Multi-Robot Collaboration with Range-Limited Communication: Experiments with Two Underactuated ASVs

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Abstract — We present a collaborative team of two under-actuated autonomous surface vessels (ASVs) that performs a cooperative navigation task while satisfying a communication constraint. Our approach is based on the use of a hierarchical control structure where a supervisory module commands each vessel to perform prioritized elementary tasks, a behavior-based controller generates motion directives to achieve the assigned tasks, and a maneuvering controller generates the actuator commands to follow the motion directives. The control technique has been tested in a mission where a set of target locations spread across a planar environment has to be visited once by either of the two ASVs while maintaining a relative separation less than a given maximum distance (to guarantee inter-ASV wireless communication). Experiments were carried out in the field with a team of two ASVs visiting 22 locations on a lake surface (approximately $30000m^2$) with static obstacles. Results show a 30% improvement in mission time over the single-robot case.

1 Introduction

A significant body of literature deals with the motion control of aquatic vehicles for autonomous navigation [11]. Interest in the field is motivated by different applications, e.g., naval system applications, harbor operations, defense and patrolling of coastal perimeters, and marine biology applications. Motion control of Autonomous Surface Vessels (ASVs) has been studied in the context of dynamic positioning for fully actuated [15] and under-actuated

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vessels [18], as well as trajectory tracking [14, 1]. Separately, collaboration in multi-robot teams [10] has been widely studied. In the intersection of these two areas - motion control of a fleet of ASVs - different approaches have been proposed, however most of them have only been validated by numerical simulations [8], or by experiments with a single real vessel and simulating the others [13]. Here, we focus on the cooperative control for ASVs and present the results of experiments with a team of two underactuated ASVs in the field performing a joint mission motivated by environmental monitoring.

We provide a list of target locations to the vessels. They must dynamically allocate locations among themselves such that each location is visited exactly once, and all obstacles are avoided. The approach proposed here is applicable to a scenario with dynamic obstacles and targets since it does not pre-plan a route. In the course of the mission the ASVs are required to maintain connectivity at all times. Unlike [16] where connectivity is maintained by measuring signal strength and the mobility controller is a spring-damper system, we use a layered hierarchical control decomposition which accommodates a dynamic environment (targets and obstacles may be added dynamically). When needed, a leader-follower configuration allows the team to allocate a target to the vessel closest to the next target, while the other vessel ensures the communication constraint is maintained. Our results from five field trials at a lake with a two-ASV team (communication constraint of 60m, in an exploration area of 300m x 100m) show a 30% improvement in exploration time compared to a single vessel.

We focus on navigation techniques for a realistic environment where several obstacles can be found. Thus, we make use of a behavior-based technique as a guidance control to take advantage of its reactivity to unpredicted conditions [9, 6]. In particular, we present the use of a behavior-based technique called the Null-Space based Behavioral (NSB) control as a guidance system for ASVs. The NSB approach has been extensively tested for the control of autonomous ground robots and results have shown robust control for formation and spread control for a team of robots [4], escorting an external agent with a team of robots [2], and the formation control of a fleet of ASVs [7].

2 Problem Description

We require a set of pre-specified locations to be visited by one (and only one) of the ASVs exactly once. During the execution of the mission, both ASVs must ensure that their relative distance does not exceed a preset bound. Needless to say, the vessels must avoid mutual collisions and collisions with obstacles in the environment. We decompose the overall mission into elementary tasks that can be then prioritized and implemented individually; in particular: 1. Avoid obstacles and inter-robot collisions, 2. Satisfy the communication constraint, and 3. Navigate to assigned target locations.

While we discuss the details in the next section, broadly speaking each ASV properly activates and combines these three modes. When the distance between the vessels is consistently lower than the communication bound, they are free to choose targets and navigate to them independently. When the distance is close to the communication range, a supervisory module on each ASV has to ensure the communication constraint is satisfied. This is done using a leader-follower policy where one of the vessels (the leader) continues with its mission, while the other (the follower) has to enforce the separation constraint adapting its motion to the leader. The navigation task moves each (single) vessel toward its assigned location. Since the vessels must avoid all collisions, the obstacle avoidance controller takes evasion action when obstacles or other vessels are within a safety margin.

The targets to be visited are dynamically chosen by the vessels on the basis of their locations. A communication sub-system ensures that a shared target and obstacle map are maintained both of which can be updated dynamically from shore, allowing dynamic missions.

3 Control Strategy

In order to achieve the proposed mission in a cooperative way, the control architecture has been organized into a three-level hierarchy, as shown in Figure 1: Supervisor, NSB, and Maneuvering control.

At the highest level, a supervisor is in charge of selecting the active tasks for the vessel and their reference values, i.e., it activates the obstacle avoidance behavior when the vessel is close to the other vessel or to a static obstacle, it defines the next target to be visited and it activates a leader-follower policy to avoid breaking the communication link. In order to make its decisions, the supervisor makes use of some information about the vessel position (read from the vessel's GPS), the map of the environment, the set of visited and un-visited locations, and information received from the other vessel's supervisor. An intermediate level implements a behavior-based technique, namely the Null-Space based Behavioral (NSB) control, to simultaneously achieve multiple tasks with different priority; the NSB, on the basis of the active tasks and their relative priority, defines motion directive for the vessel (e.g., the desired velocity and motion direction). Finally, the lowest-level controller is a maneuvering control that, taking into consideration the under-actuated actuation system of the vessel, defines the reference commands for the actuators in order to follow the motion directives received by the NSB.

3.1 The Supervisor

The supervisor module on each vessel has the knowledge of the overall mission. In particular, it knows the target map and, in order to avoid revisiting the same targets during the course of the mission, it keeps track of targets visited by the vessel itself or by the other one. When a location is reached and a new target has to be chosen, the supervisor finds the target nearest to the current vessel position among the non-visited targets different from the one

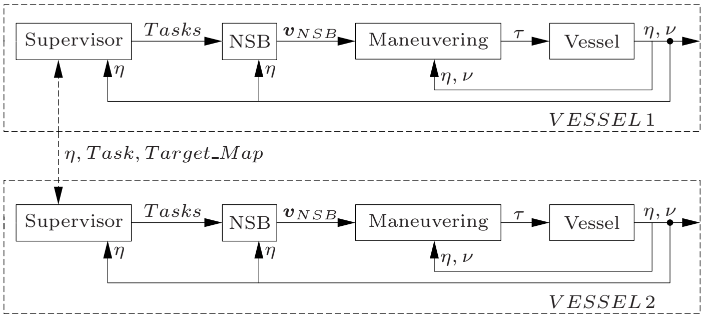

Fig. 1 Sketch of control architecture for a the team of two under-actuated vessels.

currently assigned to the other vessel. Once all the targets have been visited, the vessels are asked to reach and keep a final restoring configuration.

During the vessels' motion, the two supervisory modules are in charge of keeping the communication constraint. To fulfil this constraint, when needed, they activate a leader-follower policy to cause one vessel to take care of the communication constraint while the other continues its mission. The choice of which vessel is the leader and which the follower is negotiated between the supervisors on the basis of the distances between the vessels and their next targets. In particular, the vessel that is the closest to its next target becomes the leader while the other becomes the follower. The leader continues its mission ignoring the other vessel, while the follower has to control its distance from the leader while also trying to stay close to its target. The follower is also allowed to switch to a new target if this is closer than that previously assigned to it. If the communication link breaks or the distance between the vessels exceeds a maximum threshold, the leader stops to wait for the follower moving toward it. Moreover, the supervisory module decides when to activate the obstacle/collision avoidance. Finally, the supervisory module defines the priority order of the active tasks.

3.2 The Null-Space based Behavioral Control

The Null-Space based Behavioral (NSB) control is a behavior-based approach aimed at controlling the motion of autonomous vehicles in dynamic scenarios. In particular, the NSB, whose details can be found in [3, 2], uses a hierarchy-based structure to simultaneously achieve multiple tasks using a projection technique to delete the components of the lower priority tasks that would conflict with the highest ones. Here, the NSB is used as a guidance system for an ASV that, on the base of the active tasks and of their priority order, has to define the motion directives for the vessel.

Following the line of behavior-based approaches, the mission of the vessel is decomposed into elementary tasks. For each task a suitable task function is defined as $\boldsymbol{\sigma} = \boldsymbol{f}(\boldsymbol{p})$, where $\boldsymbol{\sigma} \in \mathbb{R}^m$ is the task variable to be controlled, m is the task function dimension, and $\boldsymbol{p} \in \mathbb{R}^n$ is the vessel position.

