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Formation Control of Multi Unmanned Aerial Vehicle Systems Based on DDS Middleware

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ABSTRACT In this paper formation control of Unmanned Aerial Vehicle System (UAVs) is introduced. $\mathcal{L}_1$ controller with potential field technique and Data Distribution Service (DDS) middleware used for the navigation of the agents, which is multi-UAVs. L1 adaptive controller used to stabilizing the general equations of motion of each UAVs and the potential field technique used to formalize the followers around the leader. The exchanging data between the leader and the followers done through publisher/subscriber DDS middleware. This $\mathcal{L}_1$ controller has a high performance coming from a robust adaptation of it. Robustness of the $\mathcal{L}_1$ controller verified using Matlab Simulation. The Lyapunov method provided the analysis and stability of the framework of UAVs.

INDEX TERMS Cooperative control, DDS middleware, leader-followers, quality of service, unmanned aerial vehicle system.

I. INTRODUCTION

In recent years most of the research focused on the unmanned aerial vehicle systems (UAVs), which are usually used in a dangerous environment, for example, it can be used in military, fire fighting, and many more. Not confined to tasks with high-risk, Unmanned Aerial Vehicle System also can use for civil applications. The multi-UAVs are superior to single-agent systems due to their numerous advantages and the capability to accomplish complex tasks more effectively. Several control schemes for a set of the autonomous aerial vehicle are formulated according to the application requirements.

Althoff *et al.* [1] developed a framework architecture for the data-driven robot. They combined ICE and KogMo-RTDB middleware. They used the RTDB middleware to easily exchange the information between the distributed robots. The connection between the distributed robots provided by using ICE and IceStorm middleware. Architecture for Real-time Control and Autonomous Distributed (ARCADE) architecture is suitable for distributed robots with a low-level of control.

Bergeon and Krivanek [2] design a bridge for multiple heterogeneous mobile robots based on the Robot Operating System (ROS) middleware. They used the bridge for communication between the robots and the centralized computer. In addition, they utilized the XBee cloud to exchange information between the heterogeneous robots.

Cui *et al.* [3] proposed a formation control of multi AUVs based on decentralized control. The graph theory utilized to make the formation between the AUVs. In addition, they studied the formation of AUVs system under the input saturation. A robust integral of the sign of the error (RISE) feedback control is utilized to stabilizing the AUV model. In addition, they used an anti-windup compensator to increase the control performance under the input saturation. Finally, they compared RISE feedback with the classical PID controller and they showed that it is more robust than the PID controller.

El-Ferik *et al.* [4] proposed adaptive containment control of multi underwater vehicle-manipulator systems (UVMs). They utilized the Potential Field function for the containment between the UVMs. In addition, they used Potential Field to exchanging the information between the UVMs. Furthermore, the network topology of the followers depended on the leader's position. Moreover, they utilized the repulsive function to avoid the collision between the UVMs. Finally, they utilized the L1 adaptive controller to stabilizing the containment control of multi UVMs.

Langerwisch *et al.* [5] proposed a cooperative control of one UAVs and six unmanned ground vehicles (UGVs)

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systems. Robot Operating System (ROS) with 3G mobile radio is utilized to exchange information between the UAVs and the UGVs in large distances. All the robots have different middleware, so the ROS utilized as a communication layer. The ROS messaging system offered information on all robots.

Li and Du [6] proposed a leader-follower formation control of multi under-actuated AUVs. The backstepping controller is utilized to stabilizing the AUV nonlinear model. In addition, the formation Reference Point (FRP) method utilized to make the formation between the AUVs. Furthermore, the network topology of the AUVs based on the virtual leader. Moreover, they studied the formation of AUVs system under the ocean disturbance.

Peng *et al.* [7] proposed a formation control of multi underactuated VTOL unmanned aerial vehicles (UAVs). The trajectory tracking algorithm and coupled attitude controller are utilized to solve the under-actuated UAV stabilization issue. In addition, the directed acyclic graph method utilized to make the formation between the UAVs. Furthermore, the network topology of the UAVs based on the virtual leader. Moreover, they studied the formation of UAVs system to track 3D trajectory.

Ribeiro *et al.* [8] proposed a cooperative control of three Unmanned Aerial Systems (UAS) with heterogeneous sensors based on Data Distribution Service (DDS) middleware. They utilized the DDS middleware to easily exchange the information between the UAVs. Moreover, they used the reliability quality of service policies in critical transportation of the information.

Akosy [9] developed a framework for heterogeneous robots based on Data Distribution Service (DDS) middleware. The DDS middleware utilized to make the heterogeneous robot's systems in higher levels of flexibility, reliability and to integrate the different robots. They used the Publisher/subscriber technique to exchange the information of two topics (metadata and mission status) between the heterogeneous robots. A set of Quality of Service policies needed before the communication between the publisher and the subscriber to be satisfied.

Adaptive formation control of multi unmanned aerial vehicles (UAVs) with time-varying is proposed by Wang *et al.* [10]. The robust back-stepping controller utilized to stabilizing the UAV nonlinear model. They considered some uncertainties in the UAV nonlinear model with some nonholonomic constraints. Also, they solved the issue of quantized tracking on each UAV signal by using adaptive quantized control.

