

Formation Control in the scope of the MORPH project. Part II: Implementation and Results^{*}

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Abstract: Based on a companion publication that introduces the theoretical foundations, this paper describes the implemented architecture for formation control of the upper segment vehicles of the MORPH project. We highlight the necessary modifications and additional elements, mainly in terms of control and estimation, to allow for the implementation in real vehicles. We illustrate the performance of the system with results from sea trials in Lisbon and in the Azores, with a number of heterogeneous vehicles from multiple partners involved in the project.

Keywords: Cooperative control under severe communication constraints; Single and multi-vehicle applications; Unmanned Underwater Vehicle (UUV) applications

1. INTRODUCTION

As described in a companion publication (Part I of this paper, see Abreu and Pascoal (2015)), the MORPH project brings together a consortium of multiple partners from the industry and academia, in an attempt to overcome difficulties with navigation and control in challenging underwater scenarios, in the context of seabed mapping or surveying; see Kalwa et al. (2012). The project proposes the use of a formation of robotic vehicles with complementary capabilities, linked by acoustic communication channels. The main idea is to avoid using fully-equipped vehicles, so that each vehicle remains small and inexpensive, while resorting to cooperation to enable effective operation in challenging environments. The formation is divided into two groups of vehicles. The *upper segment* includes the Surface Support Vehicle (SSV), used for global navigation of the formation through GPS; the Global Communications Vehicle (GCV) which should remain within acoustic range of all vehicles and is responsible for relaying information and maintaining the accuracy of inter-vehicle navigation; and the Local Sonar Vehicle (LSV) that carries a multibeam echosounder for mapping the terrain. The *lower segment* is composed of C1V and C2V, two vehicles carrying cameras and operating close to the terrain to be surveyed. See Figure 1 for an illustration of the MORPH concept. In terms of formation control, several requirements are imposed. The upper segment vehicles should keep a formation using relative-position measurements, provided by an Ultra-Short Baseline (USBL) system. However, only one USBL transceiver is available, so only one vehicle can measure its position relative to the others. Furthermore, specific geometries of the environment may block the communication link be-

tween the SSV and the LSV. As such, the formation *should not rely on the SSV-LSV link*, highlighting the importance of the GCV to relay information. As for the lower segment, no USBL is available. Thus, the vehicles should use range-only measurements to keep the formation.

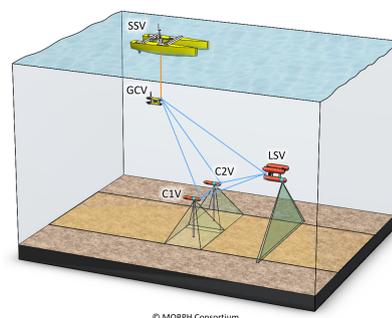


Fig. 1. MORPH formation in a flat seabed scenario.

Given this setup, in Abreu and Pascoal (2015) the problem was analysed from a theoretical standpoint. Individual controllers and path-generators were proposed for both upper and lower segment follower vehicles. An information flow applicable to the entire MORPH system was also proposed, considering the available sensors and constraints. In this paper, we show how the strategies proposed for the *upper segment* were translated into implementation on real vehicles and present the results of actual tests at sea. To this effect, we availed ourselves of a number of modules developed by the other project partners, the description of which will appear elsewhere. We single out the networked wi-fi and acoustic communications network developed by Centre for Maritime Research and Experimentation (CMRE) and the mission handler in charge of mission execution developed by Ilmenau University of Technology (IUT). The main subjects addressed in the

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present paper are: 1) the necessary modifications to the tracking controller proposed in Part I, and 2) the estimation architecture introduced to handle discrete-time, delayed measurements and communications, affected by noise and temporary losses. Space limitations preclude us from giving the details of the implementation of the lower MORPH segment described in Abreu and Pascoal (2015). For this reason, in the present paper we restrict ourselves to the upper segment.

