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Fuzzy comprehensive evaluation for the motion performance of autonomous underwater vehicles

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ABSTRACT

Motion performance of autonomous underwater vehicles (AUVs) is critical to the security and survey accuracy of AUVs. However, relationships among indices used to evaluate the motion performance are generally complicated and cannot be formulated mathematically, and it is hard to clarify how each index affects the motion performance of AUVs. In this paper, the fuzzy comprehensive evaluation (FCE) method was proposed to assess motion performance of AUVs. Focused on the landing AUV, process of the FCE method was described in detail, and the FCE system was constructed. In the FCE system, a three-level evaluating index system was built according to the motion characteristics of the landing AUV. Based on analysis of the survey process and measurement requirements of the landing AUV, the weight sets of each factor set were determined by applying the fuzzy analytic hierarchy process. The single-factor evaluation matrix was obtained by solving the membership function with ridged-shape distribution. Decision-making was completed through comparing evaluation results of the motion performance of two layout schemes. Field trials showed that the evaluation results could reflect the motion performance of landing AUVs objectively and comprehensively.

1. Introduction

The motion performance, involving motion stability and maneuverability, are critical to the survey accuracy and security of autonomous underwater vehicles (AUVs). How to design AUVs with good motion performance to meet the requirements of the survey accuracy and security and how to make a scientific evaluation on the motion performance of AUVs are always the highly concerned subjects.

In order to make AUVs have good motion performance, some researchers do their efforts on improving the shape design and layout of AUVs. Based on the linear turning theory, Henry (1994, 1995) proposed a method of designing the fixed fin size and location through investigating the turning performance of submersible vehicles. He concluded that the optimum location of fins is always near the longitudinal position of the center of buoyancy for the bare hull. Zhang (2006) optimized the position and size of the rudders by using Henry's method. Encarnacao et al. (1997) optimized the control surface size of AUV applying convex optimization method. Coe and Neu (2012) studied the influences of the asymmetrical wake and the propeller on the control surface effectiveness. Humphreys (1994) improved the low-speed maneuverability of AUVs by changing the hull shape and the volume distribution of the hull. Some focus their time on the control system design and the control algorithm to make the motion performance of AUVs play better. Nickell et al. (2005) realized the low-speed control for a streamlined AUV by incorporating a moving mass actuator with the fixed wing. Petrich and Stilwell (2011) derived a novel linear time-varying model that captured the coupled pitch and yaw motion of an AUV to address unwanted roll motion. In order to improve safety and survey quality of AUVs, Woolsey et al. (2012) developed an obstacle/terrain avoidance routine to maintain altitude over steep slopes or otherwise rough terrain by combining the vertical and the horizontal behaviors together. These studies enriched the design methods of AUVs and propelled the theory and technology of designing AUVs to mature.

Since it is time and cost consuming to evaluate the motion performance of AUVs through field trials, it is particularly valuable to assess the motion performance of AUVs at the preliminary design stage so as to choosing a better one in several design schemes and to minimize the changes after field trials. At present, researches on evaluating the motion performance of AUVs depend on field trials and focus on some individual motion performance of AUVs. Nakatani et al. (2013) investigated the dive performance of the cruising-AUV JINBEI through sea trials in a methane hydrate area.

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Santhakumar and Asokan (2013) studied the dynamic station keeping performance of a flat-fish type AUV, and proposed a method with an addition of dedicated thrusters to make the AUV keep dynamic station. Hyakudome et al. (2008) performed sea trials to investigate and improve the maneuverability of a long range cruising AUV "URASHIMA". But the motion performance of AUVs cannot just be simply judged some individual performance indices with referencing the criteria and norms for the reason that there are more than a dozen evaluation indices of motion performance of AUVs, and most of them influence each other. It should be comprehensively evaluated with scientific and reasonable method.

