International Journal of Multimedia and Ubiquitous Engineering
Vol.11, No.2 (2016), pp.239-246
http://dx.doi.org/10.14257/ijmue.2016.11.2.24

A PID Controller of Fish Pond Aerator Based on Optimal Smith Predictor Algorithm

Daping Liang

School of Electronic Information and Electrical Engineering, Tianshui Normal University, Tianshui 741000, China
contain2002@163.com

Abstract

In the process of freshwater fish farming in pond, the levels of dissolved oxygen must be monitored by creating a closed loop PID control system. But traditional PID controller has weak stability and slow response speed, because dissolved oxygen changes with delay. In this paper, a PID control algorithm with optimal Smith predictor is proposed, to eliminate negative effects caused by delay component. The result of experiment data indicates that the optimal algorithm can reduce settling time and overshoot, and has better robustness and disturbance rejection performance than traditional PID controller. Meanwhile, a hardware circuit design plan based on ARM Cortex-M3 embedded processor is supposed, which gets stronger performance than C51 MCU control system with traditional PID algorithm. The hardware selection and plan design realize high cost performance, it is valuable to small and medium freshwater aquaculture enterprises.

Keywords: *Smith Predictor, Time Delay System, Robustness, PID, Fish Pond Aerator*

1. Introduction

In the process of pond freshwater fish farming in pond, on one hand self-balancing recovery time of oxygen content in water is longer, because of limited mobility of water and poor self-cleaning function. On the other hand, a lot of fish feed and feces will be deposited on the floor of the pond, and create noxious gas to consume a lot of oxygen in water, such as methane. These two factors will reduce dissolved oxygen level very much, and cause higher death rate of fish. So dissolved oxygen level must be monitored by fish pond aerator control system, when the fish farming scale is large. The aerator works by impellers stirring water, to accelerate the process of air dissolution in water and expel the noxious gasses building in the bottom of pond, its principle is shown in Figure 1. The fish pond aerator using traditional PID algorithm could not eliminate negative effects caused by delay component, and the system control accuracy has too much influencing factors, such as stocking density, weather, temperature, water quality and sorts of fish. In the meantime, the system robustness is weak too. All these will lead to two cases: one is that impeller starts too late to supply enough oxygen to fish; the other is that impeller start and stop too frequently to protect motor from damage due to strong current. In order to solve these problems, Smith predictor algorithm which has been optimized and traditional PID algorithm are combined from the view of realizing H_∞ optimum control [1] and improving robustness, a better performance and easier to realize PID algorithm is proposed and applied to fish pond aerator system. Experimental results show the optimization controller has faster response time and higher disturbance rejection performance. Meanwhile, a control system design scheme based on ARM embedded processor is suggested.

ISSN: 1975-0080 IJMUE

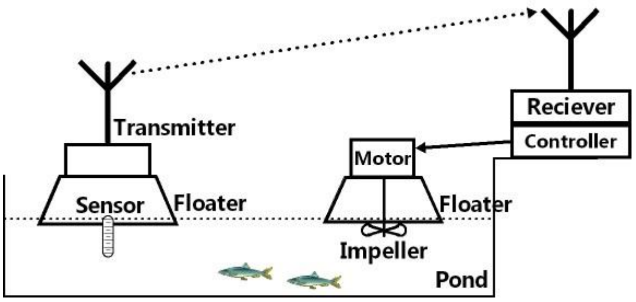

Figure 1. Fish Pond Aerator Control System Schematic

2. PID Controller Design Based on Smith Predictor

2.1. Traditional Smith Predictor Model

The traditional Smith predictor works by adding compensating elements to PID controller and substituting a similar model for controlled plant which has delay component. As shown in Figure 2 and Figure 3, when the system is nominal, the delay component $e^{-\tau s}$ can be separated from controlled plant, a feedback signal is drawn before $e^{-\tau s}$ component, so the feedback signal without delay could improve system response speed. But the calculation is proposed based on nominal model. If a exact mathematics model of the plant cannot be established, the compensation will not be effective, even negative. Besides, to separate Smith predictor link from PID controller, will add complexity and uncertainty to the controller design.

