Multi-point Mooring PID Control Based on Kalman Filtering-Genetic Algorithm-Slow Disturbance Observer Compensation

Guichen Zhang, Run Lu and Mengwei Chen
Merchant Marine College, Shanghai Maritime University, 1550 Haigang Ave, Shanghai 201306, P. R. China
Email: gczhang@shmtu.edu.cn

Abstract. An adaptive PID control technique based on the Kalman Filtering (KF) Genetic Algorithm (GA) and Slow Disturbance Observer Compensation (SDOC) is proposed for multi-point mooring system in this paper. The multi-point mooring model, which is simplified to two-point mooring, is established, its self-tuning PID mooring controller based on KF-GA-SDOC is designed. The multi-point mooring model is updated on-line with the KF and SDOC to filter and observe time-varying signal; the PID mooring control gains are adjustable parameters by selection, crossover and mutation operator of GA; the mooring control system based on KF-GA-SDOC PID is optimized. The simulation results show that the designed KF-GA-SDOC PID mooring controller can maintain good control performance under different conditions.

1. Introduction
PID controllers, having dominated marine engineering control applications, have a simple structure and robustness. The excited multi-point mooring system closely approximates a nonlinear Duffing oscillator [1-2], providing the dynamic behaviour analyse for the mooring system. GA was applied to the constrained optimization and estimation of parameters [3], and the solution of multi-objective constrained optimization problem [4]. Kalman Filter (KF) algorithm was utilized to optimize the estimation of status for ship attitude motion [5]. The combination of KF and GA was used to state estimation [6]. The statically equivalent mooring systems was optimized [7], the influence of mooring system on offshore platform under wave impact was researched [8], and the dynamic optimization of an equivalent mooring system was achieved [9]. However, PID control strategies have not been investigated in multi-point mooring positioning control system.

PID affects control performance, safety and economy. There are many optimization methods of PID, such as indirect optimization method [10], gradient method, and hill-climbing method [11] etc. In addition, simplex method [12] and expert tuning method [13] are widely used in thermal systems. Some of them are sensitive to the initial value and easily fall into the local optimization. Expert tuning method needs too much experience, since different objective functions correspond to different experience, and it takes a long time for the knowledge. However, the GA-PID does not need initial information and can find the global optimization. The positioning of multi-point mooring system belongs to stochastic optimal control, its signal and noise are multi-dimensional nonstationary random processes with time-varying and power spectrum instability. Therefore, it is necessary for the KF to use the recursive algorithm to filter the data, the KF is on-line updating multi-point mooring chaotic system. An extended state observer PID was designed to improve the stability of the mooring control
The mooring platform is slow varying characteristics and repeatable observe, it is very important to compensate the mooring control system with slow disturbance observer. It is indispensable to obtain accurate positioning data of mooring system for the slow disturbance observer compensation (SDOC); multi-point mooring self-tuning PID control system is proposed based on GA-SDOC. The multi-point mooring control system is on-line updated by KF and SDOC to filter and observe time-varying signals, while the PID parameters are update by the GA. The proposed self-adaptive PID controller is applied to a two-point mooring positioning control simulating process, the superiority of PID mooring controller based on KF-GA-SDOC is demonstrated.

2. Multi-point Mooring System and Simplification

The multi-point mooring system and its simplified process are shown in figure 1: I shows the “Kantan3” offshore exploration platform using eight-point mooring positioning technology, II represents the arrangement of eight-point mooring winch and control system, III represents the schematic diagram of the mooring system layout, IV simplifies the eight-point mooring to four-point mooring. The four-point mooring can be further simplified to a two-point mooring; V. Therefore, the multi-point mooring is a simplified nonlinear Duffing oscillator.

