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Machine Learning assisted NEO Discovery and Polarimetric Characterization with Astronomical Surveys

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1 Introduction

We are a group of over two dozen astronomers, computer scientists, data scientists and digital Big Data research platform experts at 11 universities and research institutes in South Africa and Europe. We study Near-Earth Objects (NEOs) for Planetary Defence and scientific purposes.

We present our research and development programme for algorithms and digital data analysis platforms for machine learning-assisted NEO discovery and polarimetric characterisation in astronomical surveys. Typically this is serendipitous because these surveys are designed for galactic and extragalactic science.

The morphological appearance of NEOs in astronomical images ranges from a point spread function of just a few pixels in extent to an elongated linear feature spanning hundreds of pixels. Here we focus on detection and classification of elongated linear features based solely on astronomical images. We aim for a pure and complete detection and classification to as low as possible signal-to-noise for both the smallest and the largest linear extents. In addition we want to develop the pipeline for the detection and classification as a generic software component that is generically configurable for surveys and can be interfaced or embedded in the associated astronomical data handling systems. So we want to make the approach applicable to survey images that vary in terms of image spatial resolution, image quality and depth.

2 NEO Discovery

Large area astronomical imaging surveys contain appearances of many types of linear, streak-like features. These include NEOs and other solar system objects, CCD charge bleeding, diffraction spikes, cosmic ray impacts, meteor fireballs, very elongated galaxies and (increasingly) human-made satellites. Automatic detection and classification of these classes with high completeness and precision can immensely speed up the usage of these surveys for solar system research and for Planetary Defence / Space Situational Awareness. Additionally, this detection and classification is also already valuable during the data processing and quality assessment phases.

As astronomical surveys are designed for galactic and extragalactic science it can vary how well they are suited to detect asteroids, and NEOs in particular. Here we focus on on-going surveys that our science team is involved in: various surveys performed with OmegaCAM at the VST (e.g., Iodice 2022, Wright et al 2024, Peletier et al. 2020) and the Euclid Mission surveys (Euclid Collaboration 2024). Our group also includes members of the Rubin Consortium who are interested in taking the lessons learned from Euclid and OmegaCAM to the LSST survey.

For the OmegaCAM archive it is estimated that one in twenty NEOs appear in OmegaCAM data at a signal-to-noise ratio higher than 3 (Saifollahi et al 2023). Of these, order 70% have elongations that makes them well-resolved compared to point sources (see Table 2 and Fig8 in Saifollahi et al 2023). For example, order 6.4E4

asteroid appearances are expected in just the Kilo-Degree Survey of OmegaCAM (Verdoes Kleijn et al 2024). Classical methods (using SourceXtractor and StreakDet) have been deployed on OmegaCAM to detect appearances of already known NEOs, i.e., precoveries (Saifollahi et al 2023). This achieves a recovery rate of 40% for NEOs on the risk list for streaks with S/N > 3, decreasing to 20% for the full list of NEOs. The precovery rate increases to about 50% for S/N > 10. In other words, currently the majority of NEOs with a predicted 3 < S/N < 10 remain undetected (even after visual inspection). Especially for Planetary Defence purposes it is relevant to assess whether the failed NEO precoveries can indicate errors that are unaccounted for (e.g., in their photometric model).
These results make it interesting to develop a pipeline that automatically harvests NEO candidates "blindly" from the continuously increasing OmegaCAM archive and crossmatches them with the known NEO population.
The desire for a generically applicable pipeline makes it interesting to move over to machine learning assisted methods for this. Machine learning holds the promise to make it straightforward to deploy it on the OmegaCAM archive that is heterogeneous in terms of seeing properties and image depth. A machine-learning approach was done by Irureta-Goyena et al (2025). They develop a pipeline in which a single image is automatically segmented by the Convolution Neural Network TernausNet. This is an evolved form of a UNET architecture. They achieve a completeness of 65% for S/N>3 appearances on a set of 276 visually confirmed NEO appearances in OmegaCAM r-band images. This appears a higher completeness than Saifollahi et al (2023) but this is somewhat comparing apples to oranges as the datasets are not identical. Furthermore, as this approach is a blind search it comes with false positives: the purity is estimated at 44%.

The Euclid Wide Survey, which started nominal survey operations 14 Feb 2024, is expected to contain of order 15000 detectable Near-Earth Asteroids (Carry 2018). For Euclid, Pöntinen et al (2023) developed a Convolution Neural Network for asteroid detection that has six convolution layers and a dense layer. The training is done with a YOLO loss function and is based on simulated Euclid VIS images. For simulated images, it surpasses the asteroid detection completeness (recall)
achieved by a traditional segmentation-based pipeline, detecting both fainter asteroids by 0.25–0.5 magnitudes and slower-moving asteroids resulting in a 50% increase in detected asteroids.

