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Multi-system vehicle formation control based on nearest neighbor trajectory optimization

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Abstract. In the present study, a novel optimization method in formation control of multi -system vehicles based on the trajectory of the nearest neighbor trajectory is presented. In this regard, the state equations of each vehicle and multisystem is derived and the optimization scheme based on minimizing the differences between actual positions and desired positions of the vehicles are conducted. This formation control is a position-based decentralized model. The trajectory of the nearest neighbor are optimized based on the current position and state of the vehicle. This approach aids the whole multi-agent system to be optimized on their trajectory. Furthermore, to overcome the cumulative errors and maintain stability in the network a semi-centralized scheme is designed for the purpose of checking vehicle position to its predefined trajectory. The model is implemented in Matlab software and the results for different initial state and different trajectory definition are presented. In addition, to avoid collision avoidance and maintain the distances between vehicles agents at a predefined desired distances. In this regard, a neural fuzzy network is defined to be utilized in conjunction with the control system to avoid collision between vehicles. The outcome reveals that the model has acceptable stability and accuracy.
Keywords: formation control; multi-system vehicle; nearest neighbor; optimization

1. Introduction

The formation control of systems containing multi-agents has attracted a rising attention in recent years. The different applications of such systems in underwater vehicles, unmanned aerial vehicles, rescue operations and in defense industry (Habibi *et al*. 2016, 2018a, b, 2019b, c, d, e, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a). The control of autonomous group of vehicles is a matter of interest to increase the accuracy, capability and stability of the system on one hand, and to reduce energy consumption on the other hand. The action of geometrical position of each vehicle in such multi-agent systems (MASs) to follow a defined trajectory and pattern is of great importance. Formation of MASs consists of several types (Habibi *et al*. 2017, 2019a, c, Safarpour *et al*. 2018, 2019b, 2020, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Ghazanfari *et al*. 2020, Chen *et al*. 2022a). One category is the centralized MASs in which leader-followers' communication is defined and the followers should follow the group's leader. The second type is decentralized MASs in which each member of the group has its controller. The third class in distributed in which all members has their own controller and they are in communication with each other (Ebrahimi *et al*. 2019b, c, 2020b, Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, b, Shokrgozar *et al*. 2020). Each of this classes have their own advantages and disadvantages in terms of robustness and cost. On the other hand, the goal of a MAS may be a predefined fixed pattern and trajectory or time-varying formations. Both of these types of goals has different control system (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020c, d, e, f, Bai *et al*. 2020, Cheshmeh *et al*. 2020, Li *et al*. 2020a, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020c, Zhang *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021b).

Dynamics problems are considered in many subjects of continuum and discrete rigid body mechanics (Amelirad and Assempour 2019, 2021, Al-Furjan *et al*. 2021, Dai *et al*. 2021c, Ghabussi *et al*. 2021, He *et al*. 2021, Shariati *et al*. 2021, Zhang *et al*. 2021a, Chen *et al*. 2022b, Moradi *et al*. 2022, Xiao *et al*. 2022). In the field of discrete particle dynamics, necessary and sufficient conditions for consensus in MAS were considered by (Yu *et al*. 2010, Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020b, Liu *et al*. 2020b, 2021c, Zare *et al*. 2020, Dai *et al*. 2021b, Habibi *et al*. 2021, Heidari *et al*. 2021, Huang *et al*. 2021a, Zhang *et al*. 2021b). They derived mathematical formulations for second-order systems with respect to their agents' positions and velocities. It was found that both imaginary and real parts of the Laplacian matrix affect the consensus of the network. The necessary and sufficient condition for special types of MASs was determined based on the delay time of a system. (Seyboth *et al*. 2013) presented a novel approach in controlling MASs of single- and double-integrator networks. Their approach had the capability to converge to average consensus. Using fixed information graph, (Lin *et al*. 2019)

