Memorias del Congreso Nacional de Control Automático
ISSN: 2594-2492

Adaptive Sliding Formation Control Against Disturbances for a MAV Swarm

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Abstract: In this paper, the formation control against disturbances for a quadrotor micro air vehicles swarm system is addressed. The desired formation is obtained using the leader-follower approach. In order to guarantee that the followers converge and keep their desired relative positions with respect to the leader, an adaptive sliding mode controller is proposed. The advantages of such controller rely on its robustness to bounded uncertainties/perturbations and the non overestimation of the control gain, using a minimal gain value to guarantee sliding mode, but increasing if perturbation appears. Furthermore, simulations results illustrate the feasibility and advantages of the proposed formation method.

Keywords: Multi-agent systems, MAV formation, Adaptive sliding mode, Leader-follower

1. INTRODUCTION

In recent years, the interest over the research field of unmanned aerial vehicles (UAV), specially quad-rotor type UAVs has grown due to their multiple attractive characteristics such as the vertical take off and landing (VTOL), ability to hover or their movement generated by fixed rotors as exposed in Shraim et al. (2018). There are multiple applications that take advantage of the principal features of quad-rotors such as item deployment, rescue operations in natural disaster areas or structure inspection as those reported in Elfeky et al. (2016); Yu et al. (2017); Goodarzi et al. (2015), respectively. Along with development in UAV technologies, the idea of using multiple UAVs to exploit these vehicles in the field of multi-agent systems arose as an opportunity to increase the range and robustness of their applications. Such multi-agent systems are based on the behavior of biological groups such as ants or migratory birds, where the individuals in the system, hereinafter called agents usually have limited capabilities, however their coordinated work achieves better results than the sum of their unrelated work doing the same task, explained in Parker et al. (2016). One of the main advantages when working with UAVs in multi-agent systems is the cost reduction of the mission when the necessity of a specialized model of UAV is replaced by multiple simple agents with the capacity to supply the performance of the original single UAV as in Kolaric et al. (2018). These advantages are useful in applications such as surveillance, target search and identify and mapping Paradzik and nce (2016); Hou et al. (2017); Han and Chen (2014); Min (2018), were the multi-agent system usually requires a specific formation to be kept in every moment. In order to solve the multi-agent formation problem, several researches have been reported, where the principal approaches to define the system are the leader-follower structures, behavior based and virtual structure formation Dong (2016). Leader-follower is the simplest strategy, where a leader agent share its position and orientation to control the follower agents as Yuan et al. (2017) explained; the behavior based formation is defined depending on the desired reaction of the agents according to various situations, reported in Harder and Lauderbaugh (2018) and the virtual structure stands every agent as a node of a rigid structure that denotes the formation and usually is solved using consensus theory as in Li et al. (2015).

For instance, in Nash et al. (2014), a proposal for solving a formation of mini quadrotors is shown, where the leader-follower scheme with PID as position controllers is used. In Yean and Kim (2017), PID controller is also implemented for the formation control considering disturbances. Regarding disturbances, sliding mode control is a used technique, where the multi-agent formation problems have been reported in Abbas and Wu (2013), despite the use of consensus instead of leader-follower approach, the control technique implemented is a sliding mode controller and in Ghamry and Zhang (2015) following the traditional leader-follower approach, a sliding mode control was applied in spite of wind disturbances. Although, this kind of control may bring stress unnecessarily to the system because of the chattering phenomena, a non desired effect due to high frequency oscillations on the control input. In Wang and Wang (2017) the formation problem is set using a geometrical description of a leader-follower scheme and solved using an adaptive control strategy, but unknown perturbations are not considered for the controller. Also, in Mercado et al. (2013) the formation is proposed using the leader-follower scheme and solved using sliding mode control technique, but even if perturbations are taken in consideration, the control is not able to adjust its gains.

On the other hand, in the context of MAVs with less than 100 gr weight, less than 0.15 m span. This tiny air vehicles are specially susceptible to external perturbations such as wind gusts even the air conditioner of a room, temperature or pressure changes. Therefore, these MAVs require robust controller to guarantee that the aircraft complete tasks in such perturbed environment.