Xiong *et al.* [11] proposed a multi UAVs formation control with time-varying. The linear matrix inequalities (LMI) controller is utilized to stabilizing the UAV model. In addition, they used the graph theory method for the multi UAV consensus. Furthermore, the network topology of the UAVs based on the virtual leader. Moreover, they studied the formation of UAVs system under the time-varying delay of network topology.

Yu [12] proposed a cooperative control scheme for altitude tracking of multiple UAVs based on fuzzy neural networks (FNNs) that estimate model uncertainties and actuator faults. Then the followers' altitude is estimated via a group of distributed sliding mode estimators (DSME) by means of a distributed communication topology. Moreover the fractional calculus used to develop the proposed cooperative control scheme for the follower UAVs where the suggested system showed an ultimately uniformly bounded tracking error even under sever fault scenarios with failure of multiple actuators.

Yu *et al.* [13] Studied the containment control of multiple UAVs distributed with a finite-time fault-tolerant subjected to saturation in their inputs in addition to the actuator faults. The followers' reference is anticipated by a finite-time distributed sliding mode observer and then the finite-time distributed fault-tolerant control scheme is developed to guide the follower UAVs. Furthermore a neural network (NN) as well as a first-order sliding-mode differentiator (FOSMD) and minimum parameter learning of NN (MPLNN) is adopted to deal with the input saturation and unknown linear dynamics of UAVs. The convergence of the followers to the leader's convex hull is verified by using Lyapunov theorem and graph theory.

In this study, a new framework for robust adaptive control of multi-agent cooperative tasks for UAVs is proposed. One of the UAVs will leads the other UAVs, while all the others UAVs will keep their position within the desired formation. The $\mathcal{L}_1$ adaptive controller utilized for the guidance, DDS middleware for exchanging the data between all the UAVs and Potential-Field like controller for navigation. The contributions of this paper are

- The robust control design is presented for the formation control of multi UAVs.
- We consider exchanging the information between the agents through the Data Distribution Service (DDS) middleware.
- Using Lyapunov analysis, some stability results were derived for the formation of multi UAVs systems.

The rest of this paper is arranged as follows. Section 2 introducing some preliminaries on data distribution service, potential fields approach and dynamics of the quadrotor. Section 3 describing control design with Lyapunov analysis of a fleet of UAVS. MATLAB Simulation will be described in section 4. Section 5 describing the conclusion and future research.

II. PRELIMINARIES

Before the main results, we introduce some preliminaries on data distribution service and dynamics of the quadrotor.

A. DATA DISTRIBUTION SERVICE (DDS)

In recent years, the Data Distribution Service (DDS) has been arising as OMG (Object Management Group) which is the standard publish-subscribe middleware. The publish-subscribe communication model is a useful technique in several middlewares, for example, Java Message Service (JMS), Data Distribution Service (DDS) and Microsoft Component Object (COM+). Easy and efficient dissemination of the data is the target of the DDS middleware in heterogeneous distributed environments. Moreover, DDS has a set of Quality of Service (QoS) that guarantees low delay and high performance of data transmission. We considered DDS middleware to perform our study for the formation control of UAVs. DDS middleware is based on subscription publishing architecture, so we considered the UAV leader as publishers and all UAVs followers as subscribers. For the communication between the publisher and the subscribers, a set of Quality of Service policies must be satisfied such as:

- **Durability**: Specifies whether or not a new subscriber has received information previously sent by the publisher. This QoS policy helps to isolate the system from start-up dependencies.
- **Reliability**: Specifies whether the middleware should resend samples lost by the network or not. Reliability has two settings: BEST EFFORT(not resend the lost information) and RELIABLE(resend the lost information).
- **History**: Specifies keeping the information sent or received for a subscriber by a publisher. There are two configurations: KEEP ALL or KEEP LAST. KEEP ALL does not mean the storage of infinite data by middleware.
- **Deadline**: For subscriber: defines the maximum time between samples of data arriving. For publisher: defines a promise to publish between them samples not exceeding this elapsed time.

B. DYNAMICS OF QUADROTOR

From Euler-Lagrangian equation with an external generalized force acting on the quadrotor, the translational dynamics of the quadrotor is given by

$$\ddot{\eta}_1 = -g\begin{bmatrix}0\\0\\1\end{bmatrix} + J_1(\eta_2)\begin{bmatrix}0\\0\\u/m\end{bmatrix} - \frac{k_t}{m}\dot{\eta}_1 \tag{1}$$

where the transformation matrix $J_1(\eta_2)$ related to the Euler angles: roll(ϕ), pitch(θ), yaw(ψ), given by

$$J_1(\eta_2)=\begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\psi c\phi s\theta \\ -s\theta & c\theta s\phi & c\phi c\theta \end{bmatrix} \tag{2}$$

with the assumption of $\phi \neq 90°$ and $\theta \neq 90°$, and $J_1(\eta_2)$ has the property

$$J_1^{-1}(\eta_2) = J_1^T(\eta_2) \tag{3}$$

where $c(\cdot) = \cos$, $s(\cdot) = \sin$, $t(\cdot) = \tan$.

and k_t is defined as the translational drag coefficient which is proportional to the linear velocity, and the main thrust force u is given by

$$u = f_1 + f_2 + f_3 + f_4 \tag{4}$$

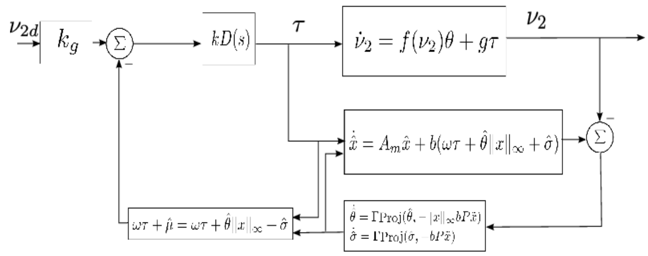

FIGURE 1. $\mathcal{L}_1$ Adaptive Control.

where f_i: upward-lifting forces which is equal to $f_i = k_i\Omega_i^2$, with k_i: positive constants and the angular speed motors are Ω_i.