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proposed an information exchange strategy for multiple unmanned aerial vehicles. They also suggested a modified open-loop Nash strategy to deal with distributed networks which traditional Nash method could not handle it. (Hu *et al*. 2015) suggested a non-continuous communication scheme which is more effective in underwater communications. They claimed that the reliability of the proposed model was more than continuous systems and could be extended to other MASs. They presented numerical simulations to demonstrate efficiency of their model. (Kia *et al*. 2015) proposed a discrete time communication interval with a lower bound of timing events. They claimed that using their model the Zeno responses were not seen in the networks anymore. The application of the model had been shown using several examples. (Oh *et al*. 2015) reviewed the articles on the multi-agent system formation control. They proposed a new categorization of the MASs on the basis of sensing ability and topology of the network. There three classes in this new categorization, position-, displacement- and distance-based classes. Different studies were investigated which are fit to this classification. (Brandão and Sarcinelli-Filho 2016) presented an application of multi-layer centralized formation control strategy using Delaunay triangulations. A detailed description of this scheme is presented and several simulations were used to illustrate and validate the method. Impulsive-control of nonlinear MASs was studied by (He *et al*. 2017). They used time intervals to extract nonlinear equations of the system and a detailed discussion on the network and delay types were presented. A discussion on the minimum time nodes was presented and the model was verified giving two example.

Mismatched compasses in the multi-agent leader-follower system resulted in formation in error in such system as discussed by (Lu *et al*. 2017). They proposed an estimation method for detection of North direction and tested their theoretical formulation using simulations with two-agent systems (Liu *et al*. 2020a, Wang *et al*. 2020, Zhou *et al*. 2020, Dai *et al*. 2021a, Guo *et al*. 2021a, Shao *et al*. 2021, Wu and Habibi 2021). Deshpande *et al*. (2018) presented a minimal, robust and distributed scheme in simple robots to make a circular pattern around an unknown position. The algorithm was tested in detailed numerical examples to observe the robustness and stability of the results. There are several studies on the employment of machine learning in the field of multi-system control (Yan *et al*. 2020, Liu *et al*. 2021a, 2022, Chen *et al*. 2022c, Jiang and Li 2022, Li *et al*. 2022c, Ma *et al*. 2022, Meng *et al*. 2022, Wang *et al*. 2022b, Yan *et al*. 2022). Particle swarm optimization problem using continuous-discrete method was proposed for system with greater than 3 agents which cannot be handled by Lagrange multiplier method. (Liu *et al*. 2018) tested their proposed model for MASs systems with <100 numbers of agents and compared the computational time for 2D and 3D formation problems with other strategies. (Liu and Bucknall 2018) investigated the articles on the formation control with an emphasis on the collision issue in the flexible patterns in multi-agent system. They discussed different approaches and it was suggested that less attention was paid to cross-platform systems in the published research. (Su and Tang 2018) studied optimization problem in formation control of MASs with time-dependent patterns. They gave three simulation examples in with fixed desired formation, unknown switching formation and time-dependent unknown formation. (Lin *et al*. 2019) solved a main challenge in the game strategies using an estimation scheme for local implementation of Nash strategies. Systems with two time scale were considered in an article by (Long *et al*. 2019) in which they divided the MAS into two subsystems of slow and fast. They also presented controllability criteria for nonlinear multi-agent system. (Nazarzehi and Savkin 2019) presented a model for controlling formation of mobile sensors in 3D space based on distributed control scheme. Comprehensive simulations were performed to show the efficiency and stability of the proposed controlled system. Combining features of two controlling systems leader-follower and virtual-structure, (Shakev *et al*. 2019) presented a stable strategy to control nonholonomic robots resulted in decentralized formation control. (Toksöz *et al*. 2019) proposed a decentralized formation control consisting pattern formation, rotation and track following capability as well as collision prevention scheme. The controller forced each individual members to move to its position while conducting their attitude. The simulations and experiments were provided in their study and the goals of the strategy were achieved successfully. Using a Q-learning algorithm, the formation of leader-follower was controlled without interfering any additional external structure in a paper by (Zema *et al*. 2019). They experimentally verified the efficiency and robustness of the proposed model. There are several other studies proposing controlling strategies in formation control of multi-system agents (Ma *et al*. 2022, Xu *et al*. 2020, 2021, Yang *et al*. 2020, 2022a, Hou *et al*. 2021, Huang *et al*. 2021b, c, Jiao *et al*. 2021, Liu *et al*. 2021d, Moradi *et al*. 2021, Recker *et al*. 2021, Santoso *et al*. 2021, Wang *et al*. 2021, Xiao and Philip Chen 2021, Zhao *et al*. 2021b, Dong *et al*. 2022, He *et al*. 2022, Luo *et al*. 2022, Yu *et al*. 2022).

