Remote parameters tuning system based on simplex-search-based model-free optimisation for motor speed control

Xiangsong Kong¹,², Zeyu Tang¹, Yisheng Zhu¹, Yining Xiao¹, Qinghang Shen¹, Shaobo Jiang¹
¹School of Electrical Engineering and Automation, Xiamen University of Technology, Xiamen 361024, People’s Republic of China
²E-mail: xskong@xmut.edu.cn

Abstract: Motor is a very widely used control device in industry. The performance of a motor speed control system is very critical for its application. The control performance can be improved through control parameters tuning. However, the parameters tuning process is difficult to implement online automatically. The traditional parameters tuning methods for a motor control system are usually experience-based, cumbersome and time-consuming. In this study, taking advantage of the high computation ability of the MATLAB, a remote motor control system framework based on the wireless network was proposed. The simplex-search-based model-free optimisation (MFO) was developed based on the MATLAB platform to optimise the control parameters. With this optimisation methodology, the performance of the control system can be improved iteratively by directly using measurements of the control performance online. This system has been realised and tested systematically. The effectiveness and the efficiency have been demonstrated by a series of experiments.

1 Introduction

Control performance is very critical for a control system [1–3]. As the motor is the most commonly used control device, to improve the performance of a motor control system is especially meaningful and valuable [4, 5]. However, in industry, many motor speed control systems are not controlled very well because of their poor parameters tuning. With the development of the information technology, the control demand gets higher and higher. To improve the motor control systems’ performance is still a very challenging task [6, 7]. The future directions for the control system parameters tuning can be summarised as given in the below subsections.

1.1 Need for high-efficiency parameters tuning method

To tune the controller parameters efficiently, high efficiency optimisation strategy is needed. For the motor speed control systems, the control performance has a close relationship with its control parameter settings. However, the relationship is difficult to be obtained. The search for the optimal settings becomes a tough task in control engineering [8]. The traditional approaches can be categorised as below:

(1) Trial-and-error: This is the easiest and the most popular method used by most of the engineers. With this method, the engineers usually tune the controller parameters by a series of trial experiments. It is usually experience-dependent, expensive and time-consuming. However, only the suboptimal results are obtained.

(2) Model-based optimisation (MBO): Model-based optimisation was conducted on a performance model. This method firstly needs a model, which is accurate enough to represent the relationship between the parameters and the control performance. Then, with the model, extensive experiments can be avoided by simulation optimisation. However, such a performance model is difficult to obtain. Due to this, MBO was seldom used on the controller parameter optimisation problems. However, some special cases exist, such as Ziegler–Nichols tuning method. Take Ziegler–Nichols tuning method for example, in essence it is a model-based method for proportional-integral-derivative (PID) parameter tuning. This method determines the PID parameters based on an experience-based mathematical formula [9, 10]. As the formula is a rough model, it can only provide relatively poor PID settings. The disadvantages of the MBO-based control parameters tuning can be listed as below: first, building an accurate performance model is often challenging and the formula constructed is usually experience-dependent; second, the parameter settings obtained are usually suboptimal.

(3) Model-free optimisation (MFO): Model-free optimisation was proposed by Kong et al. [11–14] to address the parameters optimisation problems for a type of batch processes with low operational cost and short cycle time. This methodology can incorporate high efficiency optimisation algorithms without building a model first. Due to this, this method can achieve high efficiency and avoid the model mismatch simultaneously. The controller parameter settings tuning process has the same characteristics such as a batch process. So the MFO can be extended to the control parameters tuning. However, for a motor control system, the MFO needs more computation ability supports to carry out the MFO.