The paper is organized as follows. Section 2 introduces an outer-loop tracking controller, which produces commands in surge speed u and heading angle ψ (instead of yaw rate r). In Section 3 we address the filtering and estimation architecture, including the system model used for each filter. Section 4 illustrates the performance of the complete system. Finally, in Section 5 we highlight the main contributions and achievements, and point towards directions of future work.

2. CONTROL

The tracking controller proposed in Part I, Abreu and Pascoal (2015), produced commands in surge speed u and yaw rate r . Most of the vehicles involved in the MORPH project already included inner-loops that accepted commands in surge speed u and heading angle ψ instead. As a consequence, the tracking controller was modified for implementation in the vehicles. In this section, we first describe the new controller and then briefly analyse its stability properties, using a simplified kinematic vehicle model. The inner-loop tracking errors (i.e. differences between the commanded and actual values of surge speed and heading) and the sideslip are considered negligible. This control architecture runs in the vehicles at 5 [Hz].

Using the notation introduced in Abreu and Pascoal (2015), the kinematic model assumed for the vehicle is

$$\begin{aligned}\dot{\mathbf{p}} &= R(\psi) \begin{bmatrix} u \\ v \end{bmatrix} + \mathbf{v}_c, \\ \dot{\psi} &= r,\end{aligned}$$

where

$$R(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{bmatrix}. \quad (1)$$

Assuming that we want the vehicle to track a virtual target at position \mathbf{p}_d , moving with velocity vector $\dot{\mathbf{p}}_d$, the error variable to be driven to zero is the position error

$$\mathbf{e} = R^T(\psi)(\mathbf{p} - \mathbf{p}_d), \quad (2)$$

in the body-fixed frame, with dynamics given by (4) in Part I, Abreu and Pascoal (2015). Given the low-speed missions performed in the MORPH project and the characteristics of the vehicles involved, it is reasonable to assume that the sway is negligible with respect to the total velocity, $v \approx 0$. Additionally, we also assume that the differences between the commanded and actual values of surge speed and heading angle are small enough, such that

$$R(\psi) \begin{bmatrix} u \\ 0 \end{bmatrix} \approx R(\psi_d) \begin{bmatrix} u_d \\ 0 \end{bmatrix}. \quad (3)$$

These rather strong assumptions have some implications in practice. Namely, 1) outer-loop gains have to be carefully chosen so as not to produce fast-varying references that the inner loops cannot track, and 2) small differences between

the true and the commanded heading and surge speed still exist which deteriorate the performance slightly.

Considering these simplifying assumptions, the dynamics of the error can be rewritten as

$$\dot{\mathbf{e}} = R^T(\psi) \left(R(\psi_d) \begin{bmatrix} u_d \\ 0 \end{bmatrix} + \mathbf{v}_c - \dot{\mathbf{p}}_d \right) - S(r)\mathbf{e}. \quad (4)$$

We can now define a desired velocity vector with respect to the water \mathbf{v}_d , including a feedforward term to compensate for target velocity and current, and a saturated feedback term on the position error, that is,

$$\mathbf{v}_d = R(\psi_d) \begin{bmatrix} u_d \\ 0 \end{bmatrix} = \underbrace{-\mathbf{v}_c + \dot{\mathbf{p}}_d}_{\text{feedforward}} - \underbrace{R(\psi)K \tanh \mathbf{e}}_{\text{saturated feedback}}, \quad (5)$$

where the vectorial tanh function is defined as

$$\tanh \mathbf{e} = \mathbf{e} \frac{\tanh \|\mathbf{e}\|}{\|\mathbf{e}\|}. \quad (6)$$

