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SURVEY OF TRAJECTORY TRACKING CONTROL OF AUTONOMOUS UNDERWATER VEHICLES

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Key words: autonomous underwater vehicle, trajectory tracking control, control methods.

ABSTRACT

Autonomous underwater vehicles (AUVs) are powerful instruments that enable the exploration of the ocean. In recent years, AUVs have been developed considerably. Trajectory tracking control, which has been a major research focus for many decades due to its variety of applications, is one of the key advancements in the AUV technology. This paper presents six trajectory tracking control methods: PID (proportion integration differentiation) control, fuzzy control, adaptive control, sliding mode control, backstepping control, and neural network control. A few novel methods for trajectory tracking control are also introduced. First, the concept of trajectory tracking control for an AUV and the related basic theories are explained. Then, several methods that are currently used for tracking control are presented. The advantages and limitations of these methods are identified by evaluating the characteristics of the methods. Finally, on the basis of a summary of several main methods, the future development of the trajectory tracking control of AUVs is discussed.

I. INTRODUCTION

Autonomous underwater vehicles (AUVs), indispensable tools for exploring the ocean, are built using and equipped with various high-end technologies (Sahu and Subudhi, 2014; Wynn et al., 2014). AUVs are crucial for China's marine industry, marine exploration, and development. AUVs are carrier based, they have extensive applications when integrated with various airborne equipment and tools. A submarine resource survey indicated that seabed data obtained by AUVs is very accurate. During underwater exploration, AUVs perform the required maintenance and repair for submarine's equipment, transport the necessary equipment, monitor and record the exploration. In future underwater oil production systems, AUVs will perform labor functions and play a critical role in subsea jacket inspection on offshore oil platforms as well as pipeline inspection and maintenance. In oceanographic studies, AUVs can be utilized for various measurements. They can be employed for observing and monitoring submarine volcanoes; releasing and recovering instruments related to submarine volcano monitoring; conducting seabed sampling; and performing a variety studies for fields such as biology and hydrology. AUVs can also be utilized for constructing and visualizing three-dimensional sea-bottom models (Kamaev et al., 2017), navigation and localization (Ridolfi et al., 2015; Teo et al., 2015; Paull et al., 2016), data acquisition (Khan and Cho, 2015; Llyas et al., 2015), and marine image collection (Bewley et al., 2015; Roelfsema et al., 2015). Because of the wide variety of activities performed, small volume, light weight, low noise, and good concealment, AUVs are effective underwater weapons in military affairs. AUVs can be used to set up countermeasures for mines, serve as a bait, be incorporated into antisubmarine training, and be used for emergency survival and other military activities. Trajectory tracking control is crucial in AUV implementation. The basic performance of an AUV can be enhanced by improving the trajectory tracking control. In recent years, many experts have paid considerable attention to the trajectory tracking control of AUVs, because this subject has considerable research potential (Yan et al., 2012; Zhang et al., 2012; Rezazadegan et al., 2015).

The tracking control of AUVs mainly includes path following and trajectory tracking. The main difference between path following and trajectory tracking is that the reference trajectory of path following is independent of time and that of trajectory tracking is dependent on time. Path following can be regarded as a special case of trajectory tracking; therefore, the trajectory tracking problem is more widely applicable. Many scholars have conducted trajectory tracking research, but there are still many problems that must be addressed. In comparison with mobile ground robots, the major factors that cause difficulties in controlling AUVs are listed as follows (Pyo and Yu, 2016):

(1) The hydrodynamic performance of AUVs is highly nonlinear and time varying.
(2) The center of gravity and buoyancy changes with a change in the load.
(3) The additional mass and inertia are large.

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(4) The motion of an AUV is disturbed by the ocean current and unpredictable obstacles.

Because of these factors and because AUVs have strong coupling and high nonlinearity, it is difficult to obtain a dynamics model of AUVs. In addition, when the control performance of an AUV decreases due to a change in its mechanical properties and environment, the AUV's control system is required to have the robust capability of self-adjusting and adapting to the change. The aforementioned marks the challenges of AUV trajectory tracking study.