As a next step forward we plan to develop a multi-class object detector and classifier pipeline for linear features suited for OmegaCAM, Euclid and LSST. We have started on OmegaCAM. For the asteroid streaks this project takes inspiration from Irureta-Goyena et al (2025) and Pöntinen et al (2023) and evaluate the usage of Vision Transformers. It shall generalize from asteroids to detecting and classifying satellites in OmegaCAM images we take inspiration from Stoppa et al (2024) and Paillassa et al (2020). The next steps after this are to generalize to more classes of linear features and to generalize to the Euclid and LSST surveys.

3 NEO polarimetric characterization

VSTPOL, the polarimetric mode of OmegaCAM 1 square degree imager at the VLT Survey Telescope is planned to be commissioned in 2026 (Schipani et al 2024). For

NEOs the linear polarization signal depends on refractive index of the surface material (and the angle between the incident and scattered Solar light of each scattering). NEOs can be viewed under large phase angles, sometimes exceeding 90◦, when polarisation levels may reach values of 10%-30% (Bagnulo et al 2024). This allows one to distinguish between a large and dark object and a small and bright object by combining VST's optical polarimetric results with optical photometry. VSTPOL is useful to especially quickly constrain size and composition of Near-Earth Objects for Planetary Defence purposes. Polarimetry allows to characterize object composition and size by combining a few polarimetric measurements with photometry. VSTPOL's combination of polarimetric accuracy and large field of view allows it to characterize new Near-Earth Objects with limited orbital knowledge, but significant chances of collision with Earth in the short term.

4 Astronomical science with NEOs

We plan to use our NEO and general asteroid astrometry, photometry and polarimetry also for astronomical science. Precision absolute astrometry by itself can help put on constraints on theories of non-standard gravity using the asteroids as "test particles" in the Solar System gravitational field (Tsai et al. 2023).
Combining optical polarimetry and photometry with thermal infrared photometry plus optical/near-IR spectroscopy can lift in detail the degeneracies between object size and albedo to provide definitive constraints on surface topology, physical composition and object size (Bagnulo et al 2024). This shall help constrain for example the role of NEOs and asteroids for life on Earth beyond the topic of planetary defence: NEO impacts as bringers of prebiotic material (Oba et al. 2022) and inducers of climate change (Brugger et al 2017).

5 NEOs and Astronomical Research Data Platforms

We want to develop our pipeline for the detection and classification of NEOs (and asteroids in general) as a generic software component that is straightforward to configure for different surveys and can be interfaced or embedded in various astronomical data handling systems. Furthermore, we want to interface our machine-learning-based pipelines to existing Big Data research platforms in a way that minimizes human overhead ("babysitting", manual steps), is performant (quick results) and is green (not too much energy produced by inefficient brute force computations and operations). One of our partners is the OmegaCEN Astronomical Science Data Center at the University Groningen[1]. This center has a leading role in digital Big Data platforms for ESA (Euclid Mission[2]) and for ESO instrumentation (VST-OmegaCAM, VLT-MUSE, ELT-MICADO[3]/METIS). These platforms build on their AstroWISE Information System, which was developed for astronomical research (Begeman et al. 2013). So at least for these systems we are in a good

[1] https://www.rug.nl/research/kapteyn/onderzoek/areas/instrumentation_data
[2] see also Euclid Netherlands Science Data Center
[3] see also MICADOwise.org

position to develop a NEO discovery and characterization pipeline that interfaces well with these platforms and their massive data archives, compute clusters, and databasing.

From pathfinder projects involving the expertise of ESA's Planetary Defence and NEO Coordination Centre and the OmegaCEN team we have learned the following lessons learned from taking this piggybacking approach of connecting a NEO pipeline to a Big Data research data platform whose architecture is driven by Galactic/extragalactic science. The synergies between NEO investigations and astronomical science lie in (i) common instrument and software requirements on astrometric and photometric precision calibration and (ii) common requirements on databasing and IT to handle such large datasets. The challenges lie in bridging the gap between communities and the sometimes non-natural fit with the traditional tasks of universities and science funding agencies. One way in which we address this challenge is our future plan to link the astronomical databases to the open-source Tudat orbit estimation software for automated ephemeris updates of target NEOs, and dynamical validation of new observations.

We close with providing a pointer to relevant publications involving our expertise group on the Astrophysics Data System: NEO Planetary Defense library.

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