In figure 1 II, A1-A2, B1-B2, C1-C2 and D1-D2 are eight-point mooring winches, which can work either alone or together, if one fails, the other can replace it. A, B, C and D are central control consoles. ①, ②, ③ and ④ are emergency control cabinet, ⑤, ⑥, ⑦ and ⑧ are winch remote control interface cabinet, ⑨ is main PLC, ⑩ is bridge operation cabinet, ⑪ is UPS, MWT is mooring winch transformer. The motion transfer function of the eight-point mooring includes surge, sway, heave, roll, pitch, yaw, wave frequency load transfer function and average drift force. The eight-point mooring system in figure 1 can be simplified as a single degree of freedom (SDOF) nonlinear oscillator with hydrodynamic damping [8], which is described as follows:

$$\dot{x} = y; \quad \dot{y} = F(t) - R(x) - \delta y; \quad F(t) = f_{max} \sin(\omega t); \quad R(x) \approx k_1x + k_2x^3$$

(1)
where \( x \) - displacement response of mooring platform, \( y \) - velocity of mooring floats, \( F(t) \) - oscillator excitation signal, \( f_{\text{max}} \) - amplitude, \( \omega \) - excitation frequency; \( R(x) \) - mooring restoring force, \( k_1 \) and \( k_2 \) is elastic coefficient of mooring lines.

The delay and inappropriate control gain of the mooring system will lead to instability of the control system, the equation of mooring float motion of equilibrium of \( R(x) \), the motion of a small body excited by wave and current is expressed by following delay differential equation [1, 14].

\[
\dot{x} = -c\dot{x} - k_1 x - k_2 x^3 + F(t) + g u(t-d)
\]

where \( g \) is control gains, \( d \) is time-delay parameters, \( u(t-d) \) is control signal caused by time-delay displacement.

In the 4th interval, the mooring float model can be approximated in this study. The dimensionless motion equation of the linear undamped oscillator is expressed by the following state space equation.

\[
x(\kappa) = Ax(\kappa-1) + B(u(\kappa) + w(k)); \quad y_2(\kappa) = Cx(\kappa) + v(k)
\]

where \( w(k) \) is processing noise signal, \( \Psi \) is covariance of \( w \); \( v(k) \) is measuring noise signal, \( Q \) is covariance of \( v \). \( u(k) \) is control input. \( A \) is \( 2 \times 2 \) square matrix, \( B \) is \( 2 \times 1 \) matrix, \( C \) is \( 1 \times 2 \) matrix.

3. PID Controller Based on KF-GA SDOC Design

Mooring control system is designed as KF-GA SDOC PID in figure 2, where M-S is the mooring system, \( y_0 \) is desired position of mooring platform; error \( e(k)=y_0(k)-y_4(k) \), \( y_4(k) \) is mooring system KF output, \( y(k) \) is mooring system actual output, \( y_2(k) \) is mooring system output contaminated by measuring noise; \( K_p \)-proportional gain, \( K_i \)-integral gain, \( K_d \)-derivative gain, \( u_4(k) \)-PID output, \( u(k) \) is SDOC output, \( u_4(k)=u_4(k) + u_2(k) \), \( D(k) \) is a slow time-varying disturbance signal.

![Figure 2. mooring control system based on KF-GA SDOC PID.](image)

When the sampling time is \( \kappa \), the discrete PID controller is

\[
u_\kappa(k) = u_\kappa(k-1) + K_p[e(\kappa) - e(k-1)] + K_i e(\kappa) + K_d[y_4(k) - 2y_4(k-1) + y_4(k-2)]
\]

PID adopts differential prior algorithm in equation (4), which only differentiates the system output \( y_4(k) \), not the setting value \( y_4(\kappa) \), it avoids the system oscillation caused by the change of the setting value. Recursive algorithm of Kalman filtering is given by

\[
M_n(k) = \left(P(k)C^T\right)\left[(CP(k)C^T + \Psi)\right]
\]

\[
P(k) = AP(k-1)A^T + BQB^T; \quad P(k) = \left(I_n - M_n(k)C\right)P(k)
\]

\[
x(k) = Ax(k-1) + M_n(k)(y(k) - CAx(k-1)) \quad y_4(k) = Cx(k)
\]

The error covariance \( E_{\text{cov}}(k) \) is as follows
The second-order mooring system with slow disturbance is studied, from (2), we have

\[ \ddot{x} = -c \dot{x} + gu(t) - D(t) \]  

(9)

where \( g > 0 \), \( D(t) \) is the time varying signal of slow disturbances.