1.2 Need for high-performance computation power

Traditional motor control systems are usually constructed at a low cost. They are isolated systems without any connection with other information systems. Many motor control systems are implemented on the embedded chips, such as single-chip microcomputer, digital signal processor (DSP) etc. Most of the chips have relatively lower computation power, which greatly limits the performance improvement for the traditional motor control systems. To conduct the MFO on the motor control systems, the computation power should be promoted. However, the cost for the system should not be increased. The Internet of things (IoT) provide a solution to the challenge [15, 16]. With the development of IoT, an isolated system can be extended to a networked system easily. It is possible for a motor speed control system to connect with other high-performance workstations. Based on such connection, the motor control system can improve its performance with the help of the remote workstations. Extending the capability of the motor control system provides a possibility for the implementation of the MFO on the motor control system to improve the control system performance.

According to the requirements analysis, a new motor speed control system with high-performance needs to be constructed. To improve the control performance, a high-efficiency parameters tuning methodology should be incorporated and a suitable platform that can make the methodology efficient to apply should be
constructed. In this study, the simplex-search-based MFO with iteration termination control has been proposed to deal with controller parameters tuning for the motor speed control system. To make the methodology easy to implement online, a remote control system, which is constructed based on the wireless networks and MATLAB, was proposed. With the proposed remote motor speed control system framework, the parameters tuning can be realised online automatically with high optimisation efficiency.

2 Simplex-search-based MFO for parameters tuning of motor control system

2.1 Mathematical formulation for parameters tuning

Motor speed control system is widely used in industry. The structure of the motor speed control system is shown in Fig. 1. With the motor itself and the structure of the controller been fixed, the control performance optimisation can be converted to the controller parameters tuning problem. The schematics of the control performance optimisation for the motor speed control system are shown in Fig. 2.

The parameters tuning problem can be expressed as a mathematical formula as given below:

\[
\text{max } \text{Perf} = f(x) \\
\text{s.t. } x \in \Omega,
\]

where \( x \) is the settings of the controller parameters, \( \Omega \) is the feasible region for the controller parameters, Perf is the control performance and \( f(x) \) represents the relationship between the control performance and the controller parameters. However, \( f(x) \) is usually unavailable.

The performance of the motor speed control system should be evaluated quantitatively. The Integral of Time multiply by Absolute Error (ITAE) index, which was widely used in control engineering, was selected as the evaluation index in this study

\[
\text{ITAE} = \int_0^{t_{\text{test}}} |e(t)| dt,
\]

where the error is defined as \( e(t) = y_\text{sp} - y(t) \), \( y_\text{sp} \) is the target and \( y(t) \) is the actual speed, \( t_{\text{test}} \) is the total duration for a single test. As the ITAE gets smaller, the control performance gets better.

2.2 Simplex-search-based MFO

MFO method is a suitable method for the optimisation problem of (1) and can avoid the shortcomings of the traditional methods. In this study, the simplex-search-based MFO has been proposed to the controller’s parameters tuning. This method does not need to build a control performance model. Instead, it uses directly performance measurements, ITAE, to evaluate the control performance.

The framework of how the simplex-search-based MFO method works is shown in Fig. 3. At each group of parameters settings, a fixed transient is conducted on the process, the response of the motor speed is recorded and the ITAE index is calculated. The ITAE index will then be delivered to the post-implementation module. The method will judge whether the termination rule is met. A termination rule based on the historical search information is used. If the termination rule is not met, the method will generate the next iteration point according to the simplex-search module and the corresponding settings will be delivered to the controller through the pre-implementation module. This process iterates until the termination rule is met. The simplex-search-based MFO and a special termination rule are incorporated in this method. The details of the simplex-search-based MFO can be referred to [10]. The termination rule is demonstrated in Section 2.3.
2.3 Iteration termination control rule

The parameters tuning for the motor speed control system is carried out online by direct experiments. The experiments cost should be controlled strictly. The parameters tuning often makes trivial improvements after significant achievements have already been obtained. With the traditional termination rule, too many costs are spent on only little improvements. In order to reduce the optimisation costs, an iteration termination control strategy was proposed to apply on the motor speed control system parameters tuning. With this termination control strategy, the MFO can detect the status of the optimisation progress intelligently.

