Cooperative Motion Control of a Formation of UAVs

Rômulo T. Rodrigues[†] and A. Pedro Aguiar[‡]

[†] Departament of Mechanics and Mechatronics,
University of São Paulo - EESC,
São Paulo, Brazil
[‡] Research Center for System and Technologies,
Faculty of Engineering, University of Porto (FEUP),
Porto, Portugal

***Abstract*— We address a cooperative motion control problem for a fleet of Unmanned Aerial Vehicles (UAVs). The problem partially decouples in two tasks: path-following and coordination control. The former requires the vehicle to converge and follow a desired path with no temporal constraints. The latter coordinates the elements in a fleet to travel on a desired pattern. In this paper we provide a practical and correctly provable solution by resorting to Lyapunov based nonlinear techniques to explicitly take into account the nonlinearities inherent to the mathematical model, graph theory to describe the inter-vehicle communication topology, and supported by Flight Variable Management System (FVMS) and Microsoft Flight Simulator (MSFS) to evaluate the proposed method through by Software in the Loop (SiL) simulations. Moreover, coordination in a switching communication topology is achieved.**

I. Introduction

Unmanned aerial vehicles do not only prevent human pilots from hazardous situations, but they are also a cheap and reliable solution when contrasted to other manned vehicles. A single UAV may alone fulfil a task in a simple application. However, the success of more challenging missions requires the employment of multiple vehicles working in cooperation towards the same goal. This concept is based on the advantages of distributed systems, such as robustness, flexibility and scalability, which endow a fleet of simple and cheap vehicles to perform tasks that are not feasible for an expensive single unit. Aerial robotic construction [1],[2], persistent surveillance [3], search and rescue operations [4],[5] are some applications envisioned for these systems.

Many challenges arise in a multi-UAV scenario: data fusion, coordination, collaborative planning and assignment, just to name a few. The present paper focuses on cooperative path following (CPF). The problem unravels in two tasks: i) *path-following* (PF) motion control, where a single vehicle is required to converge and keep track of a pre-specified spatial path with a desired speed assignment without temporal requirements, and ii) *coordinated control*, in which the vehicles are required to follow a desired inter-vehicle formation.

Pioneering work on the PF problem for wheeled mobile robots is described in [6]. The approach is further extended for the three-dimensional case in [7] using Lyapunov based control laws. The strategy adopted employs a virtual target point (VTP) and a tangent frame associated to the projection of the vehicle on the path, called Serret-Frenet. In this solution, the vehicle converges and remains inside a tube that involves the path. However, the radius of the tube must be less than the shortest curvature of the path, otherwise a singularity may arise. The work in [8] proposes an alternative solution to remove the singularity. The origin of the Serret-Frenet frame is not attached to the projection point, instead evolves in time according to a certain function. Using the ideas in [9] and [10], the work in [11] presents a solution by decomposing the problem in two tasks (geometric and dynamic) for underactuated vehicles. The geometric task aims to bring the vehicle and assures it remains inside a tube centered around the desired path. The dynamic assignment task assigns a speed profile to the path.

Theoretically, vehicles could share all internal and external information to improve coordination performance. However, in general, such approach is not feasible in terms of bandwidth and computational complexity. Moreover, the communication topology may vary over time due to link or even vehicle failure. A suitable communication constraints representation is a methodology based on a framework as addressed in [12]. It relates the concept of Graph Laplacian to represent links between vehicles. Particularly, the work demonstrated in [13] explicitly shows how the Graph Laplacian associated to a formation interconnection structure plays a fundamental role in assessing stability of the behavior of the components in coordination.

In [14] a model-independent for multi-agent formation control is proposed. The authors decouple the coordination problem into a planning and tracking problem. The work in [15] discusses a framework that takes into account the topology of the communication links, the logic based nature of communications and the cost of exchanging information. In [16] the authors consider an alternately connected and disconnected communication topology, therein called *brief connectivity losses*. It also discusses a second scenario, named *uniformly connected in mean*, which captures the union of communication graphs connected over uniform intervals of time. See also the work in [17], where a Lyapunov-based approach for time-coordinated path-following of multiple quadrotors is proposed.