In the present study, a novel optimization method in formation control of multi -system vehicles based on the trajectory of the nearest neighbor trajectory is presented. In this regard, the state equations of each vehicle and multisystem is derived and the optimization scheme based on minimizing the differences between actual positions and desired positions of the vehicles are conducted. This formation control is a position-based decentralized model. The trajectory of the nearest neighbor is optimized based on the current position and state of the vehicle. This approach aids the whole multi-agent system to be optimized on their trajectory. Furthermore, to overcome the cumulative errors and maintain stability in the network a semi-centralized scheme is designed for the purpose of checking vehicle position to its predefined trajectory. The model is implemented in Matlab software and the results for different initial state and different trajectory definition are presented.

2. Mathematical preliminary

2.1 Space state equation

The state space equation is expressed as follows:

$$\begin{cases} \dot{\mathbf{x}}_i = \mathbf{A}_i\mathbf{x}_i + \mathbf{B}_i\mathbf{u}_i \\ \mathbf{y}_i = \mathbf{C}_i\mathbf{x}_i \end{cases} \quad (1)$$

In this equations, vector $\mathbf{x}_i(t)$ is the state variables and vector $\mathbf{u}_i(t)$ is the control measurement of agents i in the system for $i = 1\ to\ M$ with M being the total number of the agents. Vector $\mathbf{y}_i$ denotes the represents the output of the agent i. Matrices $\mathbf{A}_i$, $\mathbf{B}_i$ and $\mathbf{C}_i$ are coefficient matrices which determine the constants of the MAS.

The problem of MAS is regarded as a graph with M agents and E number of edges or $G = (M, E)$. In this regard, the connectivity of the graph, communication between pairs of agents could be represented by an asymmetric matrix $\mathbf{D}$ with 0 and 1 components in which:

$$D_{ij} = \begin{cases} 1\ if\ i\ transform\ data\ to\ j \\ 0\ otherwise \end{cases} \quad (2)$$

Eq. (1) is the dynamical equation of the system extracted by individual agents mass and stiffness properties.

2.2 Optimization procedure based on nearest neighbor trajectory

In this study we are seeking a trajectory for each agent m which is the optimum trajectory in term of relative position to its nearest neighbor agent n. Therefore, another adjacent matrix $\mathbf{E}(t)$ is defined which is a dynamic matrix for defining the nearest neighbors:

$$E_{nm}(t) = \begin{cases} 1\ if\ n\ is\ colsest\ neighbor\ of\ m \\ 0\ otherwise \end{cases} \quad (3)$$