The main contribution of this work is the design of an adaptive formation control strategy against disturbances for a MAV swarm system. A leader-followers convention is adopted to establish a distribution for each agent. Due to its robust properties, reduced chattering and non overestimation the control gain, an adaptive sliding mode strategy is designed to keep the followers on their desired relative positions with respect to the leader despite of bounded perturbations/uncertainties, while tracking the leader along a time varying trajectory. Simulation results are conducted via Matlab/simulink, where the feasibility and advantages of the proposed formation methodology are illustrated.
The layout of this manuscript is as follows: Section II presents the problem formulation. Section III describes the preliminaries for the formation control problem. Section IV shows the design of the formation controller, Section V illustrates the results and finally some conclusions are drawn.

2. PROBLEM FORMULATION

Consider the multi-agent system conformed by N-agents:

$$\begin{cases} \dot{x}_i = f_i(x_i, u_i) \\ y_i = g_i(x_1, ..., x_n) \quad i = 1, ..., N, \end{cases} \tag{1}$$

where x_i and y_i represents the state and output of the agent i. The formation problem in two dimensions using the leader-follower approach can be described by defining a set of relative positions in x and y coordinates between the leader agent and the followers:

$$\Gamma_i = \left[\Gamma_{xi}, \Gamma_{yi}\right], \tag{2}$$

with Γ_i representing the distance between the leader agent and a the i-th follower and Γ_{xi}, Γ_{yi} being its x and y components defined over a non-inertial frame. The objective is such that the formation error goes to:

$$e_{\Gamma_i} = \Gamma_i^d - \Gamma_i = 0 \tag{3}$$

in presence of bounded uncertainties/perturbations, where e_{Γ_i} denotes the error between the actual and the desired relative position.

3. PRELIMINARIES

In this section, the mathematical model to represent the tracking dynamics of the agents, and the foundations for designing an adaptive sliding mode control is presented.

3.1 Tracking Model

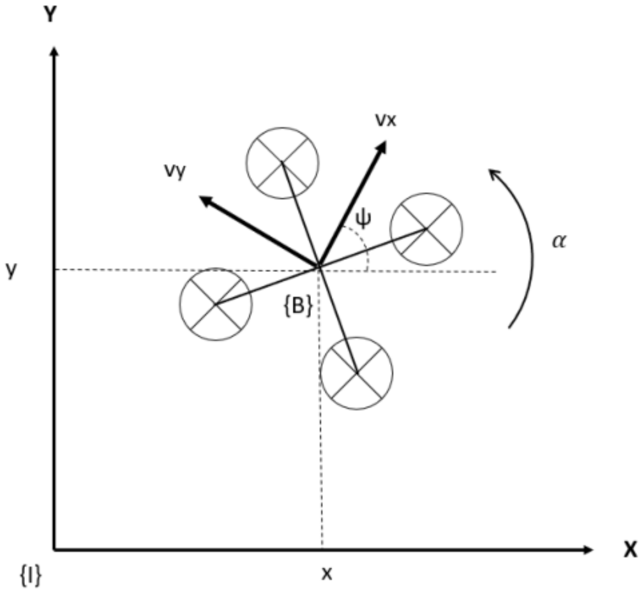

Fig. 1. Agent position in inertial frame I

The agents considered for this work are MAV type quadrotors. Let I represent a fixed inertial frame and B represent a non-inertial frame fixed to the body of the agent. The presented work deals with the formation control and desired trajectory tracking problems in presence of perturbations, hence, the assumption of a properly inner flight control exists for each agent. Given this assumption, the kinematic model for the 2 dimension tracking are represented by:

$$\dot{x} = v_x cos(\psi) - v_y sin(\psi) \tag{4}$$

$$\dot{y} = v_x sin(\psi) + v_y cos(\psi) \tag{5}$$

$$\dot{\psi} = \alpha, \tag{6}$$

where $\dot{x}$ and $\dot{y}$ are the inertial velocities v_x and v_y are the velocity components of an agent in the velocity frame, also the control inputs, where this frame is defined by the leader agent and ψ is the orientation angle.

