COORDINATED PATH-FOLLOWING CONTROL OF MULTIPLE AUVS IN THE PRESENCE OF COMMUNICATION FAILURES AND TIME DELAYS

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Abstract: This paper addresses the problem of steering a group of underactuated Autonomous Underwater Vehicles (AUVs) along given spatial paths, while holding a desired inter-vehicle formation pattern. We show how Lyapunov-based techniques and graph theory can be brought together to yield a decentralized control structure where the dynamics of the cooperating vehicles and the constraints imposed by the topology of the inter-vehicle communications network are explicitly taken into account. *Path-following* for each vehicle amounts to reducing an appropriately defined geometric error to a small neighborhood of the origin. *Vehicle coordination* is achieved by adjusting the speed command of each vehicle along its path according to information on the positions of a subset of the other vehicles, as determined by the communications topology adopted. Convergence and stability of the overall system are proved formally. This holds true in the presence of *arbitrary bounded communication delays as well as communication failures* under some mild condition on the nature of the failures. Simulations results are presented and discussed.

Keywords: Path-following, coordination, communication delays and failures, AUV

1. INTRODUCTION

Increasingly demanding scientific and commercial mission scenarios and the advent of powerful embedded systems and communication networks have spawned widespread interest in the problem of coordinated motion control of multiple autonomous vehicles. The types of applications envisioned are numerous and include spacecraft formation flying (Beard *et al.*, 2001), (Mesbahi and Hadaegh, 2001); control of multiple unmanned aerial vehicles (Song *et al.*, 2005), (Stipanovic *et al.*, 2004); coordinated control of land robots (Desai *et al.*, 2001), (Ögren *et al.*, 2002), (Ghabcheloo *et al.*, 2006); and control of surface and underwater vehicles (Encarnação and Pascoal, 2001), (Skjetne *et al.*, 2002), (Lapierre *et al.*, 2003), (Stilwell and Bishop, 2000).

To meet the requirements imposed by these applications, a new control paradigm is needed that departs considerably from classical centralized control strategies. Centralized controllers deal with

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systems in which a single (local) controller possesses all the information needed to achieve the desired control objectives (including stability and performance requirements). However, in many of the applications envisioned here, because of the highly distributed nature of the sensor and actuation modules and the very nature of the inter-vehicle communications network, it is impractical to exchange all relevant information among the vehicles and to tackle the problems in the framework of centralized control theory. For these reasons, there has been over the past few years a flurry of activity in the area of multi-agent networks with application to engineering and science problems. Namely, parallel computing (Tsitsiklis and Athans, 1984); synchronization of oscillators (Sepulchre *et al.*, 2003); collective behavior and flocking (Jadbabaie *et al.*, 2003); consensus (Lin *et al.*, 2005); formation of multi-vehicle system (Egerstedt and Hu, 2001); asynchronous protocols (Fang *et al.*, 2005); graph theory and graph connectivity (Kim and Mesbahi, 2006).

In spite of significant progress in these exciting areas, much work remains to be done to develop strategies capable of yielding robust performance of a fleet of vehicles in the presence of complex vehicle dynamics, severe communication constraints, and partial vehicle failures. These difficulties are specially challenging in the field of marine robotics for two main reasons: i) the dynamics of marine vehicles are often complex and cannot be simply ignored or drastically simplified for control design purposes, and ii) underwater communications and positioning rely heavily on acoustic systems, which are plagued with intermittent failures, latency, and multipath effects.

Inspired by the developments in the field, we consider the problem of *coordinated path-following* where *multiple vehicles are required to follow pre-specified spatial paths while keeping a desired inter-vehicle formation pattern in time.* These objectives must be met in the presence of communication related failures and delays. This problem arises for example in the operation of multiple autonomous underwater vehicles (AUV) for fast acoustic coverage of the seabed. In this application, two or more vehicles are required to fly above the seabed at the same or different depths, along geometrically similar spatial paths, and map the seabed using identical suites of acoustic sensors. By requesting that the vehicles traverse identical paths so that the projections of the acoustic beams on the seabed exhibit some overlapping, large areas can be covered in a short time. These objectives impose constraints on the inter-vehicle formation pattern. A number of other scenarios can of course be envisioned that require coordinated motion control of marine vehicles.

