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Comprehensive review on controller for leader-follower robotic system

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This paper presents a comprehensive review of the leader-follower robotics system. The aim of this paper is to find and elaborate on the current trends in the swarm robotic system, leader-follower, and multi-agent system. Another part of this review will focus on finding the trend of controller utilized by previous researchers in the leader-follower system. The controller that is commonly applied by the researchers is mostly adaptive and non-linear controllers. The paper also explores the subject of study or system used during the research which normally employs multi-robot, multi-agent, space flying, reconfigurable system, multi-legs system or unmanned system. Another aspect of this paper concentrates on the topology employed by the researchers when they conducted simulation or experimental studies.

[**Keyword***: Leader-Follower; Swarm system; Controller; Topology; Formation Control; Convoy*]

Introduction

The robot plays a crucial role in facilitating human activities either in a physical way or virtual interface. Initially, robotics technology was used to remove repetitive tasks in the industrial sector to ensure workers can execute other tasks. The expansion of robots in terms of design, movement, and application in the various fields contributed to the complexities in designing and proving the controller to control the robots. The expansion of the robotics technology now moves to another era where small robots are designed to move small things in a group or in a formation.

The trends on swarm robotics and leader-follower formation control have gained a lot of attention from researchers to solve the problem of the autonomous control, for instance, in automobile industries, space flying or satellite system, small cooperative mobile robots working together to move bulky material etc.

The development of autonomous vehicle, autonomous braking and autonomous lane changing or trailing other vehicles has been described in several researches. The autonomous vehicle requires platooning technique to avoid crashes, congestion and pollution. When vehicles move in platoon, dedicated lanes for vehicles like motorcycles, cars, and lorries are needed because they move close to each other[1]. Therefore, robust and responsive controller algorithm and hardware such as g*lobal positioning system (GPS), Lidar, radar, stereo, and ultrasound* need to be developed to assist communication between the vehicles[1].

Another area of interest is space formation flying. The space formation flying is used to solve the issue of bulky satellites. The huge satellites require huge launchers and therefore the cost increases to maintain and deploy them. According to the European Space Agency, states that the system consists of two small satellites flying 150 m apart with fine positioning and work as a huge instrument in space. Accurate GPS, inter-satellite radio links, visual sensors, and robust controllers are essential to ensure the system can work in formation[2].

The field of swarm control also focuses on mobile robot's formation where researchers and scientists try to ensure that a group of small mobile robots execute complex tasks like moving huge automotive parts or other items in warehouse. Scalable automation and warehouse management system has attracted multinational companies to invest in the automatic mobile robot, for example, Amazon has acquired Kiva System rebranded as Amazon Robotics to focus on autonomous mobile robots in their distribution centre[3].

Other companies that have a group of robots in their operations are: CarryPick AGVs in Sweden, Butler robots in India, Fetch by Fetch Robotics Freight, and Scallog System by IDEA Logistics Group[3]. The field of swarm robotics shows that the formation convoy controller and algorithm have still not matured. The study on mobile robot convoy is to ensure that a group of robots will not collide, follow the specified target, etc.

To understand the concept of the leader-follower convoy, the formation of leader-follower controller is categorized as in Figure 1, which shows that leader-follower controller is classified into two types: *(i) centralized approach and (ii) decentralized approach*. The centralized approach is a technique where the environment is known and does not change. Follower just follows all the information given by a static leader or from certain sources. The decentralized approach is a controller technique applied to the robot's convoy where the leader will move forward and is followed by the followers. The followers either get instructions from the leader directly or only interact between them. The interaction is accomplished by using link communication module.

The main objective of this paper is to review and identify the trend of the leader-follower controller technique used to control robots or vehicle system. Another objective of this paper is to identify system's type to prove the concept of leader-follower controller technique. The focus areas of this paper are; *(i) Current controller technique to control leader-follower or swarm system done by previous researchers and (ii) future challenges and limitations on the current researches.*

The paper first elaborates the controller to control leader-follower system, divided into a few sub-sections. Thereafter, in the background of review of summary of the controller, the paper elaborates key technologies and issues related to the controllers.

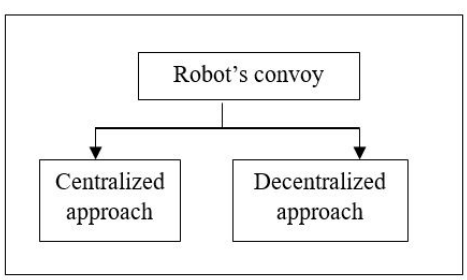

Fig. 1 — Classification on the robot's convoy approach.

Review on Leader-Follower Controller

The leader-follower formation utilizes several controller techniques. The controller for the formations is crucial to ensure the system maintains the formation and the follower can follow the leader accurately. The controllers used to control the system convoy are: Backstepping controller, Sliding mode controller (SMC), Neural network controller (NNC), Fuzzy logic controller (FLC), H∞ controller, kinematic based model controller, proportional integral derivative (PID) controller, model predictive controller (MPC), algorithm-based controller, feedback linearization, adaptive controller, and optimal controller. These controllers focus on controlling either mobile robots, mobile agents, unmanned aerial vehicle (UAV), unmanned surface vehicle (USF), Space Flying, or Satellites.

Backstepping controller

Integrator backstepping controller (IBC) was used to control multiple non-holonomic mobile robots based on two tricycles mobile robots[4]. The robots were controlled as a leader-follower system using Cartesian coordinates, but dynamics model and uncertainties of the robot were ignored. The research focused on the leader's position and the followers followed the position relative to the leader. The system outcome of the research is depicted in simulation only[4].

In another research, similar technique was used to control formation of AUV. Formation-keeping of multiple non-holonomic AUVs could be controlled using Lyapunov direct method, wherein IBC controlled the dynamics of the system formation while it moored. The simulation is divided into two parts. In the first part, there is the pair of two leaders with two followers. In this technique, the followers need to follow the leaders with targeted separation and orientation. The second part is chain formation where the first follower needs to follow the leader while the next follower will follow the initial follower[5].

In another study, the researchers focused to control the decentralized formation of three co-leaders using IBC to ensure each system maintains a certain distance from its neighbours. The controller acted as a double-integrator agent forming and maintaining desired triangle formation using constant velocity. The studies conducted concentrate on simulation only[6].

IBC was also utilized to control Quadrotor UAV formation. IBC controller for UAV was compared using simulation and experimental studies based on helical path and eight-shaped path[7].

Lyapunov direct method backstepping was employed to control under-actuated ships. The system required to follow desired trajectories while the velocity of the system remains tangential to the ship's path. The error of the coordinates was achieved to the convergence by using the Lyapunov–Krasovskii function[8].

Further, distributed backstepping method was proposed to control five non-holonomic wheeled mobile robots[9]. The approach was to make the robot converge to a desired geometric trajectories pattern while communication delays are assumed constant. The similar controller was also employed to control car-like robots[10]. Both of the controller results are elucidated by simulation graphs[9,10].

Another backstepping technique is a model-based controller combined with backstepping to maneuver spacecraft formation flying[11]. The leader spacecraft moved in the circular orbit while networked control systems were used to model the follower's motion relative to the leader. The result from the proposed method is shown in numerical simulation[11].

The general backstepping controller developed was commonly used to control non-holonomic mobile and mobile four-mecanum wheeled robot's formation[12]. Under the proposed method[12], the formation robots consist of one leader and one follower moving in circular trajectories. The controller design was based on the Cartesian coordinates and not polar coordinates to avoid singularity. The results from the controller design are simulated by including uncertainties and in the closed loop formation[12].

Formation control[9] was tested using five robots moving in the geometric pattern. The problem of the followers to track the position of the leader was solved using backstepping and Lyapunov direct design technique[13]. Multi-cooperation robot's control was solved by using an intelligent technique that includes uncertainties in the controller design[14]. Moreover, the controller presented in another study[15] was based on the series of nonlinear errors from chain form of the robot's kinematic model. The effectiveness of the control design is demonstrated via simulation results.