3.2 Adaptive Sliding Mode controller

Let us introduce the basis for designing an adaptive sliding mode controller. By considering a perturbed nonlinear system:

$$\dot{x} = f(t, x) + g(x)u + \Delta(t), \tag{7}$$

Where x represents the state, u is the control input, $f(t,x)$ and $g(x)$ are continuous functions and $\Delta(t)$ includes bounded uncertainties and perturbations. Then, in order to design the controller, the state x needs to be driven to the desired trajectory of x_d. Thus, let the tracking error be defined as $e = x_d - x$, and the following sliding surface is proposed:

$$\sigma = K_p e + K_i \int e d\tau + K_d \dot{e} \tag{8}$$

with $K_\sigma > 0$. Then, by differentiating (8), one obtain

$$\begin{aligned} \dot{\sigma} &= K_p \dot{e} + K_i e + K_d \ddot{e} \\ &= K_p(\dot{x}_d - \dot{x}) + K_i(x_d - x) + K_d(\ddot{x_d} - \ddot{x}) \\ &= \dot{x}_d - f(t,x) + g(x)u + \Delta(t) + K_{\sigma i}(x_d - x) \\ &\quad + K_d(\ddot{x_d} - \ddot{x}) \end{aligned} \tag{9}$$

By considering the following feedback linearization controller:

$$u = g(x)^{-1} - (f(x,t) + u_a(t) + K_i e + K_d \ddot{e} + \dot{x}_d), \tag{10}$$

the auxiliary controller u_a is denoted by:

$$u_a = -K_a(t)|\sigma|^{\frac{1}{2}} sign(\sigma) + K_2 \sigma \tag{11}$$

where $K_2 > 0$, and the adaptive behavior is described as:

$$\dot{K}_a(t) = \begin{cases} k_{min} & K_a \leq k_{min} \\ \beta sign(|\sigma| - \mu) & K_a > k_{min} \end{cases} \tag{12}$$

The minimal control effort is defined by the value of k_{min} ensuring its value to be different from zero, the adaption rate is denoted by β, μ is a parameter that allows to detect loss of the sliding surface in order to modify the gain as it is required. This control method is robust against bounded uncertainties and perturbations, reduced chattering, accurate and ease to implement.

4. DESIGN OF THE FORMATION CONTROLLER

The leader-follower scheme for MAV formation is chosen, where one agent is the leader and all the other agents in the system are the followers. Under this approach, the followers must reach and keep a desired distance from the leader while tracking the leader displacement even in the presence of bounded uncertainties/perturbations. In order achieve the aforementioned, a non-inertial reference frame is generated using the velocity vector of the leader agent. The y axis of the velocity frame is along the direction of the velocity vector of the leader. Let Γ_x and Γ_y be the distance from the center of mass of the leader to the centre of mass of one of the followers in the leader velocity frame (see Fig. 2). These distances are defined as:

$$\Gamma_x = -(x_l - x_f)cos(\psi) - (y_l - y_f)sin(\psi) \tag{13}$$

$$\Gamma_y = (x_l - x_f)sin(\psi) - (y_l - y_f)cos(\psi) \tag{14}$$

From here, sub-index l stands for leader and f corresponds to follower, in this case x_l and y_l stands for the position of the leader agent in the XY plane, similarly, x_f and y_f defines the position of a follower in the XY plane and ψ is the orientation angle of the leader. All these values are referred to the inertial frame. Using (13) and (14) and the translation dynamics of the agents in the XY plane, an expression for the formation error can be found by differentiating both equations with respect to time as follows:

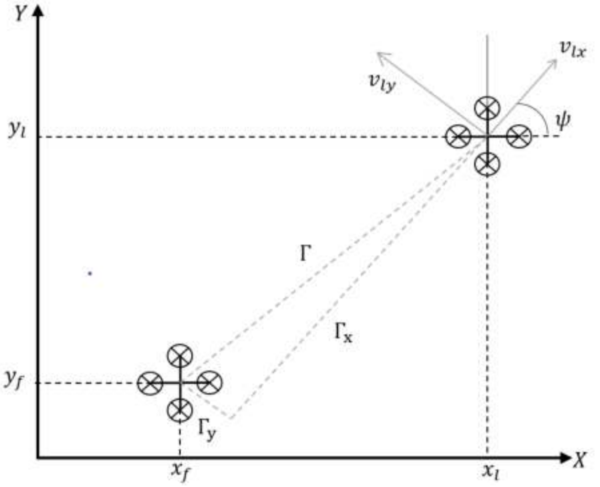

Fig. 2. Followers formation placement

$$\dot{\Gamma}_x = \Gamma_y \alpha_l + \dot{x}_f cos(\psi_l) + \dot{y_f} sin(\psi_l) - v_{lx} \tag{15}$$

Using trigonometric identities and the orientation error defined by $e_\psi = \psi_f - \psi_l$, (15) can be modified into:

$$\dot{\Gamma}_x = \Gamma_y \alpha_l + v_{fx} cos(e_\psi) - v_{fy} sin(e_\psi) - v_{lx} \tag{16}$$