Following the cooperative control architecture presented in [15] and [16], the present paper addresses a decentralized multi-vehicle control structure for a set of UAVs, where the vehicles and communication topology constraints are taken into account. High-fidelity numerical simulations using the Flight Variable Management System (FVMS) and Microsoft Flight Simulator (MSFS) are used to evaluate the performance of the proposed cooperative path-following controller.

This paper is organized as follows. Section II presents basic graph theory concepts. In Section III the problem is formally introduced, and in Section IV the proposed solution for the problem is presented. Section V illustrates the performance of the method. In Section VI concluding remarks are reported.

II. Background

The communication topology may vary over time due to link or vehicle failure. These communication constraints are properly modelled by graph theory. The fundamentals concepts are introduced next.

A digraph or directed graph denoted by $\mathcal{G}(\mathcal{V},\mathcal{E})$ or simple $\mathcal{G}$ is composed of a set of *vertices* (nodes) $\mathcal{V}$ and a set $\mathcal{E}$ that corresponds to its *edges* (arcs). Let each node of $\mathcal{V}$ represent a vehicle in the fleet, the edges of $\mathcal{E}$ the data link and $\mathcal{G}$ the inter-vehicle communication network. The ordered pair $(v_i,v_j) \in \mathcal{E}$ is called adjacent if there is an arc (v_i,v_j) joining them. The first element of the ordered pair is said to be the tail of the arc and the second is its *head*. It is stated that the arc (v_i, v_j) points from v_i to v_j and the flow of information is directed from head (transmitter) to tail (receiver). The *in-degree* of a node v_i is the number of arcs with v_i as its head. Analogously, the *out-degree* of a node v_i is the number of arcs with v_i as its tail. A graph is said to be *complete* if all vertices are pairwise adjacent.

A *path* of length m from a node v_i to v_j is a sequence of $m+1$ distinct nodes such that for $k = 0, 1, .., m-1$, v_k and v_{k+1} are adjacent. If a path links v_i to v_j, then v_i can access v_j and v_j is said to be *reachable* from v_i. If a node is reachable from any other node then it is *globally reachable*. If a graph $\mathcal{G}$ has a globally reachable node, it is called *quasi strongly connected* (QSC). If every node is globally reachable, then the graph is *strongly connected*. A graph with disjoint sets of nodes is called *disconnected*.

A matrix can be used to represent a graph. Consider the *adjacency matrix* A($\mathcal{G}$), a square matrix of size $|\mathcal{G}|$, where $a_{ij} = 1$ if $v_i v_j \in \mathcal{E}$ and $a_{ij} = 0$, otherwise. Remember that the relation $v_i v_j = v_j v_i$ is not necessarily true. The *degree matrix* of a directed graph $\mathcal{G}$, denoted by $D(\mathcal{G})$, is a square matrix whose elements of the main diagonal are the out-degrees of the respective node v_{ii}. The *Laplacian* of a graph is expressed as $L = D - A$. By definition the vector $\mathbf{1}$ belongs to its kernel $Ker(L)$, i.e. $L\mathbf{1} = \mathbf{0}$.

Let $\mathcal{G}$ be a complete graph, i.e., all possible arcs $1 \ldots \bar{n}$ exist. Consider the piecewise continuous function $p_i(t) : [0, \infty) \rightarrow \{0, 1\}$, where $i = 1, \dots, \bar{n}$.

$$p_i(t) = \begin{cases} 1, & \text{existence of arc } i \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

The switching signal is defined as the column vector $\boldsymbol{p}(t) = [p_i]_{\bar{n}\times 1}$. For each time instant, the graph $\mathcal{G}_{\boldsymbol{p}(t)}$ is defined by $(\mathcal{V}, \mathcal{E}_{\boldsymbol{p}(t)})$. Consider that, in a given interval of time T, there are q graphs defined, $\mathcal{G}_i$; $i = 1, \cdots, q$. Each graph has an associated Laplacian matrix L_i. The union graph, denoted as $\mathcal{G} = \cup_i \mathcal{G}_i$, is the graph whose arcs are the union of the arcs $\mathcal{E}_i$ of $\mathcal{G}_i$; $i = 1, \cdots, q$.

