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STUDY ON ADVANCED PERFORMANCE ESTIMATION OF HETEROGENEOUS COLLABORATIVE NETWORK FOR MARITIME DOMAIN AWARENESS

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Abstract. *Recently, researches of the heterogeneous collaborative network (HCN) composed of marine robots such as an underwater robot, a surface robot, and an aerial robot are gradually executed for maritime domain awareness (MDA). However, the development and application of the HCN have many difficulties due to time and cost. As the micro marine robot (MMR) which is a kind of the marine robot has the superiority in terms of time and cost although it has some constraints due to small size, the development and application of the MMR-based HCN (MHCN) may be effective to develop and apply the HCN. To study the advanced development and application of the HCN, a performance estimation method of the HCN using the MHCN implementation and the smoothed particle hydrodynamics (SPH) simulation is considered. Study results show the overview of the MHCN implementation, the overview of the SPH simulation and the need for additional studies.*
Keywords: Maritime domain awareness, Heterogeneous collaborative network, Micro marine robot, Virtual marine robot, Smoothed particle hydrodynamics

1. **Introduction.** Recently, researches of the HCN [1] composed of marine robots such as an underwater robot, a surface robot, and an aerial robot are gradually executed for MDA [2,3]. However, the development and application of the HCN have many difficulties due to time and cost, i.e., the HCN has much time and high cost. This means that the HCN has the problem of much development time and the high operating cost.

Among the future marine robot, the MMR [4,5] which is a kind of the marine robot has the superiority in terms of time and cost although it has some constraints due to small size, i.e., the MMR has little time and low cost. This means that the MMR has the superiority of the little development time and the low operating cost. As the MMR has the superiority in terms of time and cost although it has some constraints in terms of operating time, detection range, disturbance rejection due to small size, the development and application of the MHCN may be effective to develop and apply the HCN that has the application area of military, research, rescue, survey, inspection, working, etc.

To study the advanced development and application of the HCN, a performance estimation method of the HCN using the MHCN implementation as a time and cost reducible implementation method and the SPH [6,7] simulation as a mesh-free computational fluid dynamics (CFD) simulation method is considered.

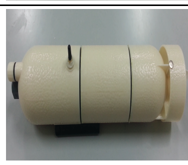
The overview of the MHCN implementation is described in Section 2 and the overview of the SPH simulation is described in Section 3. Finally, the conclusions are summarized in Section 4.

2. **Overview of MHCN Implementation.** Related to the overview of the MHCN implementation, the studies of the best practice of the HCN and the best practice of the MHCN are performed as follows.

The naval postgraduate school (NPS) in USA as the best practice of the HCN has the HCN that effectively connects the underwater, surface, and aerial systems for the MDA [1].

The research institute of marine robot education technology (RIMRET) in Korea as the best practice of the MHCN has the MHCN that effectively connects the micro-based underwater, surface, and aerial systems for the MDA [2,3]. Related to this, the RIMRET has the development cases of the MMR [4,5]. This is summarized in Table 1.

Table 1. Development cases of MMR

Year	MMR	Nation	Developer	Image
2011	S-Shark I	Korea	RIMRET	
2013	A-Shark II	Korea	RIMRET	
2014	G-Shark II	Korea	RIMRET	
2015	S-Connector I	Korea	RIMRET	

For feasible application of MMRs as components of the MHCN, it is necessary to let the MMR have the high autonomous level. Related to the definition of the autonomous level, that of a certain system can be defined in the three-dimensional space that has the bases of human interaction, complexity and intelligence. In terms of the complexity of the definition of autonomous level, the MHCN has high collaborative activity. This is shown in Figure 1.

The best practice of the MHCN of the RIMRET is a heterogeneous sensor network using MMRs [3]: the needs for the researches of sensor networks which are composed of underwater, surface and aerial robots are increasing in order to acquire the information effectively as the information from heterogeneous robots has less limitation in terms of coverage and connectivity. To solve this problem, a collaborative control method based on the acoustic information and image by the sonars of the underwater robot, the acoustic information by the sonar of the surface robot and the optical image by the camera of the static-floating aerial robot is proposed and verified. A micro surface robot (MSR) which is named S-Shark III has the abilities of surface locomotion based on the 2-degree of freedom (DOF) motion and obstacle avoidance based on the rotating 4-channel obstacle avoidance sonar (OAS). An MSR which is named S-Connector has the abilities of surface locomotion based on the 4-DOF motion and obstacle avoidance based on the 4-channel OAS detection of front, right, left and bottom [5]. A micro underwater robot (MUR) which is named G-Shark II has the abilities of underwater locomotion based on the 4-DOF motion of surge, yaw, pitch and heave and obstacle avoidance based on the 4-channel OAS and image acquisition based on the side scan sonar (SSS). A micro aerial robot (MAR) which is named A-Shark II has the abilities of aerial locomotion based on the 2-DOF motion and obstacle avoidance based on the rotating 1-channel infrared (IR). When the MUR cannot detect the obstacle using the OAS, the MAR with a camera helps the avoidance of the MUR. If the MUR detects the target using the SSS, it transmits its position information to the MAR and then the MAR transmits the position information to the MSR. And then the path planning and control of the MSR are executed for finding the target. This is shown in Figure 2.

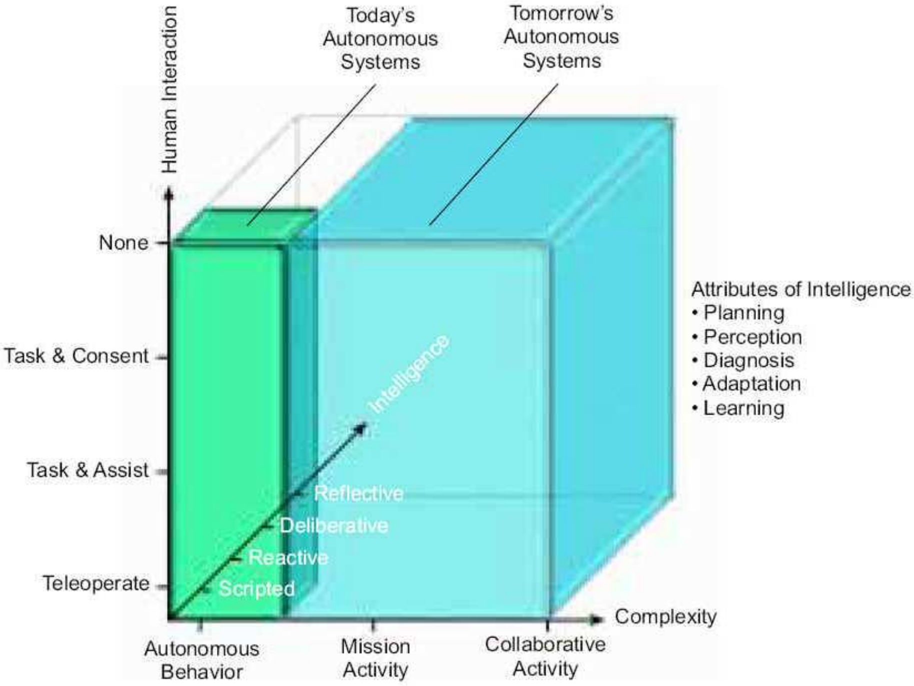


Figure 1. Definition of autonomous level

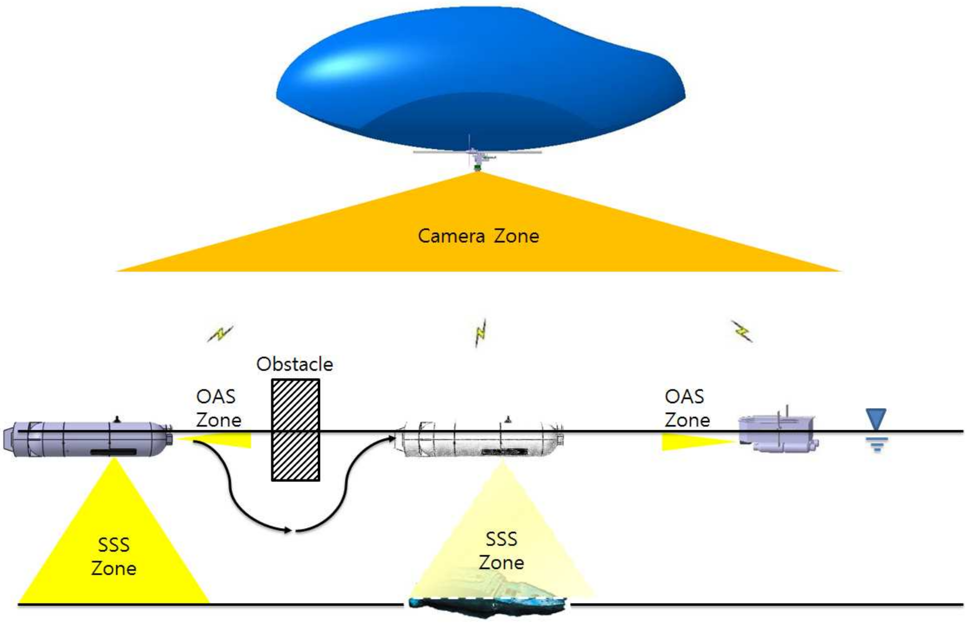
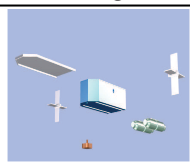
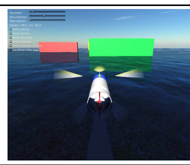
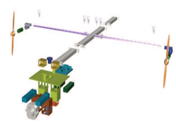
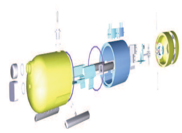


Figure 2. Heterogeneous sensor network

3. **Overview of SPH Simulation.** Related to the overview of SPH simulation, the studies of the best practice of the virtual marine robot (VMR) and the best practice of the SPH simulation are performed as follows.

The RIMRET as the best practice of the VMR has the VMR that effectively estimates the performances of MMRs. The design of MMR is implemented using the computer aided three dimensional interactive application (CATIA) program as a modeling tool and this modeling tool facilitates the easy development of the VMR by using compatible rendering tool. Related to this, the RIMRET has the development cases of the VMR [4]. This is summarized in Table 2.

Table 2. Development cases of VMR

Year	VMR	Nation	Developer	Image
2014	SRAVSim	Korea	RIMRET	
2014	URIVSim	Korea	RIMRET	
2015	ARAVSim	Korea	RIMRET	
2015	URAVSim	Korea	RIMRET	

The best practice of the VMR of the RIMRET includes the following VMRs [4]: a surface robot assembly/disassembly visualization simulator (SRAVsim), an underwater robot interaction visualization simulator (URIVsim), an aerial robot assembly/disassembly visualization simulator (ARAVsim), and an underwater robot assembly/disassembly visualization simulator (URAVsim). These are the efficient methods for estimating the performance of the HCN. In addition, the mathematical modeling is necessary to reduce the performance estimation error of the HCN. The general marine robot involves 6-DOF motions because six independent coordinates are required to define the position and orientation of a rigid body in three dimensions, i.e., it is described by the components of surge, sway, heave, roll, pitch, and yaw [8,9]. However, it is not easy to predict the water behavior in severe water situations. Analytical approaches are very limited for this event because it is almost impossible to deal with the nonlinear free-surface flows, while CFD has good ability to overcome these difficulties. Among CFDs for fluid dynamics, mesh-based CFD has been well developed and evaluated so far but still have difficulties and complexity to precisely capture the free-surface with fragmentation and reconnection like splash and breaking waves. Particle method [6] has the advantage in dealing with complicated free-surface flows because the free-surface can be naturally captured without numerical diffusion. As a mesh-free CFD method, SPH simulations using graphic processing unit (GPU) are applied to the prediction of 6-DOF ship motions in severe water condition [7].

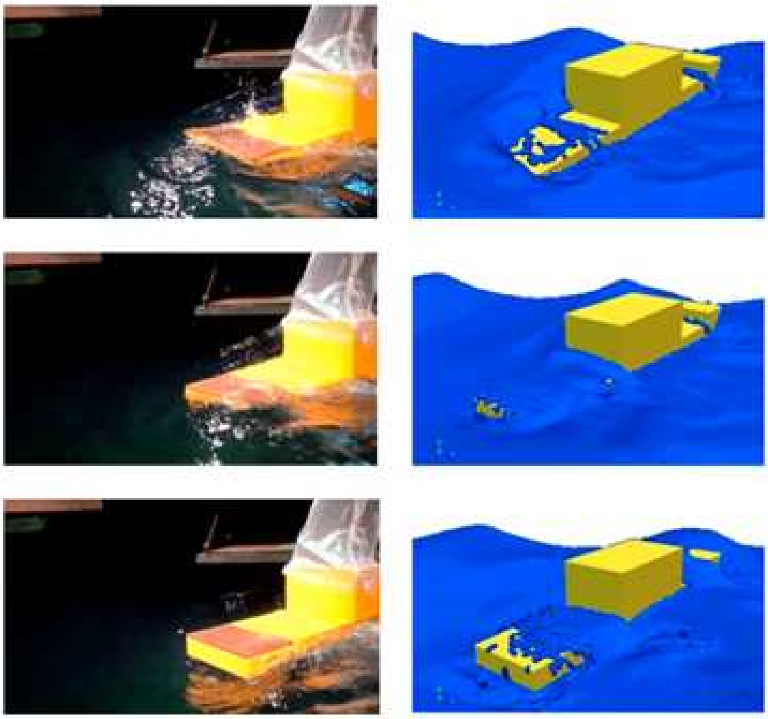


Figure 3. SPH simulation of ship behavior in severe water

Left hand and right hand sides in Figure 3 respectively show the experimental and the simulation results. The simulation results match well those of the experiment.

The SPH governing equations dealing with compressible fluids are as follows [7] and they are concerned with mass, weight function, tuning parameter, speed of sound, position vector, wave length, and wave height:

$$\begin{aligned} &\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \boldsymbol{u}) = \mathbf{0} \\ &\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla P + \boldsymbol{g} + \Theta \end{aligned} \tag{1}$$

where ρ is a density and $\boldsymbol{u}$ is a velocity vector. P is a pressure, $\boldsymbol{g}$ is a gravity vector and Θ is a diffusion term.

From these results, the performance estimation method of the HCN is proven to have meaningful methodologies such as the MHCN and the SPH.

4. **Conclusions.** In this paper, a performance estimation method of the HCN using the MHCN implementation and the SPH simulation has been well studied. The method is summarized as follows: it requires the MHCN implementation using MMRs to effectively estimate the performance of the HCN in real space; it requires the SPH simulation using GPUs to effectively and accurately estimate the performance of the HCN in virtual space. The study results showed the overview of the MHCN implementation, the overview of the SPH simulation and the need for additional studies. Through this, a basic performance estimation method of the HCN for the MDA has been established. In the future, additional studies such as an underwater interaction and a real-time visualization will be conducted for the concrete performance estimation of the HCN.

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