The commanded surge speed and heading angle are then defined as the magnitude and angle of the desired velocity vector:

$$u_d = \|\mathbf{v}_d\|, \quad (7)$$

$$\psi_d = \angle \mathbf{v}_d. \quad (8)$$

This yields the closed-loop dynamics

$$\dot{\mathbf{e}} = -K \tanh \mathbf{e} - S(r)\mathbf{e}, \quad (9)$$

where we used the fact that the rotation matrix is orthogonal, so $R^T(\psi)R(\psi) = I$. Finally, we compute the time-derivative of a radially unbounded Lyapunov function $V = \frac{1}{2}\mathbf{e}^T\mathbf{e}$ to obtain

$$\dot{V} = \mathbf{e}^T\dot{\mathbf{e}} = -\mathbf{e}^TK\mathbf{e} \frac{\tanh \|\mathbf{e}\|}{\|\mathbf{e}\|} < 0 \quad \forall \mathbf{e} \neq 0 \quad (10)$$

if $K = K^T > 0$, thus showing that the system is asymptotically stable. Note that this controller has some additional limitations compared to the tracking controller for u and r presented in Abreu and Pascoal (2015). Namely, the function $\angle \mathbf{x}$ is singular for $\mathbf{x} = 0$, so the desired speed with respect to the water \mathbf{v}_d should not approach zero. The assumptions that the sway v and inner-loop error are negligible compared to the true speed with respect to the water also hold only if \mathbf{v}_d does not approach zero.

As a final note, we recall from Abreu and Pascoal (2015) that the control system also includes a path-generator, which receives information about the position and velocity of the leader vehicle and appropriately generates a virtual target for the follower to track. The path-generator implemented in the vehicles is the one described in the above reference, without any modifications.

3. FILTERING AND ESTIMATION

The fact that measurements and messages transmitted over the inter-vehicle acoustic communication network are received by the vehicles at discrete-time instants, at low data rates, and are affected by noise and delays mandates the implementation of a filtering and estimation architecture. Figure 2 shows the information flow for the upper segment proposed in Abreu and Pascoal (2015). In this section, we start from this information flow and describe the implemented estimators.

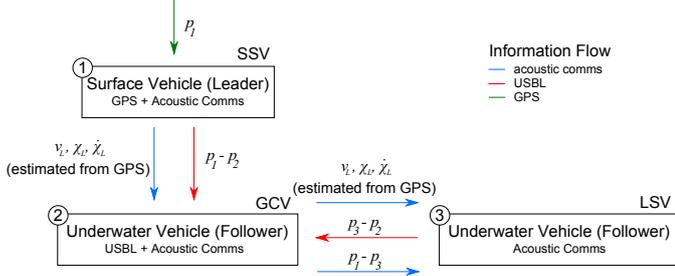


Fig. 2. Information flow on upper segment vehicles.

3.1 Leader: estimation of own path parameters

We start with the problem of estimating the path parameters of the leader vehicle: v_L (total velocity with respect to an earth-fixed frame), χ_L (course angle) and $\dot{\chi}_L$ (course angle rate). These parameters must be estimated from GPS position data on the leader vehicle itself, to be later broadcast to the followers. Given the assumption stated in Abreu and Pascoal (2015) that the leader vehicle maintains a constant velocity magnitude and its path contains only straight lines and arcs, we assume the continuous-time system model with no inputs

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 \\ \dot{\chi}_L \\ 0 \\ R(\chi_L) \begin{bmatrix} v_L \\ 0 \end{bmatrix} \end{bmatrix}, \quad \mathbf{y}(t) = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{x}(t), \quad (11)$$

where

$$\mathbf{x} := \begin{bmatrix} v_L \\ \chi_L \\ \dot{\chi}_L \\ x \\ y \end{bmatrix}, \quad \mathbf{y} := \begin{bmatrix} x \\ y \end{bmatrix}. \quad (12)$$

Note that due to the rotation matrix R and cross terms between states, the model is nonlinear. The estimator implemented in the leader vehicle is an Extended Kalman Filter (EKF), based on a finite-difference discretization of the continuous-time model. This estimator runs at 5 [Hz], the same rate at which GPS measurements are obtained (using Ashtech MB100 receivers). Figure 3 illustrates the inputs and outputs of this estimator.

Finally, note that this estimator should only be used when the mission of the leader vehicle is not defined a-priori. If it is, then the nominal path parameters should be broadcast, instead of those estimated from GPS data. In the results presented in this paper, the missions for the leader vehicle were defined a-priori and as such this estimator was not used.