Definition 1: A graph $\mathcal{G}_{\boldsymbol{p}(t)}$ is said to be **uniformly quasi strongly connected** (UQSC) if, for every $t_0 > 0$, there is a $T > 0$ such that the union graph $\mathcal{G}([t, t+T))$ is QSC.

III. Problem Statement

Consider an inertial frame $\{\mathcal{I}\}$ fixed to the ground and a body-fixed frame $\{\mathcal{B}\}$ attached to the center of gravity of the vehicle, with the x-axis indicating the front of the aircraft and the y-axis tangent to its right wing. It is possible to describe the kinematic model of an aircraft moving in the horizontal plane as

$$\begin{aligned} \dot{\boldsymbol{p}}(t) &= R(t)\boldsymbol{v}(t) + \boldsymbol{v_w}, \\ \dot{R}(t) &= R(t)S(r), \end{aligned} \tag{1}$$

where $\boldsymbol{p}(t) \in \mathbb{R}^2$ defines the position and $R(t) \in SO(2)$ the rotation matrix from body to inertial frame, i.e. the orientation of the vehicle. The vector $\boldsymbol{v}(t) = (v_a, 0) \in \mathbb{R}^2$ stands for airspeed vector where v_a is the forward speed in the wind frame, $\boldsymbol{v_w} = (v_{w_x}, v_{w_y})$ is the wind velocity with respect to the inertial frame and $S(r) = \begin{pmatrix} 0 & -r \\ r & 0 \end{pmatrix}$ is a skew symmetric matrix associated to the angular velocity r. Let $\boldsymbol{u} = (v_a, r) \in \mathbb{R}^2$ be the input vector. The path-following problem is now introduced.

Problem Statement 1: **(Path-following)** Assume a desired spatial path $\boldsymbol{p_d}(\gamma) : \mathbb{R} \rightarrow \mathbb{R}^2$ parametrized by $\gamma \in \mathbb{R}$ and a desired speed assignment $v_d(\gamma) \in \mathbb{R}$. Suppose also that $\boldsymbol{p_d}(\gamma)$ is sufficiently smooth with respect to γ and its derivatives are bounded. Design a feedback control law for $\boldsymbol{u}$ and $\ddot{\gamma}$ such that i) the position

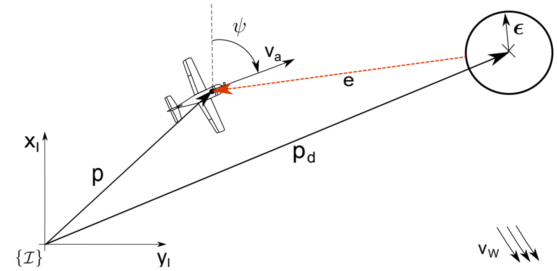

Fig. 1. Path following frame on the xy plane

of the vehicle converges and remains inside a tube centred around the desired path, i.e. $\|\boldsymbol{p} - \boldsymbol{p_d}\| \rightarrow \|\boldsymbol{\epsilon}\|$ where $\boldsymbol{\epsilon} = [\epsilon_1, \epsilon_2]^T \in \mathbb{R}^2$ is a nonzero constant vector that can be made arbitrarily small and ii) the vehicle satisfies the desired speed assignment, i.e. $\|\dot{\gamma} - v_d(\gamma)\| \rightarrow 0$.

Consider a fleet of n vehicles denoted by the set $\mathcal{N} = \{1, \dots, n\}$. Suppose each vehicle converges to its respective VTP. Therefore, if the n virtual target points asymptotically synchronize, the vehicles asymptotically reach a desired formation. The parametric variable γ_i describes the position of the ith VTP and is said to be the coordination state. The definition of desired speed profile is extended to

$$\boldsymbol{v_d} = v_L(\gamma)\mathbf{1} + \tilde{\boldsymbol{v}}_{\boldsymbol{r}} \tag{2}$$

where the elements of $\boldsymbol{v_d} = [v_{d1}, \dots, v_{dn}]$ and $\tilde{\boldsymbol{v}}_{\boldsymbol{r}} = [\tilde{v}_{r1}, \dots, \tilde{v}_{rn}]$ correspond to the desired and correction speeds of each vehicle $i \in \mathcal{N}$, respectively. The formation speed, denoted by $v_L(\gamma)$, is common to all vehicles in the flock. Let $\mathcal{N}_i$ be the set of vehicles from which the ith UAV is able to receive information. As formally stated in Section II, it is not necessarily true that $j \in \mathcal{N}_i \Rightarrow i \in \mathcal{N}_j$, since unidirectional communication is considered.

