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Model Free Control Based on GIMC Structure

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Abstract: Many control researches for complicated and uncertain system are model-dependent and therefore require some prior knowledge for the complex systems. To avoid this problem, a number of model-free controllers are proposed. However, it is difficult to determine the control performance as the controller is not designed according certain system model especially when there are uncertainties and/or nonlinear dynamics in the system. To get over this problem, the model free controller (MFC) based on generalized internal model control (GIMC) structure is proposed in this paper. The MFC is used to attenuate the disturbance or uncertainty, and the system performance is determined by the nominal model and the nominal model controller. The parameters of nominal-model controller can be easily changed for meeting the change of the desired requirements. Moreover, the robust controller in the original GIMC is disassembled and rearranged to make the proposed methods easier to use, and the proposed method makes the controller be more flexible and greatly improves the system performance. Finally, the experiment results show that the MFC can be used to control the nonlinear systems and get the expected performance. The statistical analysis of performance for servo and regulatory behaviors also shows that the proposed method can achieve a better control performance than just using model free controller.

Keywords: Generalized internal model control, model free controller, nominal model, stability, uncertain system.

1. INTRODUCTION

Although new and more powerful control algorithms have been developed, proportional-integral-derivative (PID) control is still the most used control strategy in industrial applications. Many studies suggest that of all the controllers in industrial process control, PID (or PI) controllers are used in 95-97% of the cases [1]. An attractive feature of PID controllers is their relatively simple and intuitive design. Moreover, PID controller structure does not depend on the process model. The model-free character makes PID controller can be used in most of the industrial process. Similar with PID control, Model Free Controller (MFC) does not depend on the process model which is different from the model dependent control algorithms [2-8]. In [2-4,8], the classical mathematic models are used to obtain the control inputs. In [5,7], the intelligent methods were used to model the system. No matter the classical mathematic model or the intelligent model are used to get the control inputs, the process input/output data or the prerequisite information, which makes the design procedure more complicated, is necessary. Moreover, some model dependent control algorithms cannot be generalized if the process structure is changed, for example, some Lyapunov-based adaptive controllers. However, the model-free character can reduce computational costs and eliminates the expense of system identification. Although PID belongs to model-free controllers, PID coefficients should be adjusted if the process has changed. The control performance can't be accepted ifthe parameters of the process are time variant; there is strong nonlinear dynamics; or there are some uncertainties in the process.

Recently, much effort has been done in MFC [9-13] as the model free controller has the following properties:(1) no precise quantitative knowledge of the process is requisite; (2) no process identification mechanism or identifier is used in the system; (3) no controller design for a specific process is needed; (4) no complicated manual tuning of controller parameters is required; and (5) stability analysis criteria are available to guarantee the closed-loop system stability. In [9] fuzzy PID controller was used to control a 6-DOF Stewart-Gough based parallel manipulator. In [12] a fast model-free intelligent controller based on fused emotions was used to control an unidentified practical overhead crane and this controller has the capability to deal with multi-objective control problems. Aksakalli and Ursu showed the advantage of the model-free controller is that it can

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attempt to control systems whose internal processes cannot be observed because of real world constraints in [10]. In [10,11] the model-free controllers were proposed based on the adaptive strategies as the parameters of controllers are changed according to the change of the process. Qi *et al.* [13] proposed a model free controller, whose parameters are invariable, and this MFC successfully controlled chaotic systems and other nonlinear systems. This MFC is based on higher-order differential feedback controller which only utilizes the information of the measured output and the given objective as well as the differential signals.

Although the stability of the system is guaranteed, it is difficult to determine the control performance using MFC as the system performance is determined by process and controller together, and MFC does not depend on process model. To conquer this problem, MFC based on Generalized Internal Model Control (GIMC), which provides a good candidate for achieving both performance and robustness [14], is proposed in this paper. MFC is used to weaken the plant uncertainty and stabilizes the system. A simple controller for the nominal model is used to realize the expected requirements. In order to directly apply MFC in the structure of GIMC, the robust controller of the original GIMC is disassembled and rearranged.

