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Unified Analysis of Harris Hawks and Hybrid Black Widow–Elephant Herding Optimization in SFFrFT-Based GMTI

[1]Talla Neelima, [2]Tirumala Krishna Battula
[1]Research Scholar, Department of ECE, University College of Engineering Kakinada, JNTUK, Andhra Pradesh, 533003, India.
[2]Department of ECE, University College of Engineering Kakinada, JNTUK, Andhra Pradesh, 533003, India.
Email-ID: neelimashan20@gmail.com[1], tkbattula@gmail.com[2]
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ABSTARCT

Ground moving target indication (GMTI) in synthetic aperture radar (SAR) remains difficult when weak or slowly moving targets are embedded in stationary clutter. The two reference studies address this problem through simplified fractional Fourier transform variants whose fractional power is tuned by meta-heuristic optimization. The first study develops adaptive SFrFT (A-SFrFT) using trio updating Harris Hawks optimization (TU-HHO), while the second develops improved SFrFT (ISFrFT) using hybrid black widow-elephant herding optimization (HBWEHO). This paper provides a unified analysis of both strategies, focusing on their shared signal model, fractional-domain target estimation, optimization objectives, convergence behavior, localization evidence, and computational implications. The synthesis shows that both approaches recast Doppler parameter estimation as an error-minimization problem in which the fractional transform order is selected to concentrate moving-target energy while dispersing clutter. TU-HHO is positioned as an exploitation-oriented adaptive search mechanism, whereas HBWEHO is positioned as a diversity-preserving hybrid search mechanism. Together, the studies indicate that optimized SFrFT processing can improve target localization and reduce computational cost compared with baseline SFrFT and several single meta-heuristic variants. The paper also identifies limitations in comparability, statistical reporting, and real-data validation, and proposes a consistent evaluation framework for future GMTI research.

Keywords: ground moving target indication, synthetic aperture radar; simplified fractional Fourier transform, Harris Hawks optimization, black widow optimization, elephant herding optimization, Doppler parameter estimation.

I. INTRODUCTION

GMTI is a core capability for surveillance, reconnaissance, transportation monitoring, and remote sensing applications. In SAR-based GMTI, the processing chain must distinguish a target response from background clutter while also estimating position and radial velocity. This separation is not straightforward because stationary clutter can distort the interferometric phase, weak moving targets may be hidden by low signal-to-clutter ratio (SCR), and multiple targets may exhibit different Doppler behavior during the same collection interval. The reference papers by Talla and Battula approach this problem through fractional Fourier processing. The earlier study proposes a novel intelligent GMTI model in which A-SFrFT is optimized by TU-HHO. The later study extends the same research direction by proposing ISFrFT optimized through

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HBWEHO. Both papers retain the central SFrFT idea: rotate the signal into a fractional domain where a moving target with suitable Doppler parameters forms a concentrated spectral peak while clutter remains more diffuse. The important design question is therefore not whether fractional processing is useful, but how the fractional power should be selected in a noisy and target-dependent scene. This article unifies the two methods under a common view. SFrFT is treated as the transform-layer mechanism, and the meta-heuristic method is treated as the search-layer mechanism. The fractional power is optimized by minimizing the error between actual and estimated target position. The resulting framework links radar signal processing, fractional-domain filtering, and population-based optimization into a single GMTI pipeline.

II. TECHNICAL BACKGROUND

Classical GMTI techniques such as displaced phase center antenna (DPCA), along-track interferometry (ATI), matched filtering, range cell migration processing, and sub-aperture processing have been widely used for detecting moving targets. These methods can suppress clutter or infer velocity, but their performance may degrade when the target response is weak, when targets overlap with stationary scattering, or when the assumed motion model is too restrictive. The two reference studies therefore motivate a transform-domain method that is better suited to chirp-like Doppler behavior. The fractional Fourier transform (FrFT) generalizes the ordinary Fourier transform by representing the signal in an intermediate time-frequency plane. For SAR GMTI, this is attractive because Doppler frequency and Doppler modulation rate can be interpreted through a fractional rotation. Simplified FrFT removes steps that are unnecessary for target detection, creating a lighter transform that can still focus moving-target energy. Once a target produces a narrow impulse-like response in the selected fractional domain, a filtering and inverse-transform process can iteratively recover strong and weak moving targets. Both papers define the optimization objective around fractional power. In compact form, the objective is to choose a fractional power f that minimizes an error function between the actual target position A and the estimated position B. The TU-HHO paper refers to this as adaptive SFrFT because the fractional power is tuned over a bounded interval. The HBWEHO paper refers to it as improved SFrFT because the transform is paired with a hybrid search process intended to improve detection accuracy and reduce error.