This paper reviews the results of various researchers pertaining to AUV trajectory tracking. The research on AUVs is classified into six main methods and some new methods. The process of using these tracking control methods is briefly described, and directions for future AUV trajectory tracking research are identified. This paper aims to enable readers to recognize and understand trajectory tracking control methods for AUVs. Future development trends are described on the basis of numerous studies. The present study lays a foundation for further research on trajectory tracking control for AUVs and provides some innovative ideas for scholars in related fields. The paper is organized as follows. In Section 2, the concept of AUV trajectory tracking control is presented. In Section 3, the six main methods of trajectory tracking control for AUVs are introduced, and the advantages and limitations of these methods are discussed. In Section 4, the main trends in the future development of AUV trajectory tracking control are considered. In Section 5, some concluding remarks are provided.

II. TRACKING CONTROL OF AUVS

To complete a prescribed task in an underwater environment, such as laying mines and inspecting submarine pipelines, AUVs must follow the given reference trajectory to reach the destination. A kinematic or dynamic control law is required to enable an AUV to arrive at a destination and track a given reference trajectory with a given velocity or thrust. In the inertial coordinate system (Sun et al., 2015), an AUV must start from a given initial state to track a desired trajectory. The initial position of the AUV may or may not be on the reference trajectory. A diagram of the trajectory tracking of an AUV is shown in Fig. 1. The current position of the AUV is given as $\boldsymbol{\eta} = [x \quad y \quad z \quad \psi]^T$. The reference trajectory (shown as the green dotted line in Fig. 1) is given as $\boldsymbol{\eta}_d = [x_d(t) \quad y_d(t) \quad z_d(t) \quad \psi_d(t)]^T$, where every variable is a function of time t. The given velocity is the reference control input $\boldsymbol{u}_d(t) = [u_d(t) \quad v_d(t) \quad w_d(t) \quad r_d(t)]^T$. Moreover, $\boldsymbol{u}(t) = [u(t) \quad v(t) \quad w(t) \quad r(t)]^T$ is the speed of the AUV.

The AUV tracks the reference trajectory by controlling the surge speed $u(t)$, sway speed $v(t)$, heave speed $w(t)$, and yaw speed $r(t)$ so that the error between the actual trajectory and desired trajectory converges to zero.

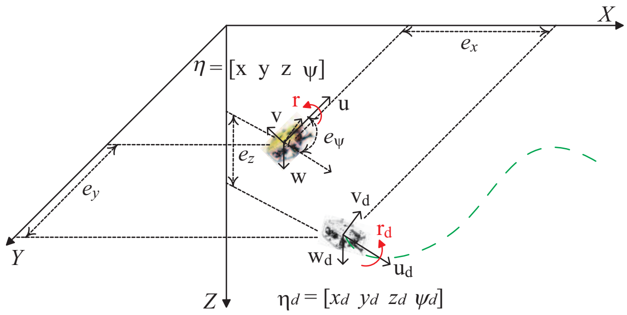

Fig. 1. Diagram of trajectory tracking.

$$e(t) = \eta_d(t) - \eta(t) = [e_x \quad e_y \quad e_z \quad e_\psi]^T \underset{t\to\infty}{\to} 0 \tag{1}$$

III. ALGORITHMS FOR AUV TRAJECTORY TRACKING CONTROL

The trajectory tracking control of AUVs has developed rapidly for decades. Trajectory tracking control methods for unmanned ground vehicles are well developed, and some are used in practical applications. However, due to the challenging working environment and the high nonlinearity and strong coupling of AUVs, most AUV research has remained in the simulation stage. Practical application of tracking control methods to AUVs remains relatively limited. AUV trajectory tracking control is a very challenging research field, and not many studies are conducted in this respect (Santhakumar and Asokan, 2012). The various control methods reported in former studies can be categorized into six groups from the viewpoint of the control algorithm used: PID (proportion integration differentiation) control, fuzzy control, adaptive control, sliding mode control, backstepping control, and neural network control.

1. PID Control

A PID controller is a type of linear controller. The control deviation, which is the position error, is generated using the reference trajectory and actual trajectory. Thus, the following is obtained:

$$\boldsymbol{e}(t) = \boldsymbol{\eta}_d(t) - \boldsymbol{\eta}(t) \tag{2}$$

Here, $\boldsymbol{\eta}_d(t)$ is the reference trajectory and $\boldsymbol{\eta}(t)$ is the actual trajectory. (The same notation is used in the explanations of the following five algorithms.) A linear combination of the proportional, integral, and derivative terms of the control deviation $\boldsymbol{e}(t)$ forms the control law of AUVs. The control law of PID control is specified as follows:

$$\boldsymbol{u}(t) = K_p \boldsymbol{e}(t) + K_i \int_0^t \boldsymbol{e}(t)dt + K_d \frac{d\boldsymbol{e}(t)}{dt} \tag{3}$$

