Relative Navigation Challenges for Active Debris Removal Missions and the Role that Artificial Intelligence Can Play

Hodei Urrutxua[1][0000−0002−9173−9593]

Universidad Rey Juan Carlos, Camino del Molino 5, 28942 Fuenlabrada, Spain
`hodei.urrutxua@urjc.es`

Active Debris Removal (ADR) missions pose demanding Guidance, Navigation and Control (GNC) requirements, and several challenges remain to be met before real debris objects can be routinely removed. Proximity operations in orbit are critical, and there is increasing interest in the GNC system being able to safely perform such operations in a fully autonomous manner. To this end, significant challenges need to be overcome, specially in the case where the target spacecraft is uncooperative and its parameters are unknown. For such a scenario there are stringent GNC requirements that have not yet been conclusively demonstrated in flight in a fully autonomously manner, such as: 1) identification of geometric and physical characteristics of an unknown co-orbiting object; 2) reliable measurement of the target-chaser relative roto-translational state; 3) guidance and navigation around an uncooperative co-orbital object; and 4) capture, stabilisation and de-orbit of an uncooperative spacecraft.

The Technical Readiness Level (TRL) of several technologies required to accomplish these ADR related goals is still low, however, since the uncooperative (and often unknown) prevents the use of readily flight-proven technologies, which rely on prior information about the target satellite, often equipped with docking systems. The control system of the chaser satellite requires the synchronisation of attitude motion with the debris target, for which an accurate estimate of the relative attitude and rotational state of the target is vital.

On-orbit servicing is a similar problem requiring close-range operations, where there have only very recently been successful missions (e.g. the Mission Extension Vehicle by Northrop Grumman), albeit with a fully known, cooperative target. Guidance and navigation around asteroids and cometary bodies is another problem that shares many of the GNC related difficulties of an ADR mission. These examples share a common ingredient: the predominance of vision-based navigation systems, consisting on a combination of visual, infrared and/or LiDAR cameras, as well as stereocameras. These systems can achieve high accuracy under good conditions, and active LiDAR sensors are one of the most popular choices, since they provide a measurement of the depth and are relatively insensitive to illumination conditions, with a wide range of working distances.

A conventional approach for visual navigation about an unknown target consists of extracting landmarks from an image of the object, and tracking their motion to estimate the body's rotational state (Pesce et al. 2019; Guo et al., 2020); unfortunately, these algorithms can be computationally intensive, they have no colour saliency and tend to have difficulty in situations with complex illumination conditions (van de Weijer et al. 2006; Rana et al. 2015); though some of the complexity can be removed if the geometry of the target is known beforehand (Opromolla et al., 2017; Pesce et al. 2020), this will not always be the case.

Machine Learning (ML) techniques can improve upon the performance of the aforementioned conventional algorithms, as they have the advantage of being resistant to non-linearities in the data, such as those caused by varying lighting conditions. Once trained, these models also tend to be fast to run, making them suitable for real-time applications. Sharma and DAmico (2020) recently presented a method for pose estimation with a monocular camera using a convolutional neural network; this work also contributed the Spacecraft Pose Estimation Network (SPEED), which has since been made publicly available through a competition on pose estimation run by the European Space Agency. Other similar research has also looked at pose estimation from monocular images (Phisannupawong et al., 2020; S. Sonawani, 2020), though in all cases the target spacecraft was known. More recently, Guthrie et al. (2021) looked into generalising the relative pose estimation problem to arbitrary, a priori unknown geometries, by using a siamese convolutional network capable of detecting and tracking inherently useful landmarks from sensor data.

Other potential applications of ML for autonomous ADR include capabilities, such as object detection techniques, whereby the target spacecraft can be located and tracked from visual images (and, if desired, also classified into categories, so the de-orbiting strategy can be adapted accordingly). A similar approach could also be used to detect specific elements of an a priori unknown spacecraft geometry, such as thruster nozzles, solar arrays, etc., for safer and relative navigation; this could also enable ADR in the absence of an existing docking mechanism, by identifying suitable locations on the spacecraft where a robotic arm could make contact, or points where harpoons could penetrate without causing breakups; image segmentation based ML techniques seem appropriate for such applications. ML techniques could also provide interesting alternatives for onboard path planning of approach trajectories, fault tolerant generation of quasi-optimal thrust and attitude profiles, design of collision avoidance manoeuvres, or autonomous decision-making under complex or incomplete information, just to cite a few.

The key limiting factor in applying ML to space applications lies in the lack of available datasets, which are large, complex and realistic enough to yield robust and well performing ML algorithms, that could be operationally used. To this end, simulated orbital and attitude dynamics, along with computer rendered synthetic imagery, and combined with actual imagery from experimental setups, can suffice for an effective training of ML models.

Acknowledgements The author wishes to acknowledge funding from research grant PID2020-112576GB-C22 (AEI/ERDF, UE). The author would also like to acknowledge Benjamin Guthrie, Minkwan Kim and Jonathon Hare, as many of the results and background for this talk are borrowed from their research collaboration on this topic.