Ocean Engineering 142 (2017) 388–410

Contents lists available at ScienceDirect

Ocean Engineering

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

# Cooperative consensus control applied to multi-vessel DP operations

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## ARTICLE INFO

*Keywords:*
Dynamic Positioning System
Multi-vessel operation
Cooperative control
Consensus
Shuttle tanker
Tugboat

## ABSTRACT

With the increasing deep water oil & gas exploration, there is also an increase of the demand for offshore operations involving multi-vessels. Such operations require high level planning and coordination, which in most cases occurs by information exchange at the operation level, being each vessel commanded independently. Examples of such operations are offloading, subsea equipment installation and research operation, always involving multiples dynamic positioned (DP) vessels. The advantage of the cooperative control arises with the reduction of the relative positioning error during station keeping or transient maneuvers.

In this work, consensus control concepts are applied combined with the DP System of each ship. The cooperative DP controller will be investigated with the analysis of the coupled dynamics of the vessels. The influence of cooperative control gains on the whole system will be discussed, using the frequency response of the open loop system. Fully nonlinear time-domain simulations and experimental results will be used to demonstrate the operation of cooperative control. Besides that, comparisons between the small-scale experiments and equivalent numerical simulations will be carried out, validating the numerical's results. The adopted design requirements are also demonstrated to be met.

## 1. Introduction

Cooperative control for multi-agent systems has attracted several researchers during the past two decades. This is due to the broad application field of multi-agent systems in many areas, particularly in formation control (Wang, 1991; Sheikholeslam and Desoer, 1992; Fax and Murray, 2004; Olfati-Saber and Murray, 2004; Chang et al., 2011), which is the object of this study. The basic idea is that multi-agent systems can perform tasks more efficiently than a single agent can. Moreover, multi-agent systems have several advantages such as the robustness regarding possible agent fault, flexibility for task execution and scalability by increasing the number of agents. Another advantage of distributed sensing is using a shared network of sensors among the agents.

In the oil & gas industry, multi-vessel operations are frequent. They are used for offshore oil transfer, sub-sea equipment installation and undersea structure launching, drilling, to name just a few. These types of operations require high level of planning and coordination between vessels, which is currently performed without automated information exchange, each ship being commanded individually. Therefore, in many of those cases a cooperative control may be applied, ensuring that the relative distances among the ships are maintained in the limited range by controlling operational parameters such as the lifting line traction. Researches in this area can be found in Ihle et al. (2004, 2006), Arrichiello et al. (2006), Feemster et al. (2006) and Smith et al. (2007). An oil transfer operation was studied in Queiroz Filho et al. (2012). To avoid the need of shore terminals, two shuttle tankers had to maintain their relative position while oil was transferred between them. In Queiroz Filho and Tannuri (2013), a cooperative control applied to two offshore tugboats was evaluated and the consensus control concepts (Beard and Stepanyan, 2003) were applied. The cooperative controller was combined with the Dynamic Positioning (DP) System of each ship in a parallel architecture. The DP controller and the cooperative controller calculated the demanded force based on the model position feedback, which were combined to position the vessels. The influence of the cooperative control gains was discussed by using the frequency response and the pole-placement analysis. Fully nonlinear time-domain simulations were used to demonstrate the advantages of cooperative control. In Queiroz Filho and Tannuri (2013), the same cooperative controller addressed in Queiroz Filho and Tannuri (2013) was applied to two small model scale tugboats. Several tests maneuvers were performed and the benefits of the cooperative controller were demonstrated.

Here, the same consensus concepts were combined to Dynamic Positioning. A new serial control architecture is proposed, in which the DP of each vessel is responsible for stabilizing its dynamics by an inner control loop and the cooperative controller is responsible for generating a reference trajectory on an outer control loop. Both controllers

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http://dx.doi.org/10.1016/j.oceaneng.2017.07.022
Received 26 July 2016; Received in revised form 18 April 2017; Accepted 5 July 2017

