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ADAPTIVE AND ROBUST MULTI-ROBOT COORDINATION FOR PERIMETER SURVEILLANCE

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Abstract

Multi-agent perimeter surveillance is an active area of research for robotics and autonomous systems. Efficient surveillance of large or complex perimeter boundaries requires distributed coordination algorithms for teams of agents. Several approaches have been explored using unmanned aerial vehicles (UAVs), ground robot swarms, or heterogeneous teams. Com- mon goals include detecting and tracking intruders, maintaining surveillance coverage over time, and adapting to uncertainties. Key techniques include decentralized control without relying on global information, emergent coordination between agents through local interactions, and distributed task allocation. Specific methods leverage maintaining dynamic communication networks between UAVs, virtual pheromones for swarm robot coordination, and integrated aerial and ground capabilities. The papers provide algorithms and simulation results demonstrating decentralized perimeter surveillance strategies. Open challenges include balancing surveillance coverage and agent connectivity, tuning agent coordination parameters, and field testing integrated systems. The research area combines aspects of distributed robotics, multi-agent systems, and swarm intelligence for perimeter security applications.

Index Terms: multi robot, decentralized algorithms, perimeter surveillance

I. INTRODUCTION

Perimeter surveillance, a critical component of security systems, demands continuous advancements to address the challenges posed by dynamic and uncertain environments. It form the basis for effective monitoring in a number of applications such as forest fires [1], and border security [2].In recent years, decentralized coordination strategies have emerged as promising solutions for ensuring effective surveillance in such complex scenarios. This paper presents a synthesis of key findings and contributions from various research papers that explore decentralized algorithms for coordinating multi-robot systems engaged in perimeter surveillance.
The landscape of security applications requires surveillance systems to adapt to dynamic changes, uncertainties, and unforeseen events. Traditional centralized approaches face limitations in scalability, adaptability, and fault tolerance. De- centralized coordination, where agents operate autonomously, share local information, and collectively achieve surveillance goals, offers a compelling alternative.

The synthesis delves into a collection of papers, each contributing unique insights and strategies for decentralized perimeter surveillance. The overarching goal is to examine how these decentralized algorithms address challenges such as dynamic team configurations, variations in perimeter length, and the need for robust adaptation to unforeseen circumstances.

By providing a comprehensive overview and analysis of these research papers, this synthesis aims to distil the key principles and findings that define the current state of decentralized coordination for perimeter surveillance. The synthesis not only highlights the effective strategies proposed but also identifies open challenges and suggests potential directions for future research in this evolving domain.

In the subsequent sections, the perimeter surveillance papers are discussed in brief as Methodology in Sections II and in Section III we explore the specific decentralized algorithms presented in the papers, outlining their key components, methodologies, and experimental validations. Section IV presents our synthesis, the focus is on understanding how these algorithms contribute to achieving scalable, adaptable, and fault-tolerant perimeter surveillance, laying the foundation for a decentralized future in security applications and we conclude our paper in Section V.

II. METHODOLOGY

The papers selected for review in this research synthesize key innovations in multi-robot perimeter surveillance. These works were chosen to provide a cross-section of approaches that demonstrate adaptability and robustness when coordinating teams of robots for patrol duties.

Kingston et al. [3] [4] establish core principles of decentralized control for unmanned aerial vehicle (UAV) teams conducting perimeter checks. This provides a useful case study for self-organized surveillance without relying on global information or a central planner. D’Alfonso et al. [5] build on such distributed methods but utilize a swarm intelligence approach to enable more dynamic responses.

Antonio A. Bono et al [6] and G. d. Carolis et al [7] both dis- cuss swarm-based algorithms for target encirclement/capturing using distributed coordination strategies and potential function based control.

Complementing these trailing studies, Jahn et al. [8] and Saldan˜a et al. [9] both tackle surveillance of perimeters in uncertain environments. Their contributions on dealing with incomplete information and changing conditions reveal control strategies to maintain patrol coverage regardless of disturbances.

Additionally, Acevedo et al. [10] address the real-world complication of limited communication capabilities between robots on patrol. Evaluating their cooperative techniques de- spite such restrictions gives practical insight. Finally, Maftuleac et al. [11] introduce triangulation and zoning concepts to maximize efficient sweeping of bounded areas. This offers another perspective on optimization for perimeter surveillance missions.

III. ANALYSIS

A. Decentralized Perimeter Surveillance Using a Team of UAVs [3]

The paper [3] and [4] proposes a decentralized algorithm for a team of UAVs to monitor the perimeter of an area. The key idea is that the UAVs coordinate by only sharing local information with neighbouring UAVs within communication range. No central controller is needed. The algorithm aims to achieve low-latency exchange configurations among the UA Vs, allowing them to effectively monitor a changing perimeter and team size.

The algorithm utilizes two main components: Reference Point Motion: UAVs follow a predefined path determined by rendezvous points and coordination variables. Rendezvous Mechanisms: UAVs exchange information at predefined locations to maintain consistency in coordination variables [3].

Perimeter surveillance using UAVs poses several challenges:

- **Dynamic Team Sizes**: The number of UAVs may change due to various factors, such as battery depletion or mission reassignment.
- **Variations in Perimeter Length**: The perimeter may expand or contract due to changes in the environment or mission objectives.
- **Fault Tolerance:** The algorithm should be able to handle failures or losses of individual UAVs

Proposed Algorithm

The paper introduces two algorithms, Algorithm A and Algorithm B, for achieving low-latency exchange configurations in a decentralized manner

1. **Algorithm A** establishes the foundation for decentralized UAV coordination in perimeter surveillance. It introduces the concept of reference point motion, guiding UAVs along a predefined path determined by rendezvous points and coordination variables. The coordination variables are crucial, enabling each UAV to keep track of its position relative to the perimeter and neighbouring agents. Rendezvous mechanisms facilitate information exchange between agents at predefined points, ensuring coordination variables are consistently updated "Fig. 1"