The researchers used a similar approach to control marine surface vehicles[16] while come other studies[17,18,19] used similar technique to solve control design of UAVs and tilt-rotor UAVs.

The cooperative behaviour of the system in another study[16] includes unknown nonlinear dynamics and ocean disturbances and the closed loop of the systems are guaranteed uniformly bounded using Lyapunov stability analysis.

The controller design based on the nonlinear model used three-dimensional space as its working space. The follower was not connected directly to the leader, but gathers information from the other follower using state estimation technique[17]. Notice that a similar scheme[18], however, the subject of study which was tilt rotor system utilized backstepping controller and one linear state-feedback controller per UAV and they were arranged in a hierarchical structure. Further, in another study[19], the proposed controller was targeted to ensure UAVs follow trajectory consisting of several sequences of waypoints. All the controller designs[16,17,18,19] were still at the simulation stage and not implemented yet, using experimental studies.

Moreover, another backstepping technique called adaptive backstepping was also used to control AUV[22], to control a system orbit in an external flow field[21] and to control second-order agents[22]. Under the proposed method[20], the leader AUV already knew the environment and the followers followed in a triangle formation. However, the cooperation method operates only in horizontal plane motion and without disturbances.

Controllability problem of the second order agent's system focused on designing a robust controller to track the orbital system and flow speed is estimated using the coordinated adaptive estimator[21]. The same technique was applied to solve spherical formation tracking control problem. Another general backstepping control design[23] was named as disturbance-observer-based formation controller. This controller was used to control *n* agents moving in the plane and the agents are described as a double integrator. Every agent must maintain a certain distance from its neighbours. Based on the simulation result, it is shown that all agents' velocity come together to a common value and no collision occurs between each communicating agent. Observers-continuous backstepping was utilized[24] for agents in 3-D space. The boundary controllers and observers were used by leader agents to estimate every agent's position based on the neighbour-to-neighbour information[22]. The result from this controller design is

demonstrated in simulation graphs. Another study exploited the backstepping technique with parametric uncertainties for Controller was incorporated with asymmetric barrier Lyapunov functions (ABLFs) to cater line-of-sight and bearing angle time-varying constraints of the system for USV[25]. A reconstruction module was used to estimate the velocity of the leader[25]. In the latter approach, disturbance-observer-based formation controller is used to controlling fully actuated unmanned surface vehicles (USVs)[26]. Table 1 shows the summary of various Backstepping controller techniques.

Sliding mode controller

Sliding mode controller (SMC) is another famous non-linear controller used by most researchers to control the leader-follower system. Various SMC controller techniques are designed, such as terminal sliding mode observer, fast terminal sliding mode, modified fast terminal sliding mode, decentralized adaptive sliding mode, decentralized sliding-mode observer, task-based adaptive non-singular fast terminal sliding mode coordination control algorithm (TANCCA), finite-time sliding-mode estimator, integral sliding mode control, low-level sliding mode control, sliding-mode formation- first order and second order, higher-order sliding mode observer/differentiator, hyperplane-based sliding mode controller (LHSMC), fuzzy sliding mode formation controller (FSMFC), super-twist sliding mode, hybrid model reference based adaptive super twisting sliding mode control, backstepping sliding mode, non-singular terminal sliding mode control (NTSMC), and immersion and invariance estimation based second order sliding mode control.

These SMC techniques are commonly used to control ocean surface vessels or unmanned surface vessels, multiple spacecraft formation flying (SFF) or rigid bodies, nonlinear vehicle following systems, nonholonomic mobile robots or multi-robot, multi-

Table 1 — Summary of leader-follower formation control using backstepping controller techniques.

Backstepping Controller Technique	Specific Controller Type	Control Problem	Level of Study
	Integrator Backstepping	Multiple nonholonomic mobile robots- two tricycle mobile robots [4].	Simulation.
		AUV formation[5].	Simulation.
		Double Integrator[6].	Numerical simulation.
		Quadrotor UAVs[7]	Simulation & Experiment
	Lyapunov Direct Method Backstepping.	Underactuated ships[8].	Simulation.
	Distributed Backstepping	Non- holonomic Wheeled Mobile Robots[9].	Simulation.
		Car-Like Robots[10].	Simulation.
	Model-Based Controller +Backstepping	Spacecraft Formation Flying[11]	Numerical simulation.
	General Backstepping	Nonholonomic mobile robots, Mobile Four-Mecanum-wheeled [9,12, 13, 14]	Simulation, Numerical simulation & Experiment only.
		Marine Surface Vehicles[16].	Simulation.
		Unmanned Aerial Vehicles(UAVs)[17,19]	Numerical simulation, Simulation.
		Tilt-Rotor Unmanned Aerial Vehicles[18].	Simulation.
		Disturbance-Observer-Based Formation Controller[23]	Simulation.
		Fully Actuated Unmanned Surface Vehicles (USVs) [26]	Simulation.
	Adaptive Backstepping	AUVs[20]	Simulation.
		Orbit in an External Flow-field[21]	Numerical simulation.
		Second-Order Agents[22].	Numerical simulation.
	Observers - Continuous Backstepping	Agents in 3-D Space[24].	Numerical simulation.
	Backstepping Technique, With The Parametric Uncertainties	Underactuated Surface Vessels (USV) [25].	Simulation.

agent system (MAS), double integrator and high-speed trains. Thus, the information here is divided based on the subject of studies; *(i) Unmanned surface vehicle, (ii) Spacecraft formation flying,* and *(iii) Wheel mobile robot.*

Unmanned surface vehicle was controlled by using low-level sliding mode control[27] while in another study the system was controlled by utilizing terminal sliding mode[28]. The author focused on using three degrees of freedoms for one leader and two followers to track the position and orientation of each vehicle with certain pre-set offset[27]. The formation scheme was divided into two parts: the first part uses formation of two vessels where the second vessel should follow the first vessel and maintains the distance between both of them using force and torque controls. Another test is to ensure that the controller stabilizes the distance of the second vessel located between the first and third vessel[27].

The terminal sliding mode was used to control one leader and two followers[28]. The controller design takes into account the external disturbances and system uncertainties. Based on the simulation, it is shown that the proposed estimation scheme can estimate external disturbances precisely. Also, the estimation error converges to zero in finite time as verified by Lyapunov stability analysis[28].

The state-of-the-art of applying slide mode control approaches for spacecraft flying formation was mentioned[29] where the researcher uses leader-follower super-twist sliding mode to control a cluster of satellites.

Finite-time sliding-mode estimator was used for controlling SFF[30,31]. In addition, terminal sliding mode and LHSMC was used to control spacecraft with external disturbances[31].

The controller was capable to control one leader and one follower of SFF in circular and polynomial forms[30]. The study showed that the controller was able to make rapid configuration in the presence of uncertainties and bounded disturbances.

Research found that finite time state estimator can control the decentralized cooperative leader-follower of spacecraft formation flight[31]. To develop the controller, low-pass linear filters are used and by using this filter, relative and absolute velocity of the system are not required. The estimator for the tracking is divided into two tasks: *(i) Decentralized sliding mode estimation and (ii) vehicle desired state tracking.*

In addition, a controller was proposed to provide finite time stability and convergence for SFF using distributed attitude coordinated control law[32]. The controller could minimize station keeping and formation keeping errors and bounded time-varying disturbance could be reduced by using the hyperbolic tangent function as was found in the numerical simulation. The controller was chattering-free because it is continuous.

Decentralized sliding-mode observer was developed[33], while another researcher conducted studies on two types of SMC, namely, fast terminal sliding mode and modified fast terminal sliding mode to control multiple SFF[34].

Decentralized sliding mode observer was used to tackle formation dilemma of six spacecrafts and one virtual leader[33]. The observer was used to produce reference attitude for each spacecraft because normally the reference attitude is only available by certain spacecraft in the group. The controller guarantees that all spacecraft could converge to targeted time reference altitude and the results were demonstrated as numerical simulations[33].