In this paper, we solve the coordinated path-following problem for a general class of underactuated underwater vehicles moving in three-dimensional space. Using the technique proposed, the problem is divided into two sub-problems. At the lower level, the path-following problem is solved for individual vehicles, each having access to a set of local measurements. Coordination is then achieved by synchronizing the so-called coordination states that capture the along path distances between vehicles. Because of the network faults, the problems brought about by temporary communication losses and delays must be addressed explicitly. To this effect, this paper proposes a framework to study the effect of communication failures and delays on the stability of the overall vehicle formation.

The paper is organized as follows. Section 2 describes the model of an underactuated AUV and formulates the path-following and vehicle coordination problems. Section 3 gives solutions to the problems of single vehicle path-following as well as multiple vehicle coordinated path-following in the case where the communications network is subjected to communication losses and time delays. Section 4 describes the results of simulation results. Finally, Section 5 contains the main conclusions and describes problems that warrant further research.

2. PROBLEM STATEMENT

Consider an underactuated autonomous underwater vehicle (AUV) not necessarily neutrally buoyant. Let $\{\mathcal{I}\}$ be an inertial coordinate frame and $\{\mathcal{B}\}$ a body-fixed coordinate frame whose origin is located at the center of mass of the vehicle. The configuration $(R, \mathbf{p})$ of the vehicle is an element of the Special Euclidean group $SE(3) := SO(3) \times \mathbb{R}^3$, where $R \in SO(3) := \{R \in \mathbb{R}^{3\times 3} : RR^T = I_3, \det(R) = +1\}$ is a rotation matrix that describes the orientation of the vehicle and maps body coordinates into inertial coordinates, and $\mathbf{p} \in \mathbb{R}^3$ is the position of the origin of $\{\mathcal{B}\}$ in $\{\mathcal{I}\}$. Denoting by $v \in \mathbb{R}^3$ and $\omega \in \mathbb{R}^3$ the linear and angular velocities of the vehicle relative to $\{\mathcal{I}\}$ expressed in $\{\mathcal{B}\}$, respectively, the following kinematic relations apply:

$$\dot{\mathbf{p}} = Rv, \tag{1a}$$

$$\dot{R} = RS(\omega), \tag{1b}$$

where

$$S(x) := \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}, \quad \forall x := (x_1, x_2, x_3)^T \in \mathbb{R}^3.$$

We consider AUVs with dynamic equations of motion of the following form:

$$\mathbf{M}\dot{v} = -S(\omega)\mathbf{M}v + f_v(v,R) + B_1 u_1, \quad (2a)$$
$$\mathbf{J}\dot{\omega} = -S(v)\mathbf{M}v - S(\omega)\mathbf{J}\omega + f_\omega(v,\omega,R) + B_2 u_2, \quad (2b)$$

where $\mathbf{M} \in \mathbb{R}^{3\times 3}$ and $\mathbf{J} \in \mathbb{R}^{3\times 3}$ include the so-called hydrodynamic added-mass M_A and added-inertia J_A matrices, that is, $\mathbf{M} = M_{RB} + M_A$, $\mathbf{J} = J_{RB} + J_A$. The symbols M_{RB} and J_{RB} denote the rigid-body mass and inertia matrices, respectively. The functions $f_v(\cdot)$ and $f_\omega(\cdot)$ capture hydrodynamic damping effects and restoring forces and moments, and are defined by

$$f_v = -D_v(v)v - \bar{g}_1(R), \quad f_\omega = -D_\omega(\omega)\omega - \bar{g}_2(R),$$