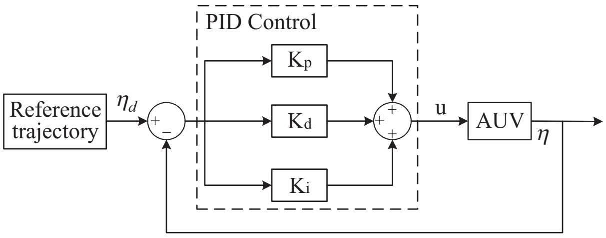

Fig. 2. Diagram of PID tracking control for AUVs.

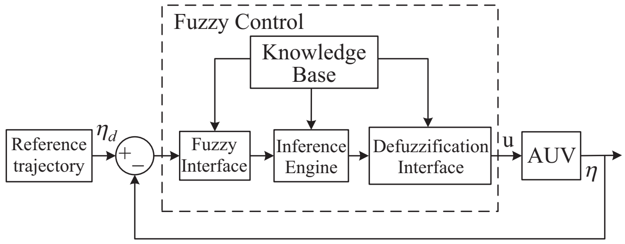

Fig. 3. Diagram of fuzzy tracking control.

where K_p, K_d, and K_i are the control parameters of PID control. If the three control parameters are selected appropriately, then the dynamic process can be rapid, smooth, and accurate. Thus, satisfactory control results can be achieved. A schematic diagram of traditional PID tracking control for AUVs is illustrated in Fig. 2. In the figure, u is the speed output.

PID control has a wide range of applications, such as industrial automatic control systems (Formentin et al., 2014), flight control systems (Kumar et al., 2015), and ground mobile robot control systems (Bouhajar et al., 2015). At present, many devices using PID control and matching controllers are extensively employed in the field of engineering. Some companies have fabricated intelligent regulators that are equipped with self-tuning PID controllers. A PID controller's parameters can be automatically adjusted by using intelligent adjustment or self-tuning algorithms.

In the early stages of AUV tracking control, PID control was extensively used. PID control provides AUV trajectory tracking control in the horizontal plane and vertical plane through the decoupling and simplification, respectively, of a dynamic model of an AUV with six degrees of freedom (Kaminer et al., 1988; Antonelli et al., 2003; Zhang et al., 2013). The outcome of the PID control algorithm depends on the PID parameters, but PID parameter tuning depends on the model of the controlled object. Owing to the high nonlinearity, strong coupling, and uncertainty of the hydrodynamic parameters in a dynamic AUV model, the model must be simplified before implementation of tracking control. The traditional PID trajectory tracking control strategy, which depends on the AUV model, cannot satisfy the demands of actual underwater trajectory tracking control in many cases. Therefore, the PID algorithm is usually combined with other intelligent algorithms for AUV tracking control. Harun et al. (2015) applied an integral backstepping control method for a translational subsystem and a PID backstepping control method for a rotational subsystem; thus, stable tracking control of an underactuated X4-AUV system was realized. Khodayari et al. (2015) designed a self-adaptive fuzzy PID controller; the control system was sufficiently stable and efficient to control an AUV in tracking the two channels of heading and depth with a stable speed. Alvarado et al. (2016) proposed an auto-tuning PID-like controller developed using neural networks to guarantee optimal PID gains in application to a remotely operated vehicle (ROV) and to achieve optimal stability of the system even under the influence of the ocean current.

2. Fuzzy Control

Fuzzy control (Ishaque et al., 2010; Xiang et al., 2016) is a type of practical control method that is based on simulating the fuzzy reasoning and decision-making ability of humans as accurately as possible. The essence of fuzzy control is to convert a control strategy based on expert knowledge to an automatic control strategy. In practical applications, the collected control information is utilized to obtain a fuzzy set of the control vector through fuzzy reasoning and fuzzy decision-making. The exact value of output is determined by the fuzzy decision made regarding the controlled object, allowing the desired control over the process to be achieved. The fuzzy controller is composed of four parts-the fuzzy interface, knowledge base, inference engine, and defuzzification interface-as shown in Fig. 3.