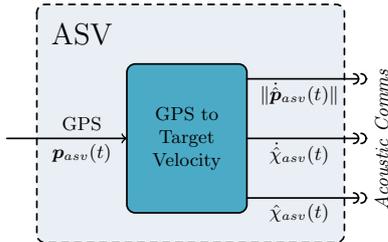


Fig. 3. Estimation of path parameters in the surface vehicle.

3.2 Follower: estimation of leader path parameters

Each follower receives the leader parameters v_L , χ_L and $\dot{\chi}_L$, but only once per communication cycle. The period of this communication cycle is 5 seconds, which is clearly too large for control purposes. As such, an estimator should be run on each follower to estimate these parameters in between communications. This estimator simply updates the information by integrating in an open-loop-like manner (prediction phase), and then corrects the estimates when it receives broadcast parameters. The continuous-time model used is

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 0 \\ \dot{\chi}_L \\ 0 \end{bmatrix}, \quad \mathbf{y}(t) = \mathbf{x}(t - \Delta), \quad (13)$$

where

$$\mathbf{x} := \begin{bmatrix} v_L \\ \chi_L \\ \dot{\chi}_L \end{bmatrix}. \quad (14)$$

Notice that due to issues inherent to the communication architecture, the received parameters are delayed by a constant time Δ . A Kalman Filter (KF) based on a discretized version of this model is used, dealing explicitly with this known measurement delay. This estimator runs in each of the follower vehicles at 5 [Hz] and receives measurements at 0.2 [Hz].

Moreover, note that the GCV receives the leader path parameters directly from the leader vehicle. The LSV, on the other hand, gets this data relayed via the GCV.

3.3 Follower: estimation of position and ocean current

Each follower vehicle needs an estimator for its relative position to the leader vehicle and the velocity of ocean current. This estimator makes use of relative-position measurements acquired by USBL and the velocity vector of the leader vehicle.

The ocean current velocity is assumed to be constant, $\dot{\mathbf{v}}_c = 0$. The continuous-time design model used is

$$\dot{\mathbf{x}} = \begin{bmatrix} R(\psi) \begin{bmatrix} u \\ 0 \end{bmatrix} + \mathbf{v}_c - \dot{\mathbf{p}}_L \\ \mathbf{0} \end{bmatrix}, \quad (15)$$

where

$$\mathbf{x} := \begin{bmatrix} \mathbf{p}_r \\ \mathbf{v}_c \end{bmatrix}, \quad (16)$$

and the position relative to the leader is denoted by $\mathbf{p}_r = \mathbf{p} - \mathbf{p}_L$. The velocity of the vehicle with respect to the water, $R(\psi) [u \ 0]^T$, is assumed to be known, but u is in fact obtained directly from the thrusters' RPMs, without considering any dynamics. This leads to reasonable performance but imposes limitations, highlighted later in this paper. An estimate of the velocity vector of the leader $\dot{\mathbf{p}}_L$ can be computed from the estimates of path parameters v_L and χ_L , provided by the estimator introduced in Section 3.2. Both $R(\psi) [u \ 0]^T$ and $\dot{\mathbf{p}}_L$ are seen as inputs to the model (15), which can be rewritten as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t), \quad (17)$$

where

$$A := \begin{bmatrix} \mathbf{0} & I_2 \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, B := \begin{bmatrix} I_2 & -I_2 \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \mathbf{u} := \begin{bmatrix} R(\psi) \begin{bmatrix} u \\ 0 \end{bmatrix} \\ \dot{\mathbf{p}}_L \end{bmatrix}. \quad (18)$$

As for the measurement model, the followers have delayed relative-position measurements with respect to the leader (SSV):

$$\mathbf{y}_1(t) = C_1 \mathbf{x}(t - \Delta), \quad (19)$$

where

$$C_1 := [I_2 \ \mathbf{0}]. \quad (20)$$

In GCV, these measurements are obtained directly from the USBL, so only the delay inherent to the USBL system is considered. The GCV also gets relative position measurements with respect to LSV; it can then compute the relative position SSV-LSV, and broadcast it to the LSV. This information relaying introduces an additional delay on the measurements received by the LSV. Consequently, both the GCV and LSV can run estimators for position and ocean current with the same structure, but the delay Δ is larger for the LSV.

