A Survey of Formation Control for Multiple Mobile Robotic Systems

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Abstract **—Multiple mobile robotic systems have been applied in many scenarios. This is because they have obvious advantages compared to single mobile robotic systems. However, their control could be challenging and is still an open problem in robotic research. This paper presents a survey of the current state of affairs on formation control of multiple mobile robotic systems. The main contribution of this paper is to comprehensively analyse different cooperative multiple mobile robotic control techniques used in various literature. Different techniques were analysed, their strengths and weaknesses identified. However, differential flatness approach of cooperative multiple mobile robots control has not gained much popularity; thus a gap of future work was determined.**

Index Terms**—Formation control architectures, cooperative control, consensus, synchronization, centralized control, decentralized control.**

I. INTRODUCTION

Multiple robot formation has attracted significant attention of many robotics researchers [1-5]. This popularity owes to the fact that a multi-robotic system has the ability to perform complex tasks faster and more commendably than a single robot [1]. Hence cooperative multiple robots are more preferable since they offer efficiency, flexibility, redundancy and manoeuvrability [1,2] of which single robots fail to offer. It is for this reason that multi-robotic systems have a broad application which include: search and rescue [7], security and surveillance [8] as well as precision agriculture [9], just to name a few.

Furthermore, with the numerous benefits of using multiple robots, many researchers are focusing on developing highly effective control architectures for accurate execution of more complex tasks [11-26]. Various literature has revealed that the control of multi robot cooperating systems could be approached from different viewpoints, namely: synchronization, coordination, cooperation and consensus control. In synchronization control each robot tracks its desired path while maintaining a synchronized formation with neighboring robots. Also, in Cooperative control the team robots share information to accomplish a common goal. Whereas in consensus the robots update their information such that they all converge to a common value. Lastly, coordination control involves maintaining certain kinematic relationship amongst the robots.

Conceptually, the numerous control architectures presented in literature can be grouped into two control approaches: decentralized (distributed) control and centralized control approaches [5]. The decentralized control approach has gained popularity over the years [3, 10, 12, 13]. In this approach, control is distributed. That is to say, each cooperative robot uses its own in-built sensors to study and gather information from its environment as well as the relative positions of neighboring robots. This information is then used by the respective robot to make its own control decision. Also, each robot is able to communicate and also share information with only neighboring robots, hence limiting the data being shared and thus reducing computational time. However, the drawback of the approach is that the controller task implementation is less accurate and less robust.

Alternatively, several researchers have used the centralized control approach for multi-robotic formation control. This approach is generally based on the leader-follower control architecture [18-24]. In this approach, a core unit (leader) accumulates and manages information about the surroundings for coordination and control of the motion of the robots (followers) therefore ensuring the achievement of the mission. Although this approach is more accurate and robust in controllability, it costs the leader a lot. Thus, there is a need for alternative approaches for the control of multi-robot formation. The main contribution of this paper is to discuss the current state of various formation control techniques used in multi-robot cooperation.

This paper is sectioned as follows: Section II discusses different methodologies for multiple robotic system control approaches, and finally Sections III and IV give some concluding remarks.

II. ANALYSIS OF FORMATION CONTROL ARCHITECTURES IN MOBILE ROBOTS

Many control designs have been proposed in literature for coordinated multiple robotic systems. For instance, in [3], the authors aimed to solve formation maneuvering for unicycle-type non-holonomic mobile robots using dynamics. The control approach involved a modeled

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Spanning tree, inter-robot coordination graph. As seen in Fig. 1, they used a leader-follower type strategy, tracking errors and coordination errors. This made it possible to quantify the formation maneuvering control objective resulting in a decentralized control system. The formation maneuverability was then tested using Lyapunov theorem and backstepping technique. With this approach, the robot formation is able to globally acquire and track the desired trajectory. However, collision avoidance strategy ought to be included in the proposed formation controller to improve it.

