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QPSO-model predictive control-based approach to dynamic trajectory tracking control for unmanned underwater vehicles

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ABSTRACT

In this paper, a model predictive control (MPC) method based on quantum-behaved particle swarm optimization (QPSO), combining with sliding mode control (SMC), is studied to solve the dynamic trajectory tracking problem of Unmanned Underwater Vehicle (UUV) in three-dimensional underwater environment. First, the kinematic controller based on QPSO-MPC is designed to obtain the velocity signal. QPSO limits the velocity of UUV within a specified range to handle the speed jump problem when compared with backstepping control. Then kinematic control is extended to dynamic control for verifying the feasibility of QPSO-MPC in the realistic dynamical UUV system. Here SMC is adopted in dynamic control because of its good robustness and anti-interference performance. The combination of kinematic and dynamic controllers can efficiently realize the trajectory tracking of UUV. The experimental simulation results prove that the algorithm proposed in this paper can solve the speed jump and the driven saturation caused by speed jump, and also can satisfy the propeller constraints of UUV.

1. Introduction

UUV (Wynn et al., 2014; Xu et al., 2016) has been widely used in ocean exploration and submarine activities due to its mobility, security, intelligence and so on. It is getting more and more attention from industry and even the military. But the design of UUV system, especially the design of its control system, is a big challenge for engineers and researchers. The trajectory tracking (Yan et al., 2012, 2015) is one of the main problems in the control system of UUV and is also the basis for the realization of various tasks. Therefore the research on it is particularly significant. The content of trajectory tracking is making UUV arrive and accurately track the desired trajectory until getting to the target location within a limited period of time. At present, the main research methods of it include: PID control, adaptive control, fuzzy control, neural network control, backstepping control, model predictive control, sliding mode control, and so forth.

PID control method (Xiang et al., 2013) refers to a linear combination of the proportional, integral, and derivative terms of the control deviation to form the control law, the design is simple and low complexity. But the performance of traditional PID control is not ideal because of the nonlinear and uncertain characteristics of UUV. Although some scholars presented a variety of PID controllers which have being improved later, like fuzzy PID control (Xiang et al., 2016), adaptive PID control (Chamsai et al., 2015) and so on. The interference suppression ability of these improved methods is mainly for the known interference and the performance is always directly related to hydrodynamic model accuracy. Therefore, the PID method can't solve the insufficient robustness.

Adaptive control method (Liu et al., 2010; Sahu and Subudhi, 2016; Pezeshki et al., 2016) is designed for uncertain objects whose dynamic model is difficult to determine. Adaptive control has little dependence on mathematical information and requires only a small amount of prior knowledge. It doesn't require precise dynamic model of UUV, all the dynamic parameters can be obtained by adaptive method. Its design can be summarized in three parts: 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 is suitable for controlling a complex system such as UUV. However, the construction of it is complex and it requires high demand for parameter changes, which affects its further application.

The essence of fuzzy control (Liu et al., 2014; Xiang et al., 2017a,b,c; Sun et al., 2017) 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

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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. So it doesn't depend on the accurate mathematical model of control system, it has a strong robustness to process and parameters' change, and also has a strong anti-interference ability. Unfortunately, fuzzy control relies on gained experience to establish the fuzzy rule; and the establishment of fuzzy rule is very subjective.

Neural network control method (Zhu et al., 2017a,b; Sun et al., 2014a,b; Xiang et al., 2017a,b,c) entails utilizing a neural network as a controller or an identifier in the control structure. It can approximate any nonlinear function with arbitrary precision. Weights between inputs and outputs of a control system are obtained by previous samples leaning. Then the weights are used to calculate the corresponding outputs for a set of inputs of system at the current time. It doesn't also need accurate dynamics model, the nonlinear performance of UUV can be fitted by neural network. It has the characteristics of non-linear, self-learning, intelligence. Nevertheless, neural network control is not only difficult to obtain the training samples, but also the learning process of sample is lagging, which makes the real-time performance of control system is poor.

Backstepping control method (Sun et al., 2014a,b; Wang et al., 2015; Xiang et al., 2015) is a common method used to realize UUV trajectory tracking at present. Backstepping control refers to use the reference system's control variables and the deviation of the control system to carry out linear combination, then control variables of the control system can be obtained. Its design is relatively simple and easy to understand, and its stability can be proved by the Lyapunov stability theory. The theory of backstepping control is to devise a backstepping controller to make the closed-loop system asymptotically stable. It can deal with the situation with large error at initial state. However, its shortcoming is also obvious. The design of backstepping control law is directly related to the state error. A large speed change is generated due to the large initial error, which will cause the speed jump phenomenon when state suddenly changes. Extended to dynamic control, this means that the required force/torque at the jump point may exceed the maximal force/torque that UUV can offer.

For the speed jump problem in backstepping control, MPC (Beal and Gerdes, 2013; Gao et al., 2016) is proposed to solve it in virtue of the constraints for UUV velocity. MPC is an advanced control methodology based on the model of plant and has three characteristics, namely prediction model, rolling optimization and feedback correction. The model of UUV is needed in MPC, but can be reasonably simplified. So it is suitable for complex systems such as UUV. The biggest attraction of MPC is that it has the capability to explicitly handle constraints. This ability comes from its model-based prediction of system future dynamic behavior, and then the constraints are acted on future inputs, outputs or state variables. For UUV system, a variety of constraints for velocities are incorporated into QPSO (Li, 2015; Zeng et al., 2016) optimization process, which can effectively solve the speed jump problem very well. QPSO is adopted in the rolling optimization process in terms of the solution quality, robustness and the convergence property. Moreover, MPC has the advantages of robustness and stability. Using rolling optimization strategy can compensate for the uncertainties caused by model mismatch, distortion and interference, this leads to better dynamic performance. Then it is extended to dynamic control, sliding mode control (Xu et al., 2015; Londhe et al., 2016; Xiang et al., 2017a,b,c) has been used in the dynamic tracking control for several decades and it has the advantage in robust character of parameter insensitivity and disturbance rejection. In order to resolve the speed jump and the driven saturation caused by speed jump, a novel dynamic tracking control of UUV is realized by combining MPC and sliding mode control in this paper.

The rest parts of the paper are organized as follows: In Section 2, the description of trajectory tracking is introduced, the kinematic and dynamic model of UUV are established. Propellers arrangement and thrust normalization are carried out for the specific "Falcon" robot. In Section 3, QPSO-MPC is used to design the kinematic controller for obtaining the desired speed. Then sliding mode control is presented and used to design the dynamic controller based on the desired speed. The combination of two controllers can eventually achieve stable trajectory tracking control for Falcon. In Section 4, the simulation results are presented and analyzed; the results highlight the effectiveness of the proposed algorithm when compared with the backstepping control algorithm. In Section 5, some concluding remarks are summarized; and the research about the trajectory tracking of UUV in the future is discussed.

2. The description of trajectory tracking and modeling of UUV

2.1. Trajectory tracking

The trajectory tracking problem means that UUV starts from a given initial position, arriving and tracking a geometric path associated with time with given velocity by using tracking control law.

Since the 3D motion situation is studied in this paper, only considering the tracking control problem under four most common degrees of freedom: surge u, sway v, heave w and yaw r. The diagrammatic sketch of trajectory tracking is shown in Fig. 1. The actual position of UUV represents $\boldsymbol{\eta} = [x \quad y \quad z \quad \psi]^T$. The geometric path associated with time (shown as green dotted line in Fig. 1) represents $\boldsymbol{\eta_d} = [x_d(t) \quad y_d(t) \quad z_d(t) \quad \psi_d(t)]^T$, every variable is a function of time t. The given velocity is the reference control input $\boldsymbol{\nu}_d(t) = [u_d(t) \quad v_d(t) \quad w_d(t) \quad r_d(t)]^T$.

UUV tracks the reference trajectory by controlling the actual surge speed u , sway speed v, heave speed w and yaw speed r of UUV, and finally makes the error between actual trajectory and desired trajectory converge to zero.

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

2.2. Modeling for UUV

Modeling for UUV covers kinematic and dynamic modeling. Kinematic modeling explains the geometric relationship between position, velocity of UUV. Dynamic modeling analyses forces changes of UUV during the accelerated motion process (Yang et al., 2015).

2.2.1. Kinematic modeling

Kinematic modeling involves the coordinate system of UUV, including two parts: the inertial coordinate and the body-fixed coordinate. The inertial coordinate, which is also called the earth coordinate, origin of it is a point on earth. The body-fixed coordinate is fixed on UUV, origin of it is the carter of UUV gravity, it moves along with UUV. UUV coordinate systems are shown in Fig. 2.

The UUV kinematics equation is:

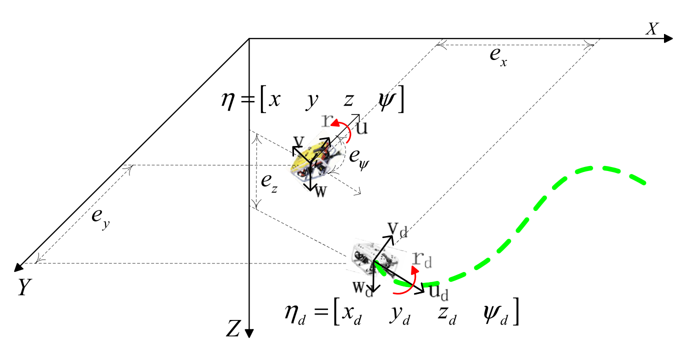

Fig. 1. The diagrammatic sketch of trajectory tracking.