The primary steps taken by the fuzzy controller are presented as follows:

(1) Select the input and output variables of the fuzzy controller, and perform the range conversion of the variables. In AUV tracking control, the position error $\boldsymbol{e}(t) = \boldsymbol{\eta}_d(t) - \boldsymbol{\eta}(t)$ is considered to be the input variable, and the speed vector u is considered the output variable.
(2) Determine the fuzzy language values of each variable and the corresponding membership function. The fuzzy language value is usually set as 3, 5, or 7. Then, the corresponding membership function for the selected fuzzy set is defined.
(3) Establish fuzzy control rules or algorithms. This step constitutes the central link in the transition from manual control to the fuzzy controller. The control law is usually composed of a set of fuzzy conditional statements (if-then structure), and the statements are tabulated in a fuzzy rule table. The corresponding control value u can be directly obtained according to $\boldsymbol{e}(t)$ in the table.
(4) Determine the fuzzy reasoning and defuzzification methods. Adaptive methods are chosen according to the various requirements of a system. Thus, a fuzzy quantity is transformed into accurate quantities to fulfill the objectives of the final control strategy.

In recent years, many scholars have conducted research on fuzzy control. Perera et al. (2011) focused on a fuzzy-logic-based intelligent decision-making system that aims to improve the safety of marine vessels by preventing collision. The applications of fuzzy control to AUVs are discussed in the following papers. Aras et al. (2013) investigated linear approximation and piecewise linear approximation control surface methods for tuning parameters of a single-input fuzzy-logic controller to enable depth control of an underwater ROV. Liu et al. (2014) proposed a fuzzy comprehensive evaluation method for assessing the motion performance of AUVs. Chen et al. (2016) presented a computed torque controller with a fuzzy inverse desired trajectory compensation technique for controlling an underwater vehicle and addressed strict constraints on position uncertainties. Ghavidel et al. (2017) presented a robust composite adaptive fuzzy controller for a multi-input-multi-output (MIMO) hybrid dynamic underwater vehicle system that adaptively compensates for unknown uncertainties and disturbances.

Fuzzy control does not depend on an accurate mathematical model of an AUV system. Fuzzy control can easily realize effective control of an uncertain and highly nonlinear system. Fuzzy control is also robust to process and parameter changes and has a strong antidisturbance ability. Fuzzy control theory can be successfully applied to achieve satisfactory control for complex systems that have strong coupling and high nonlinearity and for which a precise mathematical model cannot be established, such as AUV systems. In addition, fuzzy control does not require an online or offline learning process; has a simple calculation procedure; and is suitable for real-time control, especially for collision avoidance in an environment that contains obstacles. However, fuzzy control relies on existing experts' knowledge to establish fuzzy rules. The establishment of fuzzy rules has a high subjective randomness. Therefore, the drawback of fuzzy control is the lack of clearly defined fuzzy rules, which makes it difficult to analyze the local control rules by using mathematical calculations.

3. Adaptive Control

Adaptive control adapts to changes in the characteristics of an object and disturbances through timely correction of controlled object's performance; therefore, the entire control system can be operated efficiently and stably. Adaptive control research is aimed at uncertain objects whose dynamic model is difficult to determine. Adaptive control, a complex feedback control method, has little dependence on mathematical models and requires only a small amount of prior knowledge. There are four types of adaptive control-feedforward, feedback, model reference, and self-tuning. Here, the model reference adaptive control is used as an example to introduce adaptive control. The model reference adaptive control system is illustrated in Fig. 4. The system comprises four parts-the controlled object with unknown parameters (AUV), the reference model (which describes the desired output η_m of the control system), the feedback control law with self-correcting parameters, and the adaptive mechanism of the correction parameters. Here, a is a control parameter of the adaptive law.

The model reference adaptive controller is designed through the following three steps:

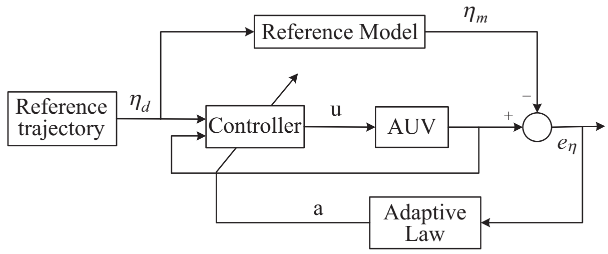

Fig. 4. Model reference adaptive control system for AUV tracking control.

(1) Select the control law including the change in parameters.
(2) Select the adaptive law that is employed to correct these parameters.
(3) Analyze the convergence characteristics of the existing system.