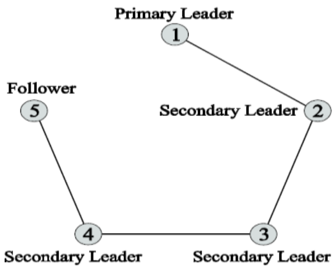

Figure 1. Graph for the pentagon formation [3].

A. Cooperative Control

In the study of [6] the author aimed to develop a multi-robot cooperative control to determine the position of a target by use of on-board sensors. This was accomplished by probabilistic localization and control method that considered the motion and sensing capabilities of the individual robots. As a result, the uncertainty of the target position anticipated in the future was lessened. The approach provides the robots with an ability to adjust their sensing topologies depending on their limited sensing abilities and the target's motion. In the future, the author plans to use the approach for topology switching method that reserve scalability.

Moreover, a cooperative visibility maintenance for leader–follower formations in obstacle environments was developed in [11]. The study concentrated on the motion coordination and control strategy for Leader–Follower formations of non-holonomic vehicles, under visibility and communication constraints in known obstacle environments. Their Control approach revolved around the leader robot using a tractor–trailer system to guarantee obstacle avoidance for both robots while the follower robot uses vision-based sensing and localization of Leader and inter-vehicle collision avoidance. Their approach guarantees the safe navigation of the multi-robot formation in known cluttered environments, using minimal vision-based data only and without the necessity for exchanging or guesstimating velocities online. However, recovery control modes must be added into the existing hybrid system to improve its effectiveness.

Similarly, on another study [13] Cooperative Path Following (CPF) control problem is solved by minimizing the number of times the cooperative robotic vehicles communicate. This is achieved by a decentralized, event-based cooperative controller which coordinates the robotic vehicles such that they follow a predefined reference geometric path while continuing in a required formation. To prove the stability and convergence, the Input-to-State Stability framework was utilized. This approach succeeded in significantly minimizing the exchange of information between the cooperative robots. However, in the future an investigation of communication losses and delays ought to be made so as to enable the testing of the vehicles underwater, using the acoustic communication channels.

Additionally, in the study of [17] a cooperative approach of multiple unmanned aerial vehicles (UAVs) is implemented to attain autonomous formation and reconfiguration. Cooperative mechanism of UAVs is made up of a distributed structure and hierarchical network which is composed of multi-UAV teams consisting of a commander, virtual leaders and followers. Then, constraint conditions and collision avoidance control strategy for leader-follower UAVs are determined. This resulted in UAVs achieving autonomous formation with a stable trend of positions and velocities.

B. Consensus Control

In the work of [10], a cooperative adaptive consensus tracking for multiple non-holonomic mobile robots was undertaken whereby the authors aimed to develop a cooperative adaptive consensus tracking for a group of multiple non-holonomic mobile robots from the view of point of networked multi-agent systems. In their control approach, they developed an integrated adaptive control strategy of a kinematic controller and a torque controller to improve consensus. They also designed an adaptive tracking controller for the uncertain dynamic model of robots based on the Lyapunov-like analysis, backstepping technique and sliding mode approach. Their robot formation succeeded in navigating the desired trajectory hence performing cooperative tasks more efficiently. However, the authors still need to address cooperative robotic systems control challenges such as robustness, resilience, scalability and flexibility.

Meanwhile, the authors in [14], addressed the problem of distributed cooperative control for multiple type (1, 2) non-holonomic mobile robot. In their control approach the author used distributed controllers designed by using a robot's individual information and its neighbours' information to create the state converge to the similar or approximately zero value irrespective of whether there's a delay of communication or not. With this approach, each robot is able to reach consensus despite communication delay by using the available information (its own and its neighbours') for feedback. Further improvements can be made by incorporating visual servoing to resolve the consensus challenges.

Likewise, another study [20] centred on solving the consensus issues of second-order multi-robot systems that are under conditions of numerous time delays, communication delays and noises. The author applied frequency domain analysis method to convert the characteristic system equations into quadratic polynomials of pure imaginary eigenvalues and thus acquiring the maximum time delay's critical stability state during noise disturbances. The system is said to be stable when all robots' delays are less than the maximum time delay, and thus consensus attained. As further study the author proposes to use the approach for higher-order systems consensus analysis.

