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Sequential Multi-Target Detection and Tracking of Low SNR Near-Earth Objects

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Traditional approaches for discovering Near-Earth Objects (NEOs) include a moving target indicator approach which involves identifying objects that move relative to the background stars in a sequence of optical images [1]. Automated software pipelines on major optical CCD surveys such as Pan-STARRS and Catalina Sky Survey (CSS) can produce tracklets of known and unknown asteroids in almost real-time. Recently, these methods have been extended for detecting and tracking multiple-objects simultaneously [2]. These methods, which are characterized as Detect-Before-Track (DBT), perform well when the apparent magnitude of the object of interest is sufficiently high compared to the noise floor and the limiting magnitude of the instrument. As the planetary defense community seeks to catalog dimmer NEOs over time, these DBT methods are no longer sufficient as individual images of the object do not contain enough signal that can be extracted (typically under SNR 2), resulting in a miss-detection. This motivates the development of Track-Before-Detect (TBD) methods in which all the data collected, including the pixel values, is used to simultaneously detect and track the objects as opposed to detecting the objects first by a thresholding approach.

In 2014, Shao et. al popularized the method of synthetic tracking for detecting NEOs. This well-established method, which has classically been used by NEO community, relies on acquiring many subsequent short exposures of a NEO of interest, thereby “freezing” their motion in an individual image

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[3]. An appropriate velocity vector is then computationally searched for by shifting successive frames relative to each other and then co-adding the shifted frames to create a long-exposure image as if a telescope were tracking the object. This method significantly decreases the losses due to a longer streaked image of the NEO since all of the signal is synthetically collected in a few pixels hence increasing the photometric signal-to-noise ratio (SNR) of the object. This batch-processing approach performs well if all of the images that are shifted-and-stacked contain some signal from the object, which is definitely not guaranteed during blind detection of NEOs.

In this paper, we formulate the problem of detecting low SNR NEOs using an information-theoretic Bayesian approach in which the position, velocity as well as the intensity of the NEO is estimated sequentially. We introduce a novel intensity-marginalized likelihood function as an effective "detector" that allows for computing and updating the probability of existence of a NEO as more data is collected. This approach also leverages Finite Set Statistics (FiSSt) based Multi-Bernoulli filter to jointly detect and track multiple NEOs as well as model the birth and death of NEO targets in images. In blind detection and discovery of new NEOs, this becomes crucial since the position and velocities of new objects are not known a priori. Preliminary results show that in the case of blind detection and discovery of NEOs, this novel method is superior to the widely used Synthetic tracking approach (see results in the Appendix). The contributions from this paper include the following:

1. Introduce sequential detection and tracking of low signal-to-noise ratio NEOs using intensity-marginalized likelihood function
2. Compare the performance of the proposed method to the current state-of-the-art synthetic tracking
3. Demonstrate the results on real data of Centaur R/B 2020 SO (originally classified as a NEO) using ground-based optical telescope observations collected by the Lunar and Planetary Laboratory at University of Arizona.

Additional Information:
Topic Area - Advancements in NEO Discovery

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Appendix

Results from Blind Detection of a single NEO

This section shows the preliminary results on simulated data and compares the performance of the proposed method to Synthetic tracking. In this simulation, a 50 image sequence of a single NEO is generated in which the NEO is not sunlit for the first 29 frames. On the 30^{th} frame, the NEO appears at the center of the image with low signal-to-noise ratio. Figure 1 shows a sample image from the dataset with a NEO at the center of the frame.

To realize the best case scenario, synthetic tracking is initialized with true velocity of the NEO. In this case, synthetic tracking boils down to simple stacking of the shifted images. The paper on synthetic tracking by Shao. et al discusses the false alarm rate associated with low pixel SNR threshold and uses an SNR detection threshold of $\sim$7. This implies that as the data is shifted and stacked, a detection of a NEO is confirmed if the pixel SNR reaches a value of 7 or higher.