The slow disturbance observer is designed as follows

\[ \hat{D} = k_3 (\hat{y} - \dot{x}) \]

\[ \hat{y} = \hat{D} + gu \]

(10)

where \( \hat{D} \) is the estimate of \( D \), \( \hat{y} \) is the estimate of \( \dot{x} \). \( k_3 > 0 \), \( d > 0 \). Define the Lyapunove function is

\[ V = \frac{\hat{D}^2}{(2k_3)} + \frac{\hat{y}^2}{2} \]  

(11)

Assume \( \hat{D} \) is very small and \( k_3 \) is the larger value, as follows

\[ \frac{\dot{V}}{k_3} \approx 0 \]  

(13)

From equations (10) and (13) to (12), we have

\[ \dot{V} = \frac{\ddot{D}}{k_3} + \frac{\ddot{y}}{k_3} + \dot{y} \left( \ddot{x} - \left( -\dot{D} + gu - k_4 (\hat{y} - \dot{x}) - c \dot{x} \right) \right) \]

\[ = \frac{\ddot{D}}{k_3} - \frac{\ddot{D}k_3}{k_3} + \ddot{y} \left( -\dot{D} + gu - k_4 (\hat{y} - \dot{x}) - c \dot{x} \right) \]

\[ = \frac{\ddot{D}}{k_3} - \frac{\ddot{D}k_3}{k_3} + \ddot{y} \left( -\ddot{D} + gu - k_4 (\hat{y} - \dot{x}) \right) \]

\[ = \frac{\ddot{D}}{k_3} - k_3 \ddot{y} \leq 0 \]  

(14)

Therefore, this observer can effectively observe \( D(t) \) and realize the compensation function. From equation (9), the control law of slow disturbance observer compensation is as follows

\[ u = u_c + \frac{\dot{D}}{g} = u_c + u_s \]  

(15)

GA optimizes PID parameters for each sampling time \( k \). Firstly, the maximum and minimum ranges of PID parameters and control accuracy are determined, and the binary code or real code is carried out, which are used to represent \( K_p \), \( K_i \) and \( K_d \) respectively. The encoded string is the operation object of GA. Secondly, the initial population is randomly generated by computer, the population size \( L \) needs to be determined according to the complexity of the calculation. Binary code is to generate random numbers evenly distributed in \([0, 1]\), and the generated random numbers \([0, 0.5]\) represent \( 0 \) and \([0.5, 1]\) represent \( 1 \). The corresponding relationship between binary string and \( K_p \), \( K_i \) and \( K_d \) is established, the size of long binary string is \( L \). The real coding discretizes the definition domains of \( K_p \), \( K_i \) and \( K_d \) into the real numbers of \( L \) discrete points. Thirdly, the fitness function \( f(K_p, K_i, K_d) \) is determined. A group of parameters are obtained by GA optimization, and the best parameters need to be selected from this set of parameters, the standard of optimization is stability, accuracy and rapidity. Fitness function and objective function are closely connected and constrained by control variables, error and rise time. Therefore, optimal control parameter is PID parameters when \( f(K_p, K_i, K_d) \) is maximum under the constraint condition.
4. Application to Mooring Control Process

From the above analysis, the auto-tuning PID process is as follows:

Step 1: At sample time \( k \), the approximate range of \( K_p, K_i, K_d \) and real encoding length are obtained.

Step 2: \( n \) individuals were randomly generated to form the initial population \( P(0) \).

Step 3: Determine the individual evaluation method. In this paper, the absolute error time integral is the performance index, which is used as the minimum objective function of PID parameter selection. The square term of control input is added to the performance index to prevent excessive control, the optimal PID parameters are as follows:

\[
J = \int_{0}^{\infty} \left( \gamma_1 |e(t)| + \gamma_2 u^2(t) \right) dt + \gamma_3 f_u
\]

(16)

where \( \gamma_1, \gamma_2 \) and \( \gamma_3 \) are the weights, \( t_0 \) is the rise time.