Following a similar procedure for Γ_y, it yields:

$$\dot{\Gamma}_y = -\Gamma_x \alpha_l + v_{fx} sin(e_\psi) + v_{fy} cos(e_\psi) - v_{ly} \tag{17}$$

Thus, by defining the position error of an agent in the formation scheme as $e_x = \Gamma_x^d - \Gamma_x$ and $e_y = \Gamma_y^d - \Gamma_y$, from (16) and (17), the following error expressions are obtained:

$$\dot{e}_x = -(\Gamma_y^d - e_y)\alpha_l - v_{fx} cos(e_\psi) + v_{fy} sin(e_\psi) + v_{lx} \tag{18}$$

$$\dot{e}_y = (\Gamma_x^d - e_x)\alpha_l - v_{fx} sin(e_\psi) - v_{fy} cos(e_\psi) + v_{ly} \tag{19}$$

$$\dot{e}_\psi = \alpha_f - \alpha_l \tag{20}$$

Finally, given the formation errors, the equations describing the formation dynamics including uncertain term can be expressed as follows:

$$\dot{\zeta} = F(\zeta, t) + G(\zeta)U + \Delta(t) \tag{21}$$

where $F(\zeta, t)$ and $G(\zeta)$ are continuous functions denoted by:

$$F(\zeta) = \begin{bmatrix} e_y\alpha_L + v_{lx} - \alpha_l\Gamma_y^d \\ -e_x\alpha_L + v_{ly} + \alpha_l\Gamma_x^d \\ e_\psi \end{bmatrix} \tag{22}$$

$$G(\zeta) = \begin{bmatrix} -ce_\psi & se_\psi & 0 \\ -se_\psi & -ce_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{23}$$

the state based on errors is defined by:

$$\zeta = \begin{bmatrix} e_x \\ e_y \\ e_\psi \end{bmatrix}, \tag{24}$$

the control input is

$$U = \begin{bmatrix} v_{fx} \\ v_{fy} \\ \alpha_f \end{bmatrix}. \tag{25}$$

Finally, the bounded perturbation/uncertainties is represented by $\Delta(t) = ||[\Delta_x(t), \Delta_y(t), \Delta_\psi(t)]^T|| \leq L$, with $L > 0$. Based on formation dynamics, a controller is proposed in order to achieve the desired formation for the MAV system. The control input for the formation is the velocity of the agents.

The adaptive sliding mode controller is designed to assure the desired formation even in the presence of perturbations. Then, to guarantee the convergence of the followers to their desired relative positions, a sliding surface is defined as:

$$\sigma = K_a\zeta + K_b\int \zeta dt + K_c\dot{\zeta} \tag{26}$$

Following the control design procedure described in (8), (9) and (10), we have the closed loop behavior described by:

$$\dot{\sigma} = -k_\gamma(t)|\sigma|^{\frac{1}{2}} sign(\sigma) - k_n\sigma + \Delta(t), \tag{27}$$

with $k_n > 0$, and k_γ defined as:

$$\dot{k_\gamma}(t) = \begin{cases} k_{min} & : \; k_\gamma \leq k_{min} \\ \beta * sign(|\sigma| - \mu) & : \; k_\gamma > k_{min} \end{cases}, \tag{28}$$

where β determines the adaptation rate, K_{min} is a parameter to ensure no zero value in the control law, moreover a minimal control effort is established. μ is a threshold to detect the loss of the sliding surface such that it allows increase, decrease or stop the adaptive gain. Therefore, this control strategy manage the control effort as it is required, and keeping the robustness property of sliding mode control to perturbation/uncertainties.

5. RESULTS

In this section, results of the proposed adaptive sliding mode formation controller (24) in closed loop with translational model (1) - (3) is presented. The resulting formation control law and the proposed five agent triangular formation were simulated under the Matlab/Simulink environment. For this purpose, a virtual leader following a sinusoidal path is simulated and the information about its orientation and displacement is provided to the followers in order drove their positions to the desired relative distance to the leader through the proposed control law, also a perturbation is introduced to the system in order to test the response of the controller. The initial conditions for the followers are $X_{f1} = [-3.5, -3, 0]^T$, $X_{f2} = [-1.5, -3, 0]^T$, $X_{f3} = [2, -3, 0]^T$, $X_{f4} = [4, -3.0]^T$ and $X_l = [0, 0, 0]^T$ for the leader. The description of this initial set is described in 3