III. METHODOLOGICAL SYNTHESIS

3.1.TU-HHO with Adaptive SFrFT

The TU-HHO-A-SFrFT model enhances the Short-Time Fractional Fourier Transform (SFrFT) through a trio updating variant of Harris Hawks Optimization (HHO). Conventional HHO is inspired by cooperative prey-capture behavior and alternates between exploration and exploitation phases. In the Ground Moving Target Indication (GMTI) framework, the search variable is not a direct target label but the fractional power that governs signal rotation. The trio updating modification strengthens population evolution by guiding candidate solutions toward lower localization error while preserving sufficient diversity to avoid premature convergence. The study compares TU-HHO-A-SFrFT with SFrFT, GWO-A-SFrFT, JA-A-SFrFT, SSA-ASFrFT, and HHO-A-SFrFT. Experimental results demonstrate that the proposed approach produces target coordinates that are closer to the actual target positions in both single-target and three-target scenarios. Furthermore, computational analysis indicates that TU-HHO-ASFrFT achieves a processing time of 105.11 time units, which is lower than the reported values for the GWO, JA, SSA, and HHO-based variants. The

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authors also report superior convergence characteristics and lower Root Mean Square Error (RMSE) values across optimization iterations.

3.2.HBWEHO with Improved SFrFT

The HBWEHO-ISFrFT model combines Black Widow Optimization (BWO) and Elephant Herding Optimization (EHO) to optimize the fractional power of the Improved Short-Time Fractional Fourier Transform (ISFrFT). Black Widow Optimization contributes reproduction, cannibalism, and mutation-inspired diversity mechanisms, whereas Elephant Herding Optimization introduces clan-based updating and separation behaviors. Within the GMTI framework, these complementary strategies are employed to minimize target estimation error through efficient optimization of the fractional power parameter.

The proposed HBWEHO-ISFrFT approach is evaluated against PSO-ISFrFT, EFO-ISFrFT, BWO-ISFrFT, EHO-ISFrFT, and the baseline SFrFT method. The reported results indicate improved convergence speed, superior fitness values, enhanced target localization accuracy, and reduced computational cost. In Scenario 1, the proposed method achieves a computation time of 0.029597s, compared with 0.13842s for PSO-ISFrFT, 0.16462s for EFO-ISFrFT, 0.07509s for BWO-ISFrFT, and 0.20214s for EHO-ISFrFT. In Scenario 2, HBWEHO-ISFrFT further reduces the computation time to 0.007229s, outperforming all comparator methods. These results demonstrate the effectiveness of the hybrid optimization strategy in improving both computational efficiency and localization performance.

IV. COMPARATIVE ANALYSIS

The two approaches share a common signal-processing foundation but differ in their strategies for exploring the fractional-order search space. TU-HHO represents an enhancement of a single optimization family, with its primary contribution being the improvement of population updating behavior within the Harris Hawks Optimization (HHO) framework. In contrast, HBWEHO adopts a cross-family hybridization strategy, combining the search mechanisms of Black Widow Optimization (BWO) and Elephant Herding Optimization (EHO). This distinction is important in Ground Moving Target Indication (GMTI) applications because effective target detection often requires both strong exploitation and sufficient diversity. Exploitation is beneficial once a promising target peak has been identified, whereas diversity helps avoid deceptive local optima caused by clutter, multiple targets, or slow-moving objects.

A direct numerical comparison between TU-HHO and HBWEHO should be interpreted cautiously. The reported runtime units, implementation environments, comparator methods, target scenarios, and initialization parameters are not identical. TU-HHO was implemented in MATLAB 2020a using a population size of 10 and 100 optimization iterations, whereas HBWEHO was implemented in Python with population sizes ranging from 20 to 100 and 100 iterations. Consequently, the appropriate conclusion is not that one optimizer is universally faster than the other, but rather that both studies support the broader hypothesis that meta-heuristic optimization of fractional powers enhances SFrFT-based GMTI performance.