The rest of this paper is structured as follows. Section 2 describes the preliminary knowledge about model free control. The details of model-free control based on GIMC structure are presented in Section 3. Section 4 gives a description of the experiment studies. Finally, Section 5 gives some concluding remarks.

2. PRELIMINARY

2.1. Model free control sysem structure

As discussed in Section 1, the model free controller does not explicitly or implicitly depend on the process model. However, the general structure of model free control system is similar with the classic control system, which includes desired inputs, controlled object, sensors, controller and so on. The system structure of a single-input-single-output (SISO) MFC control system can be shown as Fig. 1, where $r(t)$ is the desired trajectory, $u(t)$ is controller output or control signal, $y(t)$ is process output, and $e(t)=r(t)-y(t)$ is the error between the desired trajectory and the process output. Although the structure is similar with the traditional single-loop control system, the SISO model free controller neither needs a rigorous mathematical model nor an artificial intelligent model. PID controller can be a good example as a model free controller. In the absence of knowledge of the underlying process, a PID controller is the best controller [15]. The PID controller involves three terms: the proportional, the integral and derivative terms. The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is

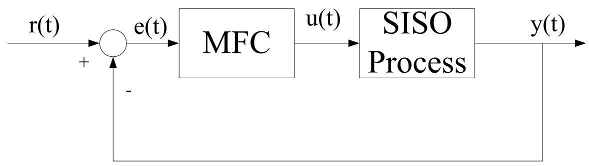

Fig. 1. Model free control structure.

$$u(t)=K_p e(t)+K_i\int_0^t e(\tau)d\tau+K_d\frac{d}{dt}e(t), \tag{1}$$

where K_p is proportional gain, K_i is the integral gain, K_d is the derivative gain and $e(t)$ is the error as shown in Fig. 1. By tuning the three gains in the PID controller algorithm, the controller can provide control action designed for specific process requirements. Similar with PID controller, the model free controller can give the control signal only depending on the process output and input. There are three major advantages using the model-free controller: (1) MFC tend to better handle changes in the underlying system as they are not tied to a prior model, (2) MFC require no open-loop training data, and (3) MFC tend to be more robust in the case of widely varying control inputs [10].

2.2. Model free control based on high order differential feedback control [13,18]

In this paper the model-free control scheme, which was proposed by Qi *et al.* [13], is chosen as a representation of MFC. Differential equation of some SISO affine systems is depicted as

$$\prod\nolimits_s : y^{(n)}=g(X,t)+d(t)+u, \tag{2}$$

where notation $\prod_s$ denotes SISO system, $u\in R$ is the control input, $y\in R$ is the system output, $t\in U_t\subset R$, $X\in U_X\subset R^n$, and $X=[x_1,x_2,\cdots,x_n]^T=[y,y^{(1)},\cdots,y^{(n-1)}]^T$ denotes output differential vector, and is also system state vector, $y^{(i)}$ denotes the i^{th} differential of y, $g(\bullet)$ is an unknown and satisfies Lipchitz increasing condition, and $d(t)$ is bounded uncertainty. System (2) can be converted into the following state space model

$$\prod\nolimits_s \begin{cases}\dot{x}_1=x_{i+1}, & 1\le i\le n-1,\\ \dot{x}_n=g(X,t)+d(t)+u, \\ y=x_1.\end{cases} \tag{3}$$

The system is also called as Brunovsky canonical form which was widely studied [16,17]. This kind of affine system has a wide background in practice. If $r^{(n)}$, $y^{(n)}$ and $y^{(n+1)}$ are continuous, there is the following MFC theorem.

