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Model Free Adaptive Robust Control Based on GIMC Structure for Nonlinear Discrete-Time System

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***Abstract*— In this paper, a novel model free adaptive robust control (MFARC) algorithm is proposed to adaptive and robust control for a class of complex and uncertain nonlinear systems, which are considered to have random noise and disturbances in the input and output data. It is shown that general inner model control (GIMC) structure can be used to overcome the trade-off that performance and robustness of controller are both taking into account. Meanwhile, model free adaptive control is employed to guarantee the performance of nominal controller with disturbance or uncertainty, where the detailed analytical models are difficult to obtain. The unique feature of this paper is that we explicitly combine data driven control technique and GIMC structure to design controller directly to omit the drawback of model linearization with dynamical uncertainties and disturbances. Simulation results show the effectiveness and applicability of the proposed control law.**

***Index Terms*— MFARC, GIMC, Nonlinear, Disturbance, Adaptive**

I. Introduction

Recently, researches on robust and adaptive control of nonlinear system have attracted great attentions from a great deal of research communities [1][2]. The main challenge in the robust and adaptive control field is to overcome the trade-off that performance and robustness of controller are both taking into account. The robustness of a controller is based on the worst case, which may never present and it is hard to obtain an excellent performance [3]. On the other hand, for most processes or systems, detailed analytical models are difficult to obtain. It is common to employ an nominal model to represent the real systems, which are variable and complex [4]. Furthermore, it is especially obvious in nonlinear system with dynamical uncertainties and disturbances. Therefore, a proper robust and adaptive controller for nonlinear system is hard to settle [5].

Most of the existing achievements of this challenge are focused on linear systems, but extensions to robust and adaptive control of nonlinear systems have also been proposed in [6] and [7]. Furthermore, the applications of fuzzy logic [8] and neural network [9] to robust and adaptive control have been recently developed. Although many methods and techniques have been proposed to tackle this problem, such as model linearization, nonlinear compensation and nonlinear mapping [10], the results of them are both objective to avoid nonlinear. In [11], a data-driven control method, model free adaptive control (MFAC), is introduced. MFAC does not depend on the model of system and it is used to attenuate the disturbance or uncertainty.

Zhou proposed a approach for this demand, a control scheme based on (general inner model control) GIMC structure [12]. In this literature, nominal performance controller and robustness controller are respectively developed. However, the affection of two controllers are coexistence and complementarity.

Inspired by [11][12][15], a novel model free adaptive robust control (MFARC) algorithm is proposed in this paper and both of high performance for the nominal plant and the high robustness for the perturbed plants are guaranteed. The most contributions are

- A MFARC structure is proposed, whose well performance and robustness of control strategy are achieved.
- The whole control algorithm is suitable designed independent to any prior knowledge of controlled system.

Consequently, the proposed control structure is simple and easy for implementation. There is no requirement for cost and extremely time consuming process of system identification, and the bounds of uncertain disturbances are assumed unknown. The proposed algorithm, although easy for implementation, still shows significant performance improvement when disturbances and noise are not negligible.

This paper is organized as follows. The primary introduction of GIMC structure and some necessary assumptions and notations are given in Section II. MFARC control laws are developed in section III. Stability and robustness of proposed control scheme is analysed in section IV. The performance of the control strategy proposed is illustrated with simulation in Section V. Section VI concludes this paper.

II. Background and Problem Statement

A. Background

In most control problems, the objective of developed scheme is to accurately follow a predefined setpoint. Some SISO non-affine discrete nonlinear systems are depicted as

$$\begin{aligned} y(k+1) = f(&y(k)+n(k),\dots,y(k-l_y)+n(k-l_y),\\ &u(k),\dots,u(k-l_u))+d(k) \end{aligned} \tag{1}$$

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where, $u(k) \in \mathbf{R}, y(k) \in \mathbf{R}$ are the control input and output of system in time index k, respectively. l_u, l_y are some unknown positive integer. $d(k)$ is the disturbance and $|d(k)| < d_M$, but d_M is unknown here. $n(k)$ is the noise of output. $f(\cdot)$ is a general nonlinear function.

In order to obtain the nominal performance controller of system (1), those following assumptions are introduced.

Assumption 1: The system (1) is controllable.

Assumption 2: Omit some finite time points, the partial derivative of $f(\cdot)$ with respect to control input $u(k)$ is continuous.

Assumption 3: Omit some finite time points, system (1) is generalized Lipschitz, that is

$$|\Delta y(k+1)| \leq L|\Delta u(k)|, for \Delta u(k) \neq 0 \tag{2}$$

where L is a constant, $\Delta y(k+1) = y(k+1) - y(k)$ and $\Delta u(k) = u(k) - u(k-1)$ are change of output and input, respectively.