Then the rotational motion of the quadrotor is given by

$$\dot{\nu}_2 = I^{-1}(-(\nu_2 \times I\nu_2) - I_R(\nu_2 \times z_e)\Omega - k_r\nu_2 + \tau) \tag{5}$$

where $z_e = [0,\ 0,\ 1]^T$, I_R: propeller inertia, $\times$: cross product, k_r: rotational drag, and

$$\Omega = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4 \tag{6}$$

The torques and force on around body frame. Translational and rotational motion of the quadrotor are given by

$$\begin{bmatrix}\tau\\u\end{bmatrix} = \begin{bmatrix}\tau_p\\\tau_q\\\tau_r\\u\end{bmatrix} = \begin{bmatrix}0 & l & 0 & -l\\ l & 0 & -l & 0\\ d & -d & d & -d\\ 1 & 1 & 1 & 1\end{bmatrix}\begin{bmatrix}f_1\\f_2\\f_3\\f_4\end{bmatrix} \tag{7}$$

where l is the distance between the mass center and the motors, and d: drag factor.

From the above equations, we can make a conclusion that the number actuation is lower than the number of degree of freedom, so the system is classified as the under-actuated system. This condition forces us to conduct careful consideration of designing the controller. The following definition of under-actuated systems considered for our case and adapted from. By considering the system below:

$$\ddot{q} = f(q, \dot{q}) + G(q)u \tag{8}$$

q: coordinates vector, f: the dynamic vector, G: input matrix, and u: control inputs. Eq 8 under-actuated if the dimension of q greater than the rank of G.

III. CONTROLLER DESIGN FOR MULTI UNMANNED AERIAL VEHICLE SYSTEMS (UAVS)

A. $\mathcal{L}_1$ ADAPTIVE CONTROL DESIGN

In this section, $\mathcal{L}_1$ adaptive control is proposed. The nonlinear form is needed to divide into linear parameters. Figure (1) illustrates the $\mathcal{L}_1$ controller block diagram.

The $\mathcal{L}_1$ controller needs linear parameterization. One way of linear parameterization is the linear time-varying form, which contains all unknown parameters. So that we can rewrite the rotational dynamics in (5) as follow:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}_m\mathbf{x} + b(\boldsymbol{\omega}\mathbf{u}_{ad} + \mathbf{f}(t, \mathbf{x}(t))), \quad \mathbf{x}(0) = \mathbf{x}_0\\ \mathbf{y} &= \mathbf{c}^\top\mathbf{x}(t)\end{aligned} \tag{9}$$

where

$$\mathbf{x} \triangleq \boldsymbol{\nu}_2, \quad \mathbf{A}_m \in \mathbb{R}^{n\times n} \triangleq \text{ a known Hurwitz matrix}$$
$$b = 1, \quad \boldsymbol{\omega} \triangleq I_{\mathrm{M}}^{-1}, \quad \mathbf{u}_{ad} \triangleq \boldsymbol{\tau} \triangleq \mathcal{L}_1 \text{ Adaptive control}$$
$$\mathbf{f}(t, \mathbf{x}(t)) \triangleq \mathbf{I}_{\mathrm{M}}^{-1}(-(\boldsymbol{\nu}_2 \times \mathbf{I}_{\mathrm{M}}\boldsymbol{\nu}_2) - I_R(\boldsymbol{\nu}_2 \times \mathbf{z}_e)\Omega - k_r\boldsymbol{\nu}_2),$$
$$\mathbf{c}^{\top} = \mathbf{I}_{3\times 3} \tag{10}$$

Now (9) can be written as:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}_m\mathbf{x} + b(\boldsymbol{\omega}\mathbf{u}_{ad} + \boldsymbol{\theta}\|\mathbf{x}\|_\infty + \boldsymbol{\sigma}), \quad \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y} &= \mathbf{c}^{\top}\mathbf{x}(t) \end{aligned} \tag{11}$$

From (11) the following state predictor is considered

$$\begin{aligned} \dot{\hat{\mathbf{x}}} &= \mathbf{A}_m\hat{\mathbf{x}} + b(\boldsymbol{\omega}\mathbf{u}_{ad} + \hat{\boldsymbol{\theta}}\|\mathbf{x}\|_\infty + \hat{\boldsymbol{\sigma}}), \quad \hat{\mathbf{x}}(0) = \mathbf{x}_0 \\ \hat{\mathbf{y}} &= \mathbf{c}^{\top}\hat{\mathbf{x}} \end{aligned} \tag{12}$$

where $\hat{\mathbf{x}} \in \mathbb{R}^n$ is the predicted state, $\hat{\mathbf{y}} \in \mathbb{R}^n$ is the predicted output, $\hat{\boldsymbol{\theta}}$ and $\hat{\boldsymbol{\sigma}}$ are the estimated parameters. Define the error $\tilde{\mathbf{x}} = \hat{\mathbf{x}} - \mathbf{x}$, $\tilde{\boldsymbol{\theta}} = \hat{\boldsymbol{\theta}} - \boldsymbol{\theta}$, and $\tilde{\boldsymbol{\sigma}} = \hat{\boldsymbol{\sigma}} - \boldsymbol{\sigma}$, and the following error dynamic is obtained