Adding penalty function in (17) can avoid overshoot, overshoot is added to the optimal index, which is as follows:

If \( ey(t) = y(t) - y(t-1) < 0; \) \( ey(t) \) is error change rate.

\[
J = \int_{0}^{\infty} \left( \gamma_1 |e(t)| + \gamma_2 u^2(t) + \gamma_4 ey(t) \right) dt + \gamma_3 f_u
\]

(17)

where \( \gamma_4 \) is the weight, \( \gamma_4 >> \gamma_1 \), \( ey(t) \) is overshoot.

Step 4: Population \( P(t) \) is manipulated by reproduction, crossover and mutation operators to generate the next generation population \( P(t+1) \). Firstly, the method of fitness scale is used to reproduction; fitness function produces fitness value, the reproduction probability of each coding string is further calculated. In each generation, the reproduction probability is multiplied by the number of code strings, the product will be the number of code strings in the next generation. Those with high reproduction probability will have more offspring in the next generation, on the contrary, they will be eliminated. Secondly, single point crossing and crossover probability is \( P_c \). Select the matching team composed of strings with \( P_c \) probability from the reproduced members, then the members of the matching team are randomly matched, the crossing position is also randomly determined. Finally, probability \( P_m \) is used for mutation. Each generation has \( N \) strings, and each string has \( M \) bits, so there are \( N \times M \) bits in total, the expected mutation number of total strings is \( (N \times M) \cdot \varepsilon \) \((0 < \varepsilon << 1)\), there are \( ((N \times M) \cdot \varepsilon) \) string bits in each generation to change from 1 to 0 or from 0 to 1. The probability of mutation is related to the fitness. The smaller the fitness is, the greater the probability of mutation is.

Step 5: After the initial population was reproduced, crossed and mutated, a new generation of population is obtained. The population of this generation is decoded into the fitness function, to see whether the result meets the stop condition, if not, repeat steps 3 and 4 until the intended target is reached.

The above five steps constitute the real coded genetic algorithm for PID parameter optimization.

5. Simulation and Results Analysis

The multi-point mooring positioning process is a typical oscillating process and has highly nonlinear dynamics which is chaotic. The second-order time delay system given by equations (1-7), (15), (16) and (17) is considered in this paper. The system parameters considered are: \( \alpha=1[1,10], \beta=[0,2], \delta=[0,0.5], \omega=[1.09,1.13]; \) \( c=0.01, d=[0,15], k_1=0.0123, k_2=0.319 \). The coefficients of equations (5-7) can be determined from the above coefficients, obtaining \( A=[0 \ 1; -0.0123-0.319 \cdot \omega -0.01], B=[0 \ 1] \) and \( C=[1 \ 0] \); the amplitude of \( w(k) \) and \( v(k) \) is white noise signal with a mean value of 0.002, \( \Psi=1 \) and \( Q=1 \); In equations (15-17): \( \gamma_5=5, D=15 \sin(1.1t), k_5=50, k_6=20 \). The number of population used in genetic algorithm is \( L=300 P_0=0.9 P_m=0.2, \) \( \gamma_1=0.95, \gamma_2=0.001, \gamma_3=2.0, \gamma_4=0.05; \) real coding is adopted, PID parameters are optimized for one hundred generations by GA. PID parameter setting range is, \( K_p=[0.9,12.0], K_i \) and \( K_d \) are \([0.2,1]\). In this study, the mooring process
parameters are non-dimensional, which has good applicability. The mooring process simulation has been done by the developed KF-GA-SDOC PID controller. The tracking and positioning performances for mooring process are shown in figures 3-8.

Figure 3 is the phase plan of the wave disturbance $D$ and the observation results $\hat{D}$, the $\hat{D}$ estimate of $D$ can observe the equivalent disturbance, the equivalent compensation is added to the multi-point mooring control and disturbance is fully inhibited. Figure 4 is the mooring oscillating result of tracking performance for the setting sine signal $y_d$, the position tracking of velocity of mooring $y$ is also approximately sinusoidal, there is overshoot at the sudden change of sine peak, which is due to the poor real-time performance of genetic algorithm. Figure 5 is the error covariance $E_{cov}$ changing with time, the observation error covariance is consistent and unbiased on line, which shows high filtering accuracy. Figure 6 shows the mooring displace $x$ for positioning result under wave, figure 7 indicates the phase plane plots of $e-u$ and demonstrated nonlinear dynamics, the phase plane plots at excitation frequency $\omega=1.1$ controlled mooring oscillations is obtained by KF-GA-SDOC PID controller. From the figures, stable oscillation is observed. Figure 8 indicates the changes of $K_p$, $K_i$ and $K_d$ in the PID tuning process by KF-GA-SDOC, GA adopts the adaptive mutation probability method, and the mutation probability is $P_m=0.2-[(1:1:L)\times0.01)/L$, the process of GA adaptive tuning PID parameters is unstable, it leads to a large amount of calculation for optimization. The simulation results show that the multi-point mooring system has strong nonlinear hysteresis and high damping capability, which can maintain good positioning performance on the wave disturbance under KF-GA-SDOC PID control.