From a localization standpoint, both methods reduce the discrepancy between estimated and actual target coordinates when compared with conventional transform-based processing. In the TU-HHO study, the actual target coordinates were reported as (7.0943, 21.088), while TU-HHO-A-SFrFT estimated (6.5239, 19.392), yielding results closer to the ground truth than competing methods. Similarly, in the HBWEHO study, the Scenario 2 three-target experiment reported estimated coordinates of (42.024, 36.355), (44.032, 30.093), and

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(1.6389, 38.968), compared with actual values of (45.787, 39.61), (47.975, 32.787), and (1.7856, 42.456), demonstrating improved localization performance.

Table 1: Comparison of TU-HHO-A-SFrFT and HBWEHO-ISFrFT Approaches

Dimension	TU-HHO with A-SFrFT	HBWEHO with IS-FrFT	Unified Interpretation
Optimization Target	Tunes the SFrFT fractional power by minimizing target position error.	Optimizes the ISFrFT fractional power to reduce detection and localization error.	Both methods formulate fractional-power selection as a data-driven optimization problem.
Search Behavior	HHO exploitation capability is strengthened through a trio updating rule.	Black widow reproduction mechanisms are hybridized with elephant herding clan updates.	The former emphasizes coordinated exploitation, while the latter balances diversity and guided population movement.
Reported Run-time	105.11time units compared with 111.36–115.05 for competing adaptive SFrFT variants.	0.029597 s in Scenario 1 and 0.007229 s in Scenario 2, outperforming PSO, EFO, BWO, and EHO variants.	Both studies report runtime improvements, although direct comparison is difficult because experimental settings differ.
Reported Accu-racy	Produces target coordinates closer to ground truth than SFrFT, GWO, JA, SSA, and standard HHO in singletarget and three-target experiments.	Produces target coordinates closer to ground truth than SFrFT, PSO, EFO, BWO, and EHO in the reported scenarios.	Both approaches improve localization accuracy after clutter suppression and fractional-domain filtering.

V. PROPOSED UNIFIED FRAMEWORK

A unified SFFrFT-based GMTI workflow can be formulated as a six-stage processing framework. Here, the term *SFFrFT* serves as an umbrella designation encompassing adaptive, improved, and optimization-enhanced simplified fractional Fourier transform techniques.

1. Acquire multi-antenna SAR returns and register channel responses to ensure consistent clutter cancellation across channels.
2. Suppress stationary clutter using Along-Track Interferometry (ATI) or Displaced Phase Center Antenna (DPCA) differencing while preserving moving-target phase information.
3. Transform the clutter-reduced signal using SFrFT over a range of candidate fractional powers.
4. Employ a meta-heuristic optimization algorithm to identify the fractional power that minimizes localization error or maximizes target-energy concentration.
5. Apply narrowband filtering in the fractional domain and subsequently perform the inverse transform to recover the target signal component.

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6. Estimate Doppler parameters, target position, and velocity, and iteratively repeat the process until all expected targets have been extracted.

The unified framework highlights the common operational principle underlying both TU-HHOA-SFrFT and HBWEHO-ISFrFT approaches. While the optimization strategies differ, both methods leverage meta-heuristic search to adaptively determine the optimal fractional-domain representation, thereby improving clutter suppression, target localization accuracy, and computational efficiency in GMTI applications.

VI. DISCUSSION

The primary strength of the proposed unified framework lies in treating the fractional power as an adaptive and learnable processing parameter rather than a manually selected transform setting. This characteristic is particularly important for Ground Moving Target Indication (GMTI) applications because clutter characteristics, target velocities, antenna configurations, and Signal-to-Clutter Ratio (SCR) values vary significantly across operating environments. When the fractional order is not appropriately selected, moving-target energy may become dispersed within the transform domain, reducing detection effectiveness. Conversely, an optimized fractional order enables stronger target-energy concentration and more effective separation of moving targets from background clutter.

The TU-HHO strategy is particularly suitable for scenarios where the optimization landscape is relatively smooth and where rapid exploitation of promising candidate solutions is advantageous. Since it extends the conventional Harris Hawks Optimization framework rather than replacing it entirely, TU-HHO offers a natural progression for comparison with other HHO-based radar signal processing techniques. In contrast, the HBWEHO strategy is better suited to complex multimodal search spaces and multi-target environments. By combining the population diversity mechanisms of Black Widow Optimization with the clan-based guidance mechanisms of Elephant Herding Optimization, HBWEHO broadens the search capability while maintaining convergence toward high-quality solutions. Consequently, in practical GMTI systems, the choice between TU-HHO and HBWEHO may depend less on average benchmark performance and more on robustness under varying operational conditions.

The reviewed studies also reveal several methodological limitations that should be addressed in future research. First, convergence plots and reported percentage improvements should be consistently interpreted with respect to the optimization objective, ensuring that lower objective values are explicitly identified as improved performance when appropriate. Second, computational time comparisons should be conducted on a common implementation platform or normalized through equivalent operation counts to facilitate fair evaluation. Third, both simulated and real Synthetic Aperture Radar (SAR) datasets should be reported using consistent scene descriptions, including target motion characteristics, SCR values, clutter models, and optimization parameter bounds. Finally, statistical significance testing should clearly distinguish between failure to reject a null hypothesis and conclusive evidence of algorithmic superiority. Despite these limitations, the two studies collectively provide valuable contributions to the advancement of fractional-domain GMTI processing. Both demonstrate that optimization-based fractional-order selection can significantly enhance target-energy concentration, clutter suppression, and Doppler parameter estimation. Their findings support the broader conclusion that optimized SFrFT-based techniques offer a promising direction for improving target detection and localization performance in SAR-GMTI applications.

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VII. FUTURE SCOPE

Future research directions emerging from this comparative analysis include:

- Developing a unified benchmark framework using identical antenna geometries, SCR values, target quantities, population sizes, and iteration limits for TU-HHO, HBWEHO, and other optimization algorithms.
- Evaluating the performance of optimized fractional-domain methods on real SAR datasets containing weak and slow-moving targets, where fractional-domain focusing is expected to provide the greatest benefit.
- Reporting key performance metrics, including localization error, RMSE, detection probability, false alarm rate, computational time, and memory consumption, within a standardized comparison framework.
- Investigating adaptive optimizer-selection strategies in which TU-HHO is employed for stable single-target environments while HBWEHO is activated in the presence of multimodal clutter or multiple target signatures.
- Exploring lightweight hardware-aware implementations suitable for real-time airborne and embedded GMTI systems with limited computational resources.
- Extending fractional-domain optimization techniques to emerging radar platforms, including multi-static SAR, cognitive radar systems, and autonomous surveillance applications.

VIII. CONCLUSION

This paper presented a unified analysis of Harris Hawks Optimization and Hybrid Black Widow– Elephant Herding Optimization for SFFrFT-based Ground Moving Target Indication (GMTI). The comparative synthesis demonstrates that both studies are founded on the same fundamental principle: the effectiveness of simplified fractional Fourier processing depends heavily on the selection of an appropriate fractional power. TU-HHO-A-SFrFT enhances this selection process through an improved HHO updating strategy, whereas HBWEHO-ISFrFT achieves similar objectives through the integration of black widow and elephant herding population dynamics. The reported experimental results indicate that both optimized transform variants improve convergence characteristics, localization accuracy, and computational efficiency relative to their respective baseline approaches. However, these findings should be viewed as complementary rather than directly competitive because the studies employ different implementation environments, parameter settings, and evaluation scenarios. Consequently, the most defensible conclusion is that optimization-driven SFFrFT processing represents a promising research direction for SAR-GMTI systems, particularly in environments characterized by strong stationary clutter, low SCR conditions, and multiple moving targets.Overall, the reviewed evidence suggests that adaptive fractional-order optimization can substantially enhance target concentration and clutter suppression capabilities within the fractional domain. Establishing a unified benchmark platform in future work would enable TU-HHO, HBWEHO, and other meta-heuristic optimization methods to be evaluated under identical radar conditions, thereby providing a more rigorous assessment of their relative strengths and limitations. Such efforts would contribute significantly toward the development of robust, efficient, and operationally deployable GMTI systems.

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