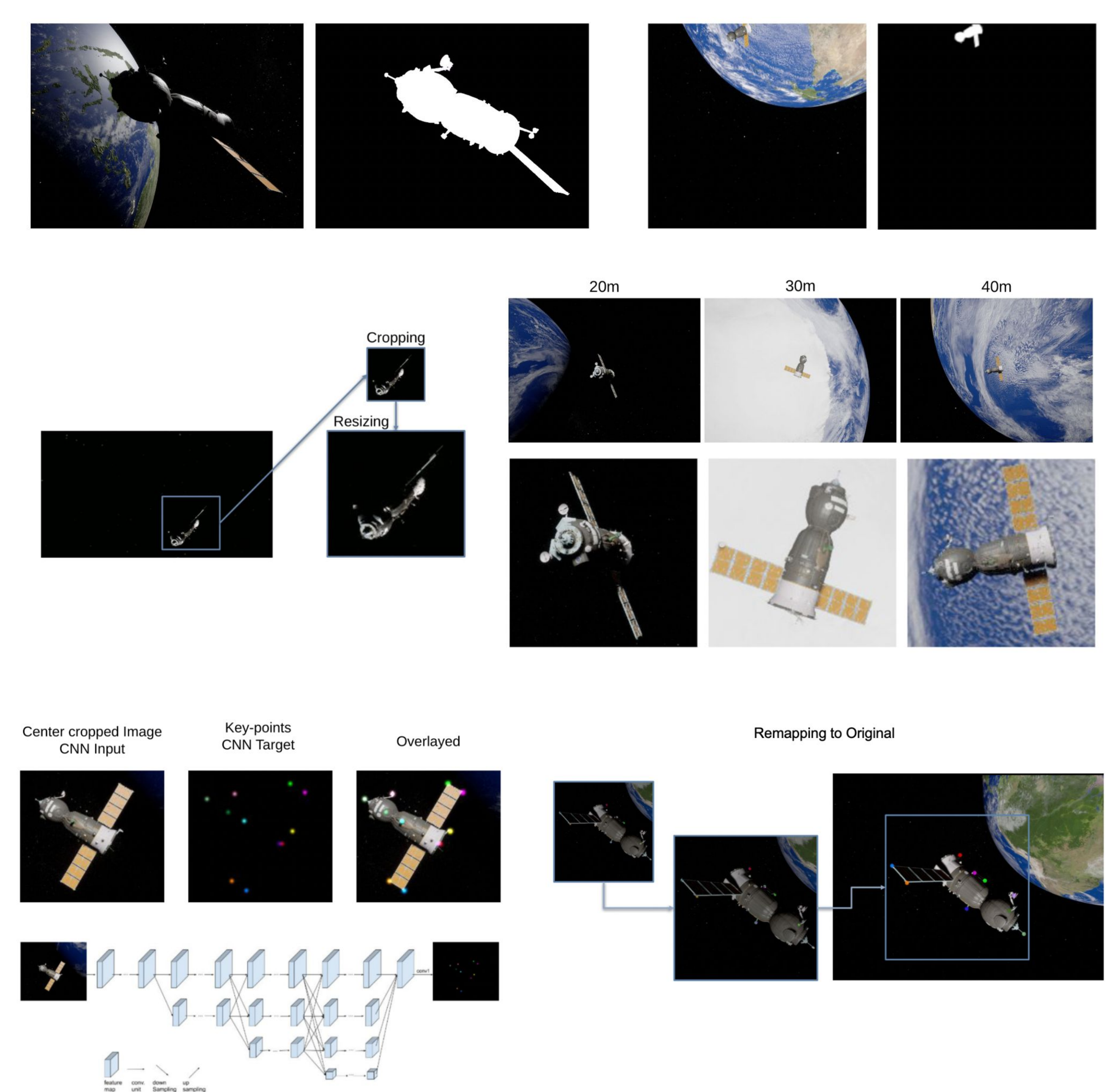
It takes advantage of robust control synthesis to overcome limitations and non-gaussian error properties of such relative navigation system and provide theoretical guarantees on mission performance for formation flying and reconfiguration.

