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Target tracking techniques for multi-robot systems: Review on the state-of-the-art

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Abstract. The field of target tracking has long been a focal point in robotics research, gaining particular prominence in the realm of multi-robot systems. Target tracking has extensive applications in diverse areas such as surveillance, search and rescue operations, and environmental detection. This paper presents an exhaustive review of the latest target tracking methodologies employed in multi-robot systems, with an emphasis on scenarios featuring both abundant and limited information availability. The review particularly addresses the challenges posed by conditions including target occlusion (partial or total), uncertainties in robots' positional data, and limitations in sensory and communicative functions. This scholarly piece synthesizes literature sourced from IEEE and Springer publications, spanning the period from 2019 to 2023. This temporal scope ensures a focus on contemporary and pertinent research outcomes. The findings of this paper indicate a significant evolution in the sophistication of target tracking techniques, particularly in complex operational scenarios. These advancements signify a notable maturation in the capabilities of multi-robot systems to efficiently handle intricate and varied tasks.

Keywords: Multi-robot systems, Target tracking, Sensor fusion

1. Introduction

The rapidly evolving field of robotics has found widespread applications across sectors such as healthcare, transportation, and surveillance. As the complexity of tasks increases, the limitations of single-robot systems become apparent, paving the way for the advent of multi-robot systems (MRS). These systems, comprising a cohort of robots, are designed to accomplish tasks that are beyond the capability of a solitary robot. Central to the functionality of MRS is the intricate interplay of coordination, communication, and collaboration among the robots [1].

In the burgeoning domain of multi-robot systems, target tracking has emerged as a significant area of research. MRS are particularly adept at deploying multiple robots to effectively locate, track, and monitor targets within an environment, enhancing the reliability and scope of tracking systems [2]. These systems have found immediate application in critical areas such as search and rescue, environmental monitoring, and other domains demanding high reliability.

The current surge in research focuses not only on refining target tracking techniques but also on understanding and mitigating the impacts of environmental factors on mission success in diverse scenarios. This paper aims to provide a detailed analysis of the prominent target tracking techniques

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developed between 2019 and 2023. It explores methods suitable for both information-rich and information-deficient environments, thereby suggesting avenues for future research. Specifically, the paper reviews three implementations for ideal scenarios and three techniques for scenarios with limited information. The insights gained from this review are instrumental in guiding applications in industries facing similar challenges.

2. Target tracking algorithms

In this segment, this paper undertakes a scholarly examination of six avant-garde methodologies pertinent to target tracking in multi-robot systems (MR-MTT). These methodologies are emblematic of the exceptional innovation and technological progression defining the contemporary MR-MTT landscape. Each methodology is characterized by its unique approach and application, cumulatively enriching our understanding of the field's evolutionary trajectory and the diverse challenges it encompasses. This spectrum ranges from robust algorithms formulated to navigate and adapt in adversarial settings to intricate graph-based techniques developed to enhance the precision of localization. Collectively, these methodologies represent the forefront of innovation in the realm of MR-MTT.

2.1. EDMR-SLTT

The deployment of multi-robot systems (MRS) for target tracking in scenarios demanding high-precision coordination and localization presents a dual challenge: ensuring accurate localization while maintaining robust target tracking. A groundbreaking contribution in this field is the work of Xuedong Wang et al., who have developed an innovative, decentralized approach to simultaneous localization and target tracking (SLTT), using an Extended Kalman Filter (EKF) integrated with Covariance Union (CU), known as EDMR-SLTT [3].

EDMR-SLTT adopts a fully decentralized framework, wherein each robot in the system independently computes and updates estimates of its own position and that of the target. Strategic information exchange between robots occurs only when they can access each other's relative measurements, and this selective communication optimizes efficiency and reduces computational load [3]. A key feature of EDMR-SLTT is its ability to maintain the positive determinism of the joint covariance matrix for the robot and target without computing the correlation term between them [3]. This aspect is critical for achieving robust and accurate tracking in complex MRS environments.

This approach finds significant applicability in domains where GPS signals are absent, such as cooperative transportation, search and rescue operations, and environmental monitoring. In such contexts, EDMR-SLTT excels by employing cooperative localization techniques, treating the target as a dynamic landmark to enhance the precision and reliability of the localization process.

One of the most notable advantages of EDMR-SLTT is its consistent state estimation in a decentralized setting, a marked improvement over the traditional centralized MR-SLTT approach. While centralized systems offer high estimation accuracy, they suffer from scalability limitations and vulnerability to central agent failures. In contrast, EDMR-SLTT stands on par with the existing state-of-the-art methods and effectively balances processing and communication costs, thereby bolstering the robustness and scalability of MRS.