Theorem 1[13]**:** (MFC theorem). For the time-variant nonlinear affine system (1) with unknown model, the MPC is described by

$$u=\bar{K}\bar{e}+\hat{u}, \tag{4}$$

where $\bar{K}=[k_n,k_{n-1},\cdots,k_1,1]$ makes the polynomial $s^n+k_1s^{n-1}+\cdots+k_n$ be a Hurwitz polynomial, the error differential vector

$$\bar{e} = [e, e^{(1)}, e^{(2)}, \cdots, e^{(n)}]^T$$
$$= [r - y, r^{(1)} - y^{(1)}, r^{(2)} - y^{(2)}, \cdots, r^{(n)} - y^{(n)}]^T$$

and $\hat{u}$ denotes the filtering signal of the control u, satisfying

$$\dot{\hat{u}} = -\lambda\hat{u} + \lambda u,$$

where λ is a positive constant.

Then the MPC has the following properties:

1) The MFC makes the closed-loop system asymptotically stable and satisfies the following convergent property

$$\lim_{t\to\infty}\lim_{\lambda\to\infty} y = r. \quad (6)$$

2) All system variables are bounded.

3) The controller is strongly robust for the function $g(\bullet)$ and bounded uncertainty $d(t)$.

The similar result has also been extended to MIMO system [13].

In order to realize the control law (4), the differentials up to nth order for $\bar{e}$ should be extracted. The following high order differentiator [13,18] can be used.

The HOD is described by n_0 order dynamic system (7) with $n+1$ order algebraic (8).

$$\sum \begin{cases} \dot{z}_i = z_{i+1} + a_i(y - z_1) & 1 \le i \le n_0 - 1 \\ \dot{z}_{n_0} = a_{n_0}(y - z_1) \end{cases} \quad (7)$$

$$\sum \begin{cases} \hat{y} = z_1 \\ \hat{y}^{(i)} = z_{i+1} + a_i(y - z_1) \end{cases} \quad (8)$$

Here, n_0 is the order of the system, satisfying $n_0 \ge n+1$, $z_1, \cdots, z_{n_0}$ are the states, a_i are the parameters, and $a_i = KC_{n_0-1}^{i-1}a^{i-1}$, $K = n_0^{n_0}a/(n_0-1)^{n_0-1}$, C_j^i is the combination expression. $z_1, \cdots, z_{n_0}$ can be deduced based on the measured signal y via (7), furthermore, calculate the estimated differentials $\hat{y}, \cdots, \hat{y}^{(n)}$ via (8).

3. MODEL FREE CONTROL BASED ON GIMC STRUCTURE

As mentioned in the introduction, it is difficult to determine the control performance if only the MFC is used. The reason for this problem is the intrinsic characteristic of MFC. However, the MFC is still a robust controller when there are plant uncertainties. It is possible to get better control performance if the robust controller and the performance controller are designed respectively, and they work together using certain structure. The GIMC structure provides a good candidate for achieving this objective [19-22]. If the transfer function of the MFC block is K_0, K_0 is a stabilizing controller for the nominal plant G_n, and assume that G_n and K_0 have the following stable coprime factorizations:

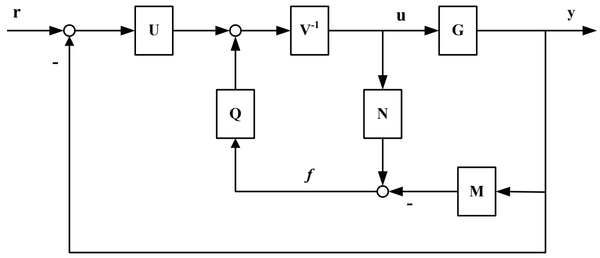

Fig. 2. GIMC structure.

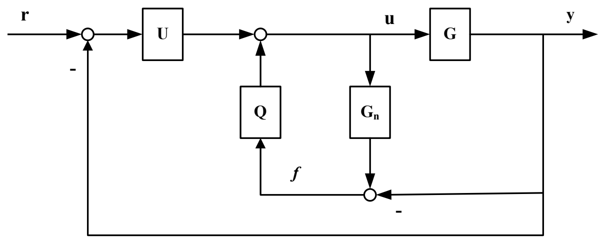

Fig. 3. GIMC structure when G_n is stable.

$$K_0 = V^{-1}U, \quad G_n = M^{-1}N, \quad (9)$$

the inner loop in Fig. 1 can be rearranged as Fig. 2 and the internal stability of the system is not changed [19,21].

As the robust controller (here, it is MFC) is used to weaken the plant uncertainty and stabilize the system, K_0 does not need to be complicated. For simplicity, V can be chosen as 1 and $U = K_0$. If both G_n and $G_n/(G_n+1)$ are stable, N and M can be set to G_n and 1, respectively. The GIMC structure will take the form as shown in Fig. 3. Outstanding feature of this controller implementation is that the inner loop feedback signal f is always zero if the plant model is perfect, i.e., if $G = G_n$, which can be seen directly from Fig. 2 or Fig. 3. The inner loop is only active when there is a model uncertainty or other sources of uncertainties [19].

If the transfer function of model-free controller denotes explicitly as K, the relationship of K and Q is [19]

$$K = (V - QN)^{-1}(U + QM). \quad (10)$$

If $V = 1$ and $M = 1$, (10) becomes

$$K = (V - QN)^{-1}(U + Q). \quad (11)$$

Then one can obtain

$$Q = (K - U)(NK + 1)^{-1} = (K - K_0)(G_nK + 1)^{-1}. \quad (12)$$

There is a problem that how to realize MFC in GIMC structure as MFC should transform into Q according to (12), but model-free controller is not directly expressed in the form of transfer function according to (4), (5), (7) and (8). According to (12), Q can be determined by K_0, G_n and K. However, Q might be too complicated to be realized by calculating (12). The complication will reduce if Q can be directly constructed by the modules of K_0, G_n and K. Using control block diagram is good method to clarify the relationships of Q, K_0, G_n and K. The block diagram of (12) can be depicted as Fig. 4. Then, the block diagram of the MFC based on GIMC

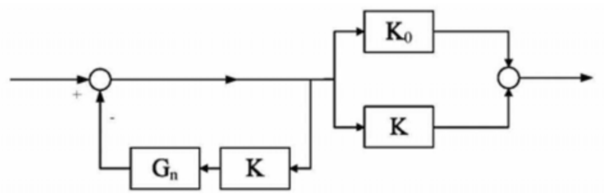

Fig. 4. Block diagram of Q.

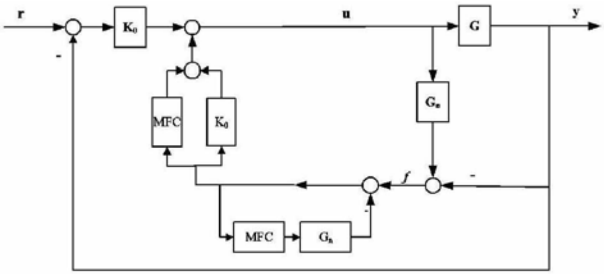

Fig. 5. Block diagram of MFC based on GIMC.

structure can be reconfigured as Fig. 5. In this block diagram, the structure of MFC does not need to be changed and the controller K_0 can be designed as a simple controller according to the nominal model G_n. Comparing Fig. 5 with Fig. 3, the robust controller G in Fig. 3 is disassembled and rearranged to several blocks, which makes the proposed methods easy to use. There is a logical question about the scope of application of Fig. 5. According to the analysis of GIMC in [19], the internal model stability can be guaranteed if the block MFC is linear time-invariant controller. It will need more analysis if the block MFC is nonlinear and/or time-invariant controller. In this paper, MFC is a linear time-invariant controller and the internal model stability can be guaranteed.

4. EXPERIMENT RESULT

Consider the following typical two-rank uncertain plant with high parameter uncertainty [22].

$$G(s)=\frac{k}{As^2+Bs+C} \tag{13}$$

with independent uncertainties:

$$k\in[1,4];\quad A\in[1,4];\quad B\in[-2,2];\quad C\in[1,6.25].$$

This system is not stable in some values of the parameters, for example, $B<0$.

Before the design of model-free controller based on GIMC structure, the nominal model must be chosen firstly. It can be identified using the output and input data. Sometimes, the nominal model usually is chosen as the normal state model according to the linear "first-principles" models which are obtained from an under-standing of the physical and chemical transformations occurring inside a process. Here the the nominal model is chosen as

$$G_n(\mathrm{s})=\frac{2.5}{2.5\mathrm{s}^2+\mathrm{s}+3.7}. \tag{14}$$

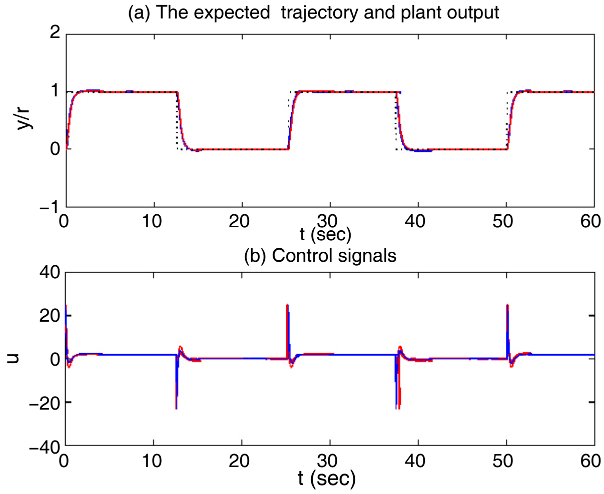

Fig. 6. The servo responses when the desired time constant is 0.2 seconds and GIMC based model-free controller is used.

Both $G_n(s)$ and $G(s)$ are stable. Using the control system toolbox of matlab 7.0, the controller for nominal model can be designed easily. Here we use the automated tuning function. The design method is chosen as Internal Model Control Tuning. We can choose two specifica-tions: dominant closed-loop time constant and desired controller order. If the dominant closed-loop time constant is chosen as 0.2 second, the desired controller order is chosen as 2, the automated tuned controller can be found as (15) for the nominal model (14).

$$K_0=3.7\frac{(0.82s)^2+0.72s+1}{0.1s^2+s}. \tag{15}$$

If K_0 controller (15) and MFC based GIMC is used where MFC parameters are chosen as λ=5, $\bar{K}$=[15,8, 1] and the plant parameters are chosen as the normal plant, except parameter B, here $B=[-2,1,2]$, the plant output y, the expected trajectory r and the control signals are shown in Fig. 6 which is the response of the servo simulation using the proposed method. Here, the dotted curve is the expected trajectory, which is a unit pulse signal with a period of 25 seconds, a pulse width of 50% of period and without phase delay; and another three solid curves outputs corresponding to the different values of $B=-2$, 1, 2 in Fig. 6(a), respectively.

If we want to change the desired performance, only the controller K_0 need to be redesigned. For example the dominant closed-loop time constant is chosen as 1.5 second, the desired controller order is also chosen as 2, the automated tuned controller can be achieved as

$$K_0=0.49333\frac{(0.82s)^2+0.72s+1}{0.75s^2+s}. \tag{16}$$

If controller K_0 chosen as (16) and the model-free controller, whose parameters are not changed, based GIMC is used, the plant output y and the expected trajectory r are shown in Fig. 7(a), and the control signals are shown in Fig. 7(b). Here the expected

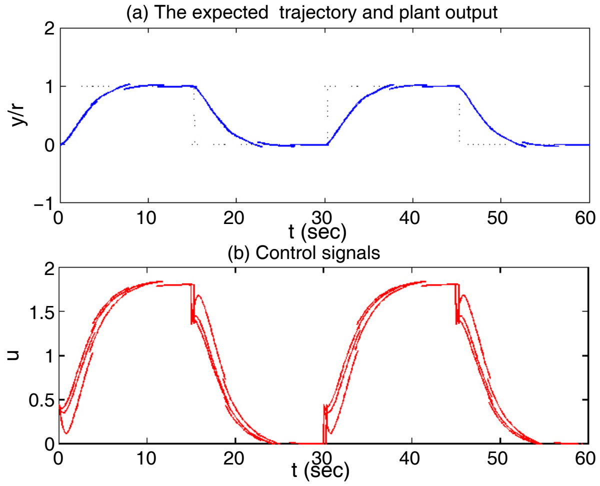

Fig. 7. The servo responses when the desired time constant is 1.5 seconds and GIMC based model-free controller is used.

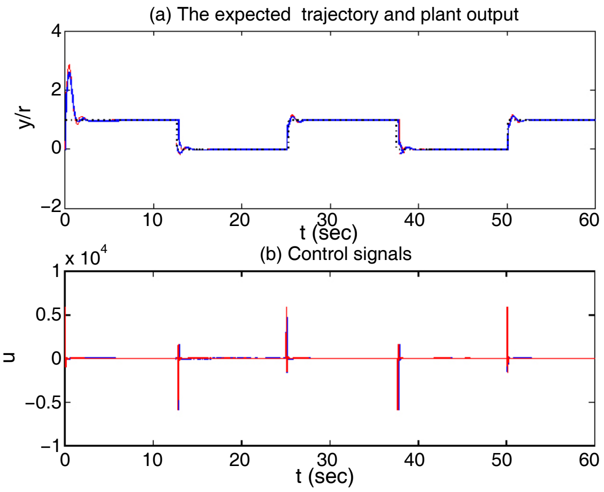

Fig. 8. The servo responses when only MFC is used.

trajectory is a unit pulse signal with a period of 30 seconds, a pulse width of 50% of period and without phase delay. For Fig. 7, it can be seen that transient response is slower than the previous one as the desired time constant is 1.5 second rather than 0.2 second.

If only MFC, whose parameters are chosen as $\lambda = 5$, $\overline{K} = [15,8,1]$, is used and the plant parameters are chosen as the normal plant, except parameter B, here $B = [-2,1,2]$, the time responses y, the expected trajectory r and the control signals are shown in Fig. 8. The dotted curve and three solid curves are the expected trajectory and plant output in Fig. 8(a), respectively.

The control performance is determined by controller K_0 when $G = G_n$, that is, $B = 1$. As can be seen from Fig. 6(a) and Fig. 7(a), the control performance is almost the same although the value of B is changed. As can be seen from Fig. 6(b) and Fig. 8(b), the control signal fluctuates too violent to be used in controlling the plant if only model-free controller is used. Table 1 presents the statistical analysis of performance for servo behaviors

Table 1. Comparison between the proposed method and MFC for servo behavior.

Variable	Figure	Max	Min	Mean	Std.dev
$\lvert y-r \rvert$	Fig. 6.a	1	0	0.034	0.14
$\lvert y-r \rvert$	Fig. 7.a	1	0	0.200	0.29
$\lvert y-r \rvert$	Fig. 8.a	1.86	0	0.025	0.14
u	Fig. 6.b	24.88	-23.1	0.86	1.71
u	Fig. 7.b	1.47	0.0	0.90	0.73
u	Fig. 8.b	5859.41	-5857.6	1.74	132.69

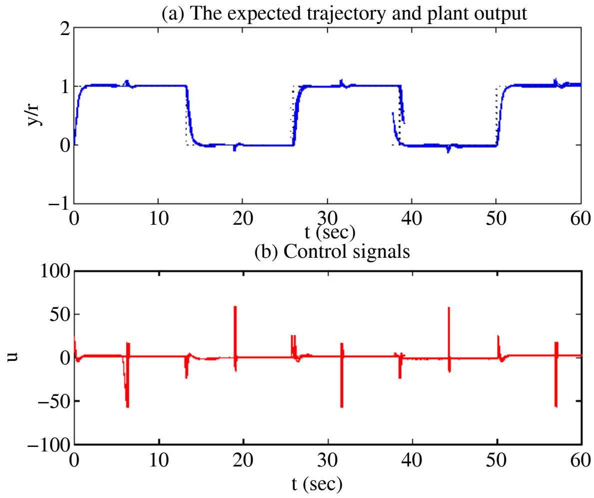

Fig. 9. The regulatory responses when the desired time constant is 0.2 seconds and GIMC based model-free controller is used.

using the proposed method and MFC algorithm. It should be noted that the solver option of configuration parameters of Matlab/simulink should be chosen as fixed-step otherwise the statistical analysis results are not right using the simulation data.

As can be seen from Table 1, it also shows that the control signal fluctuates too violent to be used in controlling the plant if only model-free controller is used. However, the proposed method can reduce the fluctuating of the control signal. This is because the MFC is used to control the uncertainty and the controller K_0 for nominal model is used to satisfy the desired requirements. Comparing Figs. 6 and 7 with Fig. 8, the similar result can also be obtained.

For the analysis of regulatory behaviors, the expected trajectory is a unit pulse signal with a period of 25 seconds, a pulse width of 50% of period and without phase delay; and an additive disturbance is added in the process output. The disturbance is a pulse signal with a period of 25 seconds, an amplitude of 0.1, a pulse width of 50% of period and a phase delay of 6.25 seconds. Using the proposed method, the regulatory response is shown in Fig. 9.

If only MFC is used, the regulatory response is shown in Fig. 10. It is difficult to find which regulatory response is better just according to the response Figs. 9 and 10. Hence, it is necessary to do a statistical analysis of performance for the regulatory behaviors using these two different control methods. Table 2 presents the statistical analysis of performance for servo behaviors

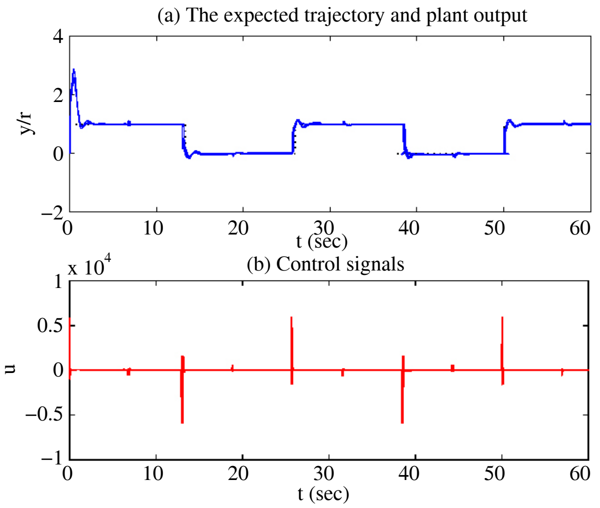

Fig. 10. The regulatory responses when only MFC is used.

Table 2. Comparison between the proposed method and MFC for regulatory behavior.

Variable	Figure	Max	Min	Mean	Std.dev
$\lvert y-r \rvert$	Fig. 9.a	1	0	0.035	0.14
$\lvert y-r \rvert$	Fig. 10.a	1.86	0	0.05	0.20
u	Fig. 9.b	58.6	-57	0.85	2.16
u	Fig. 10.b	5859.4	-5858	1.70	146.39

using the proposed method and MFC algorithm. As can be seen from Table 2, the proposed method can achieve a better regulatory response performance than only using MFC algorithm.

5. CONCLUSION

In this paper, model-free controller based on GIMC is proposed for uncertain plant. The robust controller in the original GIMC was disassembled and rearranged to make the proposed methods easy to use. Moreover, this method makes the controller be more flexible and the method greatly improved the system performance. If some specifications are changed, it does not need to redesign the MFC controller since some of the parameters of the nominal controller can be changed to meet this kind of requirement. The example showed that the technique has better control performance and it is easily to be used.

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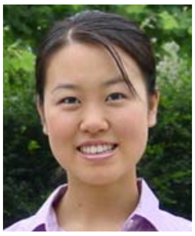

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