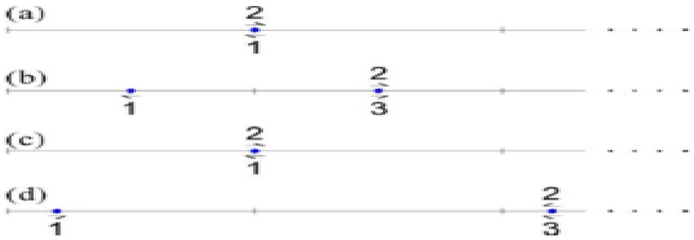


Fig. 1. Possible cases for rendezvous of agent 1 with its neighbour. (a) Agents 1 and 2 separate at their shared border. (b) Agent 2 encounters agent 3 earlier than expected and escorts it to their shared border before reversing direction. (c) Agents 1 and 2 separate at their shared border. (d) Agent 2 encounters agent 3 later than expected and escorts it to their shared border before continuing to meet agent 1. Figure from Kingston et al [3]

Theorem 1 in the paper [3] provides a theoretical guarantee, ensuring finite-time convergence to low-latency exchange configurations when correct coordination variables are known. However, Algorithm A is confined to homogeneous vehicle teams operating on a perimeter homoeomorphic to a line.

2. **Algorithm B:** Building upon Algorithm A, Algorithm B introduces enhancements to address dynamic scenarios. It extends the original algorithm to handle changes in team size and perimeter length effectively. Coordination variable updates become a continuous process during agent meetings, ensuring consistency in the information shared.

Since Algorithm B operates under arbitrary initial conditions, a step change in perimeter or team size would be analysed by simply considering new initial conditions of the team at the time of the step change. Fig. 6 shows agents tracking a changing perimeter and a situation where agents are removed from the team.

Algorithm B accommodates step changes in perimeter size but also allows good tracking for other types of perimeter growth. Dynamic adaptation is a key feature, allowing Algo- rithm B to accommodate agent reassignment, loss, and changes in perimeter size through ongoing communication and updates.

Theorem 2 provides a performance guarantee, assuring convergence to low-latency exchange configurations within a defined time for arbitrary initial conditions. The fault tolerance of Algorithm B is attributed to its finite memory property, enabling adaptation to step changes in perimeter and team size.

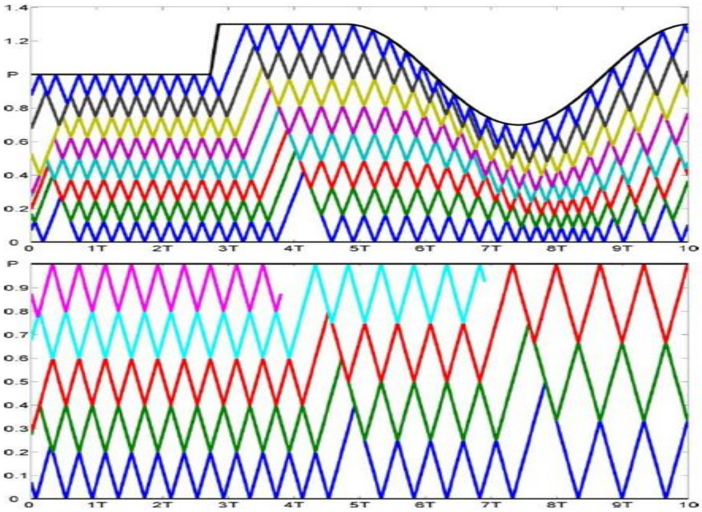


Fig. 2. Team behaviour of agents tracking changing perimeters using Algorithm B to continuously update the coordination variables for cases of (top) changing perimeter and (bottom) changing team size. Figure from Kingston et al [3]

Findings

1. **Simulation Results:** Agents effectively reach the desired steady-state configuration quickly. Exhibit appropriate reactions to step changes in both perimeter length and team size. Overlapping positions in certain regions is due to the UAVs' inability to perform precise U-turn manoeuvres see "Fig. 3"
2. **Flight Test Results:** Normalized positions of UAVs along the perimeter demonstrate the algorithm's effectiveness in a real-world scenario. U-turn manoeuvre limitations and wind disturbances impact precise positioning, but overall behaviour aligns with expectations. The shared-border position slightly deviates from the theoretical prediction due to wind effects. Despite disturbances, UAVs distribute evenly along the perimeter, showcasing fault tolerance and adaptability.

Conclusion: The paper delivers a novel decentralized surveillance solution for UAV teams with promising simulated performance. It tackles coordination challenges using distributed algorithms while meeting key performance metrics with only local UAV interactions.

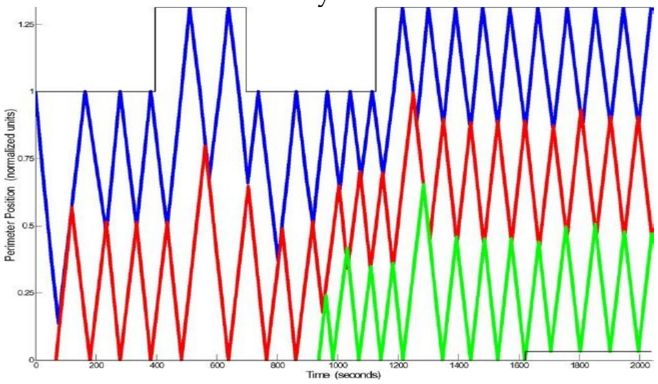


Fig. 3. UAVs are adaptable to environment change. Figure from Kingston et al [3]

B. Dynamic Perimeter Surveillance of Multiagent Systems: A Swarm-Based Approach [5]

The paper" Dynamic Perimeter Surveillance of Multiagent Systems: A Swarm-Based Approach" proposes a novel swarm- based approach for addressing cooperative perimeter surveillance tasks of rectangular areas. The primary goal of the paper is to develop a distributed control law that enables a team of mobile agents to effectively and efficiently patrol a rectangular perimeter while maintaining a consistent formation and avoiding collisions.