The controller aimed to control multiple spacecraft formation flying using two SMC types, namely, fast terminal sliding mode (FTSM) and modified fast terminal sliding mode (MFTSM). MFTSM is based on a combination of FTSM and Chebyshev neural network (CNN). The controller posed a faster rate of convergence compared to common FTSM. Besides, the controller was also considered robust against external disturbances[34].

Another controller to control spacecraft formation was elaborated in another research[35]. Decentralized adaptive sliding mode was used to control multiple rigid bodies where the rigid bodies could track the targeted time-varying attitude and concurrently maintain synchronization formation. The results from the controller design are shown in simulation graphs[35].

Another study[36] stated that task-based adaptive non-singular fast terminal sliding mode coordination control algorithm (TANCCA) could control spacecraft successfully and the spacecraft formation utilized ***n*** followers and one leader. Before the controller was designed, the desired velocity was set on each spacecraft to avoid obstacles. Then, TANCCA was designed to ensure spacecraft could perform formation and avoid unknown obstacles. However, TANCCA suffered chattering and another

controller was proposed to reduce chattering phenomena, Modified TANCCA (MTANCCA). The proposed MTANCCA had fast convergence and high precision to avoid obstacles[36].

Another common system controlled by the sliding mode controller technique was at mobile robot system. For example, integral sliding mode control, sliding-mode formation-first order and second order were used for controlling non linear vehicle following systems and three non-holonomic mobile robots, respectively[37]. The mobile robots used in this research consist of three non-holonomic mobile robots, including one leader and two followers. The formation controller did not require estimation of leader velocity but only utilized information from measurement between adjacent robots. The leader was initially provided with desired trajectory to follow and this research then was verified by another experimental study[37].

Another research to tackle mobile robot formation control problem used fuzzy sliding-mode formation controller (FSMFC) to control multi-robot formation with uncertainties[38]. The simulation and experimental study used four multi-robots called e-puck robots. The controller proved that fuzzy switching mechanism was able to ensure error states approach sliding surface quickly. Besides, system stability and desired formation pattern are guaranteed with Lyapunov theorem[38].

In addition, a controller called immersion and invariance estimation based second order sliding mode control was used to control the formation of mobile robots[39]. The approach mentioned that there were two centralized controllers: *(i) Adaptive dynamic feedback* and (ii) *immersion and invariance estimation based second order sliding mode* control. Based on the findings through simulation and experimental studies, it was interest that the controllers are smooth, continuous and robust to solve the formation dilemma by estimating the leader's linear velocity and simultaneously maintaining a certain distance from a follower[39].

Similar approaches were conducted[37] to control multi-agent system (MAS) and nonlinear vehicle following systems[40,41]. The decentralized control technique was proposed[40]. Based on the technique, the followers must maintain predefined distance to leader trajectory and should consider communication delay[40]. Another controller scheme was to ensure the string of vehicle platoon could be maintained at a rigid distance[41]. However, platoon's leader was assumed to have no acceleration while velocity errors were zero[41]. To solve the problem, the researchers then proposed another technique to overcome the assumption, called as modified constant time headway (MCTH)[41].

The hybrid model reference based adaptive super twisting sliding mode control was stated to control high-speed trains[42]. The proposed controller was non-linear model reference adaptive control (MRAC) combined with adaptive second order sliding mode control (SMC) where this controller was designed to ensure that the chattering effect could be reduced and made robust against load variation, model uncertainties, and external disturbances. The high-speed train initially was modelled as distributed and coupled mass of railway vehicle consisting of a multi-point mass model.

Another prominent finding in this robust sliding mode controller was named as non-singular terminal sliding mode control (NTSMC). These control approaches were to tackle the control problem of formation higher-order multi-agent systems combined with mismatched disturbances[44].

Another research[56] concentrated on backstepping sliding mode to control non-holonomic wheeled mobile robots (NWMRS). Systems that were used to confirm the controller's effectiveness are two types of NWMRS: (i) *Non-holonomic self-balancing two-wheeled mobile robots (NSBTWMRs)* and (ii) *non-holonomic wheeled differential-driving mobile robots (NWDDMRs).* Table 2 shows the summary of the sliding mode and its modification to handle several control problems.

Neural network controller

Four-Mecanum-wheeled omnidirectional mobile robot's vehicles (MWOVs) were used to test the fuzzy wavelet neural networks (FWNN) controller in the earlier research[14]. Concept of formation control emphasized on three-input-three-output second-order system model for MWOVs, as the plant and MWOVs were subjected to uncertainties. Even though the controller shows good performance, it does not yet cater to obstacle avoidance[14].

Then, a study mentioned that integrating neural networks could control marine surface vehicles successfully[16]. The paper stated that the vehicle's formation faced non-linear dynamics and ocean disturbances. However, the controller managed to

Table 2 — Summary of the leader-follower formation control using sliding mode controller techniques.

Sliding Mode Controller	Specific Controller Type	Control Problem	Level of study
	Low-Level Sliding Mode Control.	Unmanned Surface Vessels[27].	Simulation.
	Decentralized Sliding Mode Observer	Ocean Surface Vessels[28].	Simulation.
	Super-Twist Sliding Mode	A cluster of Satellites, Leader-Follower robot[29]	Numerical simulation.
	Terminal Sliding Mode Observer.	Spacecraft with External Disturbances[30,32].	Numerical simulation.
	Finite-Time Sliding-Mode Estimator.	Spacecraft formation flight[31].	Numerical simulation.
	Hyperplane-Based Sliding Mode Controller (LHSMC).	Spacecraft With External Disturbances[32].	Numerical simulation.
	Decentralized Sliding-Mode Observer.	Spacecraft Formation Flying[33].	Numerical simulation.
	Fast Terminal Sliding Mode.	Multiple Spacecraft Formation Flying (SFF) [34].	Numerical simulation.
	Modified Fast Terminal Sliding Mode.	Multiple Spacecraft Formation Flying (SFF) [34].	Numerical simulation.
	Decentralized Adaptive Sliding Mode.	Multiple Rigid Bodies[35].	Simulation.
	Task-Based Adaptive Non-Singular Fast Terminal Sliding Mode Coordination Control Algorithm (TANCCA)	Spacecraft[36].	Simulation.
	Sliding-Mode Formation- First Order &Second Order.	Three Nonholonomic Mobile Robots, Multi-Agent System (MAS)[37,40]	Experiment, Simulation.
	Integral Sliding Mode Control.	Nonlinear Vehicle Following Systems[37,41].	Experiment, Numerical simulation.
	Fuzzy Sliding-Mode Formation Controller (FSMFC).	Multi-robot[38].	Experiment.
	Immersion & Invariance Estimation Based Second Order Sliding Mode Control.	Mobile Robots[39].	Simulation & Experiment.
	Hybrid Model Reference Based Adaptive Super Twisting Sliding Mode Control	High-Speed Trains[42].	Numerical simulation.
	Backstepping Sliding-Mode	Nonholonomic Wheeled Mobile Robots (NWMRS) [43].	Simulation.
	Non-Singular Terminal Sliding-Mode Control (NTSMC)	Higher- Order Multi-Agent Systems[44].	Simulation.

stabilize the system and the tracking error converged to a small neighbourhood of origin[16].

Chebyshev neural network (CNN) controller was found to be able to control multiple SFF effectively[33]. CNN mentioned was used to approximate the system's non-linearity[33,34].

Another previous research to control mobile robots were proposed that Neural integrated fuzzy controller (NiF-T) comprises three types of NNC to control mobile robot: *(i) Fuzzy logic membership functions (FMF) (ii) Rule neural network (RNN)* and *(iii) Output-refinement neural network (ORNN)*[45]. Under the proposed methods, there were three tests conducted to confirm the controller efficiency on the robot's formation behaviour: (*i) Wall following, (ii) hall centering, and (iii) convoying.* The advantage of using fuzzy logic to train the neural network is that the numerical training iteration for the neural network controller could be minimized[45].