Fig. 4 shows the framework of the iteration termination strategy. The details can be referred to [13]. The main procedure can be divided into five steps as follows:

**Step 1:** Formulate the relatively optimality sequence \( Y^\prime \) by recording the historical optimal settings at each iteration;

**Step 2:** Formulate the slipping sequence \( Y^O \)

\[
Y^O \begin{cases} \frac{1}{7} \sum_{i=1}^{i=n} Y^O_i, & i \in [1, \lambda(n+1)); \\ \frac{1}{\eta(n+1)} \sum_{i=1}^{i=\eta(n+1)+1} Y^O_i, & i \in [\lambda(n+1), +\infty) \end{cases}
\]

where \( n \) is the dimension of parameters, \( \lambda \) is the slipping coefficient.

**Step 3:** Formulate the termination sequence \( Y_{MA} \)

\[
Y_{MA}(i) = \begin{cases} \frac{1}{7} \sum_{k=1}^{i=n} Y^O_k, & i \in [1, \eta(n+1)); \\ \frac{1}{\eta(n+1)} \sum_{i=1}^{i=\eta(n+1)+1} Y^O_i, & i \in [\eta(n+1), +\infty) \end{cases}
\]

where \( \eta \) is the termination coefficient.

**Step 4:** Calculate the termination factor \( \xi \). The differential sequence \( \Delta Y_{MA} \) is formulated as below:

\[
\Delta Y_{MA}(i) = \begin{cases} 1, & i \in [1, \eta(n+1)) \\ Y_{MA}(i) - Y_{MA}(i - \eta(n+1) + 1), & i \in [\eta(n+1), +\infty) \end{cases}
\]

The termination factor \( \xi \) is defined in (6), \( \xi \) indicates the ratio of the control performance improvement over the performance at the current point

\[
\xi = \frac{\Delta Y_{MA}(i)}{Y_{MA}(i)}
\]  

Step 5: Judge the termination criteria. When \( \xi \) is small, i.e. \( \xi < \xi^* \) (\( \xi^* \) is the tolerance), the progress at the current iteration is so slight that the termination criteria may be satisfied. However, to avoid the prematurity of optimisation, further verification should be conducted. The iteration terminate rule is defined as:

\[
(\xi < \xi^*) \land (k = k_0).
\]

where \( k_0 \) is the repeating coefficient which can be set by the engineers. When (7) is satisfied, the parameters tuning will be terminated. Lastly, the optimal settings will be set on the controller for the motor speed control system.

3 Remote motor speed control system based on wireless networks

As most traditional control systems are constructed based on embedded chips, their computation abilities are limited. To implement the proposed simplex-search-based MFO, the computation power of the motor control system should be extended. However, it is unable to replace the embedded system by computers or workstations because the device cost is limited. A possible solution to this is constructing a combined type control system which is composed of lower machine and upper machine. The motor is located on the lower machine. The parameters tuning can be accomplished by the optimisation module that lies on the upper machine.

The lower machine still keeps the embedded system framework, so the cost for the motor control will be limited. The upper machine may be a server which lies in the computation centre, it only carries out the computation task for the parameters optimisation. The lower machine and the upper machine are located in different places. The communication between them is critical for the whole system. In this project, the distance between the lower machine and the upper was not too far, a wireless network based on the IoT can connect them. The basic framework is shown in Fig. 5. On the upper machine, the optimisation module was developed on the MATLAB platform. The upper machine receives the speed measurements and evaluates the control performance, the optimisation module based on the simplex-search-based MFO determines the next iteration settings and sends the corresponding parameter settings to the lower machine to...
change the settings of the controller. The communication between the lower and upper machines is based on the wireless network. The detailed structure for the remote control system is shown in Fig. 6.