1. **Approach:** The proposed approach utilizes a kinematic model for single-integrator multi agent systems that incorporates both cooperative behaviour and obstacle avoidance. The problem is formulated by defining a containment region and a forbidden region as ellipsoids around the targets "Fig. 4" The swarm must operate between these regions. This model combines virtual potential fields and a consensus algorithm to guide the agents towards desired positions and maintain a cohesive formation. Additionally, it employs a collision avoidance mechanism to prevent agents from colliding with each other or with obstacles within the surveillance area.

Virtual potential fields (VPFs) are a well-established technique for obstacle avoidance in mobile robotics. VPFs assign attractive and repulsive forces to different regions of the environment.

Attractive forces pull agents towards desired locations, while repulsive forces prevent them from colliding with obstacles.

The consensus algorithm ensures that the agents maintain a consistent formation. It works by iteratively exchanging information between neighbouring agents and adjusting their velocities to align with the average velocity of their neighbours. Collision avoidance is achieved using a combination of VPFs and a collision detection mechanism. VPFs generate repulsive forces around agents and obstacles, preventing them from getting too close. Additionally, the collision detection mechanism detects potential collisions and takes corrective actions to avoid them.

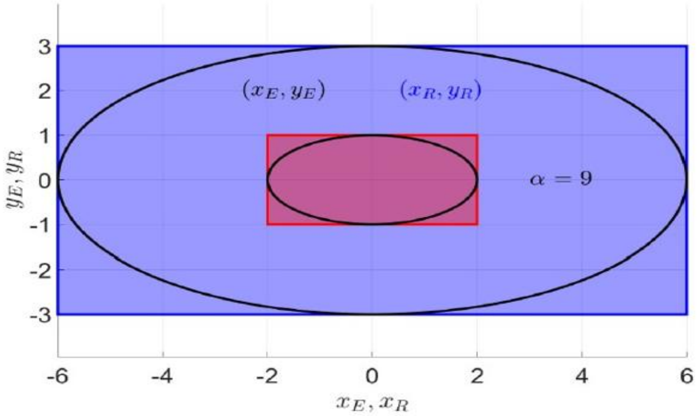


Fig. 4. Rectangular strip obtained from the ellipsoidal ring. Figure from D'Alfonso et al [5]

Results: The paper presents simulation results that demonstrate the effectiveness of the proposed swarm-based approach for dynamic perimeter surveillance. The simulations show that the agents can successfully maintain a consistent formation, avoid collisions, and effectively patrol the rectangular perimeter under various conditions. "Fig. 5" shows the results of the experiment a snapshot of the agent positions at t = 25 s. Red and blue zones describe the forbidden and the containment regions, respectively Black circles refer to the agent positions. The paper also provides theoretical analysis that supports the stability and convergence properties of the proposed kinematic model.

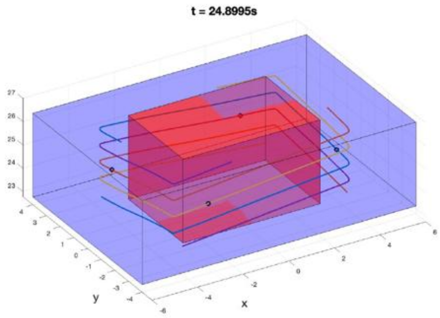


Fig. 5. kinematic model Simulation result. Figure from D'Alfonso et al [5]

2. **Findings:** The key findings of the paper can be sum- married as follows: The proposed swarm-based approach effectively addresses dynamic perimeter surveillance tasks by enabling a team of mobile agents to patrol a rectangular perimeter while maintaining a consistent formation and avoiding collisions.

The proposed kinematic model, which incorporates virtual potential fields, a consensus algorithm, and a collision avoidance mechanism, provides a robust and flexible framework for cooperative control of multiagent systems in dynamic environments.

The simulation results and theoretical analysis demonstrate the effectiveness and stability of the proposed approach, paving the way for its application in real-world scenarios.

C. A Swarm-Based Distributed Algorithm for Target Encirclement and Capturing using Potential Functions [6] [7]

Paper [6] and [7] both discuss swarm-based algorithms for target encirclement/capturing using distributed coordination strategies and potential function based control. The goal is to coordinate aerial robots in precision agriculture for tasks like multi-view monitoring. The algorithm ensures the robots encircle and confine targets through local interactions, incorporating collision avoidance and connectivity maintenance. It also handles complex polygonal regions by mapping them to a circular domain for control simplification. Paper [6] focuses on confining targets within polygons, while Paper [7] aims to encircle targets like tree canopies. Both papers demonstrate the effectiveness of decentralized swarms in surrounding and trapping targets.

The overall algorithm centers on designing an appropriate potential function that governs the individual agent behaviours to produce the desired emergent coordination. This potential encapsulates three main components - a shape tracking term to converge agents onto a desired radius around targets, a connectivity preservation term to maintain communication links between neighbouring agents, and a collision avoidance term for inter-agent safety. With the objective of enclosing targets even within complex polygonal boundaries, such as agricultural land partitions, the method leverages a novel technique of mapping the polygon vertices into an equivalent circular domain [6]. This allows formulating a straightforward control policy that handles confinement within the simpler circular region. An inverse mapping transforms the circular control back to the original polygonal frame for accurate implementation “Fig. 6”

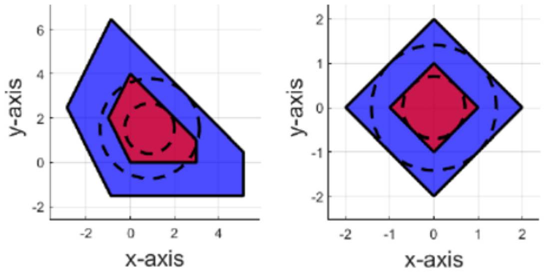


Fig. 6. Two examples of polygonal strips. The red polygons are the forbidden regions, the blue ones are the containment regions. Figure from A. Bono et al [6]

Executing gradient descent on the potential function then generates the individual agent trajectories in a fully decentralized manner, relying solely on local interactions. As the agents follow the gradients of attraction and repulsion from the potential field, the emergent collective behaviour drives the swarm to reliably encircle and entrap the targets, like tree canopies, for multi-viewpoint data gathering without losing connectivity or colliding "Fig. 7" [7]. The modular formulation combining potential-based control with circular mappings provides flexibility to handle complex environmental boundaries while meeting monitoring objectives using only local information without centralized coordination.