The system introduced in (17)-(19) is observable. However, in case measurements from a Doppler Velocity Log (DVL) system which measures $\dot{\mathbf{p}}$ are available, we can include in the model an extra measurement, $\mathbf{y}_2(t) := \dot{\mathbf{p}} - R(\psi) [u \ 0]^T$, as

$$\mathbf{y}_2(t) = C_2 \mathbf{x}(t), \quad (21)$$

where

$$C_2 := [\mathbf{0} \ I_2]. \quad (22)$$

This estimator runs in the follower vehicles at 5 [Hz]. The measurements \mathbf{y}_1 are obtained at 0.2 [Hz] and the measurements \mathbf{y}_2 , if available, are obtained at 5 [Hz].

The final architecture implemented in the upper segment follower vehicles using ROS (Robot Operating System) is illustrated in Figure 4.

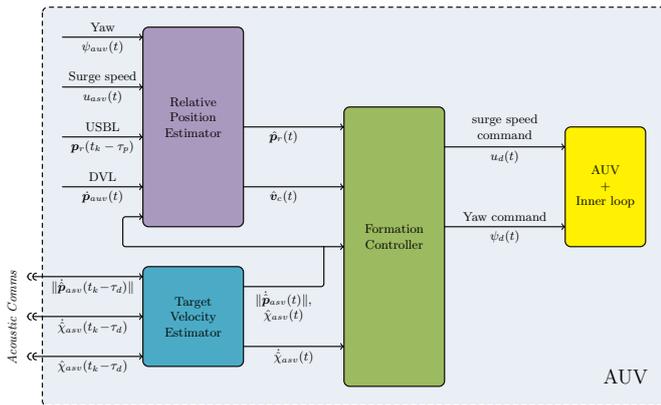


Fig. 4. Full estimation and control architecture in the underwater vehicles (followers) of the upper segment.

4. RESULTS

We now illustrate the performance of the implemented system with results from trials at sea obtained in two different locations. Firstly, we show the results of trials of the MORPH project in the Azores, where the vehicles are subject to external disturbances such as waves and

wind. Secondly, results from more recent trials are shown, conducted at a test site in Lisbon where the vehicles are much less exposed to external disturbances. These results illustrate how some issues were addressed and improvements were made to the systems used in the Azores trials.

4.1 MORPH Trials in the Azores

These results concern a mission executed during the September 2014 MORPH trials in the Azores. The trials involved multiple MORPH partners: Institute of Marine Research (IMAR), Atlas Elektronik GmbH, Centre for Maritime Research and Experimentation (CMRE), University of Girona (UdG), Ilmenau University of Technology (IUT), Instituto Superior Técnico (IST), and Jacobs University. Most of the tests in the water were carried out at Baía de Porto Pim, on the island of Faial, Azores.

The particular mission for which the results are shown here consists of several loops offset by 2 [m]. Five vehicles were involved: three MEDUSAs played the role of upper segment vehicles, while SeaCat and SPARUS played the roles of lower segment vehicles C1V and C2V. The MEDUSA-class vehicles are submersible, composed of two acrylic tubes attached to a central aluminium frame, and weigh around 30 [Kg]. They were developed at the Laboratory of Robotics and Systems in Engineering and Science (LARSyS)/ISR of the Instituto Superior Técnico - see Ribeiro (2011) for details. The SeaCat and SPARUS are heavier, torpedo-shaped vehicles developed by Atlas Elektronik and the University of Girona, respectively.