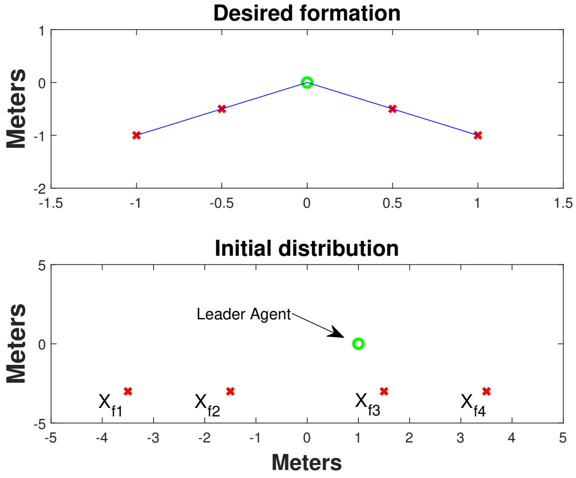

Fig. 3. Initial position of agents and their desired distribution

The gains of the controller were chosen as follows: the adaptation rate values are $\beta_{f1} = [2, 4.8, 1]^T$, $\beta_{f2} = [2, 4, 1]^T$, $\beta_{f3} = [2, 2, 1]^T$, $\beta_{f4} = [2, 2, 1]^T$. For the μ parameter the values are: $\mu_{f1} = [0.03, 0.05, 0.02]^T$, $\mu_{f2} = [0.02, 0.02, 0.02]^T$, $\mu_{f3} = [0.03, 0.03, 0.02]^T$, $\mu_{f4} = [0.04, 0.03, 0.02]^T$. The value of k_{min} was chosen globally as 0.002 . For the gain K_a the values are:$k_{af1} = [1, 3, 2]$, $k_{af2} = [1, 3, 2]$, $k_{af3} = [4, 5, 2]$, $k_{af4} = [4, 7, 2]$ for the gain k_b: $k_{bf1} = [0.01, 0.2, 0.01]$, $k_{bf2} = [0.01, 0.01, 0.01]$, $k_{bf3} = [0.1, 0.1, 0.01]$, $k_{bf4} = [0.1, 0.2, 0.01]$ finally, for the gain k_c the values are $K_{cf1} = [0.2, 0.9, 1]^T$, $K_{cf2} = [0.3, 2, 1]^T$,$K_{cf3} = [1.2, 0.9, 1]^T$,$K_{cf4} = [0.01, 0.9, 1]^T$

In Fig. 4, the formation error regarding the desired relative positions and orientation for each follower is shown. In this graph, it is possible to appreciate the perturbation introduced to the system. The magnitude of the perturbation is 4 m/s, and it was introduced as a step at the second eight of the simulation with a duration of 2 seconds. After the perturbation, the control droves again the error near to zero. Fig. 5 shows the action of the adaptive gain of the proposed control law, where the continuous activity is generated due to changing behavior of the desired reference moving along the sinusoidal trajectory and the perturbation introduced. Finally, Figs. 6 and 7 show the output values of the formation control for the velocity of