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A}_m\tilde{\mathbf{x}} + b(\tilde{\boldsymbol{\theta}}\|\mathbf{x}\|_\infty + \tilde{\boldsymbol{\sigma}}), \quad \tilde{\mathbf{x}}(0) = 0 \tag{13}$$

Consider the Lyapunov function candidate

$$V(\tilde{\mathbf{x}}, \tilde{\boldsymbol{\theta}}, \tilde{\boldsymbol{\sigma}}) = \tilde{\mathbf{x}}^{\top}\mathbf{P}\tilde{\mathbf{x}} + \frac{1}{\Gamma}(\tilde{\boldsymbol{\theta}}^{\top}\tilde{\boldsymbol{\theta}} + \tilde{\boldsymbol{\sigma}}^{\top}\tilde{\boldsymbol{\sigma}}) \tag{14}$$

The derivative of the Lyapunov candidate (14) along the trajectory of (13) is given by

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \tilde{\boldsymbol{\theta}}, \tilde{\boldsymbol{\sigma}}) &= \dot{\tilde{\mathbf{x}}}^{\top}\mathbf{P}\tilde{\mathbf{x}} + \tilde{\mathbf{x}}^{\top}\mathbf{P}\dot{\tilde{\mathbf{x}}} + \frac{2}{\Gamma}(\tilde{\boldsymbol{\theta}}^{\top}\dot{\tilde{\boldsymbol{\theta}}} + \tilde{\boldsymbol{\sigma}}^{\top}\dot{\tilde{\boldsymbol{\sigma}}}) \\ &= -\tilde{\mathbf{x}}^{\top}\mathbf{Q}\tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^{\top}\mathbf{P}b(\tilde{\boldsymbol{\theta}}\|\mathbf{x}\|_\infty + \tilde{\boldsymbol{\sigma}}) \\ &\quad + \frac{2}{\Gamma}(\tilde{\boldsymbol{\theta}}^{\top}\dot{\tilde{\boldsymbol{\theta}}} + \tilde{\boldsymbol{\sigma}}^{\top}\dot{\tilde{\boldsymbol{\sigma}}}) \end{aligned} \tag{15}$$

One can upper bound the derivative of the Lyapunov function as

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \tilde{\boldsymbol{\theta}}, \tilde{\boldsymbol{\sigma}}) &= -\tilde{\mathbf{x}}^{\top}\mathbf{Q}\tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^{\top}\mathbf{P}b(\tilde{\boldsymbol{\theta}}\|\mathbf{x}\|_\infty + \tilde{\boldsymbol{\sigma}}) \\ &\quad + 2(\tilde{\boldsymbol{\theta}}^{\top}\mathrm{Proj}(\tilde{\boldsymbol{\theta}}, -\|\mathbf{x}\|_\infty b\mathbf{P}\tilde{\mathbf{x}}) \\ &\quad + \tilde{\boldsymbol{\sigma}}^{\top}\mathrm{Proj}(\tilde{\boldsymbol{\theta}}, -b\mathbf{P}\tilde{\mathbf{x}})) \\ &= -\tilde{\mathbf{x}}^{\top}\mathbf{Q}\tilde{\mathbf{x}} + 2\tilde{\boldsymbol{\theta}}^{\top}(\|\mathbf{x}\|_\infty b\mathbf{P}\tilde{\mathbf{x}} \\ &\quad + \mathrm{Proj}(\tilde{\boldsymbol{\theta}}, -\|\mathbf{x}\|_\infty b\mathbf{P}\tilde{\mathbf{x}})) \\ &\quad + 2\tilde{\boldsymbol{\sigma}}^{\top}(b\mathbf{P}\tilde{\mathbf{x}} + \mathrm{Proj}(\tilde{\boldsymbol{\sigma}}, -b\mathbf{P}\tilde{\mathbf{x}})) \\ &\leq -\tilde{\mathbf{x}}^{\top}\mathbf{Q}\tilde{\mathbf{x}} \end{aligned} \tag{16}$$

with the adaptation law given by the following

$$\begin{aligned} \dot{\tilde{\boldsymbol{\theta}}} &= \dot{\hat{\boldsymbol{\theta}}} = \Gamma\mathrm{Proj}(\tilde{\boldsymbol{\theta}}, -\|\mathbf{x}\|_\infty b\mathbf{P}\tilde{\mathbf{x}}) \\ \dot{\tilde{\boldsymbol{\sigma}}} &= \dot{\hat{\boldsymbol{\sigma}}} = \Gamma\mathrm{Proj}(\tilde{\boldsymbol{\sigma}}, -b\mathbf{P}\tilde{\mathbf{x}}) \end{aligned} \tag{17}$$

where Proj is the projection operator-based adaptive law with a detailed note as in [14], $\Gamma > 0$ is the adaptation law rate and $\mathbf{Q} = \mathbf{Q}^{\top} > 0$, with $\mathbf{P} = \mathbf{P}^{\top} > 0$ satisfies the Lyapunov equation

$$\mathbf{A}_m^{\top}\mathbf{P} + \mathbf{P}\mathbf{A}_m = -\mathbf{Q} \tag{18}$$