For each task, the velocity reference for the vessel is specified, starting from desired values $\boldsymbol{\sigma}_d(t)$ of the task function, solving the inverse kinematic problem at a differential level. Thus, the velocity reference of the generic i^{th}-task is calculated as $\boldsymbol{v}_i = \boldsymbol{J}_i^{\dagger} \left(\dot{\boldsymbol{\sigma}}_{i,d} + \boldsymbol{\Lambda}_i \widetilde{\boldsymbol{\sigma}}_i \right)$, where $\boldsymbol{J}_i^{\dagger}$ is the pseudo-inverse of the task function Jacobian, $\boldsymbol{\Lambda}_i$ is a constant positive-definite matrix of gains and $\widetilde{\boldsymbol{\sigma}}_i$ is the task error defined as $\widetilde{\boldsymbol{\sigma}}_i = \boldsymbol{\sigma}_{i,d} - \boldsymbol{\sigma}_i$.

When the mission is composed of multiple tasks, the overall vessel velocity is obtained by properly merging the outputs of the individual tasks. A velocity vector for each task is computed as if it were acting alone; then, before adding the single contribution to the overall vehicle velocity, a lower-priority task is projected onto the null space of the immediately higher-priority task so as to remove those velocity components that would conflict with it. If the subscript i also denotes the priority of the task with, e.g., Task 1 being the highest-priority one, the overall vessel velocity is given by:

$$\boldsymbol{v}_{NSB} = \boldsymbol{v}_1 + \left(\boldsymbol{I} - \boldsymbol{J}_1^{\dagger} \boldsymbol{J}_1 \right) \left[\boldsymbol{v}_2 + \left(\boldsymbol{I} - \boldsymbol{J}_2^{\dagger} \boldsymbol{J}_2 \right) \boldsymbol{v}_3 \right], \tag{1}$$

where $\left(\boldsymbol{I} - \boldsymbol{J}_i^{\dagger} \boldsymbol{J}_i \right)$ represents the null-space projector of the i^{th}-task, i.e., it filters the velocity components that would conflict with the i^{th}-task.

To achieve the mission described in Sec. 2, three tasks have to be defined:

a) *Obstacle-avoidance*: This behavior, when active, is always the highest priority task because its goal is to preserve the integrity of the vessel. In the presence of an obstacle/vessel in the advancing direction, its aim is to keep the vessel at a safe distance from it. Thus, its implementation produces as output a velocity, in the vessel-obstacle direction, that keeps the vessel at a safe distance from the obstacle. Formally, the task function is $\sigma_o = \|\boldsymbol{p} - \boldsymbol{p}_o\| \in \mathbb{R}$ where $\boldsymbol{p}_o$ is the obstacle position, and $\boldsymbol{J}_o = \hat{\boldsymbol{r}}^{\mathrm{T}} \in \mathbb{R}^{1 \times 2}$ is the task Jacobian where $\hat{\boldsymbol{r}} = \frac{\boldsymbol{p} - \boldsymbol{p}_o}{\|\boldsymbol{p} - \boldsymbol{p}_o\|}$ is the unit vector aligned with the obstacle-to-vehicle direction. Defining as $\sigma_{o,d} = d$ desired distance, the task output is

$$\boldsymbol{v}_o = \boldsymbol{J}_o^{\dagger} \lambda_1 (d - \|\boldsymbol{p} - \boldsymbol{p}_o\|). \tag{2}$$

Possible motions in this task null-space are all the motions that do not change the distance from the obstacle. Thus, the null-space projector projects the velocity commands of the lower-priority tasks along the tangential direction of a circle centered in the obstacle and passing through the vessel itself.

b) *Move-to-target*: Defining the task function as $\boldsymbol{\sigma}_t = \boldsymbol{p} \in \mathbb{R}^2$, whose Jacobian is $\boldsymbol{J}_t = \boldsymbol{I} \in \mathbb{R}^{2 \times 2}$ and assigning the desired value as $\boldsymbol{\sigma}_{t,d} = \boldsymbol{p}_t$, then, the output of the task is a velocity, in the target direction, proportional to the distance from the target $\boldsymbol{p}_t$:

$$\boldsymbol{v}_t = \boldsymbol{\Lambda}_t \left(\boldsymbol{p}_t - \boldsymbol{p} \right) \tag{3}$$

c)*Keep the communication constraint*: To fulfill the communication constraint, a leader follower approach can be applied. The follow-the-leader task is aimed at keeping the follower (whose position is $\boldsymbol{p}_f$) at a distance d from the leader position $\boldsymbol{p}_l$. The task function mathematical definition is analogous to the obstacle avoidance task, while its output is a velocity, in the leader-to-follower direction, proportional to the difference among desired and measured distance; moreover, the desired velocity of the leader is added as a feedforward term:

$$\boldsymbol{v}_f = \boldsymbol{\Lambda}_f \left(\|\boldsymbol{p}_l - \boldsymbol{p}_f\| - d \right) \frac{\boldsymbol{p}_l - \boldsymbol{p}_f}{\|\boldsymbol{p}_l - \boldsymbol{p}_f\|} + \boldsymbol{v}_l. \tag{4}$$

3.3 Maneuvering Control

The maneuvering controller is an onboard controller aimed at steering the vessel along a desired path and moving it with a desired velocity [11, 12]. Receiving motion reference commands from the NSB, the maneuvering controller has to generate the generalized forces applied by the actuators.