Using this matrix in any time of the formation and translation of the multi-agent system the trajectory of the agent n could be optimized. In this method, the agent with the farthest agent from the group is controlled by the nearest neighbor trajectory to it not by the leader or other members. This method has advantages in communication strength in comparison to other centralized or distributed method. In this method, communication with all other members of the group is not required only communication with the nearest agent is necessary to determine the trajectory. In this manner, it is similar to centralized formation control with minimum bandwidth and computation. On the other hand, a single leader is not present in this scheme and the group could maintain stability even with absent of some of the agents. The following criteria is used to optimize the trajectory of the nearest agent:

$$e_n(t) = \min\{\|\mathbf{r}^*_{nm}(t) - \mathbf{r}_{nm}(t)\|\} \quad (4)$$

where $\mathbf{r}^*_{nm}(t)$ is the desired relative position of the agent n with respect to its nearest agent m which is determined by matrix $\mathbf{E}$ and $\mathbf{r}_{nm}(t)$ is the actual relative position of the same agents. The desired positions of the agent is determined by the goal of the group which can be predetermined or time-dependent goals. The actual relative position is defined as:

$$\mathbf{r}_{nm}(t) = \mathbf{y}_n(t) - \mathbf{y}_m(t) \quad (5)$$

The following function is defined to optimize the nearest neighbor trajectory (Su and Tang 2018):

$$H_{ij}(t) = \frac{1}{2}e_i^T(t_j)D_{ij}e_i(t) + \frac{1}{2}\int_0^{t_j} e_i^T(t_j)D_{ij}e_i(t)dt \quad (6)$$

3. Application of artificial intelligence in distance maintain

The application of the artificial intelligence in prediction and decision making processes makes it possible to avoid collisions in the multi-system vehicles (Sui *et al*. 2020, Du *et al*. 2021, Li *et al*. 2021b, 2022b, Zhao *et al*. 2021a, Cai *et al*. 2022, Wang *et al*. 2022a, Yang *et al*. 2022b). This intelligence system will help the control of systems with large number of agents (Seong-Woo *et al*. 2001, Cao *et al*. 2021b, c, d, e, f, 2022a, b, Sun *et al*. 2022). The proposed model for nearest trajectory optimization does not guarantee the collision avoidance in the multi-system. Therefore, an artificial neural fuzzy co-working system is design to be adjoined to the previously design model based on nearest trajectory optimization. In doing so, the adaptive neural fuzzy interference system (ANFIS) in Fig. 1 is proposed to make decision on the action forces on the agents to avoid collisions. In addition, with the determined vector $\mathbf{r}_{nm}(t)$ and its norm which is the distance between the vehicles, the ANFIS network will help to maintain the distance between the agents by providing the control system with the final decision on the reaction forces (Cao *et al*. 2021a, Chen *et al*. 2021, Li *et al*. 2021a, 2022a, Lv *et al*. 2021, Sun *et al*. 2021a, b, Yang *et al*. 2021, Yuan and Yang 2022, Zhang *et al*. 2022).

Inputs of the ANFIS network is the distances between agents, and relative direction and value of the speed of the agent under consideration with its nearest neighbors. Each input values could be divided into three categories. Distance of the respective vehicles could be far, medium and close to the neighbors. Based on these categories, a defuzzification phase in the first layer is done and the values of this layer are transferred to the next layer. Moreover, the relative directions of movement is very important in determination of collision. If the vehicles moves in opposite direction the collisions between them is impossible. Therefore, the relative angle between vehicles is divided into three categories based on their risk of the collision. Similarly, the speed of the objects is very important to determine the amount of the reaction forces on the agents. High speed close vehicles toward each other should impede using larger amount of forces. Each category is assigned a triangular membership function as depicted in Fig. 2 for distance classification. Similar, membership functions are assigned to other input factors.

Based on the input factors, the ANFIS network decided to impose forces on the agents in conjunction with the nearest neighbor trajectory optimization system. In very near distances and considering other two input factors, the reaction force should be very high between agents n and m. At high distances, the force are near zero and indeed the control system receives no signal on the forces from ANFIS to avoid collision.