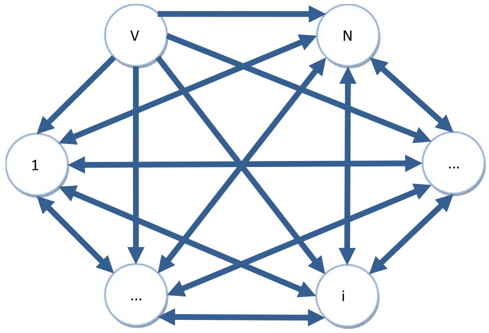

**Fig. 2-1.** Graph representing the communication between the vessels in the formation.

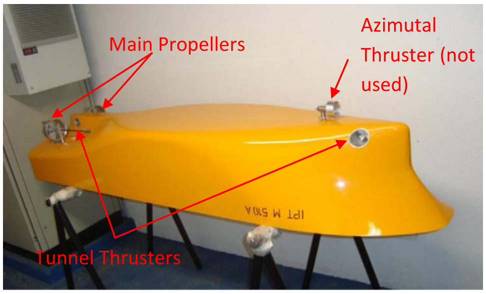

**Fig. 3-1.** DP Model (upside down) and propulsion devices information.

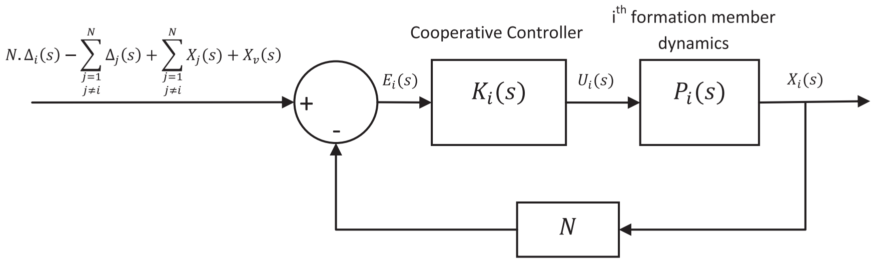

**Fig. 2-2.** Block diagram of the ith formation member.

**Table 3-1**
Model scale PSVs properties.

| Parameter | Value |
|---|---|
| Length over all LOA | 1.90 m |
| Length between perpendiculars LPP | 1.65 m |
| Beam | 0.43 m |
| Draught PSV1 | 0.115 m |
| Displacement PSV1 | 52.44 kg |
| Draught PSV2 | 0.107 m |
| Displacement PSV2 | 47.62 kg |

**Table 3-2**
Maximum available forces and moments, disregarding the azimuthal thruster and the rudders.

| Direction | Maximum thrust | Minimum thrust |
|---|---|---|
| *Surge* | 16.25 N | −9.63 N |
| *Sway* | 3.66 N | −3.66 N |
| *Yaw* | 2.56 N m | −2.56 N m |

combined led to the desired performance of the system as shown further on. An advantage of this new architecture when compared to Queiroz Filho and Tannuri (2013) is scalability, since the addition of new vessels is automatic. Another advantage of the serial architecture is that it can be easily integrated with existing DP systems, since only a communication link has to be created for the DP system to receive the reference trajectory calculated by the cooperative controller. Graph theory (Saaty and Busacker, 1966; Busacker and Saaty, 1965; Merris, 1994) was used to model vessel intercommunications. Numerical and model scale tests were performed to show the operation of the cooperative control. The performance of the system was also checked to attest that the system is operating as to the designed project criteria. All numerical tests were carried out using the Dynasim numerical simulator (Queiroz Filho et al., 2014).

## 2. The cooperative controller architecture

The vessel formation members are represented by $\mathcal{F} = \{\mathcal{M}_i : 0<i\leq N\}$ with $N\in\mathbb{N}^*$, in which all members have access to the horizontal positions of the others. A leader will be added to the formation, in which all members have access to the horizontal position of the leader. In favor of robustness, the leader will be virtual, so every formation member can thus instantiate the mathematical laws that describe its behavior. In that case, the communication link between every member and the leader is a sync signal, used to synchronize the information among the formation members. The graph of Fig. 2-1 represents the communication between the members, being $V$ the virtual leader of the formation. More about the use of graph theory to model communications in multi-agent systems and the presence of leaders can be found in Beard and Stepanyan (2003) and in Fax and Murray (2004).