The upper segment formation parameters were defined as $\delta_x = 5$ [m] for the LSV and $\delta_x = 17$ [m] for the GCV (5 and 17 [m] behind the leader, respectively). The lower segment formation control used in these trials is the one described in Rego et al. (2014) and Soares et al. (2014), and the two lower segment vehicles were configured to move 5 [m] to the right and 5 [m] to the left of the midpoint between the LSV and the GCV.

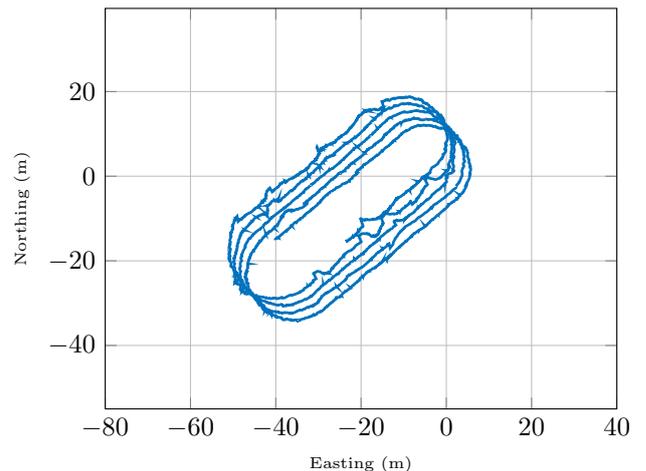


Fig. 5. SSV (leader) trajectory.

Trajectories: Figure 5 shows the trajectory of the leader vehicle (SSV) for the entire mission. The performance of SSV in following the prescribed path is affected by the somewhat inaccurate GPS data and considerable external disturbances (waves and wind) in the Azores test site.

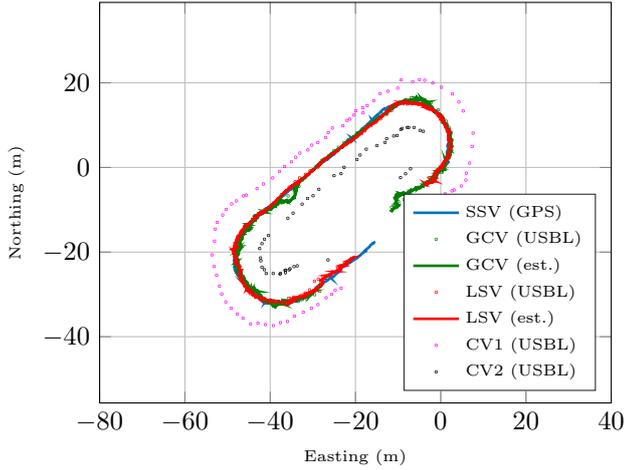


Fig. 6. Trajectories of all vehicles in one loop

Figure 6 shows the trajectory of all the vehicles of the MORPH formation. A single loop is shown for readability purposes. Although this paper describes formation control only for upper segment vehicles, the trajectories of the lower segment vehicles are also included, to illustrate that the control errors in the upper segment do not influence considerably the performance of the lower segment. The upper segment followers GCV and LSV exhibit discontinuities in the path when entering turns, although this is much more visible for the GCV. This was due to a known issue with the path-generator at the time of these trials, where the followers assumed that they were in the same segment as the leader at all times. This assumption has been lifted in the meantime, and results from other trials will show that the issue has been addressed. Other than this, the trajectories of both followers seem reasonable and do not show considerable deviations from the expected path.

Tracking error: Figure 7 shows the tracking error (difference between the actual position and the position of the virtual target that should be tracked) for the two upper segment followers in their body-fixed frames, along the selected loop illustrated in Figure 6. Peaks are visible around $t = 100$ [s], $t = 225$ [s] and $t = 350$ [s] due to the issue with the path-generator described previously. Except for these peaks and initial transients, the error is generally below 1 [m]. It does not converge to zero due to the imperfect navigation - namely, the main performance limitation seems to be the use of thrusters' RPMs measurements to obtain the surge speed without considering any dynamics.