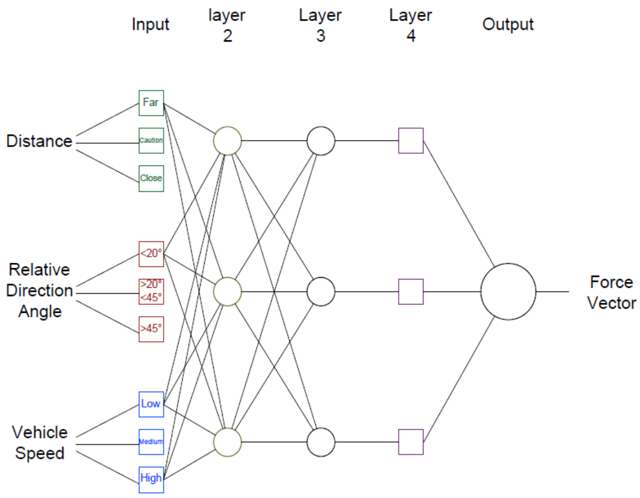

Fig. 1 Designed ANFIS system

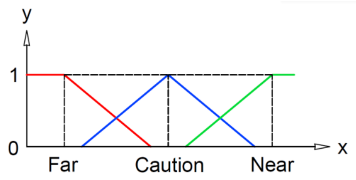

Fig. 2 Shape functions of the distance categorization of the agents

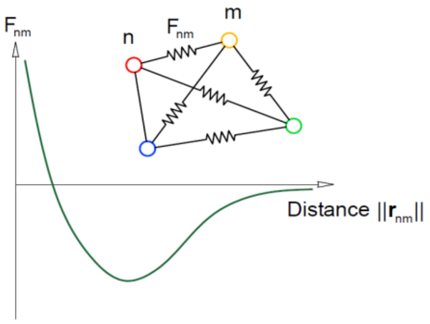

Fig. 3 Force acting on agents n and m based on their respective distance from each other as a decisive factor in ANFIS

The training processes of the ANFIS is done with different scenarios in a four-agent system and with exact simulations of the process considering nonlinear springs between agents as depicted in Fig. 3. Random velocity vectors are assigned to each agents. Moreover, distances and forces are recorded in specified time intervals. The obtained data contains 500 set of data including distance, velocity and force vectors. Among these data, 400 sets are used to train and 100 sets to test the data. It should be noted that in the designed control system the nonlinear spring system is not considered anymore and only ANFIS network is responsible to decide how and when to apply collision avoidance forces.

In Fig. 4, the correlation between train and test data as predicted by ANFIS network and provided by four-vehicle system. As seen, the high value of the correlation coefficient

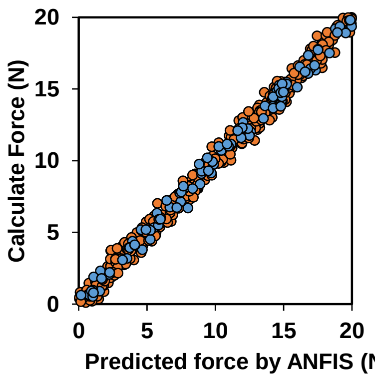

Fig. 4 Correlation between force values as predicted by ANFIS system and calculated by non-linear spring system

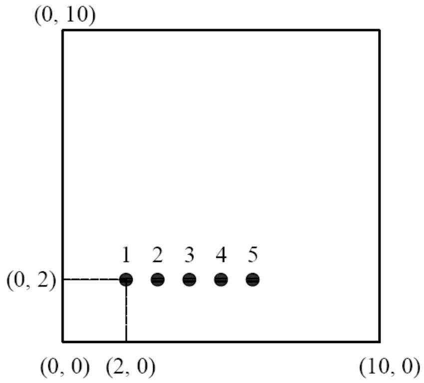

Fig. 5 Initial configuration of the five-system vehicle

$R^2 = 0.9856$ indicates that the network is well-trained and the provided data are fairly well-behaved. On the other hand, the test set of data with correlation factor $R^2 = 0.9647$ demonstrate that the design network is capable of predicting unknown condition in the collision avoidance in large member dynamic systems.

