Design of a framework for cooperative marine robots

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***Abstract*—Cooperation of robots is a mean of taking advantage of several distributed platforms. The present paper presents a solution for cooperation of marine robots. We tackle the control problems at different levels. First, local robust controllers must be designed to ensure stability of each robot. These must include elemental maneuvers that, when combined, can provide versatile trajectories. Then, cooperation algorithms must be build upon in order to achieve coherent motion of the team. The centralized, yet extensible, approach followed in this paper has already provided satisfactory results.**

I. Introduction

Cooperative robotic systems research began in the late 1980s [1], [2] mainly motivated by the interest in features such as redundancy, reliability, versatility and issues regarding the involved costs and the rapidity of execution. Over the past years, along with the expansion of wireless communication networks, the research on cooperation and coordination in robotics has enthusiastically grown.

Robotics covers a large set of applications and has consequently originated different types of solutions for different environments. While cooperation and coordination for land, surface and aerial robots have reached a common point where the implicit information exchange is often omitted, thanks to relatively high bandwidths, long range, low latency and low delay communications, for (spatial and) underwater robots, coordination and cooperation are the subjects of intensive research [3], [4].

The following sections give a brief overview of the related works and of the common approaches while introducing the main ideas of the implemented solutions for cooperation of heterogeneous marine robots.

II. Local control

Robots are guided through control laws that permit tracking reference signals whose values represent desired angular or linear positions, velocities or accelerations. The correct operation of the controllers is, at least, as important as a good localization for navigation. Important and very interesting works have been developed in the domain of robot control using a diversity of methods to achieve desired behaviors in a large variety of robotics platforms. Robotic systems are commonly nonlinear. Therefore, high performances control of robots requires nonlinear control techniques, otherwise leading to poorer, or even unstable, behaviors.

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Nonlinear control methods (see [5]) include linearization, gain-scheduled, sliding mode control and backstepping (without being extensive). Linearization techniques take advantage of the vast results on linear control theory and are well suited for systems that operate at a static point of operation. Gain-scheduled control is a natural extension of the linearization technique by linearizing the systems in several points of operation and by interpolating the control laws. Sliding mode control and backstepping methods commonly result on nonlinear feedback control laws that typically employ a model of the dynamics. In the present work, the control laws for both underwater and surface robots were derived based on the latter (see [6], for example).

Dynamics and kinematics control constitute the basic layer of our approach. It is important to keep the interaction with this layer simple and well defined while guaranteeing that the resulting behaviors can be versatile enough. Therefore, each robot can execute a set of common maneuvers specially designed for the corresponding platform. The idea of defining a set of common maneuvers simplifies the interaction and the commands given by a cooperation algorithm, for example, and can be seen as a set of tasks that the robots are able to perform.

Any path can be approximated by simple lines and circles [4]. We have identified four types of elemental motions for the robots: Line-following, circle-following, waypoint and station-keeping. The first two guarantee that each robot can follow any complex path while the last two allow versatile behaviors frequently desired in marine robots. Additionally, the robot can be operated in an ”open-loop” manner through a fifth (free) maneuver by setting the position or velocity references of the available degrees of freedom (DOFs). This also applies to maneuvers whose number of controllable DOFs is greater than the required to carry out the respective maneuver. Such an approach allows for composed motions of vehicles. For example, the depth reference can be set to a given, possibly time-varying, reference independently of the horizontal motion, which particularly appreciated under some scenarios such as bottom exploration.

III. COOPERATIVE CONTROL

According to [7], the cooperation is related with the capability of taking decisions to *redistribute resources amongst themselves (robots) in a way that enables them to accomplish their mission efficiently and reliably*. Nowadays, thousands of different robots have been developed. Coordination is a mean of taking advantage of the features of all, possibly heterogeneous, robots composing a team. Moreover, their combination makes it possible to achieve more flexibility, robustness and fault tolerance in redundant systems.

In our work, the cooperation problems are closely related with coordinated motion of the team. The literature is vast in coordination of robots, including potential fields, formation keeping, swarm behavior and optimization-based methods. We are particularly interested in the formation keeping problem which typically has two types of approaches - path following [4], [8] and trajectory tracking [9], [10]. In the path following approach, the paths are commonly known in advance by the team mates (at least piecewise). The coordination of the robots thus becomes a one-dimensional problem possibly solved by a consensus algorithm, for instance, in which an along-track variable is synchronized to achieve coordination.

Trajectory tracking differs from path following essentially in the aspect that the path is not required to be known *a priori*. Consequently, the coordination becomes a problem in which the virtual references must be synchronized in a way that the combined motion of the team robots is coherent. Virtual references can not be generated independently of the current status of the formation and of the tasks, otherwise an open-loop behavior would be obtained. The Fig. 1 illustrates the architecture of our current approach.

Coordinated trajectory tracking is a promising approach in the present work. Establishing a comparison with path following, our arguments are the following: No pre-established paths need to be known nor shared by/among the team mates; more dynamic coordinated behaviors can be obtained by varying directly the references of each robots in a consistent way; as a consequence of the latter, obstacle avoidance, for example, can be more naturally formalized in the context of trajectory tracking, and; the inclusion of maneuvers, such as station keeping, is more natural in the trajectory tracking approach than in the path following one. It should be noted that the developed framework is not constrained to trajectory tracking solutions, though.

The control scheme in [9] is used to achieve coordination of several vehicles. The approach seems to be promising since it allows for dynamic trajectory tracking and for more general positioning. Basically, the method uses formation constraint functions in order to keep a well established formation topology. Additionally, a virtual leader, whose relevant state variables are known by all the elements composing the team, is used to drive the formation along the trajectory. The main advantage of the method is that it allows for abstracting from the concerns about actual reference tracking of each robot that were already tackled in section II. As far as each robot is able to track its position reference with a bounded error and it is capable of transmitting its position to the virtual, possibly local, leader, the formation is kept and coordination is achieved. We have extended and generalized mathematically the method presented in [9] in order to include more flexible behaviors and to explore the topology of the resulting network.

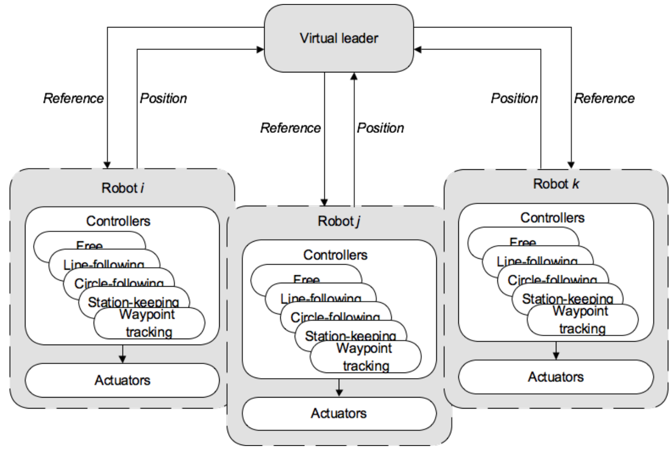

Fig. 1. An example of the developed framework with three robots

In the near future, the coordination framework will be used in real scenarios for cooperative localization and positioning. The simulations and the experiments carried out so far are very satisfactory: We have shown that autonomous surface vehicles (ASVs) are able to track their references with errors of some tens of centimeters even in the presence of the natural disturbances such as wind and currents.

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