Adaptive control has been extensively used for control systems in recent years (Zhang et al., 2013; Sahu and Subudhi, 2014) because it does not require an accurate dynamic model for the control of an object; thus, it is suitable for the control systems of AUVs. For AUV tracking control, Slotine et al. (1988) applied adaptive control to a mobile robot manipulator. Subsequently, Fossen (1991) used adaptive control to realize the path tracking control of AUVs. Antonelli et al. (2001; 2003) conducted considerable research on the adaptive control of AUVs and performed many experiments in that respect. In recent years, the adaptive control method has been applied in combination with other methods for controlling AUVs. Koofigar et al. (2014) proposed a robust adaptive controller to stabilize the motion control of an AUV that is perturbed by unknown hydrodynamic coefficients, unmodeled dynamics, and environmental disturbances. Makavita et al. (2015) presented an improved composite model reference adaptive control method for controlling AUV motion. This model can enable quick recovery of AUVs from thruster failures compared with the standard model reference adaptive control. Pezeshki et al. (2016) presented an adaptive fuzzy sliding mode control scheme for the position tracking problem. Sarhadi et al. (2017) suggested a novel model reference adaptive controller with an antiwindup compensator for AUV control; they also implemented the proposed controller in the hardware during a loop simulation of an AUV.

Although adaptive control has noteworthy advantages and has undergone more than 50 years of development, its application remains limited for four main reasons. First, it is difficult to obtain a general solution with the adaptive control theory and the adaptive control is difficult to promote. Second, the dynamic performance of some adaptive controllers' starting processes or transition processes cannot meet real-life requirements. Third, there is a contradiction between control precision and parameter estimation. Fourth, the adaptive control method is complicated and cannot be used for unified and standardized controllers.

4. Sliding Mode Control

Sliding mode control is a type of nonlinear control and is suc-

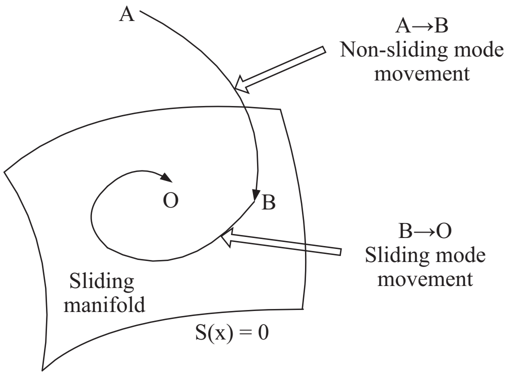

Fig. 5. Sliding mode control.

cessfully used for controlling discontinuities. The difference between sliding mode control and other control methods is that the structure of the system for sliding mode control is not fixed. During the dynamic process, the structure of the system can be changed constantly and purposefully based on the current state of the system. The basic concept of sliding mode control is designing a sliding manifold; the system can reach the sliding manifold from any point in the space through the control law in a finite time. Moreover, a sliding mode motion is performed on the sliding manifold; the system slides to a balance point, as shown in Fig. 5. A sliding manifold is not dependent on the parameters of the controlled object and disturbances. Thus, sliding mode control has advantages such as a fast response, insensitivity to parameter variation and disturbance, and no need for system online identification. These advantages make sliding mode control very suitable for the dynamic control of AUV systems (Bagheri and Moghaddam, 2009; Zhu and Sun, 2013; Xu et al., 2015; Chu and Zhu, 2016).

The design of a sliding mode dynamic controller entails two main steps-selecting a sliding manifold S(x) and designing a control law. As shown in Fig. 6, the position error $\boldsymbol{e}_\eta(t) = \boldsymbol{\eta}_d - \boldsymbol{\eta}$ is the input of the sliding mode controller, and the force $\boldsymbol{\tau}$ acting on a AUV is the output of the controller.

Sliding mode control has been rapidly developed and widely used for the AUV control problem for many decades. Zhang et al. (2015) proposed an adaptive terminal sliding mode control method for fault tolerance control for underwater vehicles. Wang et al. (2016) developed a robust nonlinear controller with terminal sliding mode control for exponentially driving an underwater vehicle on a predefined trajectory at a constant forward speed. Londhe et al. (2016) presented an uncertainty-disturbance-estimator-based sliding mode control scheme for dynamic control of an AUV system, which is effective for compensating for the uncertainties in hydrodynamic parameters and rejecting unpredictable disturbances due to ocean currents. Zakeri et al. (2016) presented dynamic model and robust control based on sliding mode control for a miniature unmanned underwater vehicle (UUV) equipped with a water jet propulsion system, and they constructed a miniature UUV to investigate the performance of the proposed water jet propulsion system and con-

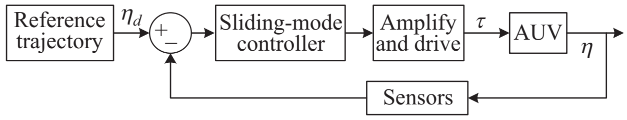

Fig. 6. Sliding mode control for AUV tracking.

Fig. 7. Structure of the backstepping controller.

trollers in regulating and tracking the desired signal.

Sliding mode control has two advantages. First, it has no sensitivity to parameter variation and the suppression of interference. Second, it does not require an accurate dynamic model. Sliding mode control is thus very suitable for the control of AUVs. However, the main obstacle for applying sliding mode control is its high-frequency switching control behavior (chattering problem). Frequent chattering causes high heat loss from the electric power circuit and excessive wear of the actuator mechanism. These factors have a substantial influence on precision equipment such as AUVs. Moreover, high-frequency oscillations can alter nonmodeled high-frequency power terms and cause a decrease in the control performance. To solve the chattering problem, many researchers have suggested improved methods. Soylu et al. (2008) stated that adaptive items can be constructed to replace traditional switching items and achieve chatter-free tracking control. Chen et al. (2011) integrated a neural network into sliding mode control to decrease the chatting problem. Li et al. (2013) established a delay-dependent condition for sliding mode dynamics in terms of linear matrix inequalities, which eliminated the chattering problem in a traditional variable structure system. Basri et al. (2014) used a simple fuzzy system to attenuate the chattering problem. Although these methods are helpful in reducing the chattering problem of sliding mode control, a satisfactory result has not yet been obtained.

5. Backstepping Control

Backstepping control is a common control strategy that is widely used in the tracking control of mobile robots, and is also suitable for AUV control. The basic concept of the backstepping control algorithm is to design a backstepping controller that enables the closed loop system to achieve asymptotical stability. The algorithm can cope with a large initial state error. The basic structure of the backstepping controller is shown in Fig. 7.

The control law of the backstepping method is defined as follows:

$$\begin{cases} u = u_d + k_1\left(e_x \cos\psi + e_y \sin\psi\right) \\ v = v_d - k_1\left(e_x \sin\psi - e_y \cos\psi\right) \\ r = r_d + k_2 \sin\left(\dfrac{e_\psi}{2}\right) + 2u_d\left(e_y \cos\dfrac{\psi_d + \psi}{2} - e_x \sin\dfrac{\psi_d + \psi}{2}\right) \\ w = w_d + k_3 e_z \end{cases} \tag{4}$$

where k_1, k_2, and k_3 are constants; u_d, v_d, w_d, and r_d are the initial velocities of an AUV that can be obtained using the following formula:

$$\begin{cases} u_d = \dot{x}_d \cos\psi_d + \dot{y}_d \sin\psi_d \\ v_d = \dot{y}_d \cos\psi_d - \dot{x}_d \sin\psi_d \\ r_d = \dot{\psi}_d \\ w_d = \dot{z}_d \end{cases} \tag{5}$$

When the position error $e_\eta(t) = [x_d - x \quad y_d - y \quad z_d - z \quad \psi_d - \psi]^T = [e_x \quad e_y \quad e_z \quad e_\psi]^T$ and reference position $\boldsymbol{\eta}_d = [x_d \quad y_d \quad z_d \quad \psi_d]^T$ are substituted into the backstepping method, the output $\boldsymbol{u} = [u \quad v \quad w \quad r]^T$ is the controlled velocity of an AUV.

Backstepping controllers are widely used in the tracking control of AUVs (Jia et al., 2012; Wan et al., 2013; Wu and Karkoub, 2014; Cervantes et al., 2016). However, the backstepping algorithm is usually combined with other control algorithms. Gao et al. (2014) presented backstepping-based adaptive control to ensure that docking errors are asymptotically stable with the feedback control and adaptation laws of a fully actuated AUV equipped with a USBL transceiver. Sun et al. (2014) extended a kinematic controller based on bioinspired backstepping control to incorporate a sliding mode control technology and thus achieved dynamic control. Liu et al. (2016) proposed a nonlinear disturbance-observer-based backstepping finite-time sliding mode control scheme for trajectory tracking of underwater vehicles subject to unknown system uncertainties and time-varying external disturbances. Liang et al. (2017) proposed an adaptive robust control system with backstepping and sliding mode control, they adopted fuzzy logic theory to approximate unknown nonlinear functions for solving the problems of nonlinearity, uncertainties, and external disturbances in the path to be traced.

The backstepping controller design is simple and its stability can be proved by Lyapunov theory. The controller can cope with a large error in the initial state; however, its drawback is obvious. Because the backstepping control law is directly related to the state error, large velocity changes are generated due to a large initial state error. The phenomenon of speed jump occurs when the state changes suddenly. Dynamic factors are considered in the design of the backstepping control law. This implies that the required acceleration and force may be beyond the control constraints at the jump points, which is a problem that must be solved in backstepping control.

6. Neural Network Control

Neural network control entails utilizing a neural network as a controller or an identifier in the control structure. This control method mainly aims at solving the control problem of a complex, nonlinear, uncertain, unknown system in an uncertain environment. A neural network can approximate any nonlinear function with arbitrary precision. Neural network control has adaption and self-learning abilities for handling complex problems involving uncertainty and can resolve problems involving large-scale, real-time calculation by using a parallel processing mechanism. The process of neural network control for AUV tracking is illustrated in Fig. 8. The position error $\boldsymbol{e}_\eta(t) = \boldsymbol{\eta}_d - \boldsymbol{\eta}$ is considered as the input of the neural network; the output of the network is the speed vector acting on the AUV obtained by the previously learned neural network. K_u is a control parameter.

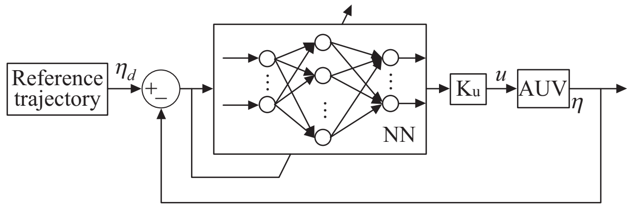

Fig. 8. Neural network control for AUV tracking.

Because a neural network does not require an accurate dynamic model, and the nonlinear performance of AUVs can be fitted by neural networks (Gao et al., 2015; Sun et al., 2016; Shojaei, 2017; Zhu et al., 2017), control methods based on neural networks have received considerable attention. Sun et al. (2013) presented a bioinspired neurodynamics model used to design a kinematic controller, which can smooth the speed value of AUVs and avoid thrust overrun. Aras et al. (2015) used neural network predictive control for the depth control of an ROV, achieving a fast system response. Gao et al. (2017) designed an adaptive neural network controller by combining a single-hidden-layer neural network and sliding mode control for underwater vehicles to trace the desired trajectory with estimated global pose information. Cui et al. (2017) studied the integration of two neural networks (a critic neural network and an action neural network) and adaptive control for the trajectory tracking problem in the horizontal plane.

Neural network control has received extensive attention in the research on AUV tracking control due to its nonlinear, self-learning, and other intelligent characteristics. However, obtaining training samples is difficult, and the sample learning process lags, which makes real-time application of the control system difficult (Wai and Lin, 2013).

7. Other Methods for AUV Tracking Control

Apart from the previously described commonly used methods, the state feedback linearization and H-infinity control methods have also been applied for the control of AUVs in recent years. The basic concept of the state feedback linearization method, proposed by Freund (1973), is transforming a nonlinear system into a linear system. Moreover, Subudhi et al. (2013) provided a structured output feedback controller based on a linear system to realize vertical tracking control of AUVs. Kamarlouei et al. (2015) applied the feedback linearization method to convert a nonlinear system into a convenient linear one and then applied a robust technique to guarantee the stability and performance of the system. The feedback linearization method is highly applicable to AUVs. However, the drawback of the method is that the exact dynamics model of AUVs must be known, which is difficult to achieve in practice. The H-infinity control method has been applied to AUVs because it is robust. For instance, Nag et al. (2013) proposed an H-infinity controller for considering the uncertainties in hydrodynamic parameters that arise due to changing operating conditions. The controller provides a suitable control action for tracking a desired point and as well as disturbance rejection. Yang (2016) addressed the problem of delay-dependent H-infinity control in the form of linear matrix inequality (LMI) for an AUV system with external disturbance. The steps of H-infinity control are linearization and planning of the control law. The control performance of H-infinity control is comparable with that of traditional PID control, which cannot entirely meet the demands of nonlinear control. In addition, the complicated design process, high designer experience requirements, and high control performance, which are similar to the requirements of tradition control methods, restrict the application of H-infinity control for use in AUVs.

IV. FURTHER STUDY

Trajectory tracking control methods for AUVs have been developed; however, some specific limitations in algorithm design exist. For example, PID control depends on the model of the controlled object and can be applied only to a single input and single output system. Fuzzy control depends on existing knowledge for establishing fuzzy rules. Moreover, fuzzy control has a high subjective randomness and a low scope of application to practical situations. The structure of the adaptive method is complicated, and obtaining a design method for unified and standardized controllers is difficult. Sliding mode control has a chattering problem. Backstepping control has a speed jump problem. In neural network control, obtaining training samples is difficult, the sample learning process lags, and the real-time performance is poor. On the basis of the past research and estimated future development of AUVs, the current research on trajectory tracking for AUVs is mainly focused on the following aspects:

1. Theoretical Research

1) Research on New Methods of Trajectory Tracking for AUVs

Novel control methods are crucial for enhancing the trajectory tracking control of AUVs. At present, considerable research on the trajectory tracking control of unmanned ground vehicles exists (Shao et al., 2015; Al-Khatib et al., 2015; Kulić et al., 2016); however, few studies have addressed the trajectory tracking control of AUVs. The trajectory tracking method for mobile ground robots can be extended to AUVs by considering the three-dimensional complex underwater environment. The exploration and pursuit of marine resources will lead people to develop new methods for AUV tracking control (Li et al., 2014).

2) Optimization of Existing Algorithms

Existing algorithms can be used in combination with trajectory tracking control algorithms to overcome the limitations of the tracking control algorithms. Many scholars have optimized existing algorithms and have verified the use of the algorithms for tracking control by using a series of simulation experiments (Chen et al., 2015). Moreover, the ergodic property of chaotic motion is used to optimize the network weights of neural network control, which can improve the search efficiency by compressing the optimal variable interval. The trajectory tracking accuracy can be improved by using a genetic algorithm to optimize the parameters of a backstepping control law.

3) Intelligent Compound Control

Intelligent compound control is an effective method for improving the performance of intelligent control (Ullah et al., 2015) and thus has attracted considerable attention from researchers. Considering the advantages of the existing tracking methods, two or more algorithms can be combined to overcome each other's drawbacks. Fuzzy control and neural network control can be used in combination with adaptive control. Fuzzy rules are obtained using the adaptive learning feature of neural networks. This simplifies the structure of adaptive control and reduces the subjective randomness of fuzzy control.

4) Simulation of the Underwater Environment and Improvement of the Performance of Algorithms

An AUV and an unmanned ground vehicle differ due to the environment in which they operate. Ocean currents increase the difficulty of AUV tracking control. The ocean current is an unknown time-varying parameter and is an external interference factor during AUV tracking control. Therefore, the robustness and stability of algorithms should be evaluated under the effect of ocean currents.

2. Application Research

1) Use of Theoretical Research for Practical Applications

At present, most of the research on trajectory tracking control of AUVs is based on the design and simulation of algorithms (Özgür et al., 2009); however, few research results have been applied in practice. Applying tracking control to an AUV for practical application will involve many technical problems such as the malfunctioning of underwater positioning, communication, target detection, and recognition technologies. This is why many control algorithms are confined to the simulation stage. Thus, the application of trajectory tracking control in practice is a major development direction (Ni et al., 2016).

2) Fault Tolerance Control

In practical applications, any system inevitably malfunctions to some extent. Therefore, fault tolerance control is sought to be the last line of defense to ensure safe operation of a system. Fault tolerance control is essential for AUV trajectory tracking control. In future research, the process by which trajectory tracking can be accomplished when the thrusters of an AUV have malfunctioned completely or partially should be identified.

V. CONCLUSION

Research on AUV tracking control has made salient progress. However, some important limitations and problems are yet to be further explored. In this paper, several AUV tracking control methods are discussed. Each of them has advantages and limitations. The most suitable control method should be chosen by identifying the characteristics of the specific objects that are controlled and requirements of the control performance. The structure, feasibility, and cost of the control method should also be considered. A combination of two or more methods can be adopted if necessary. With the development of an intelligent control technology, new control algorithms and strategies can be developed to achieve the desired control.

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