4.2 Recent trials in Lisbon

We now show the results of more recent trials in Lisbon, illustrating that the issue with discontinuities in the generated path, when entering or exiting turns, has been addressed and solved. The mission shown here involves two MEDUSA vehicles - one leader and one follower. The tests were carried out in January 2015 at Marina dos Olivais, Lisbon. No considerable currents or other external perturbations were present.

The formation parameters were set to $\delta_x = 5$ [m], $\delta_y = 5$ [m], i.e. the follower should move 5 [m] behind and 5 [m] to the right of the leader vehicle. Also, in this trial the system was adapted to allow both the leader and follower to move

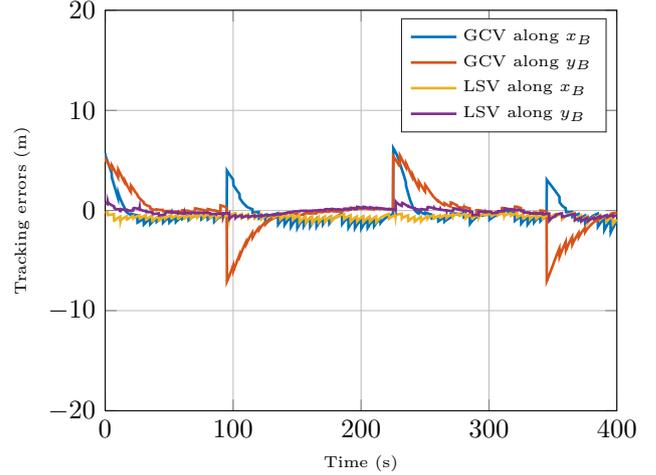


Fig. 7. Tracking error for upper segment vehicles.

underwater, while global navigation was provided by a third vehicle at the surface, not involved in the formation.

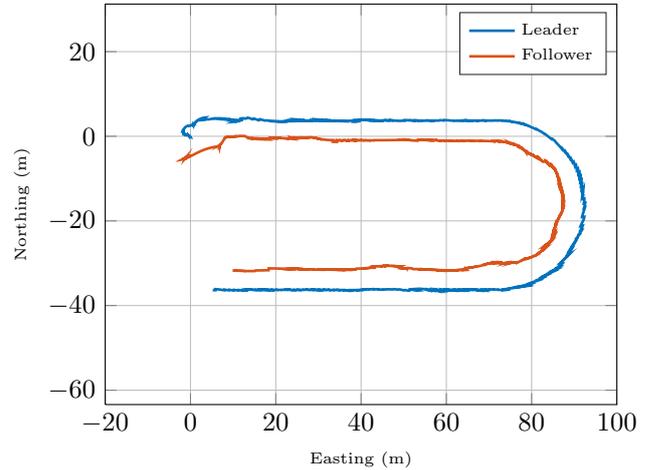


Fig. 8. Trajectories.

Trajectories: Figure 8 shows the trajectories of the leader and follower, both moving underwater. The trajectories started in the upper left-hand corner of the plot. Qualitatively, the formation seems to be maintained reasonably well. Note that no discontinuities are now visible in the path of the follower when the leader enters or exits a turn, as happened in the Azores trials.

Tracking error: Figure 9 shows the tracking error of the follower vehicle (difference between its estimated position, as obtained from the navigation filter, and the position of the virtual target that should be tracked). The peaks observed in the Azores mission are no longer visible, again showing that the issue with the path-generator was solved. Except for the initial transient and some points where the navigation data was not accurate (possibly because the USBL system failed to obtain a position), the tracking error usually remains below 0.5 [m]. Again, the direct use of thrusters' RPMs to obtain a speed measurement without considering any dynamics seems to be main factor limiting the performance of the system.