6. Conclusions
The proposed adaptive PID control strategy in this paper is based on KF-GA-SDOC for multi-point mooring nonlinear system, the algorithm in different situation is researched. KF is used to filter the data of multi-point mooring system on-line updating. The disturbance observer is designed as SDOC, which compensates for PID control. KF and SDOC together eliminate the influence of measurement
noise and improve the performance of mooring control system. PID adopts differential prior algorithm to eliminate the effect of the setting value change. GA optimizes PID parameters based on KF and SDOC, the KF-GA-SDOC algorithm will tune PID parameters to maintain the stability and the positioning performance of the multi-point mooring system. The proposed hybrid PID algorithm based on KF-GA-SDOC is inherently for nonlinear and chaotic system. The developed self-adaptive control method is applied to the simulation evaluation of multi-point mooring process. The simulation results verify the above superior features.

Acknowledgments
This work was supported by the NSFC Projects of China under grant NO 51779136.

References
[1] Mitra R K, Banik A K and Chatterjee S 2017 State feedback control of surge oscillations of two-point mooring system Journal of Sound and Vibration (386) 1-20.
[2] He W, Zhang S and Ge S S 2014 Robust adaptive control of a thruster assisted position mooring system Automatica (50) 1843-1851.
[3] Liu X, Huang G, Lin Z and Guo W 2008 Interaction force coefficients estimation of ship maneuvering based on multi-population genetic algorithm Journal of Shanghai Jiaotong University (42) 945-948.
[4] Lu C, Lin Y and Ji Z 2005 Application of genetic algorithm in ship free floatation calculation Journal of Shanghai Jiaotong University (39) 701-706.
[5] Song H, Yu G and Qu Y 2018 Monitoring and forecasting system for ship attitude motion based on extended Kalman filtering algorithm Journal of Chinese Inertial Technology (26) 6-12.
[6] Zhou W, Qi X, Chen L and Xu X 2019 Vehicle state estimation based on the combination of unscented Kalman filtering and genetic algorithm Automotive Engineering (41) 198-205.
[7] Felix-Gonzalez I and Mercier R S 2016 Optimized design of statically equivalent mooring systems Ocean Engineering (111) 384-397.
[8] Rudman M and Cleary P W 2016 The influence of mooring system in rogue wave impact on an offshore platform Ocean Engineering (115) 168-181.
[9] Fábio M G F, Eduardo N L, Silvana M B A and Paulo R M L 2016 Dynamic design optimization of an equivalent truncated mooring system Ocean Engineering (122) 186-201.
[10] Yao Y, Zhao J and Sun L 2009 Displacement-oriented optimization algorithm for motion planning of redundant manipulators Journal of Xi'an Jiaotong University (43) 75-79.
[11] Hu Y, Liu Z, Song R and Shi J 2013 Hill-climbing and pattern ant colony hybrid Bayesian optimization algorithm Journal of Huazhong University of Science and Technology (Natural Science Edition) (41) 90-95.
[12] Zhang Y, Gong D and Zhang W 2009 A simplex method based improved particle swarm optimization and analysis on its global convergence ACTA Automatica Sinica (35) 289-298
[13] Shi J and Liu Y 2013 Simple expert PID speed control of ultrasonic motors Proceedings of the SCEE (33) 120-126.
[14] Zhou X and Zhao B 2017 Extended state observer/PID compound control for inertially stabilized platform Journal of Chinese Inertial Technology (25) 6-10.