Problem Statement 2: **(Coordination)** Assume that for each vehicle $i \in \mathcal{N}_i$, the variables γ_i and γ_j, $j \in \mathcal{N}_i$ are available. Derive a control law for $\tilde{v}_{ri}$, such that, for all $i, j \in \mathcal{N}$, $(\gamma_i - \gamma_j)$ and $(\dot{\gamma}_i - \dot{\gamma}_j)$ converge to zero as $t \rightarrow \infty$.

IV. Proposed Solution

This section proposes a cooperative path-following controller for a set of UAVs and provides conditions under which the proposed solution achieves convergence of the path-following and coordination errors to a small ball around zero.

A. *Path-following*

From the path-following problem statement, the error associated with the position of the vehicle $\boldsymbol{e}$ and the error for the evolution of the parametric variable z can be defined according to

$$\begin{aligned} \boldsymbol{e} &= R^T(\psi)(\boldsymbol{p} - \boldsymbol{p_d}(\gamma)) - \boldsymbol{\epsilon} \\ z &= \dot{\gamma} - v_d(\gamma) \end{aligned} \tag{3}$$

The problem is depicted in Fig. 1. The task consists in assuring that the position error is ultimately bounded and, after a transient time, it converges to a region close to the origin. Define the composite error vector $\boldsymbol{e_c} = [\boldsymbol{e}, z]^T$. The time derivative of $\boldsymbol{e}$ is given by

$$\dot{e} = \dot{R}^T(\psi)(\boldsymbol{p} - \boldsymbol{p_d}(\gamma)) - R^T(\psi)(\dot{\boldsymbol{p}} - \dot{\gamma}\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma})$$

which, applying (1) and (3) and simplifying the remainder algebraic equation, yields

$$\begin{aligned} \dot{e} =& - S(r)\boldsymbol{e} + \Delta \boldsymbol{u} + R^T(\psi)\boldsymbol{v_w} \\ & - R^T(\psi)\dot{\gamma}\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma} \end{aligned} \tag{4}$$

where $\Delta = \begin{bmatrix} 1 & \epsilon_2 \\ 0 & -\epsilon_1 \end{bmatrix}$. By now, it shall be clear to the reader why the vehicle was set to converge and remain inside a tube centered around $\boldsymbol{p_d}(\gamma)$, and not the desired position itself. If $\boldsymbol{\epsilon}$ had not been introduced, the control variable r (yaw rate) would not appear in (4) to enforce the convergence of the error to zero, as explained in the next result.

Theorem 1: Consider the system described by (1) in a closed-loop with the control laws

$$\begin{aligned} u &= \Delta^{-1}(R^T(\psi)v_d\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma} - R^T(\psi)\boldsymbol{v_w} - K_p\boldsymbol{e}) \\ \ddot{\gamma} &= \boldsymbol{e}R^T(\psi)\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma} - \frac{\partial v_d(\gamma)}{\partial \gamma}v_d(\gamma) - k_\gamma z \end{aligned} \tag{5}$$

where $K_p = \begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix}$ is a diagonal matrix with positive eigenvalues, k_γ is a positive constant with $k_\gamma > v_d(\gamma)|\frac{\partial v_d(\gamma)}{\partial \gamma}|$, and ϵ_1 is nonzero. The origin $\boldsymbol{e_c} = \boldsymbol{0}$ is a globally asymptotically stable equilibrium point for the closed-loop system.