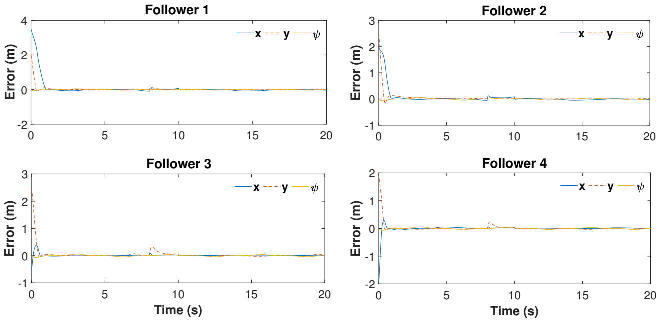

Fig. 4. Followers formation error

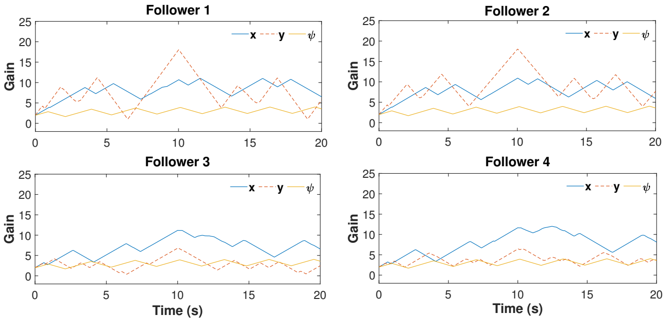

Fig. 5. Adaptive gain behavior

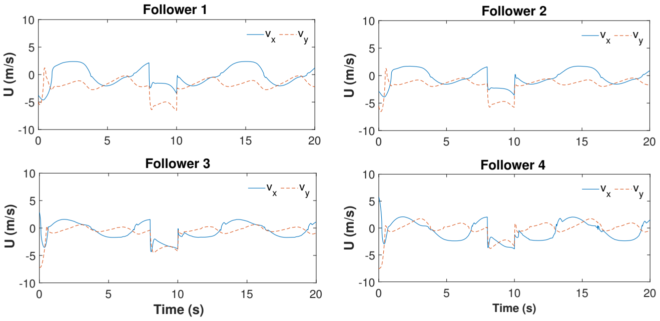

Fig. 6. Formation velocity control

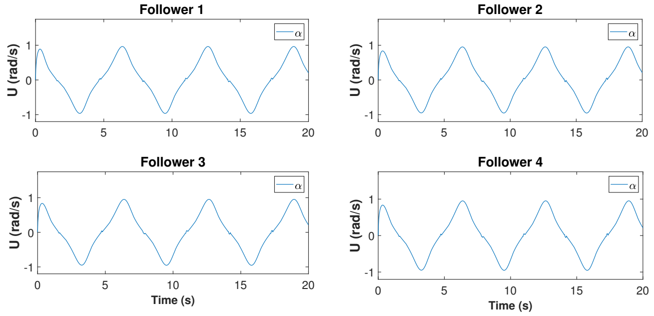

Fig. 7. Formation angular velocity control

the agents in the XY plane and the angular velocity for the orientation angle. Fig. 8 shows the evolution of the displacement of the system from the initial position to the final stable position. Follower agents are represented by red crosses and the virtual leader as a green circle. The perturbation introduced to the system can be seen in the irregularities on blue lines, but as shown in Figs. 4 and 8, this perturbation was compensated by the adaptive sliding mode control.

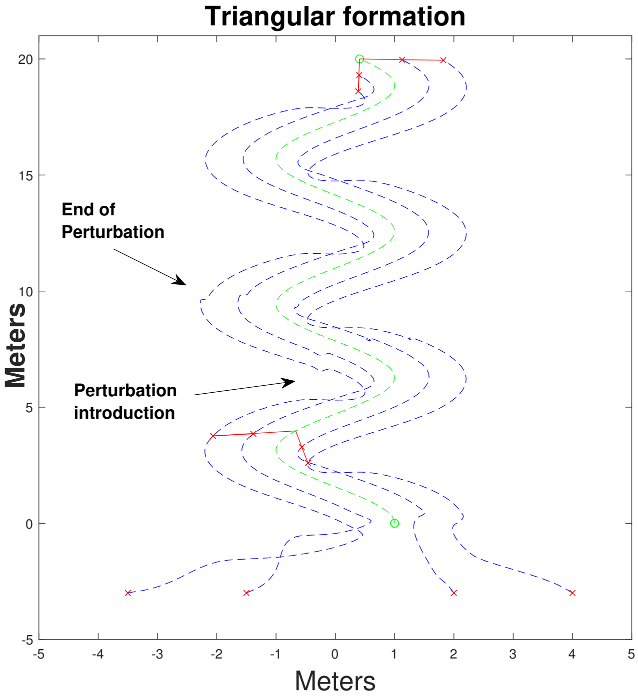

Fig. 8. Triangular formation along sinusoidal path

6. CONCLUSIONS AND FUTURE WORK

A formation control based on an adaptive sliding mode controller was achieved for a five agent triangular pattern even in the presence of bounded perturbations. The adaptive control gains allowed dynamically to reach formation as well as reject perturbations as they appeared. The strategy showed reduced chattering while use a minimal control gain to guarantee the sliding mode, but increase its magnitude as disturbances appeared. Simulation results demonstrated the feasibility and advantages of the proposed formation control scheme. Taking in consideration this results, the next step of this work is to implement the formation control in a real MAV system.

ACKNOWLEDGEMENTS

The authors thank to CONACyT and Tecnologico de Monterrey for the facilities granted to carry out this research project.

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