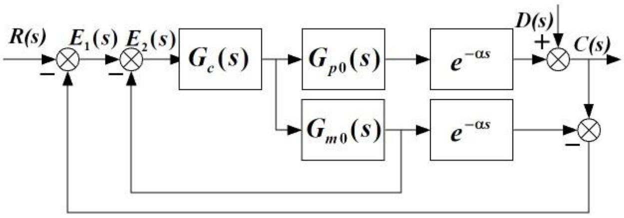

Figure 2. Traditional Smith Predictor Block Diagram

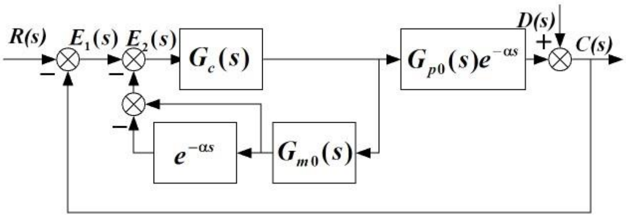

Figure 3. Simplified Smith Predictor Block Diagram

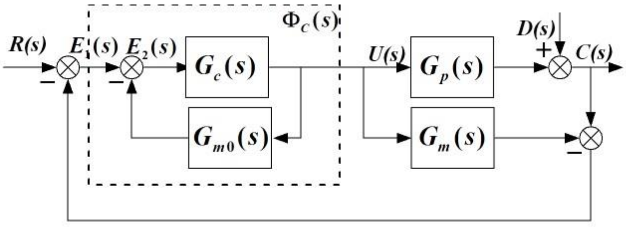

Figure 4. Optimal Smith Predictor Block Diagram

As shown in Figure 4, combined Smith predictor and PID controller by the equivalent transformation of block diagram, a PID controller model with Smith predictor, which is easier to realize, can be built. When G_M is the nominal model of the controlled plant G_p, the transfer function of Φ_C is

$$\Phi_C(s)=\frac{G_C}{1+G_C G_{M0}} \tag{1}$$

The control error from inexact prediction could be regarded as additive uncertainty. Let D(s) denote disturb signal, W denotes weight function. When D(s) is input signal, the loop transfer function of the nominal system is

$$\Phi_D(s)=\frac{C(s)}{D(s)}=W(1-G_P\Phi_C) \tag{2}$$

When the controlled plant is time delay and self-balance system, its transfer function is

$$G_P(s)=\frac{Ke^{-\alpha s}}{T_1 s+1} \tag{3}$$

The delay element can be approximated using first-order differential and inertial element, according to monomial expansion of Pade approaching. Formula (3) could be simplified like the following

$$G_P(s)=\frac{K(1-\frac{\alpha}{2}s)}{(T_1 s+1)(1+\frac{\alpha}{2}s)} \tag{4}$$

The errors can be considered system uncertainty, although the formula (4) approximate calculation will introduce them.

2.2. Discussion on Additive Uncertainty Input D(s)

A appropriate weighting function W(s) is designed for standardizing the uncertainty from signal D(s), and covering D(s) value range, so $D(s)=W(s)d(s), \|d(s)\|_\infty \le 1$.The system is hoped to have stronger robustness against uncertainty, so $\min\|W\Phi_D\|_\infty \to 0$. In general, signal function D(s) is the harshest typical input which is step signal. But the inertial signal is chosen at last, because dissolved oxygen control system has very long transition time in reality. So

$$D(s)=\frac{\alpha}{\alpha s+1} \tag{5}$$

W(s) can be chosen to equal D(s), so W(s)=D(s), because it must cover the complete range of D(s). According to the theorem [2]: L is assumed to be a nonempty open set, if Φ_C is analytic function and non-constant, the maximum of $|\Phi_C|$ will be outside the set L, when Φ_C has a zero point $1/\alpha$ in the set L, the formula (6) can be workable

$$\|W(1-G_P\Phi_C)\|_\infty \ge \left|W(\frac{1}{\alpha})\right| \tag{6}$$

So, the following relation holds:

$$\min\|W\Phi_D\|=\min\|W(1-G_P\Phi_C)\|_\infty=\left|W(\frac{1}{\alpha})\right| \tag{7}$$

Then Φ_{C0} which is the boundary value of Φ_C can be derived as

$$\Phi_{C0}(s)=\frac{W-\frac{\alpha}{2}}{WG_P}\approx\frac{(1+\frac{\alpha}{2}s)(T_1s+1)}{K} \tag{8}$$

By using a low pass filter to attenuate Φ_C , to improve its high-frequency anti-interference capability, so

$$\Phi_C(s)=\frac{1}{(T_2s+1)^2}\Phi_{C0}(s)=\frac{(1+\frac{\alpha}{2}s)(T_1s+1)}{K(T_2s+1)^2} \quad (T_2>0) \tag{9}$$