Proof: Define the composite Lyapunov function

$$V_c = V_e + V_z = \frac{1}{2}\boldsymbol{e}^T\boldsymbol{e} + \frac{1}{2}z^2$$

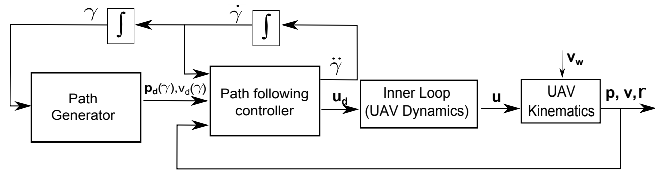

Fig. 2. Path-following motion control architecture for a single UAV

where its time-derivative is given by

$$\dot{V}_c = \dot{V}_e + \dot{V}_z = \boldsymbol{e}^T\dot{\boldsymbol{e}} + z\dot{z}$$

Since $\dot{z} = \ddot{\gamma} - \dot{\gamma}\frac{\partial v_d(\gamma)}{\partial \gamma}$, using (4) we obtain

$$\begin{aligned} \dot{V}_c =& \boldsymbol{e}^T(-S(r)\boldsymbol{e} + \Delta\boldsymbol{u} + R^T(\psi)\boldsymbol{v_w} - R^T(\psi)v_d\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma}) \\ & + z(\ddot{\gamma} - (z + v_d(\gamma))\frac{\partial v_d(\gamma)}{\partial \gamma} - \boldsymbol{e}^T R^T(\psi)\frac{\partial \boldsymbol{p_d}(\gamma)}{\partial \gamma}) \end{aligned}$$

Now, applying the control laws for $\boldsymbol{u}$ and $\ddot{\gamma}$ that are expressed in (5), yields

$$\begin{aligned} \dot{V}_c &= -\boldsymbol{e}^T K_p \boldsymbol{e} - (k_\gamma - v_d(\gamma)|\frac{\partial v_d(\gamma)}{\partial \gamma}|)z^2 \\ &= -\boldsymbol{e_c}^T K_c \boldsymbol{e_c} \end{aligned}$$

where $K_c = \begin{bmatrix} K_p & 0 \\ 0 & k_\gamma \end{bmatrix}$ and $\boldsymbol{e_c} = [\boldsymbol{e}, z]^T$.

Thus, from Lyapunov theory, it can be concluded that the origin $\boldsymbol{e_c} = \boldsymbol{0}$ is a globally uniformly asymptotically stable equilibrium point. Therefore, the position error $\boldsymbol{e}$ converges to a neighborhood of $\boldsymbol{\varepsilon}$ and the speed assignment error z converges to zero. ■

Fig. 2 illustrates a schematic of the PF control architecture. The smaller the values of $\boldsymbol{\epsilon}$ are, the closest to the neighborhood of the desired path the vehicle converges. However, the input signal may take high values in the transient. Analysing the matrix Δ, the value ϵ_2 may be set to null, but ϵ_1 cannot be zero, or Δ will not be invertible.

B. *Coordination*

Consider a piecewise constant switching signal $p(t)$, whose discontinuities are apart from each other by a minimum time span $\tau > 0$, called *dwell time*. Consider also that the communication topology may fail to be connected at any time instant, but over a defined period $T > 0$ the union graph $\mathcal{G}_{p(t)}$ is uniformly quasi strongly connected.

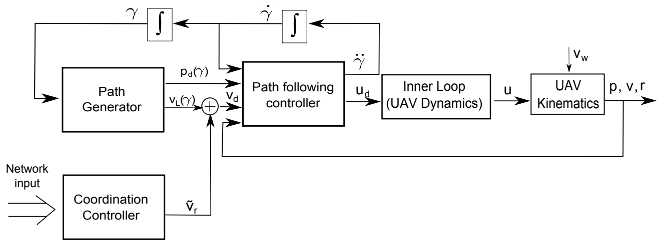

Fig. 3. Cooperative path-following architecture

The following *agreement* result, borrowed from [18], holds.

Theorem 2: Assuming that the union graph of the communication topology is UQSC, then the system

$$\dot{\boldsymbol{\gamma}} = -KL_p\boldsymbol{\gamma} \tag{6}$$

satisfies the property that for any initial condition $\gamma(0) = \gamma_0$, the coordination errors γ_i-γ_j, $\forall\, i, j \in \mathcal{N}$ converge exponentially fast to zero and $\dot{\boldsymbol{\gamma}} \rightarrow \mathbf{0}$ as $t \rightarrow \infty$.