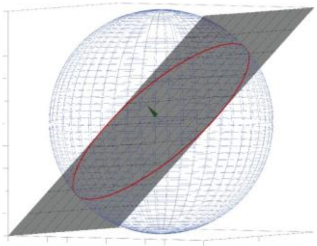


Fig. 7. A 3D visual representation of an inclined circle (red) of radius r around a Target obtained as the intersection of a sphere (blue) cantered on x0 with a plane P (grey) orthogonal to the normal vector nP∗ (green arrow). Figure from G. d. Carolis et al [7]

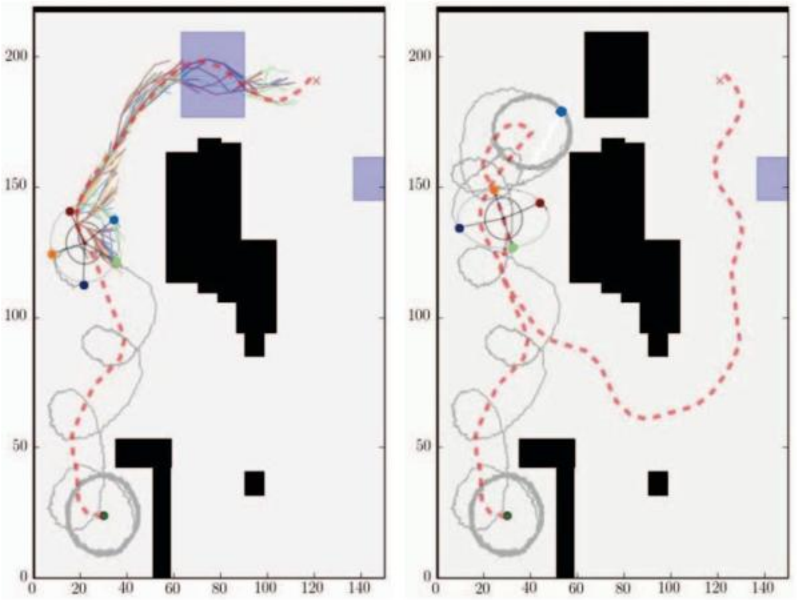
1. **Findings:** Results from both papers demonstrate the effectiveness of the developed algorithms for reliably entrap- ping and enclosing targets, even within irregular polygonal boundaries, while preserving connectivity and avoiding col- lisions. This establishes the feasibility of monitoring static and dynamic targets using coordinating swarms governed by artificial potential functions with applications in remote sensing tasks.

D. Distributed Multi-Robot Coordination for Dynamic Perimeter Surveillance in Uncertain Environments [8]

The paper proposes a system where multiple robots collab- orate to establish a virtual fence around a specified region, aiming to prevent unauthorized access by internal or external agents. The primary objective is to dynamically adjust the shape of the boundary, guiding the safe region from one location to a defined goal. The algorithms aims to com- pute trajectories through decentralized planning, continually refining plans during execution. The approach is validated through simulations, emphasizing adaptability in a dynamic environment.

Proposed Algorithm

1. **Algorithm A:** This algorithm is responsible for coordi- nating the robots to move along the perimeter of an environ- ment while maintaining a constant shape. The algorithm uses a distributed consensus algorithm to ensure that all robots have the same understanding of the current perimeter shape.
2. **Algorithm B:** This algorithm is responsible for detecting obstacles and planning collision-free paths for the robots. The algorithm uses a sensor fusion technique to combine information from the robots' sensors to create a map of the environment.



(a) $t = 65s$ (b) $t = 115s$

Fig. 8. Dynamic perimeter surveillance for five robots. In (a) the committed trajectory (red dashed line) was improved during the execution. In (b) two events happened: (i) the top obstacle was sensed, emergency stop, re planning a new trajectory and started to follow it, and (ii) one of the robots had a malfunction, but as the topology changed accordingly. Figure from A. Jahn, R. J. Alitappeh [8].

3. **Algorithm C:** This algorithm is responsible for control- ling the robots' motion to ensure that they follow the planned paths. The algorithm uses a feedback control law to adjust the robots' velocities based on their current positions and velocities.

These algorithms work together to achieve the goal of dynamic perimeter surveillance in uncertain environments. Algorithm 1 ensures that the robots maintain a constant shape, Algorithm 2 detects obstacles and plans collision-free paths, and Algorithm 3 controls the robots' motion to follow the planned paths.

Experiments

1. **Simulation:** A simulation experiment was conducted to evaluate the proposed approach for dynamic perimeter surveil- lance with a team of robots. The experiment used an ellipsoidal shape with five holonomic robots with limited velocity. The environment included partially known obstacles. The robots were subjected to localization noise with a maximum error of 7.5 meters and an average error of 3 meters see "Fig. 8".

Findings

1. **Simulation Results:** The results of the experiment showed that the proposed approach was effective in coordinating the robots to maintain a constant shape while moving along the

perimeter of the environment. The "Fig. 9" shows the trajectories of the robots over the first 20 seconds of the simulation. At the beginning of the simulation, the robots are distributed randomly within the ellipsoidal shape. They then gradually distribute themselves along the boundary of the shape and converge to a uniform distribution.

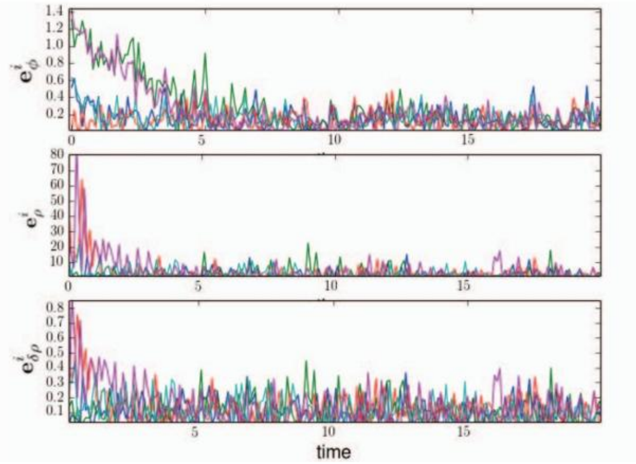


Fig. 9. Simulation results for the first 20 seconds with noisy localization. At the beginning the robots have to distribute themselves along the boundary and converge to it. Figure from A. Jahn, R. J. Alitappeh [8].

