A Deep Learning-based Framework for Operational All-vs-All Conjunction Screening using Iterative Transfer Learning*

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Abstract. The *all-vs-all* problem, for which conjunctions are screened for over all possible sets of catalogued objects, including debris on debris, is crucial for space situational awareness but a computational challenge owing to the vast and growing number of possible conjunction pairs. One potential solution to the scales and complexity posed by this problem is the exploitation of recent advancements in the field of machine learning, and notably deep learning, which are promising in a wide variety of problems due to their ability to process and exploit large datasets, infer hidden correlations, and reduce computational time during model prediction. In this context, we have been working to develop novel deep learning algorithms for detecting conjunctions which may be used as an efficient first filter or initial screening to complement and support existing operational systems by significantly reducing the number of high-risk candidate pairs [2].

In this work, we focus on the development of a more industrialised machine learning approach, concentrating principally on aspects such as the generalisation ability of the conjunction detection algorithms so that they could be deployed for regular screening as a part of an operational conjunction assessment procedure. An often-understudied aspect of machine learning models is their ability to generalise, or maintain performance, on out-of-distribution data (domain generalisation). In the case of conjunction detection, where the training procedure may be computationally expensive, a machine learning model may only provide computational benefits if a model trained today still offers sufficient performance tomorrow, and thus it is important that the model is able to generalise to future epochs. In this vein, we explore the concept of *iterative transfer*

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learning, in which a model may be periodically updated, or re-trained, on new data in order to maintain the required level of performance.
We present here the pipelines and modules constructed for testing and deploying this concept in collaboration with CNES, and explore the operational viability of our approach, in which we sought to improve robustness and establish its limitations, as well as to determine how the developed algorithms could offer new functionality or performance improvements compared to existing conjunction filtering concepts employed by CNES.
For this, three primary end-to-end pipelines were developed: model training, model inference and model evaluation, responsible for iterative retraining of the model, regular inference (e.g., using the trained model to make daily predictions) and periodically evaluating the performance of the current model respectively. Within these, the task of conjunction detection was phrased as a binary classification problem (with orbit ephemeris data as an input to the model, and a predicted yes/no conjunction label over a given screening period as an output). As such, the pipelines were integrated with the CNES PATRIUS and filtering-lib space dynamics and conjunction filtering java libraries for generating ephemerides (based on an input TLE catalogue) and conjunction reference labels (through a brute force approach) for training and evaluating the model, as well as for comparing against classical filtering approaches.
This modular approach enabled the investigation of different architectures and concepts for improving model performance, such as the use of model pre-training. This module was developed with the aim of improving generalisation based on the novel concept of self-supervised learning for time series [1], to help the model assimilate an underlying understanding of the perturbing forces affecting space objects on different timescales.
Finally, with different computational and operational requirements, each pipeline was developed to run independently at different intervals and was also developed for the CNES High Performance Computing (HPC) cluster using a PBS scheduler, which allows for tailored allocation of resources for different modules, for example use of GPUs for model training and inference, for scaling to the full all-vs-all problem.

Keywords: Conjunction assessment · Filtering · Deep learning · Machine learning · Transfer learning · Space debris · Space environment management.

References

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