Furthermore, in [24], the study sought to intertwine task and motion planning for mobile robots such that they are required to work together in order to traverse among unfixed obstacles. In their control approach the authors implemented a knowledge-oriented task and motion planning method called κ-TMP. This entails a smart combination of an interrogative task planner based on the Fast Forward (FF) technique, a physics-founded motion planner, and cognitive processes over the ontologies that cipher the information on the fault. Their method enabled the robot system to create a feasible obstacle free path of motions. However, it can still be improved by the usage of a contingency-based task planner to handle uncertainty which may emanate from the motion level to the task level.

More work was done in [23] whereby the finite-time consensus challenge for a set of non-holonomic mobile robots with a high order chained structure was addressed. The system was divided into two subsystems: high-order case and a low-order case. For the high-order case, a neighbour-based distributed high-order finite time consensus algorithm is developed using a power integrator technique and a recursive design method. Then a Lyapunov function is recursively formulated to verify the finite-time convergence, as a result an expression of the finite settling time is obtained. This is then combined with the existing low-order case results and therefore solving the finite-time consensus problem for whole systems. With this method the multi-robotic system is able to achieve states consensus in finite time.

C. Synchronization Control

The study in [26] aims to design a coordination algorithm that maintains a predefined formation and trajectory tracking for cooperative multiple unicycle robots as well as to determine the most effective controller topology. As a solution, the authors developed a nonlinear synchronization controller that considers the nonholonomic constraint of the unicycle robots and allows directed and undirected information flow amongst the robots. Lyapunov theorem was then used to test for stability. The controller offered formation robustness during disturbances and accurate trajectory tracking.

In addition, the study in [27] addressed the challenge of synchronized path following of multiple homogenous underactuated autonomous underwater vehicles (AUVs). The author used Lyapunov theory and backstepping techniques to develop geometric path following, while introducing helmsman behaviour to each path following control. In addition, path parameters were synchronized by using a combination of tools from linear algebra, graph theory and nonlinear control theory. However, additional considerations should be given to following paths simultaneously and to avoiding obstacles so as to guarantee motion safety for each AUV.

D. Coordinated Control

The study in [15] focuses on designing coordination mechanism and motion paths for cooperative target hunting Multiple Autonomous Underwater Vehicles (multi-AUV) which detect and surround an intelligent target (with unpredictable motion) in a surface-water environment. To achieve this the authors designed an integrated algorithm which merges the three degrees (the homodromous degree, district-difference degree and the dispersion degree) into the potential field function of the surface-water environment. This approach resulted in no pre-learning procedure, good real-time and an increase in the coordination of the multi-AUV system as well as overcoming local minimum problem. However, improvements ought to be made to help the AUVs withstand ocean surface-water currents while hunting.

Finally, [28] aims to solve the problem of coordinating movement of multiple autonomous underwater vehicles (AUVs) along three types of predefined multiple paths (shifted paths, parallel paths and arbitrary paths) in a required formation shape. The solution entailed incorporating a coordinated formation control based on leader-follower strategy. This enables a group of AUVs to follow predefined parallel paths and thus form a desired inter-vehicle geometric formation. In the future the proposed approach can be incorporated in a case of a leaderless team to construct a desired formation shape in a decentralized coordination.