Conclusion: The paper delivers a novel surveillance approach employing a team of robots for guiding agents in dynamic perimeter surveillance towards a specified goal. The paper tackles challenges associated with estimating boundary trajectories and efficiently maneuvering robots along these boundaries. Validation is conducted through a combination of simulations and real-world experiments, showcasing the method's adaptability across diverse scenarios and shapes.

E. Dynamic Perimeter Surveillance with a Team of Robots [9]

The paper introduces dynamic perimeter surveillance, ad- dressing the challenge of escorting agents by proposing a method where robots patrol a time-varying perimeter with de- formations. The approach includes a plan for smooth perimeter movement, yielding a twice-differentiable boundary function, and a method to compute robot trajectories without inter-robot communication. Validation is conducted through simulations and experiments with actual robots, demonstrating effective- ness in diverse scenarios.

Proposed Algorithm

The provided algorithm is a Kino dynamic motion planning technique designed for dynamic perimeter surveillance. It starts by initializing with an initial state and creating a tree structure. The main loop involves iteratively generating random control inputs and extending the tree, with a termination criterion. The algorithm aims to create a trajectory function for the dynamic boundary, using a piecewise quadratic representation.

The algorithm utilizes two main components:

Trajectory Computation: The trajectories are determined based on solving an ordinary differential equation derived from the desired counter-clockwise movement along the dynamic boundary.

Distributed Implementation: The method enables a distributed implementation where each robot independently obtains its trajectory by receiving the boundary function with a unique initial location.

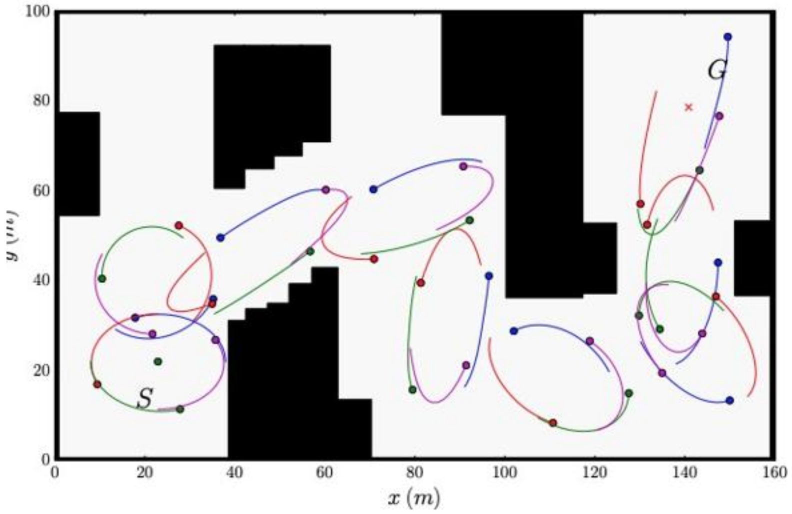


Fig. 10. Escorting an ellipse shape with constant area in an environment with obstacles. Snapshot of four robot trajectories. The small circles represent the robots and the continuous lines are the recent movement before the snapshot. Figure from D. Salda n [9].

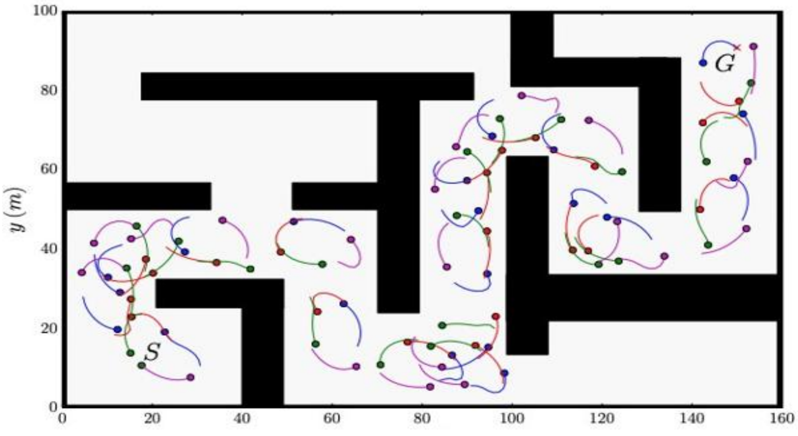


Fig. 11. Escorting a crooked-egg shape in a maze. The walls are represented by the black rectangles. Figure from D. Salda n [9].

Experiments

1. **Simulation:** The authors conducted simulations to vali- date their proposed method. They used two different scenarios: Scenario 1: The ellipse function is used to navigate in an environment with narrow spaces vertically and diagonally. The shape is transformed to pass

through the obstacles, from a starting point S to a goal point G, by adapting its orientation and its anchor see "Fig. 10".

Scenario 2: The crooked-egg shape is used to escort a constant area, from a start point S to a goal point G, in a maze see "Fig. 11"

2. **Real Robots:** The experiment was conducted in a real- world setting with four Khepera III robots. The primary objective was to guide a group of agents to a specific destination. These robots were outfitted with range sensors for obstacle detection and communication between them. The authors employed their innovative approach to create motion plans for the robots, implementing these plans through a static feedback linearization scheme.

Findings

1. **Simulation Results:** The results show that the proposed method is effective in both scenarios. The robots are able to maintain a constant linear velocity while they move around the dynamic boundary, and they do not collide with obstacles or walls.
2. **Real Robots Experiment Results:** The results of the experiments show that the proposed method is effective for dynamic perimeter surveillance in real-world environments. The robots were able to successfully escort the agents to the goal while avoiding collisions with the obstacles. The proposed method is also scalable to larger teams of robots.