Another research utilized modular neuro-fuzzy network to control the robot's movement[46], while distributed artificial neural network was used to regulate the movement of a hexapod walking robot[47]. Even though the controller was successfully controlled Pioneer robot, the study was only limited on software called Saphira simulator[46]. On the other hand, the proposed technique successfully controlled the leg's configuration of the walking robot[47].

Further, a study conducted used neural perception module to control multi-robot and adaptive neuro-fuzzy inference system (ANFIS) controller to control humanoid servant robots[48,49]. Reinforced learning was used on the robot to make sure that the systems are capable to solve role emergence and task allocation, simultaneously[48]. Four degrees of freedom arm robot with face recognition with text to speech processor could be efficiently controlled via ANFIS controller. Controller design effectiveness is proved by simulation and experimental study[49]. Adaptive neural network controller was applied to control system which focused on obstacle avoidance in the simulations[50].

Another technique called as decentralized formation using-neural network was implemented on autonomous ground vehicles to verify the concept of formation control[51]. The system presented showed that the follower had limited knowledge of the leader and information was estimated via neural networks with online adaptive weight tuning laws[51]. Table 3 shows the summary of neural network controller to control some specific problems.

Fuzzy logic controller

Fuzzy logic controller (FLC) is normally used by various studies to control mobile robot formation. There are a number of studies that consider mobile robot formation with FLC such as in[13,52,53,54,55,56,57] where they used to control the subject of studies like multi-robot formation, three pioneer robots, autonomous mobile robot, and UAVs using FLC.

Another research explained that multiple non-holonomic mobile robots could be controlled by a defined virtual vehicle that tracked leader position[13]. Virtual vehicle trajectories then are followed by a follower of the formation. The advantage of using virtual vehicle's trajectories is that the velocity of the follower can be made independent of that of the leader.

Path planning and obstacle avoidance in real time were controlled by FLC with input data sensors equipped at the robot[52]. While FLC was used for formation control of one leader and one follower mobile robot[53]. This controller is divided into two segments: (i) *Formation controller* and (ii) *Collision avoidance*. Formation controller took angle and distance as its input where as collision avoidance took left sensor, right sensor, and front laser data as its input. Then, the output from formation controller and collision avoidance was combined by the coordinator to produce another output. Though the simulation studies elucidate that the controller manages to control the formation of the robot in the form of column, line, diamond, and wedge, but in real life, sensor faces noise either from surroundings or communication delay to locate the position of the leader.

In another study, a fuzzy rule-based controller was proposed to control the robot's navigation by taking input from angle and distance[54]. The input then it used by the controller to control wheel speed and then as a result, self-navigation of the robot can be established.

In addition, formation control by three pioneer robots equipped with SICK laser scanner were tested in the simulation and experimental studies[55]. A leader in the formation knows global trajectory while the followers only depend on data from the laser scanner to avoid collision between them[55].

Another approach focused on formation flight control to control the speed and attitude of UAVs but did not consider the dynamical models as mentioned by Rezaee, et al.[56]. The controller was used to control the speed and altitude for the follower from its kinematics equation. Next, under the proposed method[57], the FLC controller was used to address self-adaptive dynamic leader selection. The followers sent a signal to FLC to inform their states or unsatisfied

Table 3 — Summary on leader-follower formation control using neural network controller

Neural Network controller	Specific Controller Type	Control Problem In papers	Remarks
	Fuzzy Wavelet Neural Networks (FWNN)	Four-Mecanum-Wheeled mobile robot[14]	Simulation.
	Integrating Neural Networks	Marine Surface Vehicles[16].	Simulation.
	Chebyshev Neural Network (CNN)	Multiple Spacecraft Formation Flying (SFF) [33,34].	Numerical simulation.
	Rule Neural Network (RNN)	Multi-Robot[45].	Simulation.
	Output-Refinement Neural Network (ORNN).	Multi-Robot[45].	Simulation.
	Neural integrated Fuzzy conTroller (NiF-T)	Multi-Robot[45].	Simulation.
	Modular Neuro-Fuzzy Network	Single robot[46].	Simulation.
	Distributed Artificial Neural Network.	Hexapod Walking Robot[47].	Simulation & Experiment.
	Neural Perception Module	Multi-Robot[48].	Simulation & Experiment.
	Adaptive Neuro Fuzzy Inference System (ANFIS) Controller	Humanoid Servant Robot[49].	Simulation & Experiment.
	Adaptive Neural Network	Ocean Surface Vessels[50].	Simulation.
	Decentralized Formation Using-Neural Network	Autonomous Ground Vehicles[51].	Simulation.

signal if they were not satisfied with the leader and current leader is switched to another leader[57].

Another research proposed formation switching-fuzzy logic to control two-wheeled mobile robot system and compared two controllers[58]. The proposed fuzzy controller and Motlagh fuzzy controller was used to control E-puck robot in the Webots simulator. The switching technique was to guarantee that robots could avoid obstacles and there were three sub-controllers for the robot to switch: *(i) Trajectory tracking, (ii) obstacle avoiding, and (iii) vehicle avoiding controller.* According to another study, the proposed fuzzy controller demon started superior performance compared to Motlagh Fuzzy Controller in terms of time traveling and distance traveling[59].

In the other studies, the researchers applied interval type-2 fuzzy logic controller (IT2FLC) to control multiple mobile robots[60,61]. The performance of controller showed that the follower robot was able to maintain certain distance from the leader and could track the leader especially when the leader moved to an unknown environment. The posture of the follower being be in similar direction as that of a leader during convoy process[60]. The paper stated that IT2FLC had better performance compared to the type-1 fuzzy logic controller (T1FLC) by utilizing less data than T1FLC[61].

The mobile robot's formation was controlled via self-tuning proportional-integral-derivative (PID) fused with fuzzy theory and stated that the controller controls the convoy effectively[62]. Table 4 shows the leader-follower formation control using FLC.

Optimal controller

The optimal controller is a controller that deals with standard problem for minimizing a cost function, and in this paper, some applications like mobile robot's formation, satellite formation flying and UAVs can maintain their coordination and formation by using this type of controller.

In the research on multiple mobile robot convoy, a finding in the research paper mentioned that multiple non-holonomic mobile robots were easily controlled via distributed smooth time-varying[63]. Another swarm autonomous system utilized radar sensory system to maintain coordination[65].

The approach[63] was a convoy formed by a group of mobile robots to hunt a target. Troop formation consists of either four hunters and one target or eight hunters and one target. The hunter's mobile robots are Hilary type robot which is two-wheel mobile robot and performance of the controllers is elucidated in simulation studies[63]. Further, controller methodology adopted by Cao, et al.[65] also quite similar to[63] where there were two types of robots: Evader and a team of a mobile robots to capture the evader. The evader state is unknown priory to other mobile robot and to hunt the evader, mobile robots were equipped with CCD camera as a vision system, sonar sensors, and encoders[65]. Vision system initially used to gather information by segmenting teammates and the evader. Then, encoders were used to estimate relative position between robots while sonar sensor was used to detect potential dangers. Another consideration in this approach is that there is an effective sector which means robot should define the region in order to avoid collision between them[65].

Table 4 — Summary on leader-follower formation control using fuzzy logic controller

Fuzzy Logic Controller	Specific Controller Type	Control Problem In papers	Remarks
	Fuzzy Wavelet Neural N etworks (FWNN)	Mobile Four-Mecanum-Wheeled Robot[14]	Simulation.
	Fuzzy Logic Controller	Multi-robot, 3 Pioneer Robots, Autonomous Mobile Robot, Unmanned Air Vehicles (UAVs)[13,52,53,54,55,56,57].	Simulation, Numerical simulation & Experiment.
	Fuzzy Sliding-Mode Formation Controller (FSMFC)	Multi-robot[38]	Experiment.
	Formation Switching - Fuzzy Logic	Two-Wheeled Mobile Robot[58]	Simulation.
	Motlagh Fuzzy Controller.	E-puck robot in the Webots simulator[59]	Simulation.
	Interval Fuzzy Type-2 Controller	Multiple Mobile Robots[60]	Simulation.
	Interval Type-2 Fuzzy Logic Controller (IT2FLC).	Multiple Mobile Robots[61]	Simulation.
	Self-Tuning Proportional-Integral-Derivative (PID) Fused With Fuzzy Theory	Mobile Robot[62]	Simulation.