In [19], the authors generalize the previous result to the system

$$\dot{\boldsymbol{\gamma}} = v_L(\gamma)\mathbf{1} - KL_p\boldsymbol{\gamma}$$

This is straightforward obtained by applying the change of variables

$$\tilde{\boldsymbol{\gamma}} = \boldsymbol{\gamma} - \mathbf{1}\int_0^t v_L d\tau$$

and

$$\begin{aligned}\dot{\tilde{\boldsymbol{\gamma}}} &= v_L\mathbf{1} - KL_p\boldsymbol{\gamma} - v_L\mathbf{1}\\ &= -KL_p\tilde{\boldsymbol{\gamma}}\end{aligned}$$

Applying Theorem 2, $\tilde{\gamma}_i$-$\tilde{\gamma}_j$ and $\dot{\tilde{\boldsymbol{\gamma}}}$ converges to zero as $t \rightarrow \infty$. Consequently, γ_i-γ_j and $\dot{\boldsymbol{\gamma}}$ converge exponentially fast to zero and v_L, respectively, as $t \rightarrow \infty$. Thus, from the above results, by setting $\tilde{\boldsymbol{v}}_{\boldsymbol{r}}$ introduced in (2) as

$$\tilde{\boldsymbol{v}}_{\boldsymbol{r}} = -KL_p\boldsymbol{\gamma} \tag{7}$$

it follows that in the manifold $\boldsymbol{z} = \mathbf{0}$ the formation achieves coordination.

Theorem 3: Consider the overall CPF system composed by n UAVs modeled by (1) in closed-loop with the PF controllers (5) and in coordination according to (2) and (7). Suppose that the Laplacian of the graph that models the communication topology L_p satisfies the UQSC condition. Then, there are suitable control gains that guarantee that the path-following and the coordination errors are ultimately bounded and, in particular, they converge to a small neighbourhood of zero as $t \rightarrow \infty$.

Proof: [Outline] The proof follows similar arguments described in [16] and [15].

First, using Lyapunov theory, it can be shown that the path-following errors $\boldsymbol{e}$ and z defined in (3) of each UAV described by (1) in closed-loop with (5) are input-to-state stable (ISS) with respect to the input $\tilde{\boldsymbol{v}}_{\boldsymbol{r}}$. Also, for the coordination system, it follows that $\dot{\gamma}_i = v_{di}(\gamma) + z$. Thus, it is also possible to show that the coordination errors $\gamma_i - \gamma_j$ are ISS with respect to the input z and consequently that the output signal $\tilde{\boldsymbol{v}}_{\boldsymbol{r}}$ is input-to-output stable. Therefore, an application of the small-gain theorem [20] allows to conclude the result. ■

Fig. 3 illustrates the cooperative path-following control architecture.

V. SIL RESULTS

In this section SiL simulations assess the performance of the proposed cooperative path-following solution. The task was supported by Microsoft Flight Simulator (MSFS) and Flight Variable Management System (FVMS). The role of the FVMS platform is to provide an interface to the GNC algorithms using MSFS. The latter is a powerful aeronautical tool that simulates the dynamical behaviour of aircraft in a reliable and very detailed manner. Fig. 4, adapted from [21], illustrates the SiL architecture. In order to communicate with MSFS, FVMS captures MSFS memory address. For more information about the system the reader is referred to [22], [21].

The SiL simulations were performed with the fixed-wing aircraft Cessna C17SP. Applying the method known as banked turn or coordinated turn [23], it is possible to define the bank angle as a function of the desired yaw rate. The wind was set to 36 kts, South. Moderate turbulence and gusts were introduced. The mission profile contains two vehicles. Both take off from the same lane with a safe time interval. Vehicle 1 broadcasts its coordination variable at a frequency of 2Hz over a UDP network. The second vehicle does not