where

$$D_v(v) = \mathrm{diag}\{X_{v_1} + X_{|v_1|v_1}|v_1|, Y_{v_2} + Y_{|v_2|v_2}|v_2|, Z_{v_3} + Z_{|v_3|v_3}|v_3|\}$$
$$D_\omega(\omega) = \mathrm{diag}\{K_{\omega_1} + K_{|\omega_1|\omega_1}|\omega_1|, M_{\omega_2} + M_{|\omega_2|\omega_2}|\omega_2|, N_{\omega_3} + N_{|\omega_3|\omega_3}|\omega_3|\}$$

$$\bar{g}_1(R) = R^T \begin{pmatrix} 0 \\ 0 \\ W-B \end{pmatrix}, \quad \bar{g}_2(R) = S(r_{\mathcal{B}})R^T \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix}$$

The gravitational and buoyant forces are given by $W = mg$ and $B = \rho g \nabla$, respectively, where m is the vehicle's mass, ρ is the mass density of the water and ∇ is the volume of displaced water. We assume that there are available a pure body-fixed control force τ_u in the $x_{\mathcal{B}}$ direction, that is, $B_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ and two independent control torques τ_q and τ_r about the $y_{\mathcal{B}}$ and $z_{\mathcal{B}}$ axes of the vehicle, that is, $B_2 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$. We also assume that the metacentric height of the AUV is sufficiently large to provide adequate static stability in roll motion. The particulars of the AUV used in the simulations at the end of the paper are those of the *Sirene* underwater shuttle described in (Aguiar, 2002; Aguiar and Pascoal, 1997).

For our purposes, we consider a fleet of $n \geq 2$ vehicles. For $i = 1,..,n$ we let $\mathbf{p}_i(t) \in \mathbb{R}^3$ and $\mathbf{p}_{d_i}(\gamma_i) \in \mathbb{R}^3$ denote the position of vehicle i and its assigned (desired) path, where the latter is parameterized by $\gamma_i \in \mathbb{R}$. We further let $v_{r_i}(t) \in \mathbb{R}$ denote the desired speed assignment for vehicle i defined in terms of parameters γ_i. Finally, $u_i = [u_{1,i}, u_{2,i}]$ and x_{p_i} denote the control vector and a conveniently defined path-following state vector, respectively, of vehicle i.

Equipped with above notation, the problems of *path-following* (PF) and *coordinated path-following* (CPF) are defined next. For the sake of clarity, the presentation is informal at times.

Path following problem. Given vehicle i and a desired path $\mathbf{p}_{d_i}$, design feedback controller laws for u_i such that all the closed-loop signals are bounded, the position of the vehicle converges to and remains inside a tube centered around the desired path, and the vehicle travels at a desired speed assignment v_{r_i}.

In the approach to the problem of coordinated path-following considered here we first require that each vehicle be attracted to and follow its assigned path; this is followed by a synchronization phase where the commanded speeds of the vehicles are adjusted so that the fleet of vehicles will reach a desired formation pattern at a desired formation speed. Obviously, the choice of pattern adopted impacts on the parameterizations γ_i of the path $\mathbf{p}_{d_i}$ to be followed. Define the along-path distance between vehicle i and j as $\gamma_{ij}(t) := \gamma_i(t) - \gamma_j(t)$. Then, coordination is said to be achieved if $\gamma_{ij} = 0$ for all $i, j \in \{1, ..., n\}$; (Ghabcheloo *et al.*, 2006). This will result in an in-line formation if the paths $\mathbf{p}_{d_i}$ are obtained as simple parallel translations of a "template" path. The above circle of ideas leads naturally to the following problem formulation.

Coordination problem. *For each vehicle $i = 1, ..., n$ derive a control law for $v_{r_i}(.)$ as a function of γ_j, $j \in N_{i,p}$ such that $\gamma_i - \gamma_j, \forall i, j$ approach zero as $t \to \infty$ and the formation travels at an assign speed v_L, that is, $|\dot{\gamma}_i - v_L|$ tends to zero.*

Before we present the solutions to above problems, we summarize some background material. We start with a brief review of algebraic graph theory. See (Godsil and Royle, 2001) for details.