TABLE I. SUMMARY OF MULTI-ROBOTIC FORMATION CONTROL TECHNIQUES

Ref.	Type of Robot formation	Control Approach	Key objective	Strength of approach	Gap/future works
[3]	Inter-robot graph using Leader-follower	Lyapunov-based decentralized control	To solve formation maneuvering for unicycle robot	Robot formation is able to globally acquire and track whole tracks of desired trajectory	collision avoidance strategy is not included in the proposed formation controller
[6]	Troop formation with sensing topology switching	Centralized cooperative control with probabilistic localization and local optimization	To develop a multi-robot cooperative control to determine the position of a target by use of on-board sensors	The approach provides the robots with an ability to adjust their sensing topologies depending on their limited sensing abilities and the target's motion	To use the approach for topology switching method that reserves scalability
[10]	adaptive consensus-based formation	Lyapunov-based adaptive tracking controller: kinematic controller and a torque controller, with backstepping technique and sliding mode approach.	To develop a cooperative adaptive consensus tracking for a group of multiple non-holonomic mobile robots from the view of point of networked multi-agent systems	Robot formation is able to navigate desired trajectory thus can perform cooperative tasks more efficiently	Address cooperative robotic systems control challenges: robustness, resilience, scalability and flexibility.

[11]	Leader–Follower formation	Leader uses tractor–trailer system while Follower uses Vision-based sensing and localization of Leader and inter-vehicle collision avoidance.	To develop motion coordination and control strategy for L–F formations of non-holonomic vehicles, under visibility and communication constraints in known obstacle environments.	Provides safe navigation of the multi-robot formation in cluttered environments, using minimal vision-based information only and without exchanging or estimating velocities online	Adding "recovery control" modes into the existing hybrid system, which activates when agent needs to pick a new (local) leader and coordinate its motion around a failed robot
[13]	variable geometric shape formations: straight line formation and circular formation	Decentralized event-based cooperative controller	To develop an efficient formation control solutions for Cooperative Path Following (CPF) control problem by minimizing the number of times the cooperative robotic vehicles communicate	The frequency of transmission over the network is significantly reduced without compromising the stability and convergence of the overall CPF system. Thus, the overall performance of the formation is improved	Investigates communication losses and delays so as to enable the testing of the vehicles underwater, using the acoustic communication channels
[14]	Leaderless consensus and leader-following consensus formation	Distributed consensus controller	To solve the distributed cooperative control problem for multiple type (1, 2) non-holonomic mobile robot	Each robot is able to reach consensus despite communication delay by using the available information for feedback is its own information and its neighbors' information	Utilization of visual servoing to resolve the consensus challenges
[17]	Hierarchical formation: commander, virtual leaders and followers	Cooperative control	To design a control strategy to enable multiple unmanned aerial vehicles (UAVs) to attain autonomous formation and reconfiguration	UAVs are able to achieve autonomous formation with a stable trend of positions and velocities	N/A
[24]	Consensus-based formation	knowledge-oriented task and motion planning method called κ-TMP	To intertwine task and motion planning for mobile robots such that they are required to work together in order to traverse among unfixed obstacles	Robot system is able to create a feasible obstacle free path of motions	Usage of a contingency-based task planner to handle uncertainty which may emanate from the motion level to the task level.
[20]	Consensus-based formation	Incorporated frequency domain analysis method in the consensus building process to convert the system's characteristic equations into quadratic polynomials of pure imaginary eigenvalues to solve them	To solve the consensus issues of second-order multi-robot systems that are under conditions of numerous time delays, communication delays and noises	The consensus of the second-order multi-robot system under delay and noise interference is attained	Application of the approach to higher-order systems consensus analysis that are under conditions of time delays and noises.
[23]	consensus-based in the form of a high-order chained structure	Lyapunov-based finite-time cooperative controller	To solve the finite-time consensus challenge for a set of non-holonomic mobile robots with a high order chained structure	The multi-robotic system is able to achieve states consensus in finite time	N/A
[15]	Troop formation	Integrated coordination algorithm based on the improved potential field resulting from combining the three degrees into the potential field function of the surface-water environment	To design coordination mechanism and motion paths for cooperative target hunting Multiple Autonomous Underwater Vehicles (multi-AUV) which detect and surround an intelligent target (with unpredictable motion) in a surface-water environment.	The approach results in no pre-learning procedure, good real-time and an increase in the coordination of the multi-AUV system as well as ability to conquer local minimum problem.	Design techniques to help the AUVs withstand ocean surface-water currents while hunting Use the approach in the 3D surface-water environment
[28]	time-varying virtual structure-based swarm formation	Lyapunov-based Synchronous controller	To design a coordination algorithm that maintains a predefined formation and trajectory tracking for cooperative multiple unicycle robots as well as to determine the most effective controller	Increased robustness of non-holonomic robots' formations during disturbances and accurate formation trajectory tracking	N/A