Moreover, optimal controller is used to control the formation of spacecraft flying. For instance, linear quadratic gaussian (LQG) controller was used to coordinate the SFF[64], wherein it was stated that the controller design was for centralized and decentralized SFF and relied only on output measurements. Simulation findings show a comparison between a centralized and decentralized approach where there is a trade-off between communication and control energy[64].

In the controller point approach[66], the controller aimed to control UAV swarm systems by utilizing switching interaction topologies between *(i) Distributed time-varying formation Lyapunov functional approach* and (ii*) Algebraic Riccati equation*. The aim of this method was to ensure the UAV system was able to convoy in time-varying formation. There were four quadrotors used in experimental studies to test their controller protocols[66].

Another method focused on the movement of multiple non-cooperative leaders and multiple non-cooperative followers by using infinite-horizon incentive stackelberg[67]. The disturbance was attenuated by H_∞ constraint to ensure the leader reaches Nash equilibrium. At the same time, the followers achieved their Nash equilibrium ensuring the incentive Stackelberg strategies of the leaders. In addition, it was stated that disturbance in the multi-agent system is captured via the system H_2 and H_∞ *norms* and robustness to time delay is defined as the maximum allowable delay. The authors explained that the graph-theoretic bounds on the extreme eigenvalues of the grounded Laplacian matrix which considers the impact of disturbances and time-delays on the leader-follower dynamics[67]. *H_∞ controller*

H∞ controller is another type of optimal controller to control the leader-follower system. H_∞ controller was used to maneuver quadrotor UAVs formation[7]. In another formation, quadrotor UAV was used as a testbed where one quadrotor acts as a leader while another two quadrotors act as followers. Formation motion of this leader-followers UAV was subjected to external disturbances and uncertainties. Based on the result acquired, this controller performs better than integrated backstepping controller[7].

Another type of H_∞ controller named linear state-feedback D-stable H_∞ controller was used to control tilt-rotor unmanned aerial vehicles[18]. In this case, the controller proposed is assigned to each UAV system to track the desired trajectory and performance of the controller is shown via a simulation study. To formulate the controller, the dynamics model of the UAV system is linearized and constant external disturbance is used to test the robustness of the controller. Table 5 shows summary of the leader-follower formation control using optimal controller and H_∞ controller.

Kinematic based model controller

Kinematic based model controller is another controller considered by most of the researchers to

Table 5 — Summary on leader-follower formation control using optimal controller and H_∞ controller

Optimal Controller	Specific Controller Type	Control Problem	Remarks
	Distributed Smooth Time-Varying.	Multiple non-holonomic Mobile Robots[63].	Simulation
	Linear Quadratic Gaussian (*LQG*) controller.	Satellite Formation Flying[64].	Simulation
	Radar Sensory System	Multiple Autonomous Robots[65].	Simulation
	UAV swarm systems with switching interaction topologies *(i)distributed time-varying formation Lyapunov functional approach. (ii) algebraic Riccati equation*	UAV Swarm Systems[66].	Experiment.
	Disturbances captured by *H2* and *H∞* Norms and Robustness to time delay is defined as the maximum allowable delay.	Multi-Agent System[67].	Simulation
	Infinite-Horizon Incentive Stackelberg	Multiple Non-Cooperative Leaders and Multiple Non-Cooperative Followers[68]	Numerical simulation.
H∞ controller	Specific Controller Type	Control Problem	Remarks
	H∞ controller	Quadrotor UAVs[7]	NA
	linear state-feedback D-stable *H∞* controller	Tilt-Rotor Unmanned Aerial Vehicles[18]	Simulation.
	H2 and *H∞* norms	Multi-Agent System[67]	Simulation.

study the effectiveness of leader-follower convoy system. This controller variety can be commonly segmented to a few applications, such as mobile robot's formation control, unmanned surface vehicle control and spacecraft formation flying. For example, model-based controller was used[26,70,71,72,73,74,75,76] to control the multiple non-holonomic mobile robots, self-reconfigurable robots, unmanned surface vessels and set of nonlinear agents.

The researchers focused on locomotion gait for multiple robots that could transform from one shape to another shape. Seven CONRO robot's modules were used for the transformation, where initially robots were in chain form and then transform to quadruped configuration. The locomotion then changed from snake gait to quadruped walking gait.

In the previous research that considered decentralized control law[71], eight leader-followers were employed. The formation of the robot applied classical guidance law and kinematics rules for modelling and controlling mobile robots. The rules were used to relate leader and follower using differential equations and formation plans of the robots were based on three different matrices: *(i) Leader-follower formation, (ii) leader-follower range, and (iii) leader-follower visibility.* However, the controller performance was only tested via simulation study[33].

Further, another approach in the kinematic based model controller was used to control several self-reconfigurable robots in convoy formation[72]. A self-reconfigurable robot had less ability to gather information from the environment and impaired.

Furthermore, other research[55] used kinematic model using Cartesian to model and control the multiple non-holonomic mobile robots. Multiple formations of mobile robots in this research combined leader-follower and communication of cross-platform technology. Another approach applied inverse kinematics-null space-based behaviour to control redundant manipulators[77].

In addition, to tackle the problem for control formation of the robot based on the relative position and orientation, researchers[73] proposed formation convoy using the kinematic model and trajectories tracking which includes either formation error or without errors. The approach[78] stated that to apply a dynamic extension of the kinematic controller, the point at the middle of the robot was used as a point to be controlled. The effectiveness of the controller proposed is elucidated via numerical simulations and experiments where, from the findings, the robot's formation converged to smooth value and the angles converge to similar angles.

Another study[74] dealt with a problem to synchronize output from nonlinear agents. The nonlinear agent's exchange information using time-varying network between leader and followers. Every follower had its own dynamics, and to solve this problem, the author proposed a decentralized type controller. The kinematic controller proposed[75] gathered information from the LIDAR sensor to generate command input velocity to another controller. Further study mentioned that the leader-follower agent with a time delay can be converted to algebraic forms before it can be controlled.

Kinematic controller[76] called as first order low pass filter kinematic design using dynamic surface control (DSC) can efficiently control fully actuated unmanned surface vehicles (USVs). Table 6 shows the summary of kinematics based controller to control leader-follower formation.

Proportional integral derivative (PID) controller

The classical controller also can be found competent to control leader-follower formation. There

Table 6 — Summary of leader-follower formation control using kinematics based model controller.

Specific Controller Type	Control Problem	Remarks
Kinematic Based Model Controller	Spacecraft Formation Flying[69].	Experiment.
	Multiple Non-Holonomic Mobile Robots, Self-Reconfigurable Robots, Unmanned Surface Vessels, Set of Nonlinear Agents[70,71,72,73,74,75,76].	Simulation & Experiment.
Kinematic Model Using Cartesian	Multiple Non-Holonomic Mobile Robots[55].	Simulation & Experiment.
Inverse Kinematics- null space-based behavior	Redundant manipulators[77].	Simulation & Experiment.
Dynamic Extension of the Kinematic Model	Unicycle-Type Robots[78].	Simulation & Experiment.
First Order Low Pass Filter Kinematic Design Using Dynamic Surface Control (DSC)	Fully Actuated Unmanned Surface Vehicles (USVs)[26]	Simulation.

are two examples of PID controller that effectively control the formation of the robot: One controlled a mobile robot using Self-Tuning Proportional-Integral-Derivative (PID)[62] and the seernl controlled a multi-agent robot using normal PID[79]. The controller is capable to reduce position error resulting from the inefficiencies of the compass sensors. The compass sensors normally experienced noise from surroundings and the convoy in this study was tested via simulation and experiment.

Besides, the authors explained that the self-tuning PID controller integrated with the fuzzy theory was able to control multi-robot convoy successfully based on the findings from a simulation study[62]. Table 7 shows summary of PID controller to control leader-follower formation.