2.1 Graph theory

The communication constraints are modeled by a digraph (directed graph) consisting of n nodes where each node corresponds to a vehicle. The set of vehicles from which vehicle i receives information is denoted by N_i. If $j \in N_i$, then there is an arc from node i to node j and we say that i reaches (or is adjacent to) j. A path of length r starting at node j and ending at i consist of $r+1$ consecutive adjacent nodes. If there is a path from node j to node i, then i is said to be reachable from j. Node k is globally reachable if it is reachable from every other node. The adjacency matrix of a digraph, denoted A, is a square matrix with rows and columns indexed by the nodes, such that the i,j-entry of A is 1 if $j \in N_i$ and zero otherwise. The degree matrix D of a digraph $\mathcal{G}$ is a diagonal matrix where the i,i-entry equals $|N_i|$, the cardinally of N_i. The Laplacian of a digraph is defined as $L = D - A$.

To model a switching graph, consider the complete graph $\mathcal{G}$ defined on n nodes, with arcs numbered $1, ..., \bar{m}$. Let $p_i; i = 1, ..., \bar{m}$ be a piecewise-continuous time-varying binary function indicating the existence or absence of arc i in the graph. Let $p = [p_i]_{\bar{m}\times 1}$ and call the corresponding switching graph $\mathcal{G}_{p(t)}$ defined as follows: if arc i exists (is active) in the graph at time t, then $p_i(t) = 1$ and $p_i(t) = 0$ otherwise. Denote by L_p the explicit dependence of the graph Laplacian on $p(t)$ and extend the notation to the degree matrix D_p, the adjacency matrix A_p, and the neighboring set $N_{i,p}$.

At this point it is important to summarize some key results on the stability and convergence of continuous-time distributed consensus algorithms.

2.2 *Distributed consensus algorithms (Moreau, 2004)*

Consider an $n \times n$ matrix $\bar{L} = [l_{i,j}]$. Define the δ-digraph associated to $\bar{L}$ as the digraph with node set $\{1, ..., n\}$ and such that an arc from i to j exists if $l_{i,j} \geq \delta$ for some $\delta > 0$. Let

$$\bar{L}(t, T) := \int_t^{t+T} L_{p(s)} ds$$

for some $T > 0$ and associate a δ-digraph to it. In the context of this paper, this construction will ensure that the resulting digraph has an arc from node i to node j if vehicle j sends information to vehicle i for at least δ seconds during any time interval of length T. Let $\theta \in \mathbb{R}^n$ be a vector which we shall later relate to the coordination states γ_i, and consider the linear time-varying system

$$\dot{\theta} = -K(t) L_{p(t)} \theta \tag{3}$$

where $K(t)$ is a positive definite diagonal matrix. The following theorem applies.

Theorem 1. If there is an index $k \in \{1, ..., n\}$, a threshold value $\delta > 0$, and an interval time length $T > 0$ such that for all $t > 0$, node k is globally reachable in the δ-digraph associated to $\bar{L}(t, T)$, then the equilibrium set of consensus states θ is uniformly exponentially stable. In particular, all components of any solution $\theta(t)$ of (3) converge to a common value as $t \to \infty$. □

As shown in (Moreau, 2004), a similar result holds true for the linear system

$$\dot{\theta}(t) = -K(t) D_{p(t)} \theta(t) + K(t) A_{p(t)} \theta(t - \tau)$$

and for any time delay $\tau \geq 0$. We are now ready to prove the main results of the paper.

3. PROBLEM SOLUTION

This section offers a solution to the coordinated path-following problem posed before. We start by summarizing a key result on PF.