2.2. GNN-based target tracking

In the realm of decentralized multi-robot target tracking, which is inherently dynamic and complex, the primary objective lies in optimizing the collective actions of robots, such as kinematic primitives, to enhance target tracking performance under the constraints of local communication. A significant hurdle in this area is the generalization of these target tracking methods across a diverse array of applications. Addressing this, Lifeng Zhou et al. have pioneered an approach that integrates a generalized learning architecture using a graph neural network (GNN) [4]. This model excels in capturing localized interactions between robots, thereby enabling decentralized decision-making. The learning model undergoes training through the emulation of expert solutions, focusing on decentralized action selection based purely on local observations and communication [4].

This methodology finds widespread application in robotics fields like surveillance, patrol, monitoring, and search and rescue, where teams of robots function as mobile sensors collaboratively planning actions to meet specific tracking objectives [4]. These objectives, such as maximizing the number of tracked targets or reducing uncertainty in their locations, are inherently submodular, characterized by diminishing returns and encompass metrics like entropy, mutual information, and visibility region.

One of the challenges in these scenarios is implementing greedy algorithms, typically used for NP-hard problems of maximizing submodular functions, especially in environments restricted to local communication among robots. To overcome these communication barriers, decentralized versions of the greedy algorithm have been formulated. These algorithms utilize neighborhood information to optimize submodular objectives, involving sequential greedy action selection for each robot and consensus-based mechanisms for multi-hop communication agreement. However, these methods often encounter delays in reaching consensus.

The paper explores learning-based strategies that train policies by emulating expert algorithms, such as greedy algorithms, for a more efficient and scalable approach to decentralized multi-robot target tracking. The GNN-based method proves its effectiveness in active target tracking scenarios involving extensive robot networks. It showcases performance comparable to expert levels and expedited execution, in some instances surpassing decentralized greedy algorithms [4].

2.3. Target tracking with self-triggered communication

In the domain of multi-robot systems, the efficiency of communication strategies plays a pivotal role in the success of decentralized target tracking. Lifeng Zhou's research delves into a scenario where robots operate along an environment's perimeter, aiming to form an optimal formation for tracking a target within that space [5]. Traditional decentralized control strategies typically enable robots to converge asymptotically to this optimal formation. However, these strategies often necessitate a continuous information exchange between robots at every time step, leading to high communication costs.

To mitigate this issue, Zhou's study introduces a novel self-triggered communication strategy. This strategy is designed to determine the optimal moments for a robot to obtain updated information from its neighbors and when it can depend on existing, albeit potentially outdated, data [5]. This method is particularly advantageous in conserving communication resources, thereby prolonging the operational life of the robots and sustaining effective target tracking.

For scenarios involving a moving target, the study presents a decentralized Kalman filter equipped with covariance crossing. This filter enables neighboring robots to share belief states, thus allowing for the amalgamation of local estimates into a unified, more precise estimate of the target's position [5]. This aspect is crucial in decentralized settings where robots have limited information exchange capabilities, leading to varying local target position estimates and impacting tracking accuracy.

The findings of this study, corroborated through simulations and practical experiments, reveal that the self-triggered strategy successfully converges to an optimal formation for target tracking. A significant reduction in communication needs is observed — less than 30% compared to constant communication methods [5]. These outcomes are validated using both simulations and real-world robot implementations, emphasizing the practical feasibility of this approach.

2.4. Target tracking with multi-robot sensor fusion

In mobile robotics, visual tracking stands as a crucial challenge, particularly in addressing the complexities of partial and complete occlusions. Thulio G. S. Amorim and colleagues have made a significant contribution to this area by developing a multi-robot sensor fusion approach for three-dimensional object tracking, employing enhanced particle filters [6]. This method is specifically tailored to overcome the hurdles posed by occlusions, a frequent and intricate issue in dynamic settings.

The essence of this approach is the integration of visual data from multiple robots. Unlike traditional methods that depend on data from a single robot and often falter in occluded scenarios, leading to diminished tracking accuracy, this cooperative strategy leverages data from a collective of robots. The individual observations of these robots are amalgamated using particle filters, effectively overcoming the limitations faced by single robotic systems when dealing with partial or complete occlusions, thereby significantly enhancing tracking performance.

A notable feature of this multi-robot sensor fusion method is its independence from global maps, a requirement that is prevalent in many existing tracking systems. This independence bestows the system with increased flexibility and adaptability, enabling efficient operation across diverse environments. Moreover, the approach exhibits robustness against occlusions, crucial for sustained and precise tracking in real-world scenarios.

Empirical evaluations reveal a balance between computational demands and tracking precision [6]. While the non-cooperative method is less computationally intensive, its tracking effectiveness substantially wanes in occlusion scenarios [6]. Conversely, the cooperative strategy, despite its higher computational load, consistently maintains accurate tracking, unaffected by occlusions, due to its proficient data fusion technique [6].

In summary, this research presents a substantial advancement in mobile robotics, offering a robust and occlusion-resistant multi-robot sensor fusion approach for visual tracking. Its efficacy is particularly notable in complex environments, outperforming conventional single-robot systems.

