Ocean Engineering 157 (2018) 152–163

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A distributed passivity approach to AUV teams control in cooperating potential games☆

Filippo Fabiani [a,*], Davide Fenucci [a,b,c], Andrea Caiti [a,b,c]

[a] Department of Information Engineering, University of Pisa, Largo L. Lazzarino, 1, 56122, Pisa, Italy
[b] Research Center "E. Piaggio", University of Pisa, Largo L. Lazzarino, 1, 56122, Pisa, Italy
[c] Interuniversity Center for Integrated Systems for Marine Environment (ISME), Genova, Italy

ARTICLE INFO

Keywords:
Autonomous vehicles
Cooperation
Distributed control
Passivity
Port-Hamiltonian
Potential games

ABSTRACT

The paper proposes a general framework to manage a team of Autonomous Underwater Vehicles (AUVs), while keeping the communication constraints, during missions execution. Virtual spring-damper couplings (passive by definition) define the distributed interaction forces between neighbouring vehicles. In this way, through passivity theory, a suitable Lyapunov function for the closed loop system is built to ensure stable convergence of the network vehicles to an equilibrium point, also providing robustness in presence of communication fading and delays, very common in the marine environment. Simulations of typical missions show the effectiveness of the proposed approach. An equivalence between this typical port-Hamiltonian framework and a specific class of potential games, the Bilateral Symmetric Interaction (BSI) one, is also established. Hence, modelling the network with passive elements, it is possible to shape the transient behaviour of the players and the reached equilibria at the end of the game.

1. Introduction

A renewal of interest has been focused recently on the analysis and control of networked systems, and particularly on distributed systems of mobile agents. Such systems provide significant benefits in efficiency, scalability, and robustness when compared to classical centralized solutions. Applications of mobile agent networks are multi-disciplinary and highly diversified. In particular, recent advances in marine robotics have made AUVs more reliable and affordable allowing the execution of tasks that are dangerous, expensive and time consuming when performed by humans. There are a lot of practical applications that can benefit from the use of a team of AUVs: these include the defence field, patrolling, surveillance of an asset or of a predefined geographical area, coverage tasks, exploration, oceanographic surveying and mapping (Curtin et al., 1993). All these application scenarios involve communication among multiple agents. In the underwater domain, due to the well known limitations of the acoustic channel (Caiti et al., 2009, 2013a; Stojanovic, 2007), it is of paramount importance to maintain desired communication performances in order to achieve the mission objectives.

Basing on recent preliminary works developed by the authors (Fabiani et al., 2016a, 2016b), this paper presents a general framework for coordinating a team of agents, applied to a group of AUVs. The *passivity* theory is exploited for guaranteeing the stable and robust convergence of the network to an equilibrium configuration, even in presence of communication delays. The term "stability" here is used to indicate that, for any initial condition which ensures the fulfilment of the communication constraints, such constraints are satisfied for the whole transient, and the proposed algorithm leads the vehicles to assume a stable, in classic Lyapunov sense, configuration. Moreover, the degrees of freedom offered by such an approach allow to tune the desired motion of the group in terms of transient behaviour and reached equilibria. In particular, it is possible to determine in advance which task has higher priority than the others without any consequence about stability. Furthermore, the behaviour of the group is made more flexible, with arbitrary split and join events, using an "energy tank" able to store and supply energy whenever required (Secchi et al., 2006): exploiting this further passive element the network topology may change depending on the emerging needs of the mission.

Downstream to what just said, an equally relevant motivation behind this work arises from the possibility to capture an ambitious and innovative point of contact between two different ways to model and control a network of agents: the one proposed here and BSI, a *potential game* that

☆ This work was partially funded by European Union, programme H2020, Project WiMUST, grant n. 645141, and by DLTM, Ligurian Cluster on Marine Technology, Project RIMA.
* Corresponding author.
E-mail address: filippo.fabiani@ing.unipi.it (F. Fabiani).

https://doi.org/10.1016/j.oceaneng.2018.02.065
Received 13 December 2016; Received in revised form 23 February 2018; Accepted 24 February 2018

exhibits symmetries across the variables. In fact, a BSI game is characterized by the notion of *pairwise* or *bilateral* strategic interaction, in which the utility function for each player depends only on its own action and that of another connected with him, whatever the behaviour of the rest of the network. If that happens for all players, the observations are said to be symmetric for each combination of connected agents. Hence, modelling the network with passive elements, which are purely design parameters, it may be possible to shape the transient behaviour of the players and, ideally, the reached equilibrium at the end of the game.