Technical approach

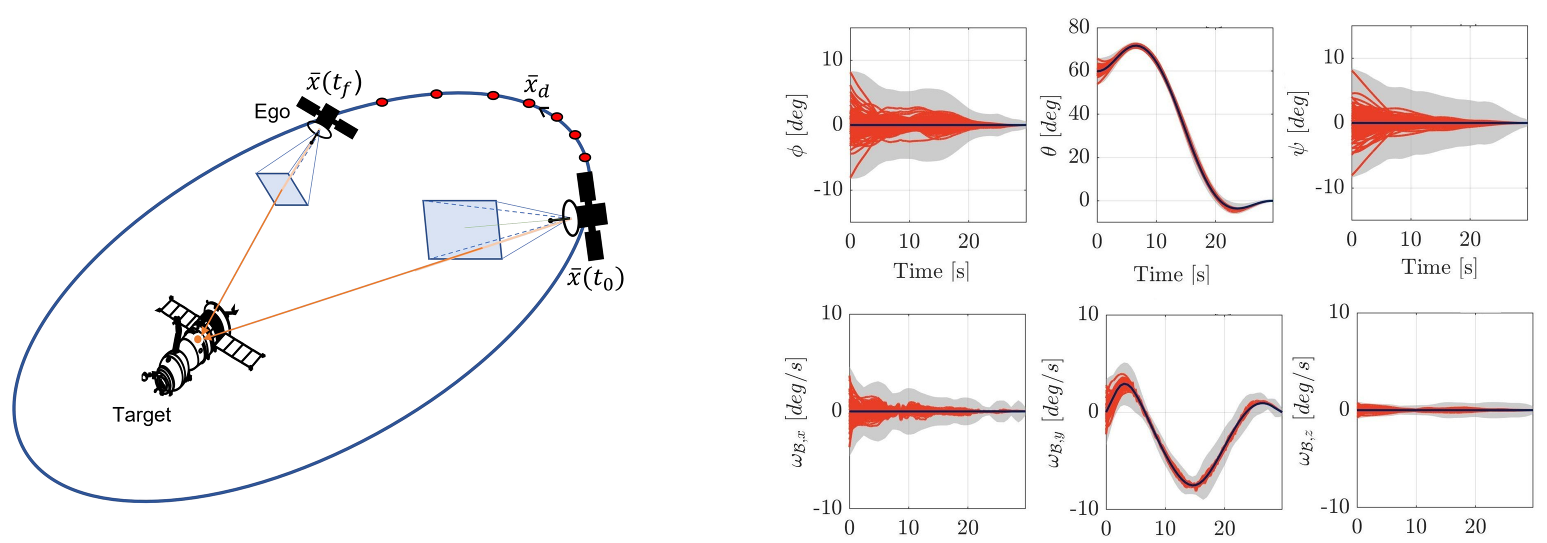
We developed a multi-spacecraft simulation engine with high fidelity dynamics and capability of generating photo-realistic camera images based on Unreal gaming engine. This simulation software is used to generate a large dataset of spacecraft images that are then used to develop and train a relative pose estimation convolutional neural network (pose-CNN) that receives camera images and outputs the relative pose of the target spacecraft. We used a large set of test images to characterize the relative navigation error of the trained pose-CNN around our nominal relative trajectory. Since the pose-CNN error is non-Gaussian, the state-dependent estimation error is characterized via a quadratic upper-bound. A linear matrix inequalities (LMIs) based approach to controller synthesis was used, guaranteed to be robust against both model uncertainties and measurement errors, resulting from vision-based estimation. This controller consists of two distinct components, one synthesized based on the nominal trajectory, while the "robust" component corrects for deviations from the nominal trajectory. Capturing the perception error using quadratic/matrix inequalities facilitates embedding them in a unified synthesis procedure that is also built upon the use of such inequalities. These inequalities in turn lead to a synthesis process that is built upon convex optimization based solutions, providing efficient and scalable control synthesis with perception in the feedback loop.



RDVS closed loop controller: Basilisk along with Unreal are the backbone of the multi-spacecraft simulation, the camera images of the ego-spacecraft are fed to a pre-trained pose-CNN that outputs target pose in own camera frame, the synthesis framework then produce control signals that are robust to errors of the pose-CNN estimates.



Inner workings of Pose-CNN: A mask-CNN network is used to find the target in a camera image, then to normalize all images they are cropped and resized. The normalized images are then fed to a pre-trained CNN that outputs the keypoint locations, after remapping to original image, these keypoints along with the camera parameters are used to calculate the relative pose of the target.



Target flyby example scenario: An example scenario of the target flyby, robust synthesis is using the pose-CNN estimates to compute reaction wheel inputs that keep the target in the center of camera.

Significance to NASA/JPL

As cameras and high power computing become standard on smallsats and with new advances in machine learning techniques, it is expected that close proximity operations such as autonomous formation flying for earth science and asteroid exploration as well as on-orbit inspection applications take advantage of this new relative navigation metrology system. While a large body of research has focused on improving camera based relative pose estimation, the unpredictable on-orbit image quality and representativeness of the training synthetic images call for a new guidance and control framework that can combat shortcomings of this new relative navigation system. RDVS is addressing this gap, taking advantage of robust control synthesis to provide theoretical performance guarantees for the closed loop system.

Acknowledgement

We would like to thank JVSRP intern Jonathan Becktor from Technical University of Denmark, William Seto from JPL; and Aditya Deole, Niyousha Rahimi, Shahriar Talebi from the University of Washington for their contributions to this project.

Publications

[A] J. Becktor, W. Seto, A. Deole, S. Bandyopadhyay, N. Rahimi, S. Talebi, M. Mesbahi, A. Rahmani, "**Robust Vision-based Multi-spacecraft Guidance Navigation Control using CNN-based Pose Estimation**", IEEE Aerospace Conference, Big Sky, MT, Mar. 2022. accepted.

[B] N. Rahimi, S. Talebi, A. Deole, M. Mesbahi, S. Bandyopadhyay, A. Rahmani, "**Robust Controller Synthesis for Vision-based Spacecraft Guidance and Control**", AIAA SciTech Guidance, Navigation, and Control (GNC), January 2022, accepted.

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