2.5. RATT

In the dynamic and challenging field of robotics, multi-robot target tracking, particularly in adversarial environments, presents a formidable challenge. Addressing this, a novel framework known as Robust Active Target Tracking (RATT) has been developed to address the pressing need for strategies resilient to sensing and communication attacks [7]. Such attacks are prevalent in hostile settings, where they can significantly impair a robot's sensors and communications, undermining its tracking capabilities. RATT represents the first robust planning algorithm designed to fortify multi-robot systems against these adversarial actions [7].

A distinguishing feature of RATT is its approach to treating communication attacks as analogous to sensing attacks. This innovative tactic enables simultaneous optimization against both approximate and direct sensing attacks, offering a robust solution to the complex problem of multi-robot coordination in hostile environments. Remarkably, RATT is not only robust but also exhibits efficiency, operating in polynomial time and concluding as swiftly as contemporary non-robust target tracking algorithms [7].

The practical applications of RATT are varied and significant. In surveillance and monitoring, for instance, RATT-equipped robots can effectively track and localize targets, ranging from invasive species in aquatic ecosystems to individuals in search and rescue missions in hazardous environments like burning buildings [7]. The system maintains its tracking efficacy despite potential attacks or malfunctions, ensuring operational reliability in critical situations.

RATT has demonstrated near-optimal tracking quality through both qualitative and quantitative assessments, surpassing various non-robust heuristics in performance [7]. Its robustness has been validated under diverse attack models, including worst-case scenarios, bounded rationality attacks, and varying estimations of the number of attacks [7]. This extensive robustness positions RATT as a pioneering solution in multi-robot target tracking, paving the way for further research and application in sectors where robustness and efficiency are paramount.

2.6. CUV-based target tracking

In the rapidly advancing field of robotics, a novel end-to-end solution for multi-robot target search and tracking (MR-MTT) has been introduced, addressing the critical issue of localization uncertainty inherent in each robot. This solution is transformative in MR-MTT, applicable across surveillance, security, and smart city management. MR-MTT is characterized by two fundamental components: estimation and control. Robots are required to estimate the state of multiple targets over time using noisy sensor measurements and simultaneously execute control strategies to search for new targets while tracking existing ones [8].

The proposed solution introduces the Convex Uncertainty Voronoi (CUV) graph, a novel environment decomposition method that forms the foundation for distributed estimation and control algorithms [8]. This graph facilitates the simultaneous management of collision avoidance and comprehensive environment coverage, vital for effective MR-MTT in dynamic settings. Notably, the CUV graph accounts for the uncertain positioning of each robot, guiding the team toward information-rich areas while ensuring complete area coverage [8].

A key attribute of this solution is its practicality, effectively bridging the gap between theoretical models and real-world applications. Contrasting with many existing approaches that depend on external hardware or central stations for communication, this system is self-sufficient, utilizing onboard sensors for localization. This autonomy from external systems like Global Navigation Satellite Systems (GNSS) enhances its robustness and adaptability, particularly in settings where positioning inaccuracies are significant, and GNSS reliance is impractical [8].

The efficacy of this approach has been corroborated through extensive simulations and hardware tests, affirming its real-world applicability. These tests showcase the system's competence in various conditions, underscoring its broad applicability in multiple domains. The incorporation of a fully distributed communication strategy based on the Robotic Operating System (ROS) further amplifies the efficiency and collaborative potential of the system [8]. This distributed framework of MR-MTT marks a significant progression in robotics, offering a practical and effective solution for complex tracking challenges in uncertain and dynamic environments.

3. Conclusion

The main body of this review paper has meticulously examined the evolving landscape of MR-MTT, shedding light on both the remarkable progress made and the ongoing challenges within this vibrant field. The discussion has encompassed a range of innovative methodologies, including the development of robust planning algorithms like RATT and the advent of the CUV graph. These approaches mark significant strides in overcoming challenges such as localization uncertainty, occlusion dilemmas, and the threat of adversarial attacks in hostile environments.

Notably, these advancements have not only fortified the robustness and efficiency of MR-MTT systems but have also expanded their utility across various sectors, including surveillance, search and rescue operations, and smart city management. The trend towards decentralized systems and the fusion of advanced algorithms highlight a move towards greater autonomy and resilience in robotic systems.

Despite these achievements, there are areas that necessitate further refinement. The equilibrium between computational efficiency and tracking precision, especially in decentralized systems, remains a critical focus. Moreover, the dependency on existing communication infrastructures and sensor technologies is a constraint that future research endeavors must seek to overcome.

Looking ahead, future research in MR-MTT is set to concentrate on the development of more adaptive, scalable, and energy-efficient algorithms. The potential integration of cutting-edge technologies such as artificial intelligence and machine learning promises to usher in a new era in this domain, paving the way for more intelligent and autonomous multi-robot systems capable of functioning in increasingly intricate and unpredictable environments. Such advancements are expected to have widespread implications, transcending the realm of robotics and impacting a multitude of sectors where efficient and dependable target tracking is crucial.

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