Model predictive controller (MPC)

Model predictive controller (MPC) is another type of controller capable to control the formation of a mobile robot. Controllers that are applied two different in studies[80,81] stated that decentralized nonlinear model predictive control could control multi-agent system omnidirectional mobile robot's formation excellently.

Several formation controller types could be used in the multi-agent system's convoy, such as virtual structure, leader-follower, behaviour-based, and model predictive control[80].

The solution of controlling omnidirectional mobile robot convoy utilized model predictive control to adjust the speed of each robot to maintain their coordination[81]. The controller enables robots to adjust the path rate to follow the path set by the researchers and this controller effectiveness has been validated with simulation and experiment.

MPC controller named as linear model predictive controller is capable to regulate multiple differentially driven wheeled mobile robots (WMRs) to the certain required target[82]. The formation of the system is adjusted to avoid obstacles by using virtual force to correct the robot's direction and maintain formation. A simulation conducted by the researcher tested the controller on the static and moving obstacles. Table 8 shows the leader-follower formation control using MPC controller.

Algorithm-based Controller

The algorithm-based controller is a new type of controller that has a lot of formulation range, for example, mutual adaptation, centralized algorithm, i.A* algorithm-search, nembrini's alpha algorithm, distributed flocking algorithms, swap-greedy algorithm etc.

A Study used an algorithm-based controller called mutual adaptation to control the formation of foot-bots and flying robots[83]. The flying robot attached itself to the ceiling and provides guidance to foot-bots. Meanwhile, foot-bots moved forward and backward to find the shortest path and at the same time, it gave feedback about its movement to the flying bots. Then, based on the feedback from foot-bots, flying bots gave instructions to foot-bots. The formation of flying bots and foot-bots was named as cooperative self-organization and the formation is elucidated via computer simulation.

Moreover, another study[84] used the formulation of caster wheel equation to regulate the movement of multiple mobile robots with dual manipulators. Each robot coordinated with other robots to handle and move the object from one point to another point without a specific geometric path. The formulation was verified by employing omnidirectional mobile base and two 7- DOF manipulators in the experiment.

i.A* algorithm-search was applied in their Unmanned Air Vehicles (UAV)[85] while centralized

Table 7 — Summary on leader-follower formation control using PID controller

PID controller	Specific Controller Type	Control Problem	Remarks
	Self-Tuning Proportional-Integral-Derivative (PID)	Mobile Robot[62].	Simulation.
	PID Controller	Multi-agent robot[79].	Simulation & Experiment.

Table 8 — Summary on leader-follower formation control using MPC controller

Model Predictive Controller	Specific Controller Type	Control Problem	Remarks
	Decentralized Nonlinear Model Predictive Control	Multi-agent System[80].	NA
		Omni-directional Mobile Robots[81].	Simulation & Experiment.
	Linear Model Predictive Controller	Multiple Differentially Driven Wheeled Mobile Robots (WMRs)[82]	Simulation.

and trajectory planner were used to manoeuvre market-based multi-robot and autonomous vehicles, respectively[86,87]. The former controller focused on ensure UAV moved on certain waypoint from the danger zone and faces risk from being fired by the enemy[85]. Further, according to the latter study[86], there were several methods of coordination for multi-robots, such as an initial framework for evaluating the task, centralized optimal approach, a distributed behavioural approach, a market-based approach, and centralized planner. The planner emphasized that the follower behaved like trailer attached to the leader and this method could eliminate communication mismatch or delay[87]. The leader's velocity and acceleration were set to ensure initially so that the followers could follow the leader accurately. The convoy utilized two radio-controlled blade MQX quadrotor vehicles and verified using simulations and experimental studies.

In addition, other researches[88,89] focused on utilizing biologically inspired swarm intelligence for robot reconfiguration (S.I.R.R) and biomimetic controller to control the multi-legged walking robot and hexapod robot. The hexapod robot could be controlled via behaviour positive feedback and velocity positive feedback control[91].

Two more researcher studies[92,93] utilized several algorithms to control the formation of a heterogeneous group of mobile robots. The algorithms utilized by them are: Global localization and Bézier trajectory-least squares tracking, extended kalman filter (EKF), and unscented Kalman filter (UKF). The target application of this system to make leader-follower to deploy and move safety barricades at the highway construction automatically. Followers had less information about the leader and had to acquire relative information from the leader only by using SICK laser range finder and Hough transform. The validity formation was confirmed by using indoor and outdoor experiments. Similar sensor was adopted[97] where multiple mobile robots use laser-based SLAM to coordinate the formation movement of the robot and uses laser-based SLAM to coordinate the formation movement of the robot

Multi-agent system or multi-robot system systems were effectively controlled[94,95,96] using distributed multi-destination potential fields, centralized and a distributed version-formation matrix and locomotion algorithm. The centralized and distributed method applied one leader and five followers during the convoy[95]. While another approach tested the algorithms developed on two hexapods robot via experimental study[96].

In another study, heterogeneous system[98] used market-based approach and local communications to control the communication between the robots. A semi-autonomous system was composed of two ground vehicles controlled by an operator for its leader while the follower that followed the leader is autonomous.

In another studies, the robot's named as differentially-driven wheeled mobile robots are controlled via artificial potential field[100]. The only leader adopted artificial potential field function and the followers only maintain separation distances from the leader. This algorithm enabled the leader to avoid obstacles and find an optimal path to the desired position.

Another study[101] stated that swarm robots comprising two or three robot system were controlled using temporal logics swarm algorithm, namely, the alpha algorithm. The behaviour of the swarm was checked using this algorithm to ensure it conformed to certain specifications. Another method[102] used multi-robot convoy controlled by centralized algorithm to inspect, repair and maintain dome and a leader connected to a follower by a string. The leader acquired information from follower and moved around the dome. The leader sent information to the follower to adjust the string and maintain certain configuration. Another robot's formation controlled by cooperative chaotic synchronized dynamics[103] used star network topology where a group of mobile robots is assigned to capture a certain target. This method is also known as a predator-prey formation.

Multiple robot system[104,105] applied multi-robot collaborative behaviour and localization and GPSO-PF algorithm, respectively. The aim of the algorithm was to ensure two hexapod robot formation could move at indoor environment where GPS signal inaccessible[104]. The formation utilized inertial sensors i.e accelerometer and gyro meter to ensure that the robot's formation could be established.

The second method adopted[105] focused on using GPSO-PF algorithm to search optimal path and also applied KLSPI algorithm to avoid obstacles. This two algorithms were only applied by the main leader, while the second leader focused to adjust the formation shape based on the data acquired from the main leader. The follower followed the

second leader and maintained distance and angle relations.

Another algorithm proposed[108] used particle swarm optimization (PSO) and cluster head gateway switch routing (CGSR) to control multi-robots. Besides, the authors also stressed on using centralized and distributed decision-making strategies. Another method proposed was by using a hybrid mechanism for system formation.

In another research[76], unmanned helicopters employed decentralized hybrid supervisory which used polar partitioning technique composed of discrete supervisor and modular structure. The follower dynamics in this formation were converted to the finite state system and after that the supervision modular technique was used to ensure that the formation moves to certain goals. The modular technique in this study was divided into three methods: *(i) Reach formation (ii) keep formation, and (iii) collision avoidance.*

In another research using UAVs[107], the system was controlled using the potential field method combined with state feedback controller. Initially, the leader tracked the flying target using an attractive potential field followed by the followers. The followers then tracked a similar target but mostly relied on the leader potential field. The advantage of this method is that the formation can avoid obstacles by sending and receiving repulsive potential field from the obstacles.

Further study in the UAV formation and swarm system by a group of micro air vehicles which was effectively controlled by modified pursuit algorithm[115]. The algorithm is to ensure that the three micro air vehicles manoeuvre in circles by generating normal and tangential acceleration tracked by an inner loop controller. The formation of these vehicles is proved by a simulation study. However, based on the simulation, the path tracking for the formation is still not optimal. Moreover, another problem in UAV multi-agent formation is addressed[111] by proposing a novel distributed leader-follower algorithm to maintain their formation. The algorithm is able to handle communication failure based on Bernoulli distribution.