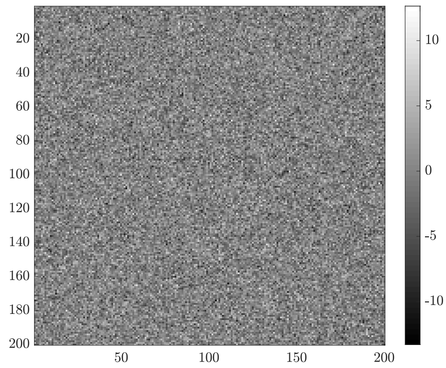
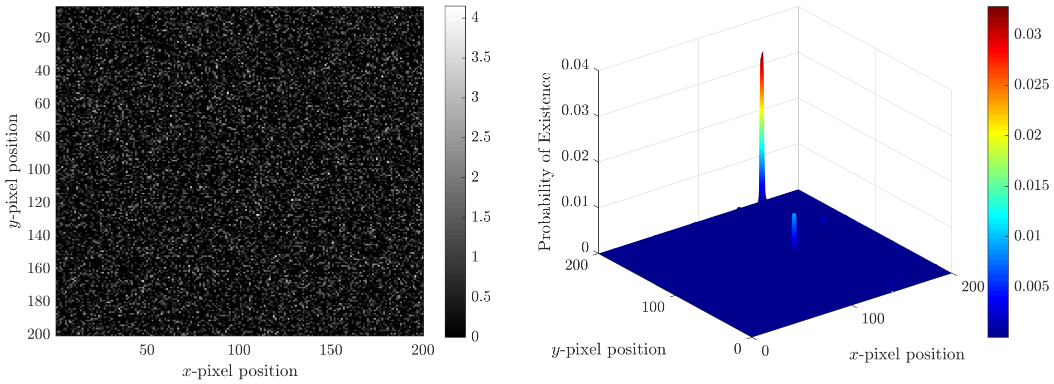


Figure 1: Sample image from the simulation showing the NEO with noise. Note that the object is barely visible in the center of the image.

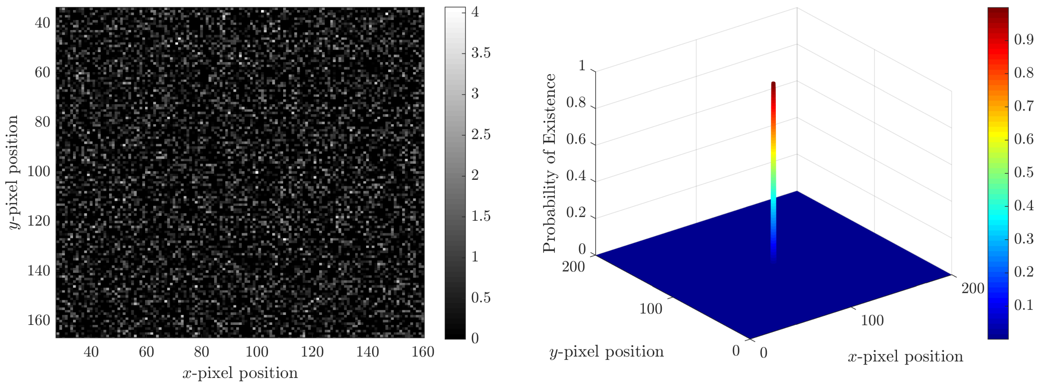
To compare the results from the proposed method, the pixel SNR of the stacked image is plotted. To confirm a detection from the proposed method, the probability of existence of an object is computed over the entire image. When this probability increases above a certain threshold, 0.95 for this simulation, a detection of a NEO is confirmed. Note that the proposed method is not initialized with the true velocity of the NEO and therefore has to simultaneously detect and track the object.



(a) Synthetic Tracking - Pixel SNR map after 29^{th} frame.

(b) Proposed Method - Probability of Existence map after 29^{th} frame.

Figure 2: Pixel SNR from synthetic tracking & existence probability from proposed method after frame 29. Note that the object appears in frame 30.



(a) Synthetic Tracking - Pixel SNR map after 37^{th} frame.