Remark 1: Assumption 1 is common for many reality systems. Assumption 2 is a typical restrained condition for general nonlinear system. Assumption 3 can be treated as a limitation to the rate of the adjustment of control energy. These assumptions are reasonable and acceptable.

Lemma 1 [13]: The nonlinear system (1), assumption 1-3 are satisfied and $\Delta u(k) \neq 0$ for all k, can be described as the equivalent form

$$\Delta y(k+1) = \phi(k)\Delta u(k) \tag{3}$$

where, $\phi(k)$ is time-variant parameter, called pseudo partial derivative (PPD). The proof of this Lemma is presented in the appendix.

B. GIMC Structure

The GIMC structure was first proposed in [12], which is a good candidate for achieving both performance and robustness.

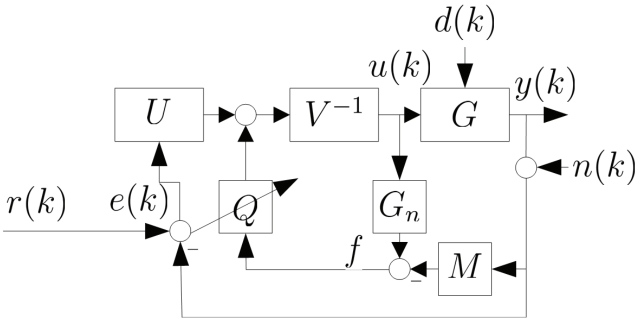

Fig. 1. The control structure of GIMC

Lemma 2 [12]: For a stabilizing controller K_0 and a nominal model G_0, if they have the following coprime factorizations

$$K_0 = V^{-1}U, G_0 = M^{-1}G_n \tag{4}$$

Then every K stabilizes the feedback system can be written as

$$K = (V - QG_n)^{-1}(U + QM) \tag{5}$$

where $Q \in H_\infty$ is determined arbitrarily as long as

$$det(V(\infty) - Q(\infty)G_n(\infty)) \neq 0 \tag{6}$$

The way of implementing this controller is shown in Fig. 1. $r(k)$ is setpoint, G is the plant, $u(k)$ and $y(k)$ are input and output, respectively. G_n is the nominal model, U and V^{-1} are nominal control, Q and M are robust control. In this paper, disturbance $d(k)$ and noise $n(k)$ are both taking into account. As the robust controller is used to weaken the uncertainty and stabilize the loop, the nominal controller K_0 is simple.

III. Control Scheme

In this section, the control scheme is divided into two steps:

- Design a nominal performance controller K_0 to satisfy the requirements of performance.
- Design a robust controller Q to satisfy the robustness requirements of system.

Remark 2: Q is only active when there is a input of f. So that the robust controller Q will not affect the performance of nominal controller K_0.

A. Nominal Controller Design

As mentioned in former, nominal controller can be designed without robust controller Q. The control diagram is simplified as Fig.2, the nominal controller is K_0, the nominal model is G_0. Assuming there exist two PPD, $\hat{\phi}_1(k), \hat{\phi}_2(k)$, satisfy that

$$\Delta y_m(k+1) = \hat{\phi}_1(k)\Delta u(k), \Delta e(k+1) = \hat{\phi}_2(k)\Delta u(k) \tag{7}$$

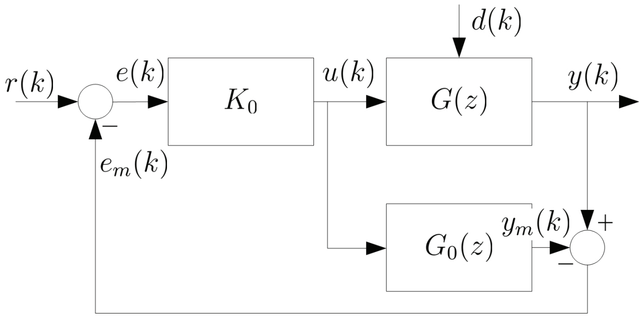

Fig. 2. The control structure of nominal controller

Lemma 3 [13]: The PPD, $\phi(k)$, is bounded. minimum and maximum boundaries of $\phi(k)$ are

$$\phi_m < |\phi(k)| < \phi_M(k) \tag{8}$$

Details of the theoretical basis and the mathematical proof of Lemma 3 are given in [14].

Theorem 1: The nominal controller and nominal model are described in Fig. 2. If $\hat{\phi}_1(k) = \hat{\phi}_2(k)$, and $|\Delta u(k)| \neq 0$. The tracking error $e_y(k) = r(k) - y(k)$ will be guaranteed to satisfy $\lim_{t\to\infty} e_y(k) = 0$.