The proposed approach is based on the positive influences of several pioneering works, such as the one in (Leonard and Fiorelli, 2001), refined and extended in (Ogren et al., 2004) and (Zhang and Leonard, 2010). Here the artificial potentials and virtual leaders allowed to manage a group of multiple autonomous vehicles, also manipulating the team geometry and its direction of motion. Motivated by biological inspiration, such works focused also on gradient climbing missions in which the mobile sensor network sought out local maxima or minima in the environmental field; moreover, a convergent cooperative Kalman filter for exploration missions provided the estimates to drive the centre of the formation to move along level curves of the environmental field. In (Olfati-Saber and Murray, 2002), natural potential functions were obtained from structural constraints of a desired formation: in this way, the synthesized controller for each vehicle was able to steer and move agents exploiting only local informations, also avoiding collisions. With the same concepts in mind, the author of (Olfati-Saber, 2006) proposed a theoretical framework for the design and analysis of several distributed flocking algorithms, in presence or lack of obstacles. Another pioneering work that exploited artificial potentials to solve the constrained coverage Problem is in (Poduri and Sukhatme, 2004). In particular, the deployment of the mobile sensor network was addressed: each node was treated as a virtual charged particle, in order to synthesize an algorithm able to maximize the covered area and minimize the number of nodes of the network itself. Recently, in (Williams and Sukhatme, 2013a, 2013b), a mobility control that switch between a set of smooth, constraint-enforcing potential fields, satisfying local and non-local constraints composition was proposed. That potential-based control also drove the agents to maximize connectivity and maintain established links; the constraint satisfaction was achieved using a switched model of interaction which regulated link addition through repulsive potentials between constraint violators.

In the recent years, the authors proposed cooperative control algorithms based on the behavioural approach paradigm (Caiti et al., 2012) and its adaptation as potential BSI game (Caiti et al., 2013b), to maintain desired communication performance and fulfil each agent task. The main drawback of such algorithms were the absence of stability guarantees along the whole motion of the agents: as a matter of fact, they were able to provide only the local stability of equilibria points. In this context, the port-Hamiltonian framework allows to model the sensors network in a suitable, passive fashion, e.g. in (Fiaz et al., 2013; Vos et al., 2014, 2015). Passivity techniques have been widely studied in the domain of bilateral teleoperations for the control of a traditional single-master/single-slave system (Hokayem and Spong, 2006; Secchi et al., 2008), or for a more complex single-master/multiple-slaves system (Franchi et al., 2012). In spite of take advantage of the operator's intelligence for solving complex tasks as in bilateral teleoperations, the proposed framework seeks to provide full autonomy to the agents in order to accomplish the cooperative mission.

The paper is organized as follows: Section 2 presents the essentials mathematical and theoretical tools implied in the framework, i.e. graph theory, port-Hamiltonian systems and game theory; Section 3 outlines the implementation details of the cooperative algorithm and demonstrates the stability of the proposed solution including delays on communication links. After that, Section 4 provides several consideration about the relationship between the proposed approach and BSI games. Section 5 exploits the energy tanks approach proposed in (Franchi et al., 2012) to enlarge the set of possible stable manoeuvres within the network, while Section 6 illustrates and discusses the effectiveness of the proposed framework in several application scenarios. Finally, Section 7 summarizes the work and draws the main conclusions.