Fig. 2 a) The ASV motion reference model; b) Two vessels during the experiment.

Basing on the model for ASV in [11] and considering the underactuated propulsion system of the vessel (see Figure 2.a), a maneuvering controller is designed following the approach proposed in [17]. From this approach, the maneuvering control can be expressed as the sum of a heading autopilot and a surge control aimed at causing the vessel to follow the velocity reference commands. The heading autopilot is aimed at controlling the heading of the vessel to make it move in the desired direction χ_{NSB}. In particular, it regulates the propulsion torque and the rudder angle to correct the orientation of the vessel. The surge control has to make the norm velocity of the vessel to track the value generated by the NSB; however, the vessel has to move at full speed only when the orientation error is null. Thus, the surge control works as a PI controller regulating the advancing direction multiplied by a scaling factor depending on the orientation error. Following the control architecture of Figure 1, the output of the NSB, that is a velocity vector generated for a material point, can be geometrically represented through its norm U_{NSB} and its direction χ_{NSB} that are given to the maneuvering control as desired surge and heading/advancing direction.

4 Experimental Results

In this section the experimental results of the mission execution with the proposed control architecture are illustrated. The platform used for this experiment consists of two Autonomous Surface Vehicles (ASVs) designed by the University of Southern California's Robotic Embedded Systems Lab. Each ASV is an OceanScience QBoat-I hull with a length of 2.13 m and a width of 0.71 m at the widest section. Each ASV is equipped with an onboard computer, a wireless bridge, and a navigation package consisting of a GPS unit, a three-axis accelerometer, a compass, and a rate-gyro; the vessels weighs approximately 50 kg with instrumentation and batteries. The software for each vessel was written in C++ running under the linux operating system. Multiple processes manage mission planning, navigation, control and the communication between the vessels.

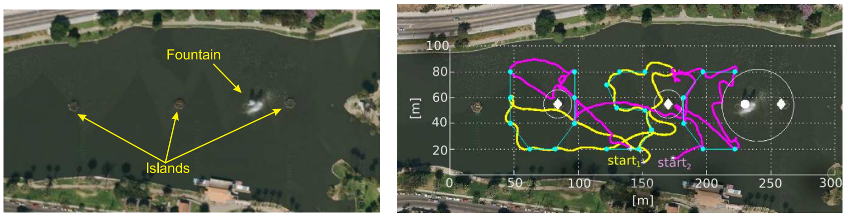

Fig. 3 a) Experiment site at Echo Park Lake, Los Angeles; b) Path followed by the vessels during the first experiment, overlaid on the environmental map.

The mission for the team of two ASVs was to visit a set of 22 target locations spread in the Echo Park lake in Los Angeles (see Figure 3). Additionally, a communication constraint of a maximum distance of 60 m was to be maintained, and collisions between the vessels and with external static obstacles (small islands present in the lake) were to be avoided.

The GPS coordinates of the locations to be visited were provided to the ASVs at the beginning of the experiment. The two vessels had to autonomously navigate, communicate and cooperate to visit all the locations while avoiding multiple visits to any location and preserving the communication constraint. Figures 3.b and 4 show the paths followed by the two vessels at the experimental site in the course of three different trials. In particular, Figure 3.b shows the obstacles' positions and the safety areas of the obstacle avoidance functions (activated only when inside these areas) overlaid on the environmental map. In this trial is clear that all the locations were visited while none of them was visited multiple times.

Figure 5.a shows the relative distance between the vessels during the experimental trial of Fig. 3.b. The leader-formation task was activated by the supervisory modules when the relative distance between the vessels was