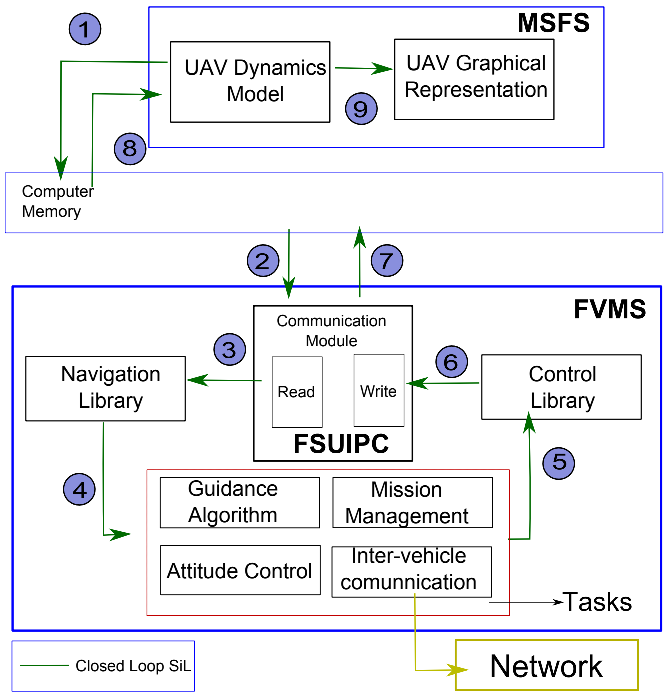

Fig. 4. Software in the Loop architecture [21].

transmit its coordination variable, but it is able to receive messages from vehicle 1. Some messages are lost due to link failures, setting up the UQSC communication topology.

Fig. 5 illustrates the mission evolution over time where snapshots of both vehicles taken at different instants of time show how the synchronization takes place. Shortly after vehicle 2 (red) takes-off from position (0,0), vehicle 1 is approximately 2000 m ahead at (0, 2000). The fourth snapshot shows that both vehicles are following their desired path in a coordinated fashion. More precisely, Fig. 6 evidences the synchronization behaviour by showing that the coordination error $\xi = \gamma_1 - \gamma_2$ approaches zero. As a consequence of computational and network delays, the error exhibits a slightly oscillating pattern.

Fig. 7 shows the true airspeed and heading of both vehicles. Vehicle 2 increases its speed as it catches up vehicle 1. Once both vehicles are in coordination, the vehicles' true airspeeds stabilize around a similar value. The UAVs slightly face the wind to compensate the 36kts wind speed vector, directed perpendicular to the desired trajectory. Finally, Fig. 8 shows the communication signal for a given time interval. The packet losses and

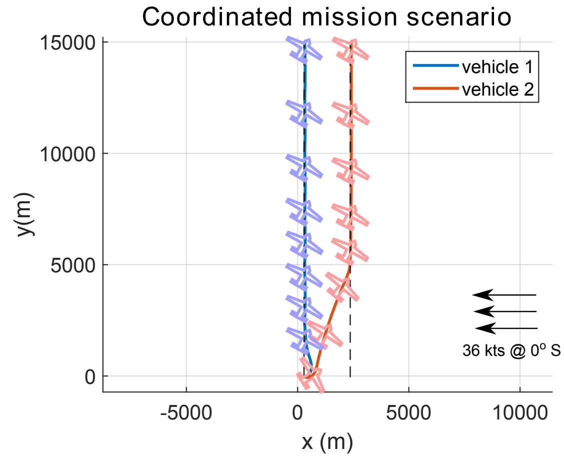

Fig. 5. Vehicle 1 (blue, left) and vehicle 2 (red, right) displacement evolution along time

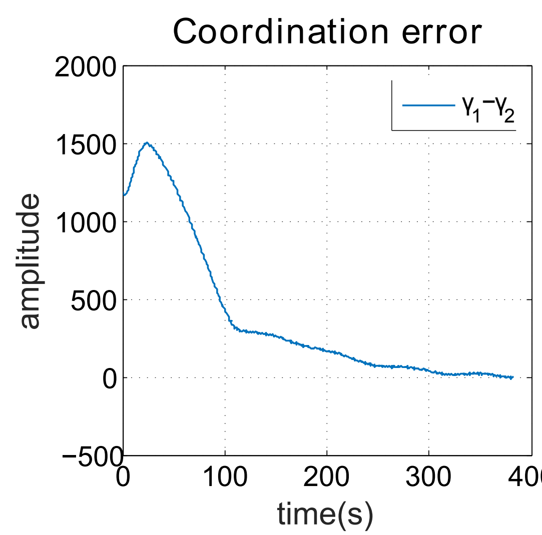

Fig. 6. Time evolution of the coordination error

the communication sampling time influence the coordination convergence. Yet, as long as a UQSC network is maintained, the consensus problem is solved.