4. Results

In the following, three examples are presented to observe the robustness and stability of the proposed model in multi-system vehicle formation control. In doing so, a group of 5 vehicle in two-dimensional space is considered to be positioned in a line. The vehicles are able to communicate with each other and find the closest vehicle. The initial positions of each vehicle is shown in Fig. 5. The vehicle are numbered from 1 to 5 with number 1 located at coordination (2, 2) and other vehicles are aligned along horizontal axis with equal distance of 1 unit. The area of interest for formation pattern and trajectory is a 10 by 10 unit area with lower left corner at (0, 0). These vehicles has the same dynamical characteristics so that in similar situation they theoretically behave the same. We assume that the vehicles as a particle with mass and the rotational inertia are neglected. The model in the present study could be generalized for 3D problems.

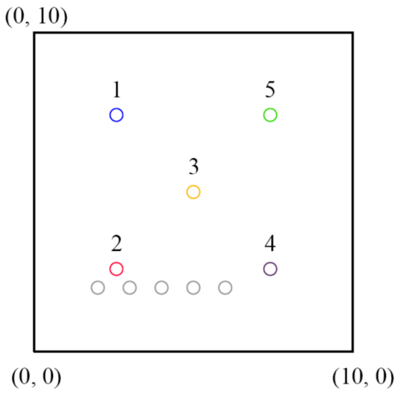

Fig. 6 Formation pattern in example 1

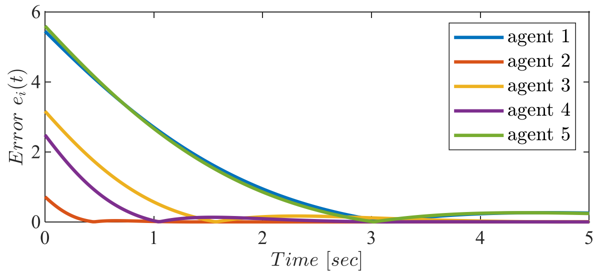

Fig. 7 Error of formation pattern in example 1 during time

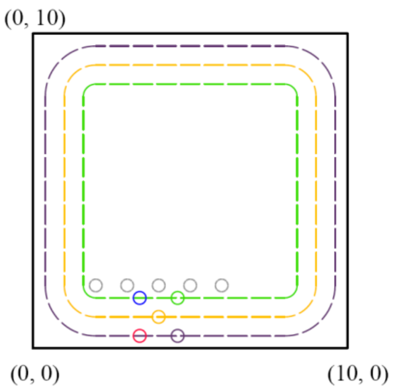

Fig. 8 Formation pattern in example 2

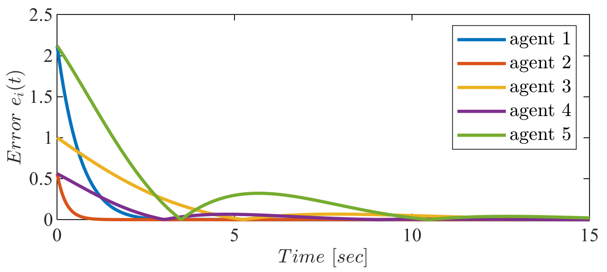

Fig. 9 Error of formation pattern and trajectory following in example 2

The first example is to construct a formation in the center of the area as depicted in Fig. 6. The trajectory of the center member is predefined and final relative positions also defined as follows:

$$\begin{aligned} \mathbf{y}_3(t) &= (5,5) \\ \mathbf{r}_{13}(t) &= (-2,2) \\ \mathbf{r}_{23}(t) &= (-2,-2) \\ \mathbf{r}_{43}(t) &= (2,2) \\ \mathbf{r}_{53}(t) &= (2,-2) \end{aligned} \quad (7)$$

Using the above relations the final position and trajectory of five vehicles were simulated. In the predefined desired configuration vehicle number 3 is located in the center interested area and it has to travel 3.1623 unit distance to reach its desired location. Vehicle number 1 should move to the upper left corner of the final formation pattern with a distance of 5.4458 unit from its initial position. As well, vehicles 2, 4 and 5 has to travel 0.7174, 2.4843 and 5.5959 units, respectively, to reach their final positions. Since, the ultimate stable velocity of all vehicle are equal, the time to reach their desired positions are approximately proportional to their travel distances. Such formation patterns is typically utilized in search and rescue missions.