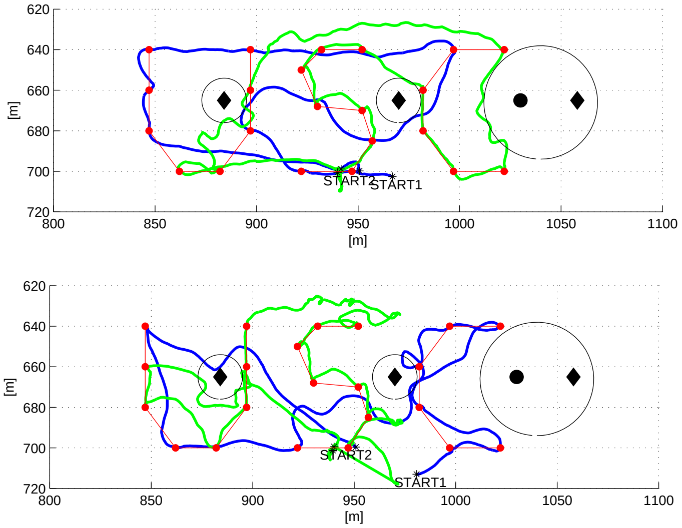

Fig. 4 Vessel paths for the second and third trials.

greater than 50 m. While the relative separation was below this value, the vessels moved independently. Since the leader-follower task is one-dimensional, the null-space projection of the task allows the system to attempt achieving lower-priority tasks, thus, the follower can use internal movements of the leader-follower task (i.e., movements that don't change the relative distance between the vessels) to try to achieve lower priority tasks (e.g., move toward the target). When the distance between the vessels exceeds 60 m, the leader stops to wait for the follower moving toward it. This situation arises when the follower encounters an obstacle along its path which activates the obstacle avoidance task with highest priority, thus causing the follower to lag.
A video of the experimental data (GPS and compass readings of the vessels) is available at `http://webuser.unicas.it/arrichiello/video/collabASV.mpg`. The video shows the dynamic behavior of the vessels while reaching the locations, avoiding collisions and obstacles. Moreover, it shows the activation of the leader-follower policy (represented by a change of color of the vessels) when out form the communication range.

Figure 5.b shows the desired and measured norm of velocity of one of the vessels during the first 400 s of the mission. It is worth noticing that the requested velocity is saturated to 1 m/s,moreover the assigned velocity decreases close to 0 when reaching the assigned location. The more irregular behavior after the first 300 s is due both to the leader-follower task and to the obstacle avoidance task.

We have performed several mission trials. The duration of each trial was between 13 and 14 minutes, during which time all targets were visited, no

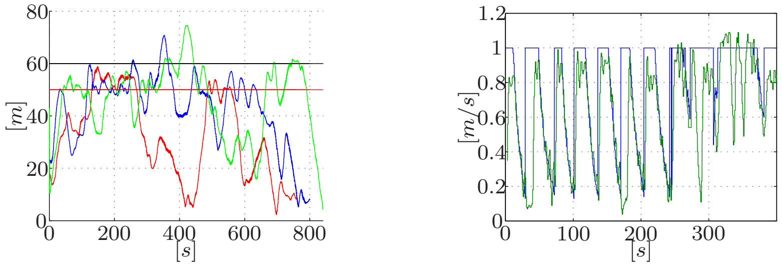

Fig. 5 a) Plot of the relative distance between the vessels during three field trials. The leader-follower strategy is activated when the distance is greater than 50 m. The leader has to stop and wait for the follower when the distance greater than 60 m; b) Plot of one of the vessels' desired and measured velocity during the first 400 s of an experiment.

target was visited more than once, and the communication constraint was respected. The same mission has been also executed with a single vessel to provide a speedup benchmark. The mission with the single vessel (with the same target locations as in the two vessel case) takes approximately 20 minutes, thus the use of two vessel shows a 30% improvement in mission time over the single vessel case. While the present system works well, we believe that in the case of static targets, better results can be achieved by advance planning the target assignments in order to optimize the execution time. Our focus in the immediate future is to work with dynamic settings in which obstacles can be added or detected during the mission execution, and targets may appear or disappear during run-time. In principle, the control strategy proposed here will be effective in such settings.

5 Conclusion

In this paper, we presented a collaborative exploration technique for a team of two under-actuated ASVs designed for marine biology and oceanography experiments. The control approach, based on a behavior-based technique coupled with a maneuvering controller, was experimentally tested in a lake in Los Angeles. The mission consisted of multiple targets that had to be visited while maintaining the communication link between the vessels, i.e., ensuring that the relative distance never exceeded a threshold. The robots successfully navigated to all the targets while avoiding collisions and obstacles, validating the presented control approach. In the future, we plan to use the presented techniques for large scale biological sampling experiments in marinas and lakes with obstacles with two or more ASVs. To extend the proposed technique to a larger team of ASVs we will start from the technique proposed in [5] to deal with Mobile Ad-hoc NETworks (MANETs) and ensure the global connectivity of the team while executing the assigned mission. We also plan to investigate the team's

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