3.1 *Path-Following*

A solution to the path-following problem (defined in Section 2) was given in (Aguiar and Hespanha, 2004; Aguiar and Hespanha, 2006) where the control laws require that $\dot{\gamma}_i$ and $\ddot{\gamma}_i$ be known. Set $\dot{\gamma}_i(t) = v_{r_i}(t) = v_L + \tilde{v}_{r_i}$. Notice that only the time derivative of v_L can be computed accurately. However, it can be shown that in the control laws of (Aguiar and Hespanha, 2004; Aguiar and Hespanha, 2006), if the terms $\dot{\gamma}_i$ and $\ddot{\gamma}_i$ are replaced with v_L and $\dot{v}_L$, respectively, the resulting path-following closed-loop system becomes input-to-state stable (ISS) with input $\tilde{v}_{r_i}$ and state x_{p_i}. This leads to the following result that we state without proof.

Theorem 2. There is a control law for u_i as a function of x_{p_i}, v_L, and $\dot{v}_L$ that renders the closed-loop PF system i ISS with Lyapunov function W_i satisfying

$$\dot{W}_i \leq -\lambda_1 W_i + \mu_1 |\tilde{v}_{r_i}|^2 + d_1^2, \tag{4}$$

$$\underline{\alpha}_1 \|x_{p_i}\|^2 \leq W_i \leq \bar{\alpha}_1 \|x_{p_i}\|^2 \tag{5}$$

where $\lambda_1 > 0$, $\mu_1 > 0$, $\underline{\alpha}_1 > 0$, and $d_1 \geq 0$.

3.2 *Coordination*

Consider now the coordination control (CC) problem with a switching communication topology parameterized by p, as defined in Section 2, and with a communication delay of $\tau \geq 0$ from any transmitter to any receiver.

Recall that coordination states γ_i are governed by $\dot{\gamma}_i = v_{r_i}$. We let the decentralized feedback law for the reference speeds v_{r_i} be a function of the information obtained with time delay τ from the neighboring vehicles as follows:

$$v_{r_i} = v_L - k_i \sum_{j \in N_{i,p(t)}} \gamma_i(t) - \gamma_j(t - \tau) \tag{6}$$

where v_L is the assigned speed to the fleet of vehicles and $k_i > 0$. Notice that with this choice of control law, the term $\tilde{v}_{r_i}$ in v_{r_i} for which the time derivative is not available is

$$\tilde{v}_{r_i} = -k_i \sum_{j \in N_{i,p(t)}} \gamma_i(t) - \gamma_j(t - \tau). \tag{7}$$

Theorem 3. [*No delays*] Under the conditions of Theorem 1 and communications with no delays ($\tau = 0$), control law (6) solves the coordination problem, that is, $|\dot{\gamma}_i - v_L|$ and $|\gamma_i - \gamma_j|, \forall i, j$ tend to zero. Moreover, $\tilde{\mathbf{v}}_r = [\tilde{v}_{r_i}]_{n \times 1}$ vanishes as $t \to \infty$.

Proof: When there are no communication delays, the coordination system is described by

$$\dot{\gamma} = v_L \mathbf{1} - K L_{p(t)} \gamma,$$

where $\mathbf{1} = [1, ..., 1]^T$ and $K = \text{diag}[k_i]$. Consider the change of variables $\theta_i = \gamma_i - v_L t$. Then,

$$\dot{\theta}(t) = -K L_{p(t)} \theta(t).$$

Using Theorem 1, $|\theta_i - \theta_j|$ and therefore $|\gamma_i - \gamma_j|$ converge to zero exponentially. Thus, $L_p \gamma$ vanishes and consequently $\dot{\gamma}_i - v_L$ and $\tilde{v}_{ri}$ tend to zero as t goes unbounded. □

Theorem 4. [*Finite delays*] For any delay $\tau \geq 0$, Theorem 3 holds true provided that each vehicle receives information from at least one of the other vehicles at all time, that is, $|N_{i,p(t)}| \neq 0, \forall t, i$.