Conclusion: The paper addresses the challenges related to estimating boundary trajectories and moving robots along the boundaries. The proposed method is validated through simu- lations and real-world experiments, demonstrating flexibility in different scenarios and shapes.

F. Cooperative perimeter surveillance with a team of mobile robots under communication constraints [10]

This paper presents a decentralized algorithm for cooperative perimeter surveillance using a team of heterogeneous mobile robots with different speeds and communication ranges. The goal is to maximize the frequency of visiting all locations along the perimeter, known as the refresh time, under conditions of limited communication between robots [10].

The key idea is to partition the perimeter into non- overlapping segments, with each robot patrolling a segment proportional to its maximum speed as shown in" Fig. 12". Robots meet periodically at segment boundaries to exchange coordination information. This path partitioning strategy optimizes refresh time and ensures periodic communication and information sharing [10].

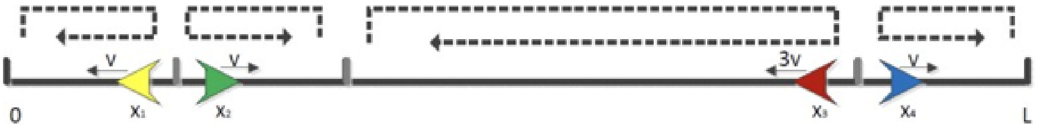


Fig. 12. Path-partition strategy applied to the cooperative perimeter surveil- lance problem with the team of four mobile robots. Figure from Acevedo et al. [10]

A distributed algorithm is presented where robots use lo- cal information exchange to reach global coordination. Two coordination variables, the total perimeter length and sum of robot speeds, allow robots to calculate their assigned perimeter segments. Convergence time scales linearly with the number of robots, outperforming prior quadratic scaling results as shown in ”Fig. 13” [10].

The strategy is validated in MATLAB simulations and experiments with Pioneer robots. Performance is evaluated using refresh time metrics. The system adapts to dynamic teams, perimeter changes, and information propagation. Fault tolerance to robot failures is also demonstrated.

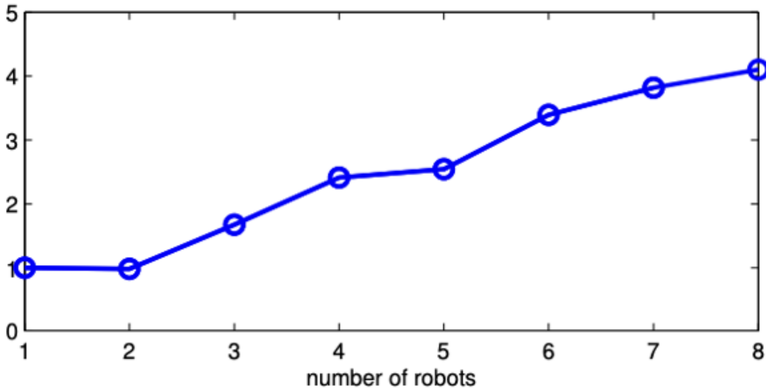


Fig. 13. Relation between the convergence times using the algorithm-based on one-to-one coordination and the algorithm described in this paper. Figure from Acevedo et al. [10]

Proposed Algorithm

1. **Problem Formulation:** The perimeter surveillance problem is mathematically formulated to define key parameters like refresh time, robot speeds, positions and constraints. Criteria for optimization and theoretical bounds on performance are analysed.
2. **Strategy Development**: A novel path partitioning strategy is developed where the perimeter is divided into non- overlapping segments proportional to each robot’s maximum speed. This optimizes the refresh time while ensuring periodic inter-robot communication.
3. **Algorithm Design**: A decentralized coordination algorithm is designed where robots calculate segments using local information exchange and convergence to global optimization scales linearly. Coordination variables like total perimeter length and sum of speeds enable efficient calculation using only data from immediate neighbours.
4. **Simulation Testing**: Extensive MATLAB simulations compare convergence times and validate correct perimeter partitioning and adaptation to dynamic changes.
5. **Robot Experiments**: Multi-robot experiments using Pioneer robots implement path planning, collision avoidance, and perimeter following in real-world conditions. The decentral- ized algorithm coordinates heterogeneous robots to converge to partitions.
6. **Performance Evaluation**: Quantitative metrics like maximum and average refresh times are tracked throughout experiments, along with perimeter positions over time and information propagation latencies. The robustness to robot additions, failures, and environment changes is evaluated.

Findings

The path partitioning perimeter surveillance strategy optimizes refresh time by 15-46% over other published methods based on mathematical and experimental analysis [10]. The decentralized algorithm enables correct segmented partitions calculating only 3% of convergence times compared to a one-to-one coordination algorithm as shown in "Fig. 14".

Convergence to steady-state partitions scales linearly with the number of robots, enabling the efficient coordination of 6 robots within 4 perimeter crossings in experiments. Average refresh times within 5% of the theoretical minimum bound are demonstrated in perimeter following experiments across dynamic scenarios as shown in " Fig. 15".

New information is propagated to all robots within time scales consistent with the analytical latency bound as validated by robot detections in experiments.

Adaptation to robot additions and perimeter changes leads to re-convergence to new optimized partitions within 110 seconds during experiments as shown in "Fig. 15" [10].

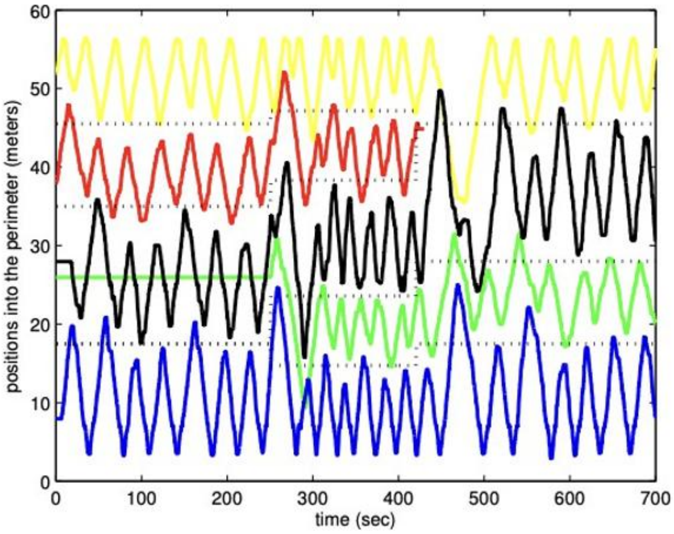


Fig. 14. Perimeter positions xi of the robots along the perimeter in the first experiment. Each color represents a different robot. The dotted lines indicate the theoretically optimal perimeter division. A video of the experiment can be seen in http://www.youtube.com/watch?v=WqRKXqcuWKg. Figure from Acevedo et al. [10]

G. Local Policies for Efficiently Patrolling a Triangulated Region by a Robot Swarm [11]

This paper addresses the problem of enabling surveillance and patrol of an unknown environment using a heterogeneous robot swarm. The key capabilities involved are: Coordinated dispersal and exploration to map the environment Structured triangulation of the mapped space to enable efficient navigation. Patrol and revisiting of locations within the triangulated network

Proposed Algorithm

- **Mapping robots**: These simple robots rely on bearing-only sensors and local communication to incrementally build a triangulation of the unknown environment using the MATP algorithm:
- **Initialization:** Two mapping robots are manually placed to establish an initial triangle by aligning their local coordinate frames.
- **Dispersal:** The initial two robots begin a breadth-first decentralized exploration by moving apart while maintaining communication links. When robots encounter unexplored space beyond the current radio range, new robots are introduced to leapfrog triangulation edges further. Localization: As new robots join; they use bearing sensors to localize themselves in the frame of three visible robots that form feasible triangles according to pre-defined geometric constraints. This determines the new robot's position. Triangulation: After localizing itself, the new robot completes an available triangle by checking the edges between itself and the reference robots. If multiple feasible edges exist, it picks the shortest edge.

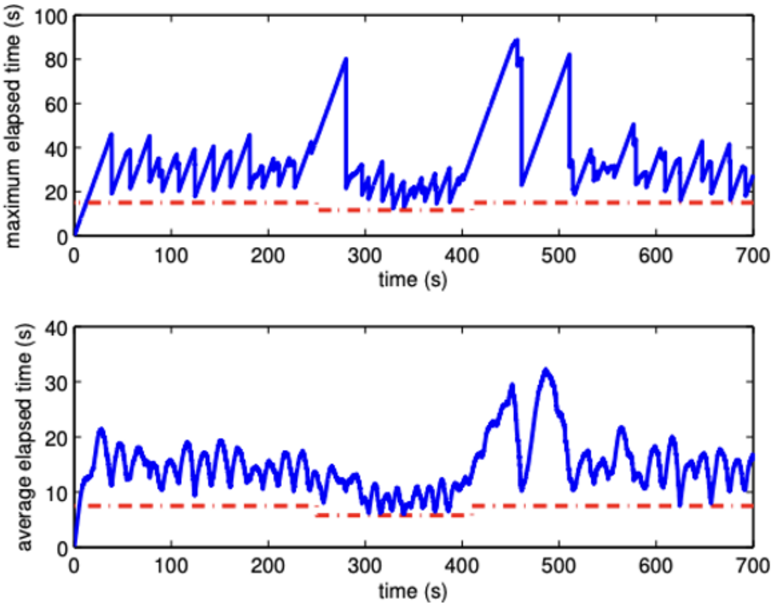


Fig. 15. Maximum (above) and average (below) values for the refresh time. The red dash-dotted line indicates the lower bounds defined in expressions, according to the robot's capabilities over time. Figure from Acevedo et al. [10]

Patrolling robots: More capable robots use navigable triangulation to visit and monitor locations via repeated re-visiting. Two decentralized algorithms are evaluated: Least Recently Visited (LRV): The time elapsed since the last visit is recorded at each vertex. At each step, the patroller selects the edge to the neighbouring vertex with the maximum last visit time. After traversing an edge, its time is reset to 0. Least Frequently Visited (LFV): The number of visits is recorded at each vertex or edge. At each step, the patroller greedily selects the lowest- count neighbour to visit next. Visit counts are incremented when traversing that vertex or edge.

Findings

The key findings from analysis and experimentation are: MATP reliably builds locally navigable triangulations without inter-robot distance estimates even using noisy bearing-only measurements. Final graphs are planar and degree-bounded as shown in ″Fig. 16″.

LRV risks exponentially long worst-case intervals between revisits for some vertices but performs well on average.

LFV tracking on graph edges rather than vertices ensures constant worst-case revisit times within a polynomial factor of the optimal. Both LRV and LFV display efficient coverage in practice as shown in″ Fig. 17″. Adding patrollers reduces average revisit intervals nearly linearly. Reliance on a fixed triangulation limits adaptively to environment changes after initial mapping.

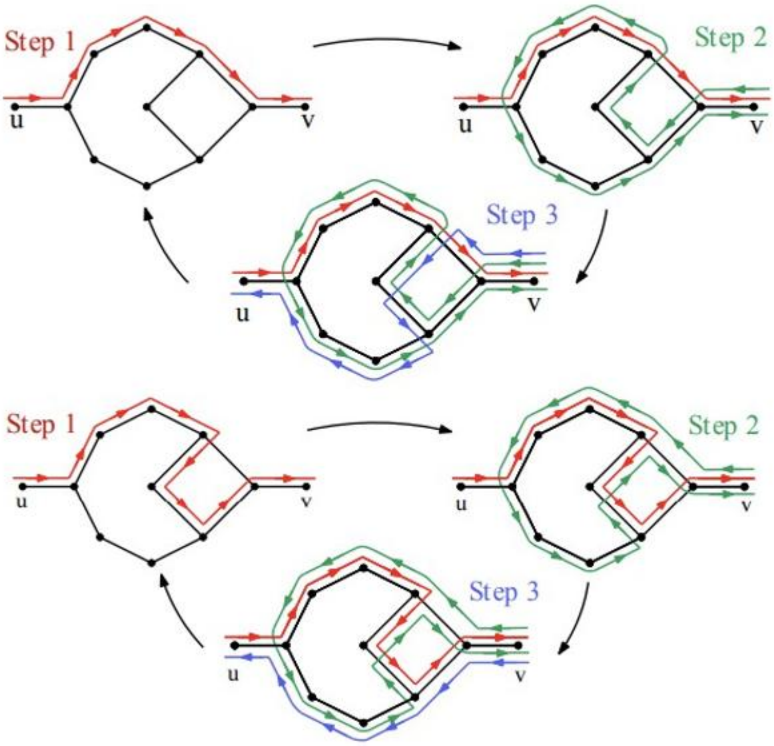


Fig. 16. Two possible alternating paths for the LRV-v strategy on each component of the graph GD. Figure from Maftuleac et al. [11]

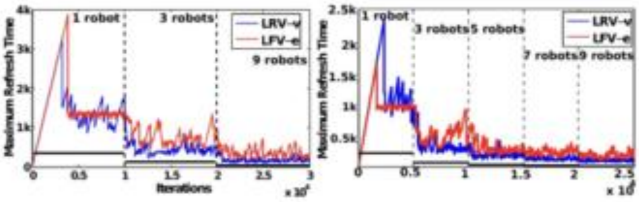


Fig. 17. Maximum refresh time in a simply (left) and non-simply (right) connected space. Figure from Maftuleac et al. [11]

IV. SYNTHESIS

The six papers investigated several approaches for coordinating groups of autonomous agents to perform perimeter surveillance tasks. There were some common themes as well as differences in the specific methods and objectives. A quantitative analysis of the results provides insights into the current state of the field and opportunities for further progress. Several papers proposed vector field-based approaches using artificial potential functions to locally control each agent's movements Papers [3], [4], [5], [8] [9]. This decentralized approach allows for scalable and resilient behaviour as the number of agents increases. Papers [5] and [9] presented mathematical models and analysis to prove the approaches could achieve containment within a target area and avoid collisions. Paper [6] [7] synthesis centers on leveraging artificial potential functions for implicit decentralized coordination while overcoming constraints like complex environments or motion restrictions through appropriate transformations/abstractions.

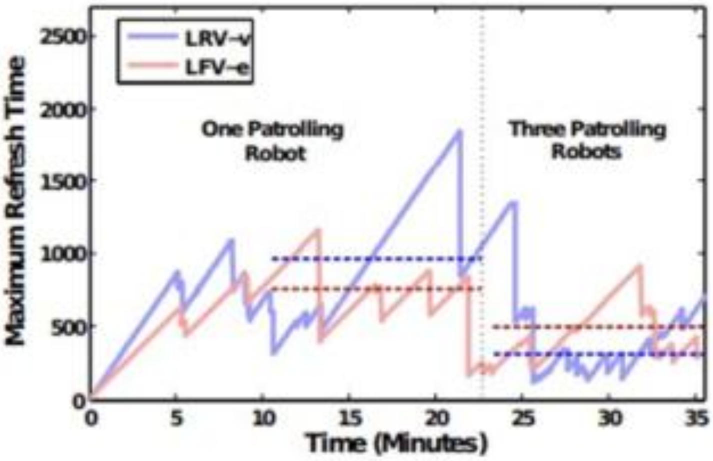


Fig. 18. Robot experiment. Figure from Maftuleac et al. [11]

In contrast, Paper [8] used an adaptive control strategy to track a global reference signal, progressing toward formation control but requiring more centralized computation. Papers [10] and [11] analysed geometric strategies for agents moving on a perimeter, making assumptions like continuous movement or intruders crossing the perimeter at discrete points that may not generalize well to complex, time-varying scenarios.

A majority of the papers [3], [4], [9], [10], [11] focused on static formations around a target shape or area, with Papers [5] and [9] mathematically proving the agents could achieve rotating surveillance behaviours. Only [5] tested dynamically encircling shapes in simulation. This indicates the field may still be progressing toward proven solutions for continuous perimeter surveillance of non-static areas using mathematical analysis.Quantitatively, Papers [3] and [9] presented the most rigorous theoretical analysis, proving properties like convergence and deriving bounds on parameters to achieve goals. However, their models assumed first-order agent dynamics that may not reflect real vehicles.

In summary, the research synthesized here indicates that vector field-based approaches using artificial potentials show promise for coordinating perimeter surveillance, with mathematical analyses progressing to prove critical properties. However, more work appears needed to generalize solutions to complex, dynamic scenarios and environments while evaluating approaches quantitatively with realistic agent models and performance metrics. Coordinating continuous rotating behaviours also warrants further mathematical analysis to verify real-world feasibility.

V. CONCLUSION AND FUTURE WORK

In summary, the papers emphasize the potential of decentral- ized coordination strategies for effective perimeter surveillance in dynamic and uncertain environments. These strategies offer scalability, robustness, and adaptability, making them well- suited for real-world applications. The absence of centralized bottlenecks, coupled with the ability to tolerate failures and dynamically adapt to changes, positions decentralized coordination as a robust and flexible technique for ensuring continuous surveillance in complex security spaces. The phrase" Decentralized coordination: The key to robust and adaptable perimeter surveillance" crisply captures the central theme, emphasizing the pivotal role of decentralized strategies in addressing the challenges of modern security landscapes and paving the way for the integration of distributed intelligence in future perimeter monitoring systems.

Further real-world validation with larger, long-duration robot teams in dynamic environments is needed to mature perimeter surveillance approaches. A key focus should be enhancing coordination algorithms to reliably handle communication constraints like delays, losses, and disruptions that are pervasive in real-world settings. Additionally, adaptive machine learning techniques may help optimize system parameters for peak efficiency amidst uncertainties. Over-all, advancing distributed coordination to be resilient against unpredictable communications during monitoring remains an open challenge.

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