The error of location of each is plotted in Fig. 7. As seen, the error of the positioning agents at early time of motion is very high due to large distance between initial and final positions. However, after reaching the desired position an overshoot is seen in all the agents' error and after that a stable position is acquired. The strategy adopted here shows a robust and accurate results. As predicted in the previous paragraph, the timing of each vehicle to reach its desired position is proportional to the displacement. Moreover, the dynamical properties of all vehicle are similar and it is seen in the curves with similar slopes in the beginning of their motion. The over shoot of each vehicle has direct correlation with its distance. This phenomena is related to the designed feedback control system. In general, the errors of the vehicle after reaching their destinations are very small and this shows the reliability of the proposed model.

The second example is a predefined trajectory following for each agent. The trajectories are shown in Fig. 8. The same color code of Fig. 6 is used here to simplify the graph. In addition, agents have to maintain their formation during the path. Therefore, at first place, they are forced to make a formation pattern on one point of trajectory and afterward start to follow the path. This problem has an additional task for the MAS vehicles to maintain their positions on the trajectory. However, our strategy is to keep the relative position at a minimum value of error with respect to nearest agent. Therefore, new equations of defining vectors of relative position is needed which is defined inside the code. The formation pattern is very similar to the formation pattern on the previous example. The only difference is the location and the outer boundary of pattern which is smaller in this example. Vehicle 3 located at the center of the pattern and should follow a square trajectory with round corners in counterclockwise direction with constant speed. Other vehicles have similar trajectories. Vehicles 2 and 4 has the same trajectory with a distance gap between them and vehicles 1 and 5 have also the same condition. The path of the vehicles 1 and 5 are outer path and path of vehicles 2 and 4 is the inner path. Since, this path does not maintain the initial formation pattern, the priority is given to the path following rather than maintaining the formation pattern. Such trajectories are very useful in searching the boundary of an area.

The absolute values of error is shown in Fig. 9. Similar to Fig. 7, in this figure after over shooting a stable minimum error is observed except for corners of the paths in which the system experiences new condition and a small time required to be stable again. Vehicles 1 and 2 located at the left side of their initial formation pattern location and their route are alongside the desired path. Thus, in these vehicles the overshoot is barely recognizable. Vehicle 2 takes less time to reach its initial position on the path. On the other hand, in vehicles 3, 4 and 5 since the initial movements have a considerable angle with starting point of the path. Therefore, overshoots are seen in their error graphs.

The results of the given examples reveals that the proposed scheme to control formation and tracking is capable of performing the tasks satisfactorily. The small values of errors between desired positions and actual positions and stable behavior of the strategy ensure the ability of the model to be implemented in actual projects.

5. Conclusions

In the present study, a novel optimization method in formation control of multi-system vehicles based on the trajectory of the nearest neighbor trajectory was presented. In this regard, the state equations of each vehicle and multisystem was derived and the optimization scheme based on minimizing the differences between actual positions and desired positions of the vehicles were conducted. This formation control was a position-based decentralized model. The trajectory of the nearest neighbor was optimized based on the current position and state of the vehicle. This approach aids the whole multi-agent system to be optimized on their trajectory. Furthermore, to overcome the cumulative errors and maintain stability in the network a semi-centralized scheme was designed for the purpose of checking vehicle position to its predefined trajectory. The model was implemented in Matlab software and the results for different initial state and different trajectory definition were presented. The results reveal that small values of errors between desired positions and actual positions and stable behavior of the strategy ensure the ability of the model to be implemented in actual projects.

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