Proof: In this case the coordination dynamics can be written as

$$\dot{\gamma}(t) = v_L \mathbf{1} - K(t) D_{p(t)} \gamma(t) + K(t) A_{p(t)} \gamma(t - \tau). \tag{8}$$

Define $\theta_i = \gamma_i - v_L^* t$ with $v_L^* = \frac{v_L}{1+k\tau}$ and $k_i(t) = \frac{k}{|N_{i,p(t)}|}$ for some $k > 0$, that is, $K(t) = k D_p^{-1}$. With this coordinate transformation, the coordination dynamics take the simple form

$$\dot{\theta} = -k\theta + k D_p^{-1} A_p \theta(t - \tau).$$

The rest of the argument is similar to that in Theorem 3. □

Notice that in the presence of communication delays the variables $\dot{\gamma}_i$ tend to v_L^* and not to the correct assigned speed v_L. Moreover, the error $v_L - v_L^*$ is amplified for large delays.

The main result of the paper is stated next.

Theorem 5. [*PF-CC combination*] Consider the system that is obtained by putting together the path-following and the coordination subsystems studied before. With the control law defined for the two subsystems, the complete system is ISS with input d_1 and states $x_p = [x_{p_i}]$ and γ.

Proof: Close examination of (4), (7), and (8) shows that the path-following and coordination control subsystems form an interconnected cascade system. Since the cascade interconnection of two ISS system is ISS, the result follows. □

Remark 6. We can lift the constraint $|N_{i,p}| \neq \emptyset$ from Theorem 4 and drive the variables $\dot{\gamma}_i$ to v_L by using

$$v_{r_i} = \begin{cases} \bar{v}_L - \dfrac{k}{|N_{i,p}|} \displaystyle\sum_{j \in N_{i,p}} \gamma_i(t) - \gamma_j(t - \tau), & N_{i,p} \neq \emptyset \\ v_L, & N_{i,p} = \emptyset \end{cases}$$

instead of (6), where $\bar{v}_L = (1 + k\tau) v_L$. However, in this case we need to know the delay τ to compute $\bar{v}_L$.

4. AN ILLUSTRATIVE EXAMPLE

Consider the CPF control of three underactuated AUVs. Vehicle 2 is allowed to communicate with vehicles 1 and 3, but the latter two do not communicate between themselves directly. To simulate losses in the communications, we considered the situation where both links fail 75% of the time, with the failures occurring periodically with a period of 10[sec]. Moreover, the information transmission delay is 5[sec]. Notice that during failures all the links become deactivated. Therefore, from Theorem 4 the control law (6) cannot be applied. To overcome this problem we used the control proposed in Remark 6 with $k = 0.1[\text{sec}^{-1}]$. The AUVs are required to follow paths of the form

$$\mathbf{p}_{d_i}(\gamma_i) = [c_1 \cos(\frac{2\pi}{T}\gamma_i + \phi_d), c_1 \sin(\frac{2\pi}{T}\gamma_i + \phi_d), c_2\gamma_i + z_{0_i}],$$

with $c_1 = 20\,\text{m}$, $c_2 = 0.05\,\text{m}$, $T = 400$, $\phi_d = -\frac{3\pi}{4}$, and $z_{0_1} = -10\,\text{m}, z_{0_2} = -5\,\text{m}, z_{0_3} = 0\,\text{m}$. The initial conditions are $\mathbf{p}_1 = (5\,\text{m}, -10\,\text{m}, -5\,\text{m})$, $\mathbf{p}_2 = (5\,\text{m}, -15\,\text{m}, 0\,\text{m})$, $\mathbf{p}_3 = (5\,\text{m}, -20\,\text{m}, 5\,\text{m})$, $R_1 = R_2 = R_3 = I$, and $v_1 = v_2 = v_3 = \omega_1 = \omega_2 = \omega_3 = \mathbf{0}$. The reference speed v_L was set to $v_L = 0.5[\text{sec}^{-1}]$.