4 Experimental setup

The experimental device was developed in this project for verification. The remote communication of the motor speed control system was fulfilled based on the wireless network. The device is composed of three parts, including the lower machine, the upper machine and the wireless network. In this project, the lower machine was designed based on a single-chip microcomputer with the type HT66F70A. A brushless direct-current (DC) motor with a plastic fan was used, and the model type of the motor is MG513. A driver IC TB6612FNG was used to drive the motor. A plastic fan was used as the load. The upper machine was a workstation with MATLAB® installed. The simplex-search-based MFO was accomplished on the workstation. A human–machine interface (HMI) was developed based on the MATLAB GUI. Fig. 7 shows the demonstration for the HMI. For the wireless networks, a low cost, ultra-low power (ULP) 2 Mbps RF transceiver IC, NRF24L01, was used. This IC provides 2.4 GHz ISM (Industrial, Scientific and Medical) band.

In this study, a PID-type controller was adopted for the test. The PID rule was constructed as follows:

\[ k_p + \frac{k_i}{s} + k_d \cdot s, \]  

(8)

where \( k_p \) is the proportion gain, \( k_i \) is the integral gain and \( k_d \) represents the derivative gain. The PID parameters of the motor speed control system can be defined as \( x = [x_1, x_2, x_3]^T \). The feasible region in this project is shown in Table 1.

As the controlled object and the structure of the motor speed controller have been determined, the performance of the system can be improved only by tuning the parameters.

In this study, without loss of generality, the setpoint of the motor speed was set to 80 rpm/min. The transient for the parameters tuning was set from 0 to 80 rpm/min with a time duration of 7.5 s. The performance of the control system was evaluated based on the speed response under the transient.

5 Results and discussions

To verify the effectiveness of the simplex-search-based control parameter tuning method on the remote motor speed control system, the proposed method has been implemented on the experimental device.

5.1 Simplex-search-based MFO without iteration termination control

Without loss of generality, a random PID parameters settings was selected as the initial guess: \( x^{(0)} = [1, 0.1, 0.01]^T \). The optimisation was started from \( x^{(0)} \). At first, the simplex-search-based MFO without the iteration termination control was conducted. This MFO methodology used a fixed maximum iteration number to control the optimisation process. The optimisation terminated until the maximum iteration number was achieved. Finally, the optimal parameters settings has been obtained as \( x^{(99)} = [0.0258, 0.1416, 0.5342]^T \). Fig. 8 shows the results of the simplex-search-based MFO. From Fig. 8a, we can see the iteration trajectory. From

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**Table 1** Feasible region of the controller parameters

| Parameters | \( x_1 \) | \( x_2 \) | \( x_3 \) |
|------------|----------|----------|----------|
| low limits | 0        | 0        | 0        |
| upper limits | 30      | 10       | 5        |
Figs. 8b and c, it can be seen that the optimisation significantly improved the control system’s performance. It was indicated that the simplex-search-based MFO is efficient. The ITAE index at the 99th iteration was 169.9375. However, from Fig. 8a, it was seen that the ITAE for the motor speed control system descended quickly in the first <30 iterations, and during the rest 70 iterations, no significant improvement was achieved. So, it is really necessary to reduce the optimisation costs with improved optimisation termination control rule.

5.2 Simplex-search-based MFO with iteration termination control

To test the efficiency of the termination control rule, the simplex-search-based MFO with iteration termination control was conducted. In order to compare with the traditional MFO, the same initial guess $x^{(0)}$ was used. With the improved optimisation process control rule, the optimisation can be terminated intelligently without human intervention. The termination factor was set to 10 in this project. Fig. 9 shows the iteration trajectory of the revised method. It can be seen from the figure that the iteration costs was greatly reduced. It only needed 55 iterations for the optimisation. Fig. 9b shows the trajectory of the termination factor. The optimal point was the 55th settings $x^{(55)} = [0.0304, 0.1429, 0.5329]^T$. From Fig. 9c, it can be seen that the control response was nearly the same as Fig. 8c. The ITAE index at the 55th iteration was 153.1875, which was even smaller than the first optimisation test without the iteration termination control. It means the simplex-search-based MFO with the intelligent termination control rule can significantly reduce the optimisation costs, meanwhile obtain nearly the equivalent optimal solution.