Notation. $\mathbb{R}$, $\mathbb{R}_{>0}$ and $\mathbb{R}_{\geq 0}$ respectively denote the set of real, positive real, non-negative real numbers. Vectors and matrices are denoted by bold characters, while scalars and sets by italics. Unless otherwise specified, 0 and $\mathbf{I}$ denotes the zero and identity matrices of suitable dimensions (context-dependent). $\mathbf{A}^\top$ denotes the transpose of $\mathbf{A}$; $\mathbb{S}^n$ denotes the set of symmetric $n \times n$ matrices; for a given $\mathbf{Q} \in \mathbb{R}^{n\times n}$, the notations $\mathbf{Q} \succ 0$ ($\mathbf{Q} \succcurlyeq 0$) and $\mathbf{Q} \in \mathbb{S}^n_{\succ 0}$ ($\mathbf{Q} \in \mathbb{S}^n_{\succcurlyeq 0}$) denote that $\mathbf{Q}$ is symmetric and has positive (non-negative) eigenvalues. $|\cdot|$ denotes the cardinality of a set, $||\cdot||$ the Euclidean norm, $\otimes$ and $\times$ the Kronecker and Cartesian product, respectively.

2. Background and preliminaries

This section provides the essentials from the main analytical and theoretical tools required for the upcoming mathematical treatment. In particular, some reminders on graph theory, passivity, port-Hamiltonian systems and game theory will be very useful for a proper understanding. We remark here that we are using the jargon of different, though converging, research fields. Therefore, in the rest of the paper we may refer to the AUVs with the terms agents, vehicles or players, indistinctly.

2.1. Graph theory

A graph $\mathscr{G} := (V, E)$ is formally defined by a finite set of *nodes* (or *vertices*) V and a set of *edges* $E \subset V \times V$, connecting pairs of nodes. The node set $V := \{v_1, v_2, \dots, v_l\}$ has $l = |V|$ elements, while the edge set $E := \{e_1, e_2, \dots, e_m\}$ contains $m = |E|$ elements. Given $e_j \in E$, then there exist a pair $v_i, v_j \in V$ such that $e_j := (v_i, v_j)$; in this way, v_i and v_j are said to be *adjacent*, while (v_i, v_i) is called a self-loop. If the edges in graphs are to be interpreted as enabling information to flow between the vertices on the corresponding edge, these flows can be directed as well as undirected. Hence, *direct* and *indirect* graph can be distinguished. In the first case, edges have a fixed direction (i.e. the *tail* and the *head* of the edge are setted), while in the second case, if (v_i, v_j) belongs to E, then (v_j, v_i) belongs to E too. However, for indirect graph, one can arbitrarily assign an orientation to each edge. Any key feature of a graph can be described by means of matrices. In particular, the *incidence matrix* $B(\mathscr{G})$ is a $l \times m$ matrix defined as follows:

$$[B(\mathscr{G})]_{ij} := b_{ij} = \begin{cases} -1 & \text{if } v_i \text{ is the tail of } e_j, \\ 1 & \text{if } v_i \text{ is the head of } e_j, \\ 0 & \text{otherwise.} \end{cases}$$

The l rows of $B(\mathscr{G})$ correspond to the nodes of $\mathscr{G}$, while the m columns denotes the edges of such graph. For further details on the graph theory, refer to (Mesbahi and Egerstedt, 2010).

2.2. Port-Hamiltonian systems and passivity

The port-Hamiltonian framework, introduced in (Maschke and Van der Schaft, 1993), allows to model complex (non-linear) systems as energy storing and energy dissipating components, connected via ports to power conserving transmissions and conversions. It is an energy-based framework in which each element interacts with the system via a port, that consists of a couple of dual effort and flow quantities, whose product gives the power flow in and out of the component. As well described in (Van der Schaft, 2006), let $\mathbf{x} \in \mathbb{R}^n$ denotes the local coordinates for an n-dimensional state space manifold $\mathscr{X}$, $\mathbf{u} \in \mathbb{R}^m$ the control input and $\mathbf{y} \in \mathbb{R}^m$ the output of the system. The generalized input-state-output dynamics expressed in terms of port-Hamiltonian framework is given by: