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Optimization Design of Track Control Algorithm Based on Convolutional Neural Network

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Abstract: At present, the track control of unmanned surface vessel (USV) is mainly divided into direct track control and indirect track control, both of which have their advantages in the aspect of USV track control. Though having high control precision, the former still fails to meet the related requirements. To tackle this problem, the nonlinear model predictive control (NMPC) algorithm was optimized based on the convolutional neural network (CNN) in order to design a direct USV track controller. In consideration of the nonlinearity and time lag problems that are likely to occur in USV track control, the convolutional neural network was used to solve the optimal control sequence of the predictive control algorithm. The simulation test indicates that this algorithm has effectively improved the accuracy and real-time performance of track control.

1. Introduction

Unmanned surface vessel [1] (abbreviated as USV) is a surface vessel with unmanned operation. Featured by strong maneuverability, fast speed, and automatic operation, USV mainly takes the place of man to execute some special tasks which are dangerous for man.

Accurate track control is the fundamental guarantee for USV to execute various tasks and a research hotspot in the field of USV motion control. USV may be impacted by external disturbance in practical navigation environment, which will then give rise to model uncertainties.

USV track control algorithm is mainly divided into two types: direct control algorithm, which directly acts on the track with high control precision and high algorithm complexity; indirect control algorithm [2-3], which transforms the track control problem into a course control. An indirect control algorithm decomposes the track control system into a double closed loop control system, where the inner loop consists of the traditional course control algorithm while the course algorithm is used in the outer loop. Although its control precision is relatively low, it can directly use the existing autopilot technology, which is its advantage and makes it more suitable for engineering application.

In view of the nonlinearity and time lag problems that USV track control is prone to, the nonlinear model predictive control (NMPC) algorithm was used in this paper to perform direct USV track control, and the optimal control sequence of the predictive control algorithm was solved via the convolutional neural network (CNN) algorithm in order to further improve the accuracy and real-time performance of track control. The feedback correction was adopted for the model predictive control to cope with various uncertain problems (including system disturbance, model mismatch, etc.). Furthermore, the local optimization problem was solved on line through the rolling optimization strategy, thus reducing the online optimal calculation workload and elevating the response speed of the algorithm to a great extent.

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2. Direct track control through CNN-optimized NMPC algorithm

2.1. Controller design

To solve the nonlinearity and time lag problems in USV track control, the direct USV track control was realized via the NMPC algorithm, the optimal control sequence of which was solved through the CNN algorithm, to further improve the accuracy and real-time performance of track control. The overall flow of this nonlinear model predictive controller is shown in Fig. 1.



Fig. 1 Overall flow of nonlinear model predictive controller.

The NMPC-based track controller directly controls USV track according to the preset track information and initial state information of the USV. In the NMPC-based USV track control system, the output quantity of the track controller consists of the controlled quantities of USV rudder angle and navigational speed. After receiving the feedback signal (including USV position coordinates, and course angle information) of USV state quantity, the controller will conduct self-correction of internal predicted output values and then local optimization using the CNN algorithm to acquire the controlled quantities of USV rudder angle and navigational speed at the next moment [4-5]. The NMPC track controller mainly includes USV prediction model, objective function and constraint information. The controller design contents will be hereby introduced from the abovementioned three aspects.

The control flow of the NMPC-based USV track control system is shown in Fig. 2. First, the preset track information is discretized to acquire the information of the first target track point. After then, the NMPC-based track controller will do actions according to the information of this target track point, calculate the controlled quantity of USV rudder angle and the needed navigational speed, followed by trajectory tracking. The next track point on the discretized track information is obtained to repeat the above actions until the last point on this track information.



Fig. 2 Flowchart of track control algorithm.

2.2. USV prediction model

Generally, the motion state of USV is described by six degrees of freedom: rolling, pitching, yawing, swaying, surging and heaving. For the sake of such description, a USV coordinate system (Fig. 3) needs to be constructed, which contains the fixed coordinate system $o - x_1y_1z_1$ (abbreviated as "fixed system") and kinetic coordinate system G - xyz (abbreviated as "kinematic system"). The former is an inertial coordinate system fixed on the earth, while the latter is an attached coordinate system moving with the vessel. In the kinetic coordinate system, the origin is set as the gravity center G of USV, Gx is the direction of horizontal plane of the USV, Gy is the direction of its transverse section and Gz is the direction of longitudinal midship section. The positive direction follows the right-handed system.



Fig. 3 USV coordinate system

The motions parameters involved in $o - x_1y_1z_1$ are listed in Tab. 1, where X, Y and Z are the projections of the external force borne by USV on the attached coordinate system G - xyz; K, M and N are the projections of USV torque on the attached coordinate system G - xyz; u, vand ware the projects of USV speed on the attached coordinate system G - xyz; p, q and rare the projections of angular speed of USV on the attached coordinate system G - xyz; p, q and rare the projections of USV gravity center under the inertial coordinate system $o - x_1y_1z_1$; ϕ , θ and ψ are three Euler angles of USV in the inertial coordinate system $o - x_1y_1z_1$; where ϕ is heeling angle, θ is trim angle and ψ is azimuth angle.

Degree of freedom	Force and torque	Navigational speed and angular speed	Position and Euler angle
Surging	Х	u	Х
Swaying	Y	V	у
Heaving	Z	W	Z
Rolling	К	р	φ
Pitching	М	q	θ
Yawing	Ν	r	ψ

Tab. 1 Motion parameters of USV.

The USV navigational conditions in ocean can not only be expressed by the speed vectors u, v and w and the angular speed vectors p, q and r but also by the derivatives $\dot{x}, \dot{y}, \dot{z}$ of position vectors in the fixed coordinate system and the derivatives $\dot{\varphi}$, $\dot{\theta}$ and $\dot{\psi}$ of attitude vectors of Euler angle. The

expression mode can be determined by researchers according to the requirements of their own research projects. In addition, the "kinetic system" and "fixed system" in USV still present the following transformation relation [6]:

a)The coordinate transformation formula between derivatives $\dot{x}, \dot{y}, \dot{z}$ of position vectors and speed vectors u, v, w:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{y}} \\ \dot{\mathbf{z}} \end{bmatrix} = \mathbf{T}_{\mathbf{V}} \begin{bmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{w} \end{bmatrix}$$
 (1)

Where, the transformation matrix T_V is as below:

$$T_{V} = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\cos\psi + \sin\phi\sin\psi\\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\sin\theta\sin\psi - \sin\phi\sin\psi\\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$$
(2)

The high attention is paid to USV motion on the horizontal plane in the direct USV track controller design, and the influences of heeling, trimming and heaving on USV motion are temporarily neglected. Therefore, the six degrees of freedom model (1) and formula (2) of USV are simplified to obtain its three degrees of freedom model as below:

$$\begin{vmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{y}} \\ \dot{\mathbf{y}} \end{vmatrix} = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{r} \end{bmatrix}$$
(3)

Where \dot{x} and \dot{y} are the derivatives of x-coordinate and y-coordinate of USV position information, respectively; $\dot{\psi}$ is the derivative of USV heading angle; ψ is USV heading angle; udenotes the longitudinal component of USV speed; vis the transverse component of USV speed; r is the angular speed of USV.

During the navigation process of USV, the influence of lateral drift angle on USV motion can be neglected under $u \gg 0$ and $v \approx 0$ conditions, and then Eq. (4-6) can be further simplified into the following form:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{y}} \\ \dot{\boldsymbol{\psi}} \end{bmatrix} = \begin{bmatrix} \cos \psi & 0 \\ \sin \psi & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{r} \end{bmatrix}$$
(4)

It is known that the relationship between angular speed rand rudder angle δ of USV can be expressed by Eq. (5), where Kis turning ability index of USV; T is its tracing ability index. The values of Kand Tcan be acquired through zig-zag maneuver test of USV, and the concrete calculation method is described in Literature [7].

$$T\dot{r} + r = K\delta \tag{5}$$

Formula (5) is substituted into formula (4), followed by discretization processing at sampling time T_s , and then the following difference equation can be obtained:

$$\begin{cases} x(k) = x(k-1) + u * T_{s} * \cos \psi \\ y(k) = y(k-1) + u * T_{s} * \sin \psi \\ \psi(k) = e^{-\frac{T_{s}}{T}} \psi(k-1) + k \left(1 - e^{-\frac{T_{s}}{T}}\right) \delta(k-1) \end{cases}$$
(6)

In USV track control, if the matrix form of state quantity is set as $\chi = [x \ y \ \psi]^T$ and that of controlled quantity as $u = [u \ \delta]^T$, then according to the relationship between the input controlled quantity and output state quantity by USV, the general expression of nonlinear USV discrete model can be acquired as:

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$$\chi(t+1) = f(\chi(t), u(t))$$
(7)

2.3. Objective function

In the NMPC-based track controller, the selection of objective function should sufficiently reflect the degree to which the track is taken for reference in USV trajectory tracking. By reference to the soft constraint method expounded in Literature [8], the prediction model of USV track control is combined to design the following objective function:

$$J(k) = \sum_{i=1}^{H_p} \left\| \boldsymbol{\chi} \left(k + i | t \right) - \boldsymbol{\chi}_d \left(k + i | t \right) \right\|_{\mathcal{Q}}^2$$

$$+ \sum_{i=1}^{H_c - 1} \left\| \Delta \mathbf{u} \left(k + i | t \right) \right\|_{\mathcal{R}}^2 + \rho \varepsilon^2$$
(8)

Where H_p is the prediction time domain of NMPC track controller; H_c is its control time domain; ρ is weight coefficient; ϵ is relaxation factor.

This objective function not only considers the tracking ability of USV for the present track but also considers the increment constraint of controlled quantity, so it effectively avoids the mutation of controlled quantity. Furthermore, the relaxation factor is added into the objective function to guarantee feasible solutions.

2.4. Constraint conditions

According to the control features of USV itself, the rudder angle constraint and navigational speed constraint should be considered during the output of controlled quantity. The rudder angle constraint and increment constraint of controlled quantity of rudder angle of USV model in this paper are as follows:

$$\begin{cases} -35^{\circ} \le \delta \le 35^{\circ} \\ -35^{\circ} \le \Delta\delta \le 35^{\circ} \end{cases}$$

$$\tag{9}$$

The USV navigational speed constraint and its increment constraint are:

$$\begin{cases} 0m/s \le u \le 6.17m/s \\ -6.17m/s \le \Delta u \le 6.17m/s \end{cases}$$
(10)

To sum up, the USV nonlinear track control problem can be expressed by the following optimization problem with limited time domain:

$$\min_{\boldsymbol{\chi}(k), \mathbf{u}(k)} J(\boldsymbol{\chi}(k), \mathbf{u}(k))$$
s.t. $\boldsymbol{\chi}_{k+1,t} = f(\boldsymbol{\chi}_{k,t}, \mathbf{u}_{k,t}), k = t, \dots H_p - 1$

$$\mathbf{u}_{\min} \leq \mathbf{u}(k) \leq \mathbf{u}_{\max}$$

$$\Delta \mathbf{u}_{\min} \leq \Delta \mathbf{u}(k) \leq \Delta \mathbf{u}_{\max}$$
(11)

2.5. Algorithm flow and steps

The real-time performance and accuracy of the optimization algorithm have a direct bearing on the control effect of the designed track controller. As it is difficult to acquire an analytical solution to the nonlinear objective function, in view of the local optimization problem shown in formula (11), the CNN algorithm is hereby used to solve the optimal control sequence, and the concrete solving steps are as follows:

(1) Initialize parameters: initial temperature, cooling rate and ending temperature are T0, q and Tend, respectively, which correspond to number of iterations L at each temperature, and take the controlled quantity matrix at the current time as the initial feasible solution matrix u_0 ;

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(2)Solve the local optimal solution for the current temperature T, namely repeat step (3) to step (6);

(3) Random generate a new solution u_1 for the current feasible solution matrix u_0 within the constraint range of controlled quantity;

Solve the increment $dJ = dJ(u_1) - dJ(u_0)$ of the objective function Jshown in formula (11) (4)relative to feasibility solution matrixes u_0 and u_1 , that is, $dJ = dJ(u_1) - dJ(u_0)$;

Determine the present local optimal solution according to the judgment conditions, namely, (5) if dJ < 0, the new solution u_1 can be regarded as the optimal solution to substitute u_0 ; or otherwise calculate the acceptable probability $\exp\left(\frac{-df}{T}\right)$ of the new solution, and when the acceptable probability satisfies $\exp\left(\frac{-df}{T}\right) > rand$ (rand is a random number within the interval of (0,1)), it can also be considered that the new solution u_1 is the optimal solution, and then it is used to substitute u_0 ; If this is not satisfied, u_0 will be still considered as the optimal solution;

The end condition is set so that the present optimal solution will be output when temperature T is attenuated to the end temperature Tend. If this end condition is not met, Step 2 will be repeatedly executed after the present temperature T is attenuated according to the cooling rate.

3. Simulation test

3.1. Overview of test vessel

The basic parameters of the test vessel in this paper are seen in Tab. 2.

Main parameter	Vessel length/m	Length between perpendiculars/m	Draft/m
Numerical value	8.075	8	0.6
Molded depth/m	Full-load displacement/T	Maximum navigational speed /kn	Cruising speed /kn
1.15	3.2	12	6

Tab.	2	Main	USV	parameters
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In formula (6), the turning ability index Kand tracing ability index Tof USV can be acquired through a $\frac{10^{\circ}}{10^{\circ}}$ zig-zag maneuver test of the test vessel. The zig-zag $(\frac{10^{\circ}}{10^{\circ}})$ maneuver test of the test vessel was performed on a calm lake face, and the obtained heading angle-rudder angle relation change curve of the test vessel is shown in Fig. 3-3. The USV test data were fitted through the calculation method mentioned in Literature [9-10], and the solved values of parameters Kand Tof the test vessel are 0.49 and 1.94, respectively.



Fig. 4 Zig-zag maneuver test result

3.2. Simulation verification

Through the test vessel parameters given in Tab. 2, the track control effect of the designed track controller optimized based on the CNN algorithm will be simulated. The parameters are set as follows:

Initial state of USV: position coordinates (0,-22), course angle $\psi = 0^{\circ}$ and navigational (1)speed v = 0m/s.

(2) Preset the curve trajectory information: an arc trajectory with origin being (0,0) and radius being 20 m. The expected tracking velocity is $v_d = 3m/s$.

Set the sampling time as 50ms. (3)

(4)Controller parameter setting: prediction time domain is $H_p = 10$, control time domain is

 $H_p = 10$ and weight matrixes are $Q = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 100 \end{bmatrix}$ and $R = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix}$. Parameters of CNN-optimized controller: initial temperature is $T_0 = 200$, end temperature is $T_{end} = e^{-3}$ and cooling

rate is q = 0.9, which correspond to number of iterations L = 200at each temperature.

The simulation test was verified under interfered and non-interfered conditions, respectively. Under the interfered circumstance, the external interference signal is set as 25% of the USV navigational speed, and the influence of interference signal on USV track control system can be expressed by formula (12):

$$\begin{aligned} x(k) &= x(k-1) + v * T_s * \cos \psi \\ y(k) &= y(k-1) + v * T_s * \sin \psi + 0.25 * T_s * v \end{aligned} \tag{12}$$

Where T_s is sampling time, which is here taken as $T_s = 1$.

Under the non-interfered circumstance, the results obtained through the tracking simulation test of the preset arc trajectory are displayed in Fig. 5-Fig. 7.

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Fig. 7 Change curves of controlled quantities

From the trajectory tracking effect graph and error change curves of state quantity, for the set arc trajectory, the NMPC-based direct track controller can adjust the controlled quantities of USV rudder angle and navigational speed and rapidly track the preset trajectory according to the USV state information at the current time, and moreover, the final tracking error is zero. It can be seen from the change curves of controlled quantities that when the trajectory tracking is started from the position where the USV receives the set arc trajectory information, the controlled quantities of rudder angle and navigational speed will make fast response until the USV tracks the preset trajectory. At the time, the navigational speed will be stabilized at the expected speed, and the controlled quantities of rudder angle and navigational speed will remain unchanged, thus realizing accurate track control of the present arc trajectory.

An interference signal is added to the designed track controller. By reference to formula (4-5), the interference signal corresponding to real-time USV navigational speed is set, and the acquired track control curve and the interference signal curve in the process are shown in Fig. 8-Fig. 11.

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Preset trajector

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Fig. 10 Change curves of controlled quantities (interfered)



Under the interfered circumstance, it can be seen from the trajectory tracking effect graph that at the initial stage when USV receives the preset trajectory information, the trajectory tracking effect is poor, but based on the idea of NMPC, that is, "prediction comes first and control second", the interference signal is predictively compensated based on the NMPC-SA based track controller after a certain while, so the control effect turns better slowly. Till the later stage, the accurate track control of

the present arc trajectory can be basically realized through the compensation of rudder angle.

4. Conclusion

In consideration that the traditional particle swarm algorithm could easily get stuck in the local optimum, an improved algorithm was proposed by virtue of the jumping characteristic of CNN algorithm. The practicability of this algorithm was improved through the multi-objective optimization. The simulation results manifest that the improved algorithm can optimize the path smoothness during USV autonomous navigation, improve the path safety and satisfy the requirements for USV global path programming. Directing at the nonlinearity and time lag problems, which could easily take place in USV track control, the direct USV track control was conducted based on the NMPC algorithm. The CNN algorithm was employed to solve the optimal control sequence of the predictive control algorithm, and thus the practicality of the algorithm was improved. According to the simulation results, the improved algorithm has effectively improved the accuracy and real-time performance of track control.

References

- [1] Yan Rujian, Pang Shuo, Sun Hanbing, et al. Development and Mission of surface unmanned ship [J]. Journal of Marine Science and Application. 2010(04).
- [2] Jian Xiong Long. A Ships Parameter Identification Colony Algorithm (J). Applied Mechanics and Materials. 2013 (347).
- [3] Han Chunsheng, LIU Jian, Yu Fuxing, et al. Automatic Ship Track Control based on PID Algorithm [J]. Automation Technology and Application. 2012(04).
- [4] Hu Yao-hua, XU Su-wu. Design of Ship Track Controller with predictable expected Course[J]. Control Theory and Application. 2010(12).
- [5] Chen Xueli, CHENG Qiming. Research on neural Network Controller for Ship Track Maintenance [J]. Journal of Hohai University (Natural Science edition). 2001(05).
- [6] K LLSTR m Claes G. Autopilot and track-keeping algorithms for high-speed Craft Control Engineering. 2000.
- [7] Velagic Jasmin, Vukic Zoran, Omerdic Edin. Adaptive Fuzzy Ship Autopilot for track-keeping. Control Engineering. 2003.
- [8] Wang Y D. Course Auto-rudder Design of Surface Unmanned vehicle Based on AdRC algorithm [D]. Dalian Maritime University, 2014.
- [9] Xu Jianping. Research on an Algorithm of Ship Adaptive Rudder [D]. Dalian Maritime University, 2012.
- [10] Mei Qiang, LI Lina, Chen Guoquan, et al. Optimization and Performance Evaluation of Fuzzy self-tuning PID Heading control Algorithm [J]. Journal of Hefei University of Technology.