(b) Proposed Method - Probability of Existence map after 37^{th} frame.

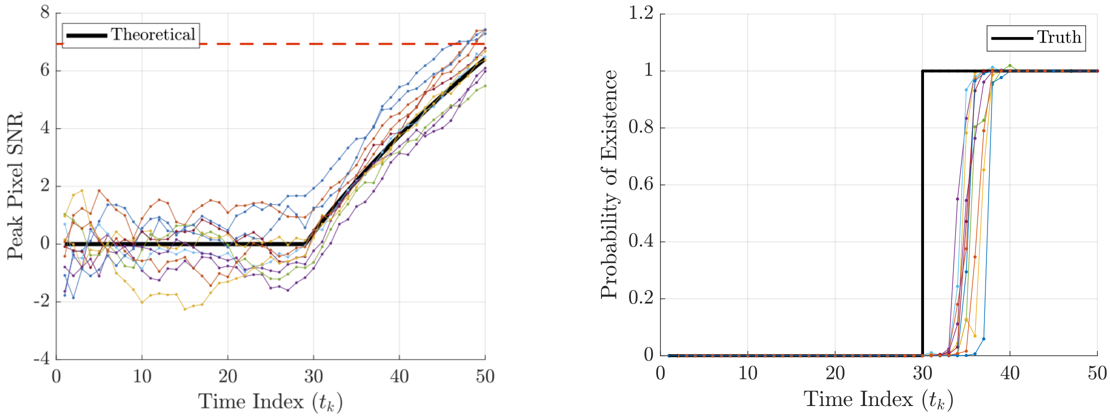
Figure 3: Pixel SNR from synthetic tracking & existence probability from proposed method after frame 37.

Figure 2 shows the results after processing the first 29 frames from the dataset. Since the object appears in the 30^{th} frame, we expect synthetic tracking to stack noise for the first 29 frames. Additionally, we expect the probability of existence of an object from the proposed method to be small and it is 0.04.

Figure 3 shows the results after processing the first 37 frames, i.e. 7 frames after the NEO appears. In this case, synthetic tracking is only able to increase the object's peak pixel SNR to just above 4, which is well under the SNR threshold of 7. Hence, it is barely visible in the stacked image. However, the proposed method estimates the probability of existence of an object at the center of the frame to be 0.99 and therefore confirms the NEO detection.

Additionally, 10 Monte Carlo runs are performed to compare the results to the theory. It is well-known that image stacking increases the SNR by the square-root of the number of images used. Therefore, we expect synthetic tracking to increase the SNR after the object appears in the 30^{th} frame. Additionally, the expected probability of existence increases from 0 to 1 after the object appears in the 30^{th} frame.

This implies that the proposed method is able to blindly detect the NEO with less data than synthetic tracking. This is due to the fact that synthetic tracking is stacking "data", which results in adding noise for the first 29 frames. Hence, many more frames are required after the object appears to increase the overall SNR of the object in the stacked frame. However, the proposed method is stacking "information", in some sense. Therefore, when the object is not present in the first 29 frames, the information content is therefore close to zero. Hence, when the object appears and the information increases, the proposed method is able to quickly confirm the NEO detection. This distinction will be shown mathematically in the final paper.