A study focused on fault-tolerant concept for their kinematic of car-like robots[109]. The advantage of the algorithm is to ensure that the formation can be maintained even though the linear velocity and position sensors get damaged. By using this algorithm, the distance between leader and follower can be reduced and the follower will not leave the leader. The author compares the algorithm, variable structure feedback construction algorithm (VFSCA) and applied conventional methods (LSA) and based on the finding, VFSCA performs better than LSA to reduce tracking error.

In further exploration, the formation of non-holonomic mobile robots are easily controlled via novel decentralized algorithm control[110] and another type of robot's formation, multi-robot system (MRS) is definitely controlled by Swap-Greedy algorithm[112]. The aim of the study[110] was to ensure that multiple non-holonomic mobile robots can move and avoid collision and heading successfully. Due to non-holonomic behaviour, initially the robot's group was converted to known consensus by smooth and continuous control law. The algorithm enabled the followers to switch a leader and the formation can be recovered again after switching is done[112].

Multiple systems, multiple uncertain Euler-Lagrange systems are controlled by adaptive distributed control algorithm while multiple non-cooperative leaders and multiple non-cooperative followers are regulated by infinite-horizon incentive Stackelberg[67]. Further, in another study[114], multi-robot's formation is cascaded while the multi-agent system in the paper uses a decentralised mean field algorithm for controlling purpose. Table 9 shows the formation control of the leader-follower using algorithm-based Controller.

Feedback linearization (FL) controller

Feedback linearization is another type of non-linear controller used by several researchers to control the formation of the robot.

Input-output feedback linearization controlled multiple differentially driven wheeled mobile robots (WMRs)[82]. The controller designed was to find the linear model of a nonlinear mobile robot. The controller able to ensure each robot could detect obstacles and update the inputs. Simulation results showed that the controller could control the robot's formation in the static and moving obstacles. Besides, the controller was also able to control the robot's convoy in unstructured environments efficiently.

A formation of car-like robot and heterogeneous group of mobile robots[117,118] were controlled by full-state linearization via dynamic feedback. The full-state feedback linearization using dynamic feedback for the controller was verified using a simulation

Table 9 — Summary on leader-follower control using algorithm-based controller

Algorithm-based Controller	Specific Controller Type	Control Problem	Remarks
	Mutual Adaptation	Small Wheeled Robots[83] - Foot-Bots - Flying Robots	Simulation.
	Caster Wheel Equation	Multiple Mobile Robots with Dual Manipulators[84].	Experiment.
	i.A* Algorithm-Search	Unmanned Air Vehicles (UAV)[85]	Simulation.
	Centralized Planner Trajectory Planner	Market-Based Multirobot, Autonomous Vehicles[86,87].	Simulation, Simulation & Experiment.
	biologically inspired Swarm Intelligence for Robot Reconfiguration (S.I.R.R) Biomimetic Controller	Multi-Legged Walking Robot, Hexapod Robot[88,89].	Simulation, Simulation & Experiment.
	Distributed Flocking Algorithms	Multi-Agent Networked Systems[90].	Numerical simulation.
	Behaviour Positive Feedback Velocity Positive Feedback Control	Hexapod Walking Robot[91].	Simulation & Experiment.
	Global Localization & Bézier Trajectory-Least Squares Tracking Extended Kalman Filter (EKF) Unscented Kalman filter (UKF)	Heterogeneous Group Of Mobile Robots[92,93]	Simulation & Experiment.
	Distributed Multi Destination Potential Fields	Multiagent[94]	Numerical simulation.
	Centralized And A Distributed Version-Formation Matrix	Multi-Robot System[95]	Simulation.
	Locomotion Algorithm	Multi-Agent Robots[96]	Simulation.
	Laser-Based SLAM	Multiple Mobile Robots[97].	Experiment.
	Market-Based Approach - Local Communications	Heterogeneous Systems[98].	Numerical simulation.
	Operator Control For The Master And Autonomous Control For The Slave	Semi-autonomous system - two ground vehicles[99].	Simulation & Experiment.
	Artificial Potential Field	Differentially driven Wheeled Mobile Robots[100].	Simulation.
	Temporal logics swarm algorithm or Alpha algorithm	NetLogo simulation[101].	Simulation.
	Centralized Algorithm	Multi-Robot Dome[102].	Simulation.
	Cooperative Chaotic Synchronized Dynamics	Two-Wheeled Mobile Robots[103].	Simulation.
	Multi-Robot Collaborative Behavior And Localization	Multi-Robot Navigation Indoor Environment[104].	Simulation.
	GPSO-PF Algorithm	Multiple Robot System[105].	Simulation.
	Decentralized Hybrid Supervisory - Polar Partitioning Technique - Discrete Supervisor - Modular Structure	Unmanned Helicopters[106]	Simulation.
	Potential Field Method Combined With State Feedback Controller	Unmanned Aerial Vehicles (UAVs)[107].	Simulation.
	Particle Swarm Optimization (PSO)	Multi-Robots[108].	NA
	Cluster Head Gateway Switch Routing (CGSR)	Multi-Robots[108].	NA

(*Contd.*)

Table 9 — Summary on leader-follower control using algorithm-based controller (*Contd.*)

Algorithm-based Controller	Specific Controller Type	Control Problem	Remarks
	Fault-Tolerant Concept	Kinematic of Car-Like Robots[109].	Simulation & Experiment.
	Novel Decentralized Algorithm Control	Non-holonomic Mobile Robots[110].	Simulation & Experiment.
	Novel Distributed Leader-Follower Algorithm	Multi-agent Systems (UAV) [111].	Simulation.
	Swap-Greedy Algorithm	Multi-robot System (MRS) [112].	Simulation.
	Adaptive Distributed Control Algorithm	Multiple Uncertain Euler-Lagrange Systems[113].	Simulation.
	Infinite-Horizon Incentive Stackelberg	Multiple non-Cooperative Leaders and Multiple Non-Cooperative Followers[67].	Numerical simulation.
	Cascade Robot Formation System	Multi-Robots[114].	Simulation.
	Modified Pursuit Algorithm	Micro Air Vehicles[115].	Simulation.
	Decentralized Mean Field Algorithm	Multi-agent system[116].	Simulation.

study[117]. The simulation study was conducted via MATLAB and three-dimensional (3D) robot simulator Gazebo with robot server player.

Another study[119] focused on multiple group vehicle convoy in the triangle form with the followers following the leader in the constant distance. Five vehicles were used as the subject of study and the formation validated via simulation. The simulation study for this research included uncertainties and noise from environments.

Another type of FL controller[118] static feedback linearized controller and dynamic feedback linearization was able to control multiple non-holonomic mobile robot's formations. This controller was able to control one leader and one follower using P3AT robots. To apply the controller, the follower's motion was converted to a separate trajectory tracking phase before normal trajectory tracking for non-holonomic applied. The effectiveness of the proposed controllers was verified using simulation and experimental studies. According to the findings, the static feedback linearized controller had lower efficiency by having noisier angular velocity compared to the second proposed controller. Table 10 shows leader–follower formation control using feedback linearization controller.

Adaptive controller

Adaptive controller is another type of controller reviewed in this paper. Various techniques utilizing adaptive controller were founded in[120,121,122,123,124,125].

In the paper[120,121], the authors used distribute adaptive controller named as dynamic surface control technique to control high-order nonlinear time-varying multi-agent systems and a group of non-identical agents. The controller was used to control robotic manipulators where the followers only required the first two states instead of full states[120]. Based on the simulation conducted, it was found that any obstacles caused by unknown time-varying parameters could be eliminated and errors converge to zero. The second approach [121] was nearly similar to the first, but the formation motion differed where the followers used to surround leader uniformly in a circular motion.

Furthermore, multi-agent systems were controlled by distributing an adaptive controller using only local information[122]. Leader dynamics are independent of the followers but interconnected with the follower's state. The formation of the system is shown via simulation test.