The Laplace transform of the adaptive control signal $\mathbf{u}_{ad}$ is selected to be

$$\mathbf{u}_{ad}(s) = -\frac{\mathbf{C}(s)}{\boldsymbol{\omega}}(\hat{\boldsymbol{\mu}}(s) - \mathbf{k}_g\mathbf{r}(s)) \tag{19}$$

where $\hat{\boldsymbol{\mu}}(s)$ and $\mathbf{r}(s)$ are the Laplace transform of $\hat{\boldsymbol{\mu}}(t) \triangleq \hat{\boldsymbol{\theta}}(t)\|\mathbf{x}\|_\infty + \hat{\boldsymbol{\sigma}}(t)$ and $\mathbf{r}(t) \triangleq$ reference signal, respectively. Feed-forward gain is given by $\mathbf{k}_g \triangleq -\frac{1}{\mathbf{c}^{\top}\mathbf{A}_m^{-1}b}$. If the filter $\mathbf{C}(s)$ is selected to be

$$\mathbf{C}(s) \triangleq \frac{\boldsymbol{\omega}k\mathbf{D}(s)}{\mathbf{I} + \boldsymbol{\omega}k\mathbf{D}(s)} \tag{20}$$

with DC gain $\mathbf{C}(0) = \mathbf{I}$. The selection of $\mathbf{D}(s) = \frac{\mathbf{I}}{s}$ yields first order strictly proper transfer function

$$\mathbf{C}(s) = \frac{\boldsymbol{\omega}k}{s\mathbf{I} + \boldsymbol{\omega}k} \tag{21}$$

Substituting (20) into (19), the Laplace transform of the adaptive control signal becomes

$$\mathbf{u}_{ad}(s) = -k\mathbf{D}(s)(\boldsymbol{\omega}\mathbf{u}_{ad}(s) + \hat{\boldsymbol{\mu}}(s) - \mathbf{k}_g\mathbf{r}(s)) \tag{22}$$

Remark from [15], if the derivative of $\mathbf{f}(t, \mathbf{x})$ with respect to $\mathbf{x}$ has a uniform bound

$$\left\| \frac{\partial \mathbf{f}(t, \mathbf{x})}{\partial x} \right\| \leq \mathbf{d}_{f_x} = \mathbf{L} \tag{23}$$

that holds uniformly $\forall \mathbf{x} \in \mathbb{R}^n$, then the following $\mathcal{L}_1$-norm condition has to be satisfied for $\mathcal{L}_1$ adaptive control

$$\|\mathbf{G}(s)\|_{\mathcal{L}_1}\mathbf{L} < 1 \tag{24}$$

where

$$\mathbf{G}(s) \triangleq \mathbf{H}(s)(\mathbf{C}(s) - \mathbf{I}), \quad \mathbf{H}(s) \triangleq (s\mathbf{I} - \mathbf{A}_m)^{-1}b \tag{25}$$

The analysis of this nonlinear $\mathcal{L}_1$ adaptive control in detail can be seen in [15] and [16].

B. FORMATION CONTROL

The communication network of multi UAVs cooperative system can be modeled by potential fields function, which is two parts attractive and repulsive potentials see figure (2) for the flowchart of formation control of multi-UAVs using attractive and repulsive functions.

The dynamic equation of 'n' robots considered by potential field technique can be express as follows: [17]

$$\ddot{x}_i = u_i \quad i = 0, 1, 2, \ldots \tag{26}$$

where the position of i^{th} robot denoted by $x_i \in R^2$. The desired formation control law can be express as follow:

$$u_i = f_{c_i} + \sum_{j=1}^{n} f_{a_{ij}} - b\dot{x}_i \tag{27}$$

where

$$f_{c_i} = -\nabla_{x_i}V_{c_i}(x_i) \tag{28}$$

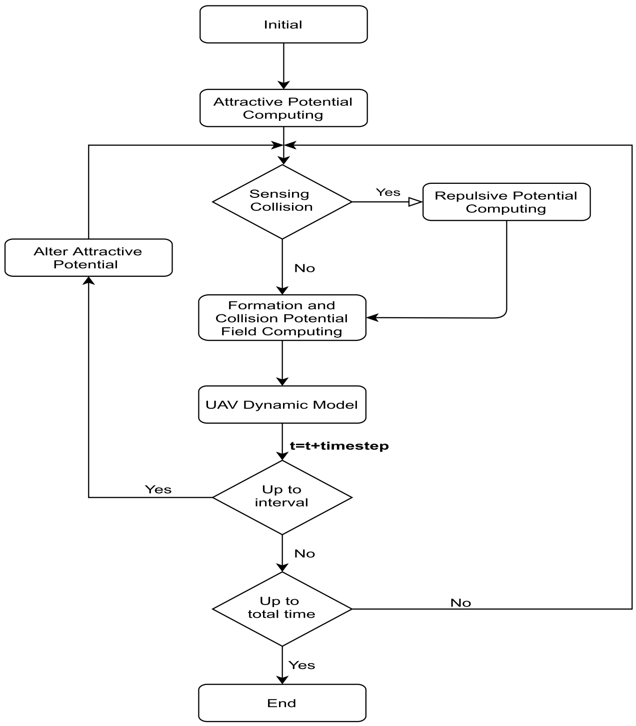

FIGURE 2. **Flowchart of formation control using potential fields.**

where the force of the follower i and the leader (center) denoted by f_{c_i}. This term holds with distance r all followers around the leader.

$$f_{a_{ij}} = -\nabla_{x_i} V_{a_{ij}}(x_i, x_j) \tag{29}$$

where the force between the follower j and the follower i represented by $f_{a_{ij}}$. This term repulses with distance L all the followers from other.