VI. Conclusion

This paper addressed the cooperative path-following problem. In the solution adopted, the CPF is divided in two almost decoupled problems: path-following and coordination. The former assures that the vehicle follows a virtual target. Meanwhile, the latter adjusts the VTP evolution along the desired path. The control laws herein discussed are supported by nonlinear Lyapunov stability theorems and graph theory.

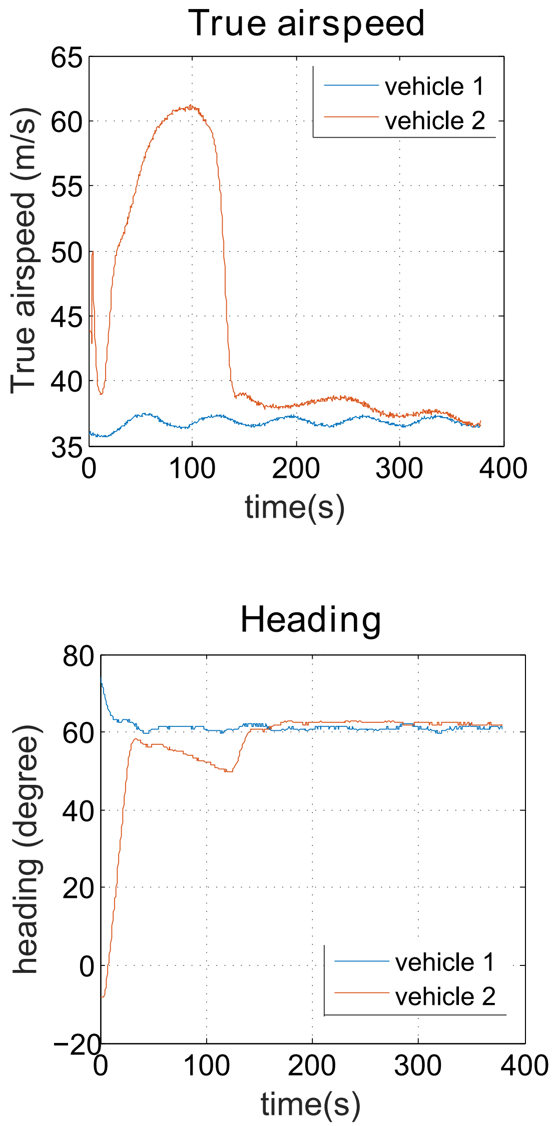

Fig. 7. True airspeed input variable and heading of the vehicle

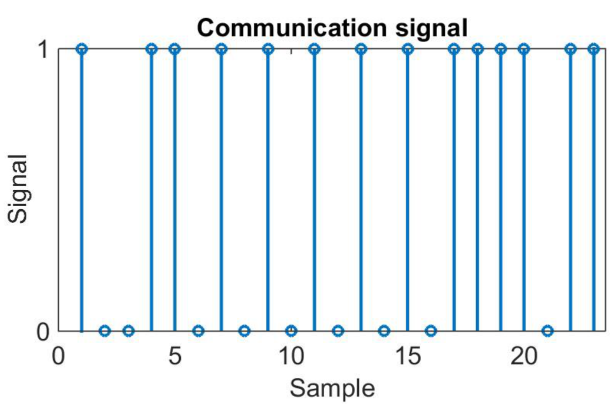

Fig. 8. Communication signal in a given representative time interval with duration of 11.5 seconds. 0: no message received, 1: message received

The results from SiL simulations show that the performance of nonlinear path-following is satisfactory under bad atmospheric conditions. The dynamics of the vehicle are not explicitly addressed in the control law presented for control design. This allows the kinematic controller to be applicable to other vehicles, equipped with different dynamic controllers. The coordination results confirm that it is possible to achieve coordination in a switching inter-vehicle communication topology. Moreover, as expected, the results report that in a uniformly quasi strongly connected topology, even under intermittent link failures, the coordination is accomplished.

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