In one research study, another multiple vehicle convoy could be controlled by the adaptive controller and the robust adaptive controller was elaborated[123], while in another research[124], mobile robots were easily maintained in their convoy position by adaptive controller using the vision-based technique. The adaptive controller was used to solve the problem of relative distance relative estimation based on leader-follower error model[123]. The adaptive controller using vision-based as in [124] used pin-hole camera attached followers and the lock feature image of a leader. Leader's velocity was not estimated in this study but only depends on the desired image plane of a leader. According to the researcher, the system was stable based on the experimental study conducted by them.

Table 10 — Summary on leader-follower formation using feedback linearization controller

Feedback Linearization Controller	Specific Controller Type	Control Problem.	Remarks
	Full-state linearization via dynamic feedback	Car- Like Robot. Heterogeneous Group of Mobile Robots[92,117,119.].	Simulation & Experiment.
	Dynamic Feedback Linearization	Multiple Non-Holonomic Mobile Robots[118].	Simulation & Experiment.
	Static Feedback Linearized Controller	Multiple Non-Holonomic Mobile Robots[118.].	Simulation & Experiment.
	Input-Output Feedback Linearization	Multiple Differentially Driven Wheeled Mobile Robots (WMRs)[82].	Simulation.

Table 11 — Summary on leader-follower formation control using adaptive controller

Adaptive Controller	Specific Controller Type	Control Problem In papers	Remarks
	Distribute Adaptive Controller - Dynamic Surface Control Technique	High-Order Nonlinear Time-Varying Multi-Agent Systems, Group of Non-Identical Agents[120,121].	Simulation.
	Distribute Adaptive Controller Using Only Local Information	Multi-agent Systems[122].	Simulation.
	Adaptive controller and robust adaptive controller.	Multiple Vehicle[123].	Simulation.
	Adaptive Controller Using Vision-Based.	Mobile Robot[124].	Experiment.
	Distributed Adaptive Protocol.	Multi-Agent System[125].	Simulation

Distributed adaptive protocol[125] was used to control the swarm of the multi-agent system to make the system maintain their coordinates. The protocol consensus guaranteed is only achieved if communication is bidirectional, but if communication is unidirectional, the protocol is locally stable. Table 11 shows the summary of the leader-follower control using adaptive controller.

Key Technologies and Current Issues

The swarm robotics or specifically leader-follower convoy systems rely on several technologies. The main characteristics of this technique are focused on the controller that is normally applied to the robotics system or any system that uses the leader-follower concept. Here we focus on some key technologies from the review and the current issues that need to be tackled.

Real and robust application

Most of the wheel mobile robots that are proposed to apply leader-follower techniques in this study are only limited to the simulation study. Besides, even if several leader-follower controllers utilizing WMRs are tested in the experimental studies, the robots are actually very small. The controller techniques are still not tested on the bigger scale hardware, such as unmanned guided vehicle (UGV) normally used in the factories and warehouse.

Furthermore, the controller techniques mentioned in this review already tested in the simulation study are considered concept techniques because to test the real application is quite expensive; for instance, to test leader-follower controller technique on the space formation flying (SFF) or satellite system is costly. Besides, actual data from the companies or agencies are quite hard to be acquired to be included as parameter for controllers because the data are commonly considered secret by companies. Thus, the parameters to be included as plant parameters to the controller are considered either outdated or are based on the assumption which leads to non-robustness of the controller.

In addition, to apply the leader-controller technique, various sensors and hardware in the form of fast processing on-board system, fault tolerant and backup system are still not yet explored and mentioned by many researchers. Thus, the technologies that need to be explored should focus on comparing the results from a simulation study with the experimental tests. Even the simulation results are quite impressive, it does not guarantee the system poses similar behaviour in the field tests. After the controller is done on WMR, the controller should also be tested and implemented on the real applications robots. Moreover, the leader-follower controller methods tested on the SFF should utilize more updated data and parameters. The small scale on-

board controller system, higher sensitivity sensors, and backup system should be developed to realize the technique proposed.

Knowledge-base and commercialization

The current commercialization trend on the UAV system focuses on the DIY or Do It Yourself UAV. Even though UAV now can be found in the small form but technique as leader-follower controller is not being used by the operator or user. UAV users normally will fly UAV using remote controllers that are supplied as a package as UAV tools when they buy UAV in the market. Fewer UAV users feel to test or to apply knowledge related to the controller algorithm on their system. Thus, the trend of marketing UAV in the form of DIY should be changed to be knowledge-based marketing where software and controller technologies should be packaged as alternative options to the users.

Cost and maintenance

Cost of the system equipped by the leader-follower controller depends on the hardware or controller board, sensors and any hardware equipped at the system. For instance, the leader-follower controller technique that requires at least five robots or five UAV systems for the convoy will affect the overall cost of operation. The cost of operation does not include maintenance of the system in case any fault occurs. Thus, based on the review, most of the researchers use simulation to prove their controllers.

Ethical issues

Another aspect that needs to be considered when applying the leader-follower controller in the robot convoy system is ethical issues. The system convoy can be misused by some users that may apply the convoy system on illegal matters. For instance, they may use a leader-follower flying system to smuggle things or to do surveillance operation on others.

Conclusion

In this review paper, several articles on the previous studies about controller on swarm robotics, leader-follower formation, and convoy system have been elaborated and summarized. This paper has thoroughly discussed controller utilized by leader-follower multi-system platooning in order for the system to track reference trajectories, avoid obstacles, distance estimation by follower to follow leader and orient the platoon in the certain target. Multi-systems employed by many researchers in their controller studies are autonomous vehicles, multiple mobile robot system, non-holonomic robots, and omnidirectional robots. Another commonly used system is spacecraft formation flying that moves around the orbit, the multi-agents unmanned aerial vehicles (UAV) and the unmanned surface vehicles (USV). It is clear that the advantages of using robot's convoy or leader-follower techniques are small and multiple robots can be used for huge missions like terrain monitoring, surveying, etc. The controller techniques is studied are segmented into: *(i) Back stepping controller, (ii) Sliding mode controller, (iii) Neural network controller, (iv) Fuzzy logic controller, (v) Optimal controller, (vi) Kinematic based model controller, (vii) Proportional integral derivative (PID) Controller, (viii) Model predictive controller (MPC), (ix) Algorithm-based controller, (x) Feedback linearization,* and *(xi) Adaptive controller.* From all these controller segments, various other controller names, capabilities and applications have been discovered. Controllability and stability of the controllers were normally tested using Lyapunov stability analysis wherein it is discovered that most of the controllers designed guarantee the formation system to converge to the desired objectives. In order to prove controller effectiveness, it can be said almost 70% of the research makes use of simulation or numerical simulation and fewer studies verified the results obtained from simulations with experimental studies. The results might not be appropriate when the system needs to be applied in real time and during practical missions.

Future challenges

Most of the researchers claim that they have completed their controller technique using simulation study but there are several future challenges that should be considered. The challenges are: *(i) Convoy of reconfigurable robot, (ii) collaboration of leader-follower between ground robot and unmanned ariel vehicle, (iii) formation control of outer pipe or in-pipe robotic using either multiple mobile robot or unmanned system,* and *(iv) collaborative leader-follower technique using vision system.*

Recommendation

There are many factors that influence the implementation of the leader-follower controller in the real system. For instance, cost and size of the controller board used to execute the controller

methods, reliability of the system and application of the system in the real-time, system efficiency, etc. Some recommendations are made to ensure that the controller techniques mentioned in this review become fruitful and benefits others:

(a) For ongoing and current research projects, consideration should be given to the experimental study and not limit to simulation for the controller proof.

(b) The application of the leader-follower technique should be vastly applied to another field that requires a large number of workers in the agricultural field. Application for leader-follower controller techniques on the tractors convoy for plowing and UAVs for spraying herbicides or fertilizing crops.

(c) More consideration on applying the techniques reviewed in this paper to a humanoid robot that can reduce human repetitive jobs.

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