The repulsive and attractive functions, as well as the damping of vehicle, can proceed as control law

$$u_i = P_{tt_i} + P_{rep_{ij}} + Da \tag{30}$$

where:

P_{tt_i} The center function of i robot.

$P_{rep_{ij}}$ The repulsive function i,j robot.

Da Damping action.

First, the general equation of the center function of non-holonomic system in R^2 as follows:

$$P_{tt} = -\nabla_{\xi_i} V_{c_i}(\xi_{f_i}) \tag{31}$$

with

$$V_{c_i} = \frac{1}{2} K_c (d_{c_i} - r)^2 \tag{32}$$

where a positive constant represented by Kc and the Euclidean distance from the leader to the follower i denoted by $d_{c_i} = ||\xi_{f_i} - \xi_c||$. Therefore, the function of control as follows:

$$\xi_{\mathbf{f_i}} = \begin{bmatrix} \mathbf{y_f} \\ \mathbf{x_f} \end{bmatrix} \xi_{\mathbf{c}} = \begin{bmatrix} \mathbf{y_l} \\ \mathbf{x_l} \end{bmatrix}$$

$$d_{c_i} = \sqrt{(y_f - y_l)^2 + (x_f - x_l)^2} \tag{33}$$

$$\Longrightarrow V_{c_i} = \frac{1}{2} K_c (d_{c_i} - r)^2 \tag{34}$$

By differentiate V_{c_i}, we will get a center function as follows:

$$P_{tt} = -\nabla_{\xi_{f_i}} V_{c_i}(\xi_{f_i}) = -\frac{\partial V_{c_i}(\xi_{f_i})}{\partial \xi_{f_i}} \tag{35}$$

Using chain rule,

$$-\frac{\partial V_{c_i}(\xi_{f_i})}{\partial \xi_{f_i}} = -\frac{\partial V_{c_i}}{\partial d_{c_i}} \frac{\partial d_{c_i}}{\partial \xi_{f_i}} \tag{36}$$

we can get from equation (34)

$$\frac{\partial V_{c_i}}{\partial d_{c_i}} = K_c (d_{c_i} - r) \tag{37}$$

Suppose

$$d_{c_i} = D^{\frac{1}{2}} \tag{38}$$

then we will get from equation (33)

$$D = (y_f - y_l)^2 + (x_f - x_l)^2 \tag{39}$$

By differentiate d_{c_i} after using the chain rule we obtain:

$$\frac{\partial d_{c_i}}{\partial \xi_{f_i}} = \frac{\partial d_{c_i}}{\partial D} \frac{\partial D}{\partial \xi_{f_i}} \tag{40}$$

where

$$\frac{\partial d_{c_i}}{\partial D} = \frac{1}{2} D^{-\frac{1}{2}} \tag{41}$$

and

$$\begin{aligned} \frac{\partial D}{\partial \xi_{f_i}} &= \frac{\partial D}{\partial y_f} + \frac{\partial D}{\partial x_f} \\ &= 2(y_f - y_l) + 2(x_f - x_l) \end{aligned} \tag{42}$$

then

$$\frac{\partial D}{\partial \xi_{f_i}} = 2(\xi_{f_i} - \xi_c)^T \tag{43}$$

By substitute (41) and (43) in (40) we obtain:

$$\frac{\partial d_{c_i}}{\partial \xi_{f_i}} = \frac{1}{2} D^{-\frac{1}{2}} 2(\xi_{f_i} - \xi_c)^T \tag{44}$$

then equation (44) can rewrite as:

$$\frac{\partial d_{c_i}}{\partial \xi_{f_i}} = \frac{1}{d_{c_i}} (\xi_{f_i} - \xi_c)^T \tag{45}$$

Last, replace (45) and (37) in (36). The center potential as follows:

$$P_{tt} = \frac{-K_c}{d_{c_i}} (d_{c_i} - r)(\xi_{f_i} - \xi_c)^T \tag{46}$$

Second, the repulsive function in R^2 as follows:

$$P_{rep} = -\nabla_{\xi_{f_i}} V_{a_{ij}}(\xi_{f_i}, \xi_{f_j}) \tag{47}$$

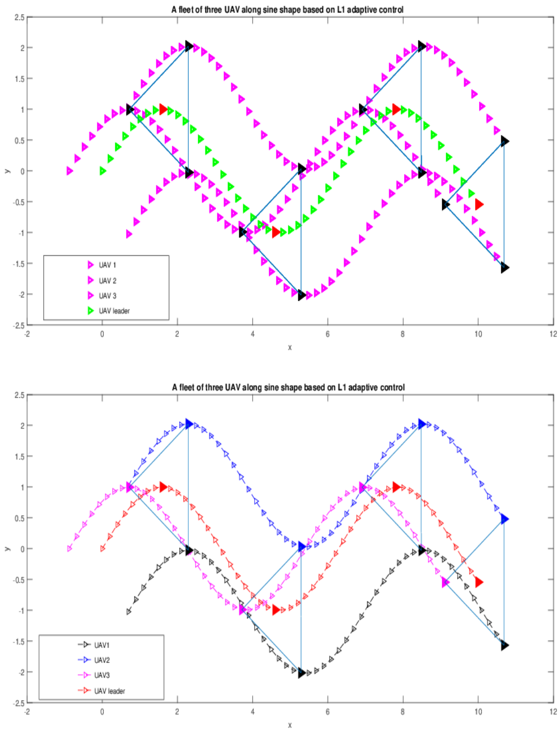

FIGURE 3. The map of a fleet of three agents through full communication. based on L_1 Adaptive control.