There are many methods of comprehensive evaluation (CE) based on fuzzy set theory (Zadeh, 1965), grey system theory (Deng, 1989, 1993), systems engineering theory (Saaty, 1977) and artificial intelligence theory (Kishikawa and Tokinaga, 2000). With in-depth and expansion of researches on the CE theory, the CE has rapidly penetrated into and widely applied to many fields of engineering, economy and finance, transportation, social, meteorology, etc. Numerous practical problems have been successfully solved by using various CE methods (Piplani and Wetjens, 2007; Karsak and Tolga, 2001; Palanikumar et al., 2012; Zhang and Li, 2010; Oeltjenbruns et al., 1995; Zeng et al., 2011; Wang et al., 2011; Pai et al., 2007; Saaty, 1990; Sirbiladze et al., 2010). Also worth mentioning is that each method has its advantages and disadvantages, and that different theoretical basis makes each CE method have different decision-making process and application objects. Table 1 lists characteristics of some commonly used and well-known CE methods.

Since each CE method has its advantages and disadvantages and application objects, an appropriate CE method should be selected according to the characteristics of the object to be evaluated. For the problem of evaluating the motion performance of AUVs, it has the following characteristics. (1) Motion performance of AUVs is a function of hydrodynamic coefficients which are directly influenced by geometrical parameters of AUVs. Researchers do their best to try to find the relationships between hydrodynamic coefficients and geometrical parameters (Perrault et al., 2003a, 2003b; de Barros et al., 2008; Santhakumar and Asokan, 2013; Tang et al., 2009). But studies show that change of one shape parameter of the AUV hull can lead to changes of multiple hydrodynamic coefficients. There are still no clear relational expressions between the hydrodynamic coefficients and the shape parameters. (2) The hydrodynamic coefficients cannot be used to assess the motion performance of AUVs directly. Nonlinear combinations of various hydrodynamic coefficients constitute more than a dozen evaluation indices of the motion performance of AUVs. Moreover, there are also no definite expressions between motion performance and evaluation indices. (3) Most of the evaluation indices influence and restrict each other, and it remains to conduct further researches on how one index influences another. The above vagueness and uncertainties cause a fuzzy boundary to evaluate the motion performance with good or bad and make it a hard work to give a crisp decision.

Considering that motion performance evaluation of AUVs is a fuzzy concept with multiple indices, the authors try to introduce the fuzzy theory to assess the motion performance of AUVs. The concept of fuzzy sets describing imprecision or vagueness was introduced by Zadeh (1965) and was first applied to economic field to solve those problems, in which the object to be evaluated is affected by multiple factors, and relations among the factors and object are not clear. With development of fuzzy theory, the fuzzy comprehensive evaluation (FCE) was developed and has been widely applied in decision-making and evaluation processes in imprecise situations (Mujumdar and Sashikumar, 2002; Dahiya et al., 2007). This paper aims to introduce the FCE method to assess the motion performance of AUVs and hope to provide a valuable and scientific reference for layout scheme selection at the preliminary design stage by using the FCE method. Two layout schemes of a landing AUV were used as a case study to

Table 1
Characteristics of some well-known CE methods.

Methods	Theoretical	Advantages	Disadvantages	Application objects
Fuzzy CE	Fuzzy set theory	A. Combination of qualitative and quantitative methods B. Obtaining solutions of problems with multi-levels C. Avoiding the drawbacks of the only solution	A. There is subjectivity in determining weights. B. There may be duplication of information.	The evaluation object with a vague boundary is affected by multiple factors, and relations among the factors and object are not clear.
Analytic hierarchy process	System engineering theory	A. Obtaining solutions with high reliability and small errors	A. Numbers of indices to be evaluated generally cannot be more than 9.	The evaluation object is limited to those with no more than 9 indices in subset of factors.
Grey relational analysis	Grey system theory	A. Data need not be normalized and calculation is simple B. Without a lot of samples	A. It is difficult to define curve similarity of time variables. B. Sometimes it may draw a wrong conclusion. C. Result is affected by the selected factors.	The evaluation object is a grey system, in which part of the information is clear and part is not clear.
CE based on neural network	Artificial intelligence theory	A. Network with adaptive ability and fault tolerance	A. Accuracy of the evaluation results is not high. B. Requiring a lot of training samples.	The evaluation object can be a large complex system with non-linear and non-locality.

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