To test the efficiency of the simplex-search-based MFO from different initial points, another starting point $x^{(0)} = [0.2, 0.1, 0.001]^T$ was selected randomly. With the iteration termination control, the MFO terminated the optimisation at the 60th iteration. The optimised settings was $x^{(60)} = [0.1857, 0.0699, 0.2247]^T$. The ITAE at $x^{(60)}$ was 54.5. Although, the starting points were different, similar optimisation trajectory was obtained in this test. It indicated that the MFO is effective from different start points. Comparing Fig. 10c with Fig. 9c, the control performance of this test was better than the test above. The reason for this phenomenon was because the simplex-search is a local optimisation algorithm.

The repeatability of the simplex-search-based MFO from the same initial parameters settings had been verified. Two optimisation tests from the same $x^{(0)} = [0.1, 0.1, 0.01]^T$ were conducted. The results are shown in Fig. 11. Fig. 11a shows the optimisation trajectories for the two tests. The optimal point obtained by the first test was $x^{(36)} = [0.0199, 0.1361, 0.3022]^T$. The corresponding ITAE was 60.75. The optimal point obtained by the second test was $x^{(40)} = [0.0040, 0.1648, 0.3348]^T$, with the corresponding ITAE 104.125. It can be seen that the two tests from the same initial parameters were different. As the simple-search is a deterministic algorithm, the reason for the difference is due to the stochastic nature of the motor control system. It can be seen clearly that the ITAE responses at the same initial settings were different in these two tests. However, the two tests achieved the similar optimisation performance. Fig. 12b shows the trajectories of the
termination factors in the two tests. The trajectories were different either. The optimisation for the two tests terminated at different iterations. The verification indicated that the simplex-search-based MFO is effective.

5.3 Optimisation module on the upper machine
The optimisation module was developed by the MATLAB platform on the upper machine. The module includes two parts. The first part is the simplex-search-based MFO, which is the core of the module. The second part is a HMI, which was developed based on the MATLAB GUI. The optimisation process of the simplex-search-based MFO can be configured and conducted by the HMI. The whole optimisation process can be automatically finished without human intervention. With this module, the engineers only need to set the initial settings for the optimisation parameters. The optimisation can be conducted automatically. Fig. 12 shows the results of a single optimisation on the HMI. The platform provides a possibility for the realisation of online and automatic parameters tuning.

6 Conclusion
To improve the control performance of the traditional motor speed control system efficiently, a remote motor control system framework based on the wireless networks was constructed. In the framework, an upper machine was added to enhance the computation power of the control system. The upper machine was used as the optimisation platform. It was indicated that the method proposed was suitable for the motor speed control. It was verified that with the iteration termination control, the costs for the MFO can be greatly reduced with nearly the same optimal results. This method can be implemented on the motor speed control problem. This framework of the remote motor speed control system provides a solution for control performance improvement with relatively low cost. With the help of such remote control system, the control performance of the motor speed control system can be optimised automatically. This framework is very easy for implementation. However, to improve the parameters tuning efficiency, more high-efficiency algorithms should be developed further.

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Fig. 10 Results of the simplex-search-based MFO with iteration termination control from $x^{(0)} = [0.2, 0.1, 0.001]^T$
(a) Optimisation trajectory,
(b) Trajectory of the termination factor,
(c) Control response optimised

Fig. 11 Reproducible results of the simplex-search-based MFO from the same $x^{(0)} = [0.1, 0.1, 0.01]^T$
(a) Optimisation trajectories for comparison,
(b) Trajectories of the termination factor for comparison
8 References

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