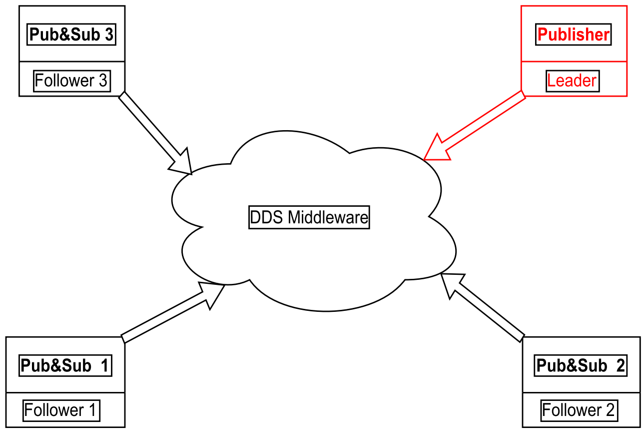

FIGURE 4. The structure of group of multi UAVs based on publisher/subscriber DDS middleware.

TABLE 1. The parameters of quadrotor model.

Mass	m	$0.52\ kg$
Gravity Acceleration	g	$9.8\ m/s^2$
Drag's Translational	k_t	0.95
Drag's Rotational	k_r	0.105
Ratio of Drag & Thrust	d	$7.5e^{-7}\ kg.m^2$
Inertia of x-axis	I_x	$0.0069\ kg.m^2$
Inertia of y-axis	I_y	$0.0069\ kg.m^2$
Inertia of z-axis	I_z	$0.0129\ kg.m^2$
Arm Length	L	$0.205\ m$
Propeller Inertia	I_R	$3.36e^{-5}\ kg.m^2$

where

$$V_{a_{ij}} = \begin{cases} \frac{1}{2}K_a(d_{ij}-L)^2 & d_{ij} < L \\ 0 & Otherwise \end{cases} \tag{48}$$

where a positive constant denoted by K_a and the Euclidian distance represented by $d_{ij} = ||\xi_{f_i} - \xi_{f_j}||$. Then the function of control as follow:

$$\xi_{\mathbf{f_i}} = \begin{bmatrix} \mathbf{y_{f_i}} \\ \mathbf{x_{f_i}} \end{bmatrix} \xi_{\mathbf{f_j}} = \begin{bmatrix} \mathbf{y_{f_j}} \\ \mathbf{x_{f_j}} \end{bmatrix}$$

$$d_{ij} = \sqrt{(y_{f_i} - y_{f_j})^2 + (x_{f_i} - x_{f_j})^2} \tag{49}$$

Last, the repulsive function as follows:

$$P_{rep} = \frac{-K_a}{d_{ij}}[d_{ij} - L][(x_{f_i} - x_{f_j})^T + (y_{f_i} - y_{f_j})^T] \tag{50}$$

IV. SIMULATION RESULTS

The potential field and $\mathcal{L}_1$ adaptive controller without/with DDS middleware is implemented. The quadrotor model selected here has the parameters as mentioned below [16]

And the controller parameters selected as. $\gamma = 10^6$, $k_p = 10$, $k_d = 10$ and distance $L = 2$. In the results of formation control, two scenarios have been considered.

- **Formation of UAVs without DDS middleware:** Figure (3) is shown how the set of three UAVs can make formation around their leader in 2D space.
- **Formation of UAVs with DDS middleware:** The DDS middleware was not considered for the system has the result in figure (3) but now it is considered. The figures (4) shown the structure of a group of multi UAVs based on DDS middleware and the publisher/subscriber quality of services (QoS) shown in table (2).

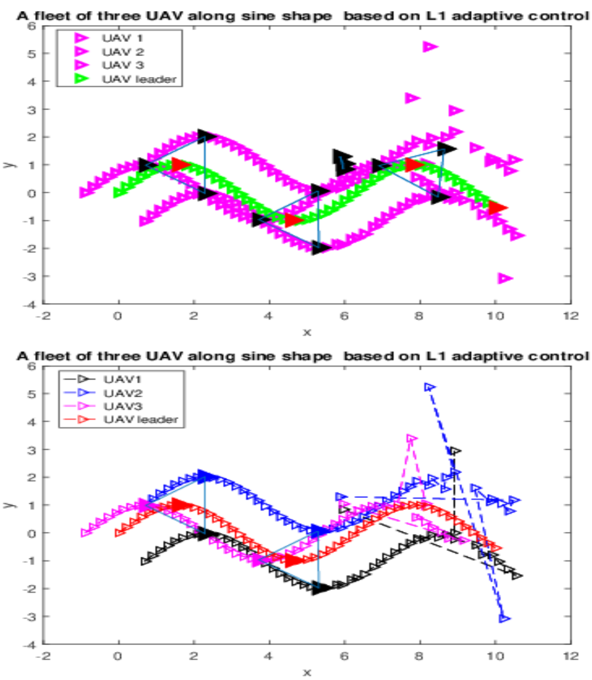

FIGURE 5. A fleet of three UAVs agents through publisher/subscriber DDS middleware quality of services QoS Policies1.

