Consensus Control for Vessel Traffic: the state of Arts and Prospects

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Abstract: With the rapid increase of port throughout, the number of vessels increases and the vessel traffic form become more complex. Therefore, how to realize the maximum utilization of limited navigation resources becomes one of the hottest issues. The consensus and coordination control of multi-agent systems could be adopted in the vessel traffic systems to improve the navigation efficiency and ensure safety in the water traffic. This paper reviews related work of the application of multi-agent system consensus control in the vessel traffic. In-depth analysis and discussion is made on swarming, distributed coordination control, consensus with external disturbances, and formation problems in the water traffic system. And also some challenging problems and prospects are presented.

1. Introduction

Waterway transportation is an important part of transportation, and China's water transportation has borne 93% of the trade volume and the heavy burden of north coal and south transportation, and the port has removed 95% of the imported crude oil from china [1]. With the waterway capacity rising and the developments of large-scale, quick running, and specialization of vessels, channel capacity is clearly affected by the water depth condition, the trend of the channel and scale, anchorage condition, berth condition and many factors, leading to the phenomenon of a large number of ships detention and congested port, thereby seriously affecting the development of the port. Therefore, it is one of the hot issues to improve the efficiency of navigation and ensure the safety of water transportation as well as realizing the coordinated development of economic and social benefits of navigable waters.

A networked control system is a device or a set of devices to manage, command, direct or regulate the behavior of other devices or systems [2]. In engineering and mathematics, control theory deals with the behavior of dynamical systems. For many years now, data networking technologies have been widely applied in industrial and military control applications. And the MAS (multi-agent system) is one of the networked control systems. In multi-agent systems, the agents coordinates, serve with each other to finish the tasks. Distributed coordination in multi-agent systems has received much attention in these years, which has a wide application of satellites, robots, vessels in some complex environments. Consensus is the key problem in multi-agent systems. The consensus problem could be implicitly described by that the states of all agents of the multi-agents uniform lastly by local
communication coordination, with the evolution of time. The MAS consensus is the primary condition of realizing coordination. The key point of the consensus is to design the consensus protocol or algorithm to make all the states of agents tending to the same value [2-4].

Based on the vessel traffic flow characteristics, combination with watershed feature, regulation and other restrictions, the traffic consensus research is a method of discussing the coordination control of vessel traffic. This paper surveys the recent application of consensus control in vessel traffic flow, and also, presents some prospects of future work including aspects of modeling, swarming, formation, and distributed coordination.

2. Water Traffic MAS

2.1 Multi-Agent System of Vessel Traffic

A typical networked multi-agent control system includes sensors, controllers and actuators. Ozkan [5] first proposed the idea of using MAS in water traffic system, and, Chmielewska [6], Ye [7], Xiao [8]. et al simulated the water traffic flow system with this method. Solving the maritime traffic problem by MAS is feasibility owing to distributed characteristic of water traffic, autonomous and intelligence of every vessel, besides that, easy to construct traffic model based on MAS, the dynamic feature of traffic object could be satisfied by autonomy and adaptation. Liu. et al [9] meticulous profound study to construct the vessel traffic multi-agent system, based on the perception, action, reasoning, communication and decision making. The multi-agent vessel traffic system model denotes that the vessels have the capacity of detecting the external environment (sensors), information analysis and decision (controllers), and kinetic energy (actuators). Compared with the model of NCSs, the vessel traffic multi-agent system, which as shown in Fig.1, it is clear that the vessel multi-agent traffic systems satisfy all the characteristics of the multi-agent systems. Due to the complexity of the environment of the vessel traffic flow, the construction would be more complex.

![Fig.1 The Construct of Multi-Agent System of Vessel Traffic](image)

2.2 Model of Vessel

M. Inaishi [10] first proposed the concept of vessel agent. The vessel agent is an entity that resides in the Marine environment, which can explain the data of events happened in the environment, and then perform actions that affected the environment, and also have the autonomy, reasoning ability, planning ability and learning ability. Thus, the agent model can be classified as based on simple reflex-type, model reflex-type, object type, and learning type.

With the explanation of the vessel agent, Liu. et al [9] combined the multi-agent theory and water traffic flow to detailed define the vessel agent again, denoting that the vessel agent is the computing entities in the navigation environment, which can act appropriately according to the changes in
environment. It is the abstract or mathematical description of vessel agent, reflecting the interaction between the vessel agent and navigation environment.

Assume that the environment of the vessel agent is a finite set of discrete instantaneous states, represented by $E$:

$$E = \{ e_0, e_1, e_2, \ldots \}$$

Though the realistic environment is continuous, can be modeled by the discrete environment achieved the desired accuracy. $A_c$, which is finite set and changes the states of environment, denotes a series of executable abilities of vessel agent. Apparently, $e_0, a_0$ is the initial environment and initial state, respectively

$$A_C = \{ a_0, a_1, a_2, \ldots \}$$

The basic model of interaction between vessel agent and vessel navigation environment [23]:

$$a_n = Ag((e_0, a_0, \ldots, e_n))$$

From the formula (3), it is clear that based on the history states so far, the vessel could decide what action will do next. The formula also presents that behavior of two vessel agents is equal, if and only if $R(Ag1, Env) = R(Ag2, Env)$, and the complete behavioral equivalent when if and only if they are behavioral equivalent to all environments.

Until now, some issues still exist in the vessel multi-agent model.

- It is hard to build a suitable vessel agent model due to poor maneuvering performance. The accuracy of the model would determine the quality of control performance. One single-integrator kinematics model and high-order integrator kinematics model cannot satisfy the complexity of the vessel behavior, therefore, we should consider the mixed order method to build the model for vessel multi-agent system.

- The external disturbances is complex including not only the maneuvering performance, other around vessels, obstacles, restrictions on navigation rules but also weather factors such as wind, flow, and fog.

- The information communication between the vessels cannot avoid delay, such as time-delay, packet dropouts, and fading channel.

3. **Consensus problem**

The research [4] on the multi-agent systems coordination control includes tracking control, flocking/swarm, distributed filtering, controllability and consensus. In which, the consensus problem is the basic and the most important problem. Consensus is also viewed as consistent state, mainly study on that state of all agent approach a mutual interest object with the communication between them. The consensus phenomenon of water traffic, actually, can be analyzed by the theory of consensus of MAS, which is shown in Fig.2. And these problems would be detailed described in the below parts.

Asymptotically consensus of multi-agent with leader can be denoted by formula (4)

$$\lim_{t \to \infty} \| x_i(t) - x_0(t) \| = 0, \quad \lim_{t \to \infty} \| v_i(t) - v_0(t) \| = 0$$

Where $x_0(t) \in \mathbb{R}, v_0(t) \in \mathbb{R}$ is the initial location state and initial velocity state of leader, respectively.
3.1 Water traffic consensus control problem

Multi-agent swarm behavior is an important research topic of complexity science, deriving from behavior phenomenon of natural biological. By the computer simulation, Reynolds [3] simulated this motion and proposed the famous animation model-Boid Module, adopting three simple rules to describe behavior phenomenon of natural biological. (1) Avoid collision between adjacent individuals (2) The speed and direction of the adjacent individual are asymptotically consistent. (3) Center aggregation, each individual changes the current position and moves toward the average position of its neighbor. Saber [4] studied swarm control problem with obstacle avoidance by defining an artificial potential function, the individual can realize the formation control and speed of all intelligent bodies without collision. The water traffic system can be viewed MAS based on singular system.

Xiao [13] applied the swarm control into water traffic consensus of inland river transportation, the ship cannot meet the requirement of two-way navigation relative to narrow channel. In order to avoid collision or stranding accidents, the vessel needs to obtain the traffic conditions of the surrounding environment in time, also the navigation information of other vessels through the communication equipment such as vessel traffic service (VTS), satisfy the below conditions:

$$\begin{align*}
\|x_i - x_j\| &> d \\
\|v_i - v_j\| &\to 0 \\
d/v_i &> t_0
\end{align*}$$

(5)

Where d is the safe distance between ships, and $t_0$ is the passage time before anchor. Which means that when the velocity of vessels approached consistence, the possibilities of collision or stranding of vessels will degrades due to the interaction of them. Su [14] proposed a collision avoidance decision method for vessels, based on information fusion, including vessel agent, VTS agent to achieve more accurate and economical ship collision avoidance decision. The stability of the MAS of vessel traffic systems should also be considered due to the position of vessels variable as times goes on, therefore, time-delays systems, switched systems and impulse systems could also be adopted in the MAS vessel traffic to solve the stability problems.

3.2 Distributed coordination control consensus problem

Vessel enters or leaves the harbor in one same port, so the maximum benefit of vessel navigation is that the vessel arrive the port and directly into the port without any delay. In addition, the port is prohibited to prohibit the anchorage of dangerous vessels such as Liquefied Natural Gas LNG[15], it is necessary to arrange the sailing time and speed reasonably.

In multi-state traffic situation, it cannot be considered as a point of mass because of its nonlinear, it is necessary to consider the distributed collaborative control method of nonlinear multi-agent to realize...
multi-state traffic situation. Xu [16] proposed a decentralized, multi-agent based schema to adaptively control massive traffic lights, which promotes the large-scale green transportation.

In multi-agent systems, the purpose of the distributed cooperative control is to design the control protocol to solve the consensus problem, if and only if all the agents satisfy:

\[ \lim_{t \to \infty} (x_i(t) - x_j(t)) = 0 \]  

(6)

And we could consider the distributed collaborative control in the water traffic from three aspects: (1) in civilian water traffic, such as in China, the water traffic direction mainly concentrate on North and South, so the direction of water traffic has a high degree of consensus. (2) The position of vessel traffic also has a high degree of consistence due to the fixed route [21]. (3) At some certain ports, the distance between the vessels and speed of the vessel also has the feature of consensus.

3.3 Consensus of water transit capability with disturbances

A External environment disturbances

Traffic is not only related to its own behavior, but also influenced by many conditions of the port. The geographical environment of the port channel, the traffic organization and dispatch of vessels during the navigation of the port waterway, the diversification of the form of activities constitute the complexity of the network control system of the ship. The influence of port conditions mainly includes: natural conditions, channel scale, port service level, port function and layout. Due to these disturbances, simulation model of Marine traffic flow based on the combination of Agent and CA [17, 18] improving the simulation efficiency of Marine traffic flow.

B Vessel behavior disturbance

Vessel behavior disturbance includes crossing, meeting and turning back and docking in the harbor channel. Similar to the analysis of the traffic flow consensus, the port capacity is limited by the characters of vessel behavior. Combine the advanced technology in the field of artificial intelligence, making up for the shortages of traditional method, constructing the intelligent model which can reflect the actual traffic situation and characteristic could effectively solve the complex and nonlinear problem of the simulation of vessel traffic flow. However, the different classes of vessels, safety distance and berth service level should also be considered in the MAS. The external disturbance and behavior disturbance can be solved by robust control in the MAS [2], in order to realize the optimum control the adaptive control protocol would be used.

4. Formation control

Formation control is a generalization of consensus control, the agent should not only maintain a certain formation but also avoid collision between agents. Two main ways of formation control, based on the conventional control algorithm multi-agent formation and behavior intelligent algorithm multi-agent formation. The former is appropriate for static and stable environment. And the scope of application of the latter one is wide, which can adjust according to the change in the external environment, but needs more long time.

The application of vessel formation involves military and civilian aspects. In military aspect, such as aircraft carrier in the navy, all battleships cooperative combat centre aircraft carriers. Civilian navigation also exist the phenomenon of vessel formation, such as vessel lock formation. There are some issues induced by the vessel formation control. (1)The vessel types of collocation consensus, for some certain vessel lock, the dangerous vessels and the passenger ships should up and down formation in the vessel lock. (2)Scale collocation consensus, in order to improve the efficiency of the port, avoiding the big vessel collocated with small one situation, the scale collocation reasonably is an important rule.(3) ship-type standardization consensus, which that can improve the utilization of the lock.(4) time consensus means that same type vessel approaches consensus in finite time. All the above consensus problems will be more challenging but be more significant in practice.
5. Conclusion
Based on the feasibility of MAS theory used in the water traffic, this paper conclude the development of the application of MAS in water traffic, and proposed some consensus phenomenon in the vessel traffic. We discuss the application of consensus problem in four aspects, including swarm, distributed coordination, consensus with disturbances and formation control. And as far as we know, there is less work contributed to consensus theory applied in water traffic, and wish these challenging problems will be solved by consensus theory.

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