The vehicles are also required to keep a formation pattern that consists of having them aligned along a common vertical line. Figure 1 shows the trajectories of the AUVs. Figure 2 illustrates the evolution of the coordination and path-following errors while the communication links fail periodically. Clearly, the vehicles adjust their speeds to meet the formation requirements and the coordination errors $\gamma_{12} := \gamma_1 - \gamma_2$ and $\gamma_{13} := \gamma_1 - \gamma_3$ converge to zero.

5. CONCLUSIONS

The paper addressed the problem of steering a group of underactuated AUVs along given spatial paths, while holding a desired inter-vehicle formation pattern (coordinated path-following) in the presence of *communication failures and delays*. The solution proposed builds on Lyapunov based techniques and addresses explicitly the constraints imposed by the topology of the inter-vehicle communications network. Furthermore, it leads to a decentralized control law whereby the exchange of data among the vehicles is kept at a minimum. Simulations illustrated the efficacy of the solution proposed. Further work is required to extend the methodology proposed to address more general problems in the presence of communication failures and delays; for example, state-dependent time delays which occur naturally due to the spreading in the relative positions of the AUVs and because of the reduced speed of propagation of acoustic waves in water.

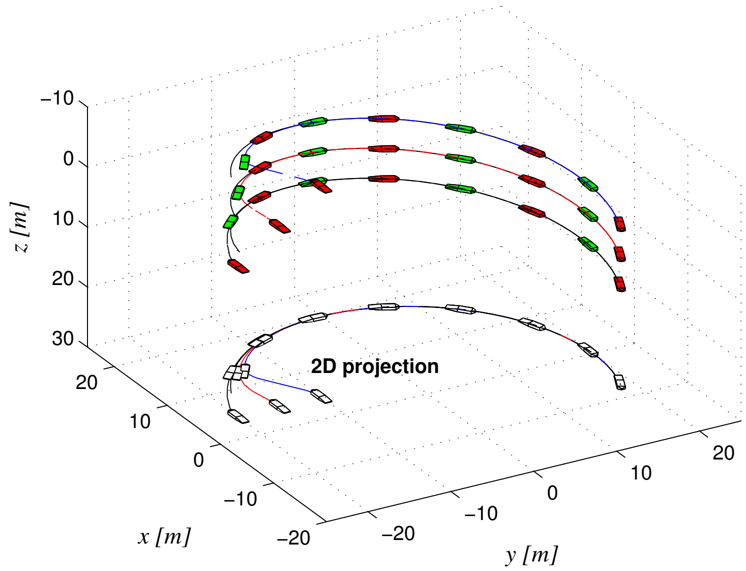

Fig. 1. Coordination of 3 AUVs, with communication failures and delay

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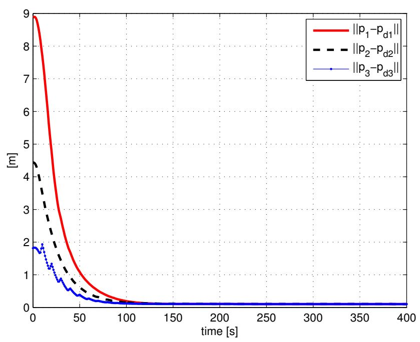
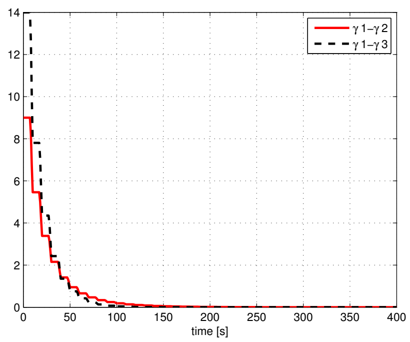


(a) Path-following errors



(b) Vehicle coordination errors

Fig. 2. 75% of temporal communication failures; time delay 5[sec]

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