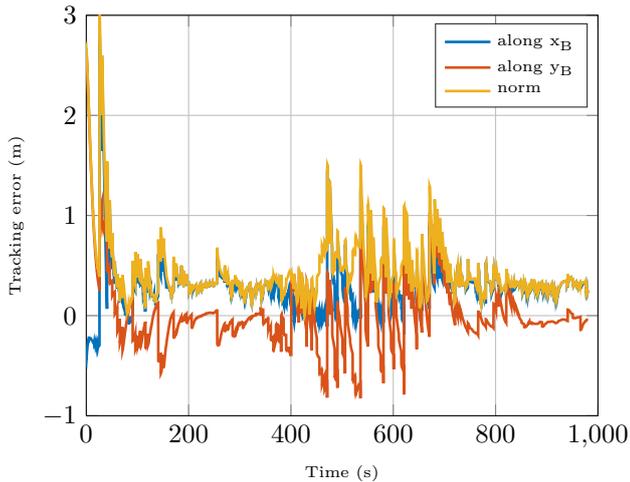


Fig. 9. Tracking error.

5. CONCLUSION

In this paper and the companion paper Abreu and Pascoal (2015), we presented solutions for formation control in the scope of the MORPH project. In Part I, we developed strategies for formation keeping using relative-position or range-only measurements, considering the limitations and requirements of the project. The problem was analysed from a theoretical standpoint. Control strategies were presented, along with stability conditions obtained using tools from nonlinear systems theory. We also proposed an information flow strategy, ensuring that all vehicles have access to the necessary signals to maintain a formation. The results of simulations showed promise for practical implementation. In this paper (Part II), we discussed the adaptation of the strategies for *upper segment formation control* to allow implementation in the vehicles involved in MORPH. In terms of control, some modifications were necessary to ensure compatibility with inner-loops of all the vehicles. Then, filtering and estimation blocks were introduced to handle noisy, discrete-time, possibly delayed measurements. Finally, the performance of the complete system was illustrated with results from sea trials, in different test sites. In the Azores trials of the MORPH project, in September 2014, the complete 5-vehicle formation was involved. Generally, the results were promising, and the position errors of the upper segment vehicles remained below 1 [m]. Although not shown here, these strategies have been tested successfully in different vehicles, namely SeaCat and G500 (from University of Girona).

The results also helped identify the major limitations of the system. The most limiting issue seems to be the use of direct RPM measurements from the thrusters as a measurement of surge speed u , without considering any vehicle acceleration/deceleration dynamics. Work is currently ongoing at IST to identify a simple dynamic model that can be incorporated in the filter, in order to produce better estimates of u . Note that this is particularly challenging for underwater vehicles because these dynamics are reasonably fast, and no high-rate position measurements are available. Another subject currently being addressed is testing of the strategies for *lower segment formation control* proposed in Part I.

Finally, note that the system has already been adapted to allow the leader vehicle to move underwater, with global navigation provided by a surface vehicle. Future work on formation control in the scope of the MORPH project will focus on lifting the assumption that the vehicles move on a constant horizontal plane, allowing for formation-keeping in a truly 3D environment. The next phase of the MORPH project will address the development and at sea testing of the systems for cooperative formation control in close vicinity of a vertical wall by using sonar data.

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This work, done in the scope of the EC MORPH project, focused on the implementation and at sea testing of the systems in charge of relative navigation and formation control of a group of heterogeneous vehicles. To this effect, we availed ourselves of the tools and modules for system implementation, mission programming, and mission control developed by other partners in the project. We are extremely grateful to all the MORPH partners for the tremendous effort that led to the successful implementation of a MORPH architecture for multiple vehicle cooperation. We are especially indebted to CMRE for the development of the networked wi-fi and acoustic communications network and to IUT for the mission handler in charge of mission execution, as well as fruitful discussions on relative navigation. Our sincere thanks go to our colleagues from ATLAS, UGirona, CNR, and IFREMER for their commitment to participate in distributed hardware-in-the-loop simulations and with their vehicles in a series of tests that were instrumental to fine-tune all components of the MORPH architecture. We thank also our colleagues at IMAR/DOP/UAzores for the fruitful exchange of ideas at the crossroads of science and technology and the superb logistics that they put together for the tests in the Azores. A word of appreciation goes to the project coordinator Joerg Kalwa for his support and encouragement.

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