Obviously, when $T_2\to 0$, $\Phi_C\to\Phi_{C0}$ and $\|W\Phi_D\|_\infty$ will achieve optimal performance. When formula (9) is substituted in formula (1), the PID controller's transfer function can be computed as

$$G_C(s)=\frac{\Phi_C}{1-G_{M0}\Phi_C}=\frac{(1+\frac{\alpha}{2}s)(T_1s+1)}{K(T_2^2s^2+(2T_2-\frac{\alpha}{2})s)} \tag{10}$$

Smith predictor and PID controller can be combined to build a new controller according to the block diagram of Figure 3, whose transfer function can be computed using

$$G_{SC}(s)=\frac{G_C}{1+(G_{M0}-G_M)\Phi_C}=\frac{(1+\frac{\alpha}{2}s)(T_1s+1)}{K(T_2^2s^2+(2T_2+\frac{\alpha}{2})s)} \tag{11}$$

Apparently, the transfer function is PID controller too, which can more easily be realized in technology. The formula (11) variable T_2 is an adjusting coefficient, which has a direct effect on system robustness and nominal performance. If T_2 decreases, the precision of system nominal model can be improved, the working frequency band can be enlarged, but the robustness will be weaken. If T_2 increases, the opposite conclusions can be drawn. So a compromise robustness and nominal performance can be given, when an appropriate T_2 is chosen. In general, the T_2 values are from 0.2α to 1.2α.

2.3. Model Identification of the Controlled Plant

The theoretical calculation and experimental data suggest that the dissolved oxygen level in pond can be self-balancing, its model can be described by delay and inertial linkage, whose transfer function is shown as formula (3). In formula: K is coefficient of water conductivity, T1 is equivalent time constant, α is delay time of dissolved oxygen content changing. The parameters of self-balancing delay system can be determined by reaction curve method [3].

Dissolved oxygen data monitoring uses primary cell dissolved oxygen sensor for fish farming. The area of pond is about 2000 square meters, the depth is about 1.8 meters. According to Chinese water quality standard for fisheries [4], appropriate dissolved oxygen level should be about 10mg/L. So initial level of oxygen is set by 5mg/L, running the impellers, sampling time is set by 1 min, then the system ascending curve data can be given. The key problem using reaction curve method is choosing accurate curve inflection point, which can be given by using Matlab's 5 order polynomial fitting to process experimental data to smooth the ascending curve trend, as shown in Figure 5. To draw a curve's tangent extension line across point P, 3 relevant parameters of system transfer function can be given, including dissolved oxygen changing delay time $\alpha=480$, time constant $T_1=1980$, coefficient of conductivity $K=0.9$.

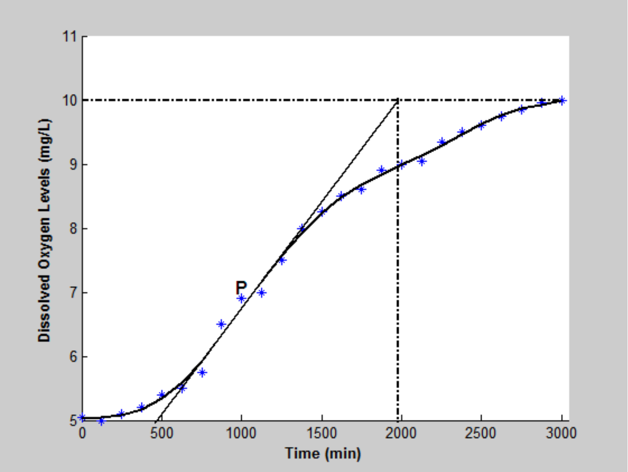

Figure 5. The System Ascending Curve

2.4. PID Controller with Smith Predictor Tuning

According to the above transfer function parameter values and formula (11), the new PID controller with Smith predictor transfer function can be compute using

$$G_{SC}(s)=\frac{U(s)}{R(s)}=\frac{(1+240s)(1980s+1)}{0.9(500^2 s^2+(2\times 500+240)s)} \tag{12}$$

Then the differential equation can be derived as

$$225000u''+1116u'=475200r''+2220r'+r \tag{13}$$

The formula (13) can be transformed into discrete difference equation [5] , as shown in formula (14)

$$\begin{aligned}&225000\frac{u(k+1)-2u(k)+u(k-1)}{T^2}+1116\frac{u(k)-u(k-1)}{T}\\&=475200\frac{r(k+1)-2r(k)+r(k-1)}{T}+2220\frac{r(k)-r(k-1)}{T}+r(k)\end{aligned} \tag{14}$$

If the sampling time is unit time, T=1, the digitized controller's output u(k) can be given by

$$u(k)=0.5[u(k+1)+u(k-1)]-1.06[r(k+1)-2r(k)+r(k-1)] \tag{15}$$

According to formula (15), a program based on PID algorithm with Smith predictor can be made, to improve the system dynamic performance.