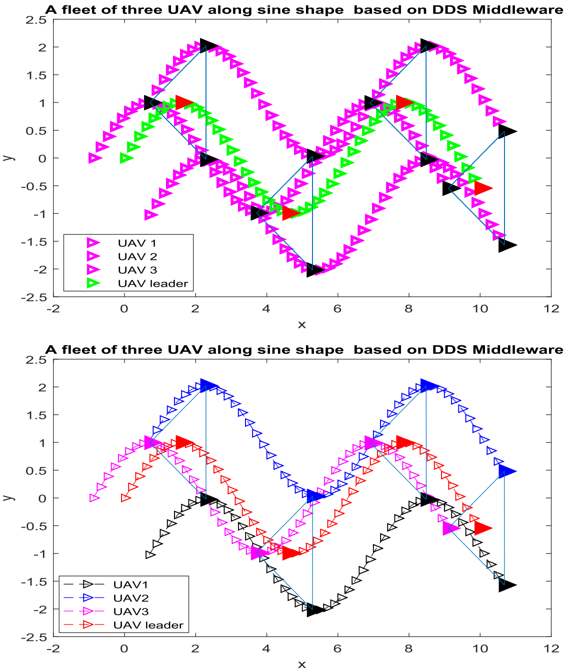

FIGURE 6. **A fleet of three UAVs agents through publisher/subscriber DDS middleware quality of services QoS Policies2.**

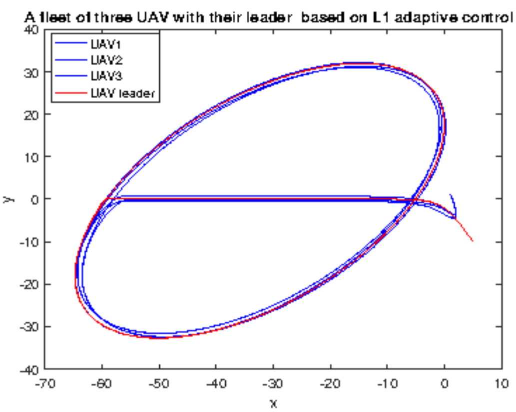

FIGURE 7. **2D Semi circle of multi-UAVs with 40% constant uncertainty in the inertia matrix through DDS middleware.**

TABLE 2. **The publisher/subscriber DDS middleware quality of services (QoS).**

QoS Policies	QoS Policies 1		QoS Policies 2	
	Publisher	Subscriber	Publisher	Subscriber
Durability	Volatile	Volatile	Volatile	Volatile
Reliability	Best Effort	Best Effort	Reliable	Reliable
History	Keep Last	Keep Last	Keep All	Keep All
Deadline	Infinite	Infinite	Infinite	Infinite

Figure (5) and figure (6) are shown how the set of three UAVs can follow their leader in 2D space through publisher/subscriber DDS middleware with quality of services QoS policies 1 and QoS Policies 2 respectively. Furthermore, the parameters uncertain in the inertia matrix is considered in figure (7) and figure (8). Figure (7) and figure (8) are shown how the set of multi UAVs with 40% and 100% constant uncertainty in the inertia matrix can follow their leader in 2D

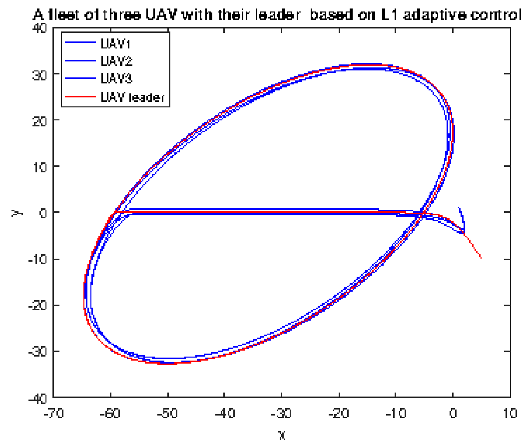

FIGURE 8. **2D Semi circle of multi-UAVs with 100% constant uncertainty in the inertia matrix through DDS middleware.**

Semi-circle through DDS middleware with quality of QoS policies 2 respectively.

V. CONCLUSION

In this paper, a new framework for formation control of multi UAVs is presented. The formation control of multi navigation is developed based on the $\mathcal{L}_1$ adaptive controller, DDS middleware and potential field technique. The $\mathcal{L}_1$ adaptive control is used to stabilize the dynamic model of the UAVs, and the exchanging data between the leader and the followers done through DDS middleware. Furthermore, the attractive and repulsive potential fields are used to control UAVs' positions and hold them to their desired paths with respect to their leader. In the case of exchanging the data between the leader and the followers through DDS middleware, the $\mathcal{L}_1$ adaptive controller showed high performance. Simulation results prove that the DDS middleware and $\mathcal{L}_1$ adaptive controller increased performance. The autonomy of the batteries and energy consumption in the model will consider in future work.

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