			topology		
[27]	Behavior-based formation	Synchronized helmsman behavior-based control developed on Lyapunov theory and backstepping techniques.	To addressed the challenge of synchronized path following of multiple homogenous underactuated autonomous underwater vehicles (AUVs).	Enables direct inter-vehicle speed adaption with minimized communication variables and synchronization and stabilization of the multi-AUV systems	Incorporation of simultaneous paths following and obstacles avoidance
[26]	Leader–Follower based inter-vehicle geometric formation	Coordinated formation control	To solve the problem of coordinating movement of multiple autonomous underwater vehicles (*AUVs*) along three types of predefined multiple paths (shifted paths, parallel paths and arbitrary paths) in a required formation shape	The team of AUVs is able to follow predefined parallel paths and thus form a desired inter-vehicle geometric formation	Incorporating proposed approach to a leaderless team to construct a desired formation shape in a decentralized coordination

III. Discussion

A comprehensive literature analysis was made on the different techniques used by researchers to control a group of cooperative mobile robots. Thus, Table1 shows summary of these techniques.

It can be seen from the analysis summary that most authors have used the decentralized control architecture [3, 6, 10, 14, 18, 20]. In this control architecture some authors have used a form of distributed formation control known as the consensus-based control approach [13, 17, 18, 21]. In consensus the robots update their information such that they all converge to a common value. This has high computational time. Moreover, [11] incorporates information feedback in the consensus building process. Although this improves robustness and situational awareness of the team, it does not cater for situations of communication breakdown. Also [5] incorporates an adaptive robot control scheme to address environmental uncertainties occurring in the dynamic or kinematics of the system. However, this still poses a challenge to flexibility and robustness. Alternatively, [15] incorporated an input-output feedback linearization and distributed linear model predictive control. That is severely damaged member are ex-communicated. This improves on the robustness of the system.

Furthermore, some authors have used decentralized synchronous formation control [26, 27], of which is a simpler control structure, has high motion coordination performance and strong robustness. However, communication constraints including time-varying delays and data sampling renders this method ineffective. To minimize the formation error, the cross-coupling control can be incorporated.

Alternatively, with cooperative and coordinated formation control [3, 11, 14, 17], a centralized control architecture approach is used. This is mostly based on the leader-follower formation approach [3, 11, 14, 17]. That is, the leader robot has sensors and thus more information than the follower robots. The follower robots blindly execute the leader’s motion commands. This approach increases accuracy and robustness but unfortunately costs the leader robot.

The major drawback is that there is a weak disturbance rejection property. Also, the motion of the leader robot does not dependent on the followers, meaning there is no feedback from the followers to the leader. Thus, failure of the leader results in the failure of the whole system.

Finally, in a nutshell, a good formation control architecture should ideally have: Scalability, Robustness, flexibility, topology switching ability, collision avoidance at group level and stability. Thus, for a cooperative control strategy to be effective, the team ought to have an ability counteract unanticipated situations or environmental changes sensed while the cooperative task is being carried out. An agreement should be reached on the appropriate action to be carried out with minimum computational time. Hence more much work remains to be done to develop strategies capable of yielding all of the above characteristic

IV. Conclusion

The main contribution of this paper is to comprehensively analyse different cooperative multiple robotic control techniques used in various literature. Many articles were reviewed and gaps for improvements were identified. It can be concluded after an extensive review of many literatures that differential flatness approach of mobile cooperative multiple robotic system control has not gained much attention among robotic researchers. Thus, there exist a gap for research in this area. Hence, future work will concentrate on the use of differential flatness to solve control problems of a nonlinear cooperative wheeled mobile robots.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

LT conducted the research; ED and LT analyzed the data; LT wrote the paper; all authors had approved the final version.

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