Proof: From Fig.2, we can obtain that

$$y(k+1) = y(k) + \phi(k)\Delta u(k) + d(k) \tag{9}$$

$$y_m(k+1) = y_m(k) + \hat{\phi}_1(k)\Delta u(k) \tag{10}$$

Define error $e_m(k) = y(k) - y_m(k)$. (9) minus (10), then

$$\Delta e_m(k+1) = \tilde{\phi}(k)\Delta u(k) + d(k) \tag{11}$$

where, $\tilde{\phi}(k) = \phi(k) - \hat{\phi}_1(k)$, $\Delta e_m(k+1) = e_m(k+1) - e_m(k)$.

It is clear that

$$e(k) = r(k) - e_m(k) \tag{12}$$

then, we can obtain

$$\Delta e(k+1) = \Delta r(k+1) - \Delta e_m(k+1) \tag{13}$$

Substitute (7) into (13)

$$\begin{aligned} \Delta r(k+1) &= (\tilde{\phi}(k) + \hat{\phi}_2(k))\Delta u(k) + d(k) \\ &= \Delta y(k+1) + (\hat{\phi}_2(k) - \hat{\phi}_1(k))\Delta u(k) \end{aligned} \tag{14}$$

It is assumed $|\Delta u(k)| \neq 0$, then

$$\begin{aligned} \Delta e_y(k+1) &= e_y(k+1) - e_y(k) \\ &= \Delta r(k+1) - \Delta y(k+1) \\ &= (\hat{\phi}_2(k) - \hat{\phi}_1(k))\Delta u(k) \end{aligned} \tag{15}$$

if $\hat{\phi}_1(k) = \hat{\phi}_2(k)$, then $\lim_{t\to\infty} \Delta e_y(k) = 0$.

Next, we will proof that $\lim e_y(k+1) \to 0$.

For system $G(z)$, the input $u(k)$ and output $y(k)$ can be used to estimate the nominal controller. For estimating PPD, a cost function is proposed in [13]

$$\begin{aligned} J(\phi(k)) = &|y(k) - y(k-1) - \phi(k)\Delta u(k-1)|^2 \\ &\mu|\phi(k) - \hat{\phi}(k-1)|^2 \end{aligned} \tag{16}$$

solve (9) for maximum or minimum with respect to $\phi(k)$

$$\hat{\phi}(k) = \hat{\phi}(k-1) + \frac{\eta\Delta u(k-1)}{\mu + |\Delta u(k-1)|^2}(\Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1)) \tag{17}$$

where, $\lambda > 0$ is a punishment factor, $\eta \in (0,1]$ is a step factor.

Define $\tilde{\phi}(k) = \phi(k) - \hat{\phi}(k)$ is the error of PPD. From Lemma 3, $\phi(k)$ is bounded. Then we can obtain that $\tilde{\phi}(k)$ is also bounded. Assuming there exist a constant ϵ, satisfy

$$|\tilde{\phi}(k)| < \epsilon \tag{18}$$

After a period of parameters tuning, it is assumed that the error of estimate of PPD is approximate to real value of PPD. Then, we can obtain that $\lim \Delta e_m(k+1) \to d(k)$.

$$\begin{aligned} \lim e_y(k+1) &= \lim(r(k+1) - y(k+1)) \\ &= \lim(r(k+1) - y(k) - (y(k+1) - y(k))) \\ &= \lim(r(k+1) - (r(k) + \Delta e_m(k+1))) \to 0 \end{aligned} \tag{19}$$

Meanwhile, $\lim_{t\to\infty} \Delta e_y(k) = 0$, Then, $\lim_{t\to\infty} e_y(k) = 0$.

Remark 3: The nominal control algorithm proposed here has no relationship with any prior knowledge of function $f(\cdot)$ in (1). Since it is designed via I/O data from system (1), this method can extend to any nonlinear system with similar structure of I/O data.

B. Robust Controller Design

In this subsection, we will consider how to develop the robust controller Q. According to (5), K is determined by Q, K_0 and G_0. Q can be designed using standard robust control techniques. However, it is difficult to give a mathematic model of $G(z)$ and a new technique of robust controller design is proposed. Hereby, we address the model free direct design problem from the input/output data.

Introduce a dual Youla parameter $R \in H_\infty$ [14]

$$G = (G_n + VR)(M - UR)^{-1} \tag{20}$$

Then, the actual system could be represented by the dual Youla parameter R. Using (20), the equivalent diagram in Fig.1 can be shown by Fig. 3.