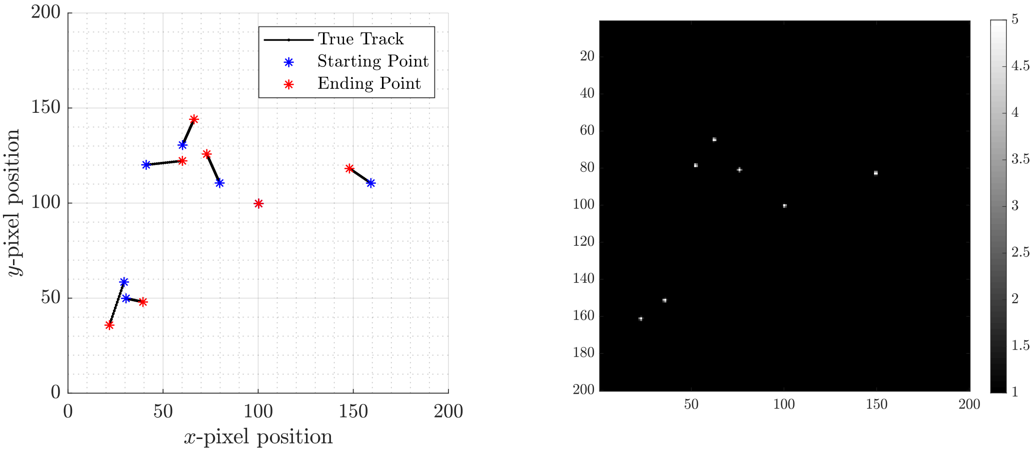


(a) Synthetic Tracking - Peak Pixel SNR as the data is processed. (b) Proposed Method - Probability of Existence.

Figure 4: Pixel SNR from Synthetic Tracking & existence probability from proposed method compared over 10 Monte Carlo runs. Note that the object appears in frame 30. It is important to note that in order to reach a pixel SNR of 7 using synthetic tracking, theory suggests that more than 50 frames are required, i.e. more than 20 frames from when the target initially appears. However, the proposed method confirms the target's existence well under 40 frames, i.e. under 10 frames from when the target initially appears, based on the Monte Carlo runs.

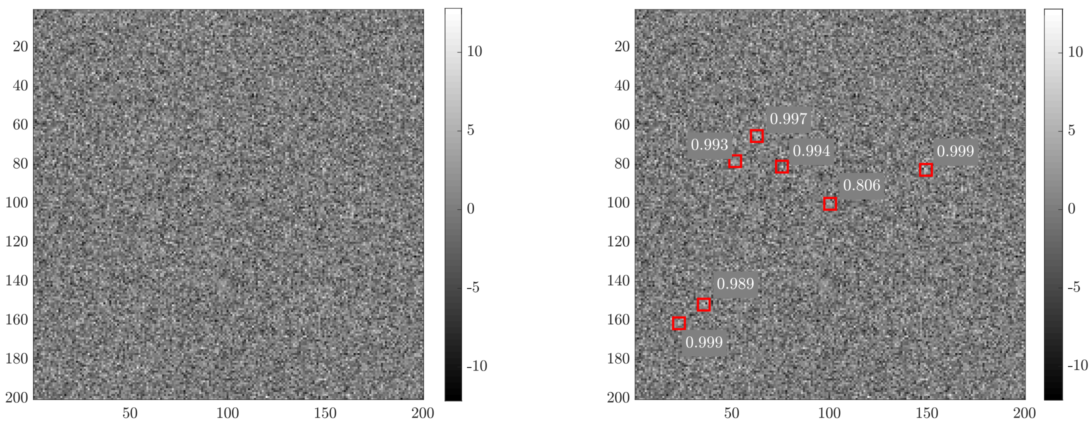
Multi-Target Results

This section shows the preliminary results of the proposed method for tracking multiple targets simultaneously on simulated data. A sequence of 45 images containing 7 NEOs are generated in which the peak pixel SNR of the objects vary from 1.6 to 2.1. Figure 5a shows the true tracks of the objects in pixel space. Note that all the objects appear and disappear from the images at different times. Figure 5b shows the true object intensities and their location without noise for the 18$^{\text{th}}$ frame of the dataset. Figure 6a shows the same objects with noise corresponding to the 18$^{\text{th}}$ frame of the dataset. Finally, Figure 6b shows the same image overlayed with the position estimates from the filter along with the estimated probability of existence of each object.



(a) True object locations over 45 frames. (b) Object locations & intensities for 18$^{\text{th}}$ frame.

Figure 5: True target tracks along with their intensities.



(a) Noisy image.

(b) Target detections overlayed.

Figure 6: Image 18 of the dataset. The left image shows raw frame and the right image shows the target estimates from the filter along with the probability of existence.