3. Embedded Control System Hardware Circuit Design Based on ARM Cortex-M3

In general, C51 MCU is chosen as the PID controller to build a fish pond aerator system, because of lower cost and maturer technology. But C51 MCU could not realize more than one high-density CPU resources occupied program in the meantime, such as multichannel PWM output, data acquisition, error calculation and data display. The function of PID controller algorithm cannot be realized completely, because C51 performance is weak. So the higher performance MPU should be chosen to improve system performance by taking full advantage of the optimal control algorithm. For higher cost performance, the economic type in high performance MPU product series should be chosen. Based on above considerations, Cortex-M3 series STM32F103x processor is suitable for building high performance multivariable process control system, which is ARMv7 architecture economic type [6].

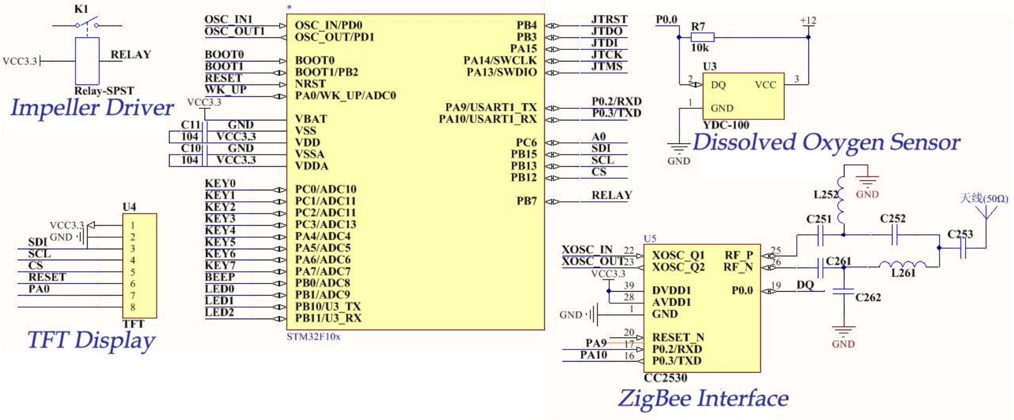

Figure 6. The System's Hardware Design Diagram

As shown in Figure 6, the control system hardware circuit consists of functional units, such as dissolved oxygen data acquisition, wireless signal transmission, parameter setting, abnormal alarm and motor drive. Dissolved oxygen data monitoring uses primary cell dissolved oxygen sensor. Sensors are attached with floaters(such as life buoy) which are anchored in position, and distribute evenly on the surface of water. The data collected by sensors is transferred to STM32F103x processor by ZigBee. ZigBee is the latest LAN wireless transmission protocol, whose effective communication distance can be up to 3000m. Its power consumption is low, two 5v batteries can supply for more than one year. It is stabler and lower cost than Bluetooth technology, and its circuit design is easier too. It can meet the need of signal transmission in range of pond. The differential equation model which is discretized according to formula (11) can compute the controller output, and transfer to PWM duty cycle which drive impeller to reduce the system error by solid state relay. Furthermore, different low level of the dissolved oxygen can set different alarm, the system parameters can be easily set by key and touch screen.

4. Experimental Data Analysis

The dissolved oxygen data sequence which is collected by sensors, are regarded as points which are drawn on the coordinate plane by Matlab software. A curve can be fitted by processing these points with Matlab sixth order multinomial. The smoothed system time response curve is shown as Figure 7. The curve fitted by processing another data sequence which is controlled by traditional PID control system is superposed on the previous curve for contrast.

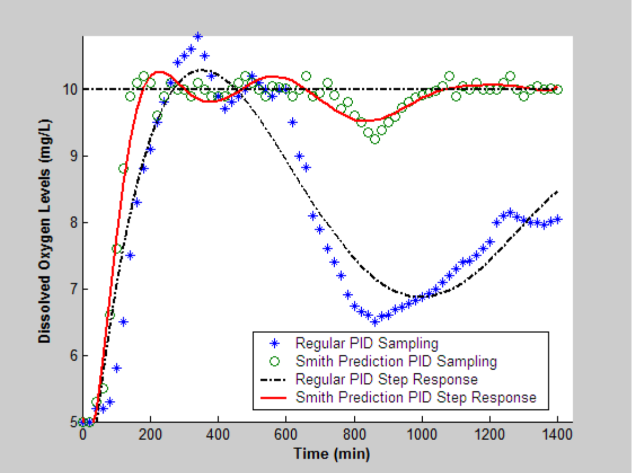

Figure 7. Comparison of Two Kinds of Response Curves

Apparently, the optimal PID controller with Smith predictor algorithm reduces system response oscillation and settling time, enhance the robustness and disturbance rejection performance. The system rise time decreases from 240 min to 120 min, and the overshoot is down to less than 2%.After the steady state is achieved, disturbance rejection time reduces from 800 min to 300 min, and the output error amplitude from disturbance decreases from 60% to 5%, the system has no steady state error (by contrast, the traditional PID control system cannot eliminate steady state error completely after been disturbed). The system dynamic performance is improved obviously.

5. Conclusion

This paper designs optimal PID control algorithm with Smith predictor to improve fish pond aerator system dynamic performance for the strict requirement of dissolved oxygen level in the process of fish farming. Meanwhile, a hardware circuit design plan based on ARM Cortex-M3 embedded processor is supposed, which gets stronger performance than C51 MCU control system with traditional PID algorithm. The hardware selection and plan design realize high cost performance, it is valuable to small and medium freshwater aquaculture enterprises.

References

[1] U. Min, “Robust Control Theory”, Higher Education Press, Beijing, **(2010)**.
[2] J. C. Dolye, “Feedback Control Theory, Macmillan Publishing Company”, New York, **(1992)**.
[3] S. Ren, “Automatic Instrument and Process Control”, Publishing House of Electronics Industry, Beijing, **(2009)**.
[4] GB11607-89, Water Quality Standard for Fisheries, Beijing, **(1989)**.
[5] H. Shousong, “Principle of Automatic Control, Science Press”, Beijing, **(2013)**.
[6] F. Shurui, “Principle and Application of Cortex-M3 Embedded Processor”, Publishing House of Electronics Industry, Beijing, **(2011)**.
[7] J. He, Y. Geng and K. Pahlavan, “Toward Accurate Human Tracking: Modeling Time-of-Arrival for Wireless Wearable Sensors in Multipath Environment”, IEEE Sensor Journal, vol. 14, no. 11, **(2014)**, pp. 3996-4006.
[8] W. Ou, Z. Lv and Z. Xie, “Spatially Regularized Latent topic Model for Simultaneous object discovery and segmentation”, The 2015 IEEE International Conference on Systems, Man, and Cybernetics, **(2015)**.
[9] W. Wang, Z. Lu, X. Li, W. Xu, B. Zhang and X. Zhang, “Virtual Reality Based GIS Analysis Platform”, 22th International Conference on Neural Information Processing, Istanbul, Turkey, **(2015)**.
[10] W. Ke, “Using Simulation to Explore Distributed Key-Value Stores for Exascale System Services”, 2nd Greater Chicago Area System Research Workshop (GCASR), **(2013)**.
[11] J. He, Y. Geng, F. Liu and C. Xu, “CC-KF: Enhanced TOA Performance in Multipath and NLOS Indoor Extreme Environment”, IEEE Sensor Journal, vol. 14, no. 11, **(2014)**, pp. 3766-3774.

[12] S. Zhou, L. Mi, H. Chen and Y. Geng, “Building detection in Digital surface model”, 2013 IEEE International Conference on Imaging Systems and Techniques (IST), **(2012)**.

[13] N. Lu, C. Lu, Z. Yang and Y. Geng, “Modeling Framework for Mining Lifecycle Management”, Journal of Networks, vol. 9, no. 3, **(2014)**, pp. 719-725.

[14] Y. Geng and K. Pahlavan, “On the accuracy of rf and image processing based hybrid localization for wireless capsule endoscopy”, IEEE Wireless Communications and Networking Conference (WCNC), **(2015)**.

[15] G. Liu, Y. Geng and K. Pahlavan, “Effects of calibration RFID tags on performance of inertial navigation in indoor environment”, 2015 International Conference on Computing, Networking and Communications (ICNC), **(2015)**.

[16] J. He, Y. Geng, Y. Wan, S. Li and K. Pahlavan, “A cyber physical test-bed for virtualization of RF access environment for body sensor network”, IEEE Sensor Journal, vol. 13 no. 10, **(2013)**, pp. 3826-3836.

[17] W. Huang and Y. Geng, “Identification Method of Attack Path Based on Immune Intrusion Detection”, Journal of Networks, vol. 9, no. 4, pp. 964-971.

Author

Daping Liang, He received his M.S. degree in control theory and control engineering from North University of China in Taiyuan, China. He is currently a lecturer in Tianshui Normal University. His research interest is mainly in the area of embedding control system and robust control theory. He has published several research papers in scholarly journals in the above research areas and has participated in several books.