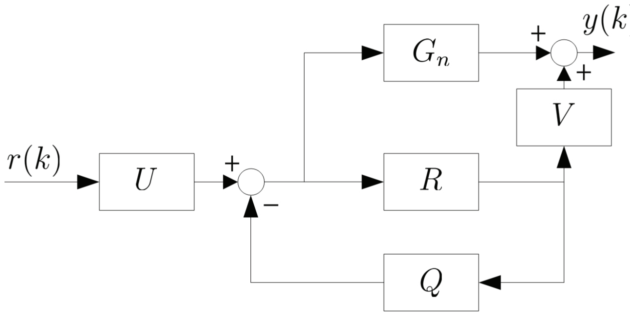

Fig. 3. Equivalent block diagram

As shown in Fig.3, the transfer function between r and y, denoted by T_{ry}, can be obtained

$$T_{ry} = \frac{U(G_n + RV)}{1 + RQ} \tag{21}$$

The problem has been degenerated to design a proper Q that the output of G_{ry} track a predefined output and it corresponds to the nominal control performance as well as possible. Inspired by [15], a data-driven control strategy, Virtual Reference Feedback Tuning (VRFT), is employed to tackle this problem. More detail analysis and description of VRFT can be found in [15].

Given a reference model $M(z)$, which is given by the designer and related to the nominal controller. For general system, the conventional VRFT algorithm can be formally stated in the following four steps:

step1: Choosing a suitable filter $|L(z)|^2 = |1 - M|^2|M|^2\frac{1}{\Phi_u}$, and calculate:

$$\begin{aligned} e_L(t) &= L(z)e(t) \\ u_L(t) &= L(z)u(t) \end{aligned} \tag{22}$$

where $e(t) = r(t) - y(t)$ is a error signal with $y(t) = M(z)r(t)$.

step2: Select the controller parameter vector θ, and consider the form of controller $\beta(z)$. Use proper parameters and make sure that

$$Q(z;\theta) = \beta^T(z)\theta$$

where, $\beta(z)$ is a discrete-time transfer function vector defined as

$$\beta(z) = [\beta_1(z), \beta_2(z), \ldots, \beta_n(z)]^T \tag{23}$$

step3: Minimize the following performance index

$$J_{MR}(\theta) = \|(\frac{U(G_n + RV)}{1 + RQ} - M(z))W(z)\|_2^2 \tag{24}$$

where, $W(z)$ is a frequency weighting function.

step4: The parameter vector is minimized in an explicit function of the data:

$$\hat{\theta}_{ML} = [\sum_{t=1}^{N} \varphi_L(t)\varphi_L(t)^T]^{-1} \sum_{t=1}^{N} \varphi_L(t)u_L(t)^T \tag{25}$$

where, $\varphi_L(t) = \bar{\beta}(z)e_L(t)$.

However, since the dual Youla parameter R is described as [14]

$$R = U(G - G_n)[V(1 + GK_0)]^{-1} \tag{26}$$

and it is difficult to give a distinct express of R, but we can use the closed-loop experimental data set $\{r(t), u(t), y(t)\}$ to minimum the $J_{MR}(\theta)$.

IV. Robust Stability

The controller is designed via data-driven technique, but stability issue of the resulting closed-loop system is not explicitly address. Therefore, it is essential to analyse the robust stability characters of closed system. The nominal controller K_0 and robust controller Q need to confirm some stability conditions before its implementation.

For K_0 in Fig. 2, the closed loop could be described as

$$\delta_K = \frac{K_0(G - G_n)}{1 + K_0(G - G_n)} \tag{27}$$

Using the small-gain theorem, the condition of stability is

$$|K_0\tilde{G}| < 1 \tag{28}$$

where, $\tilde{G} = G - G_n$ is the mismatch of model.

For Q, the resulting of Youla parameter is undetermined. According to (20), the equivalent diagram can also be presented as Fig.4.

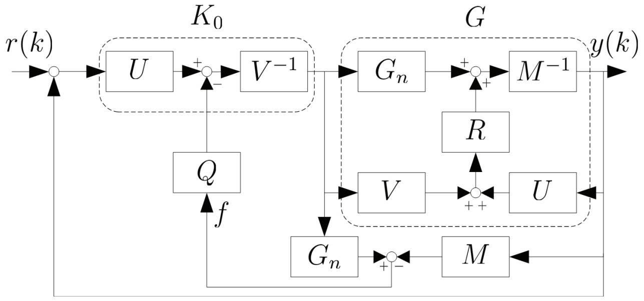

Fig. 4. Equivalent block diagram

To avoid the instability situation, some constraints should be add to the controller design of Q.

Consider a stability controller K_s and the closed loop is given by

$$M_s = \frac{K_sG}{1 + K_sG} \tag{29}$$

For controller Q, it can be represented as in Fig. 4. In order to guarantee stability, all poles could be within the open unit circle. Define

$$\begin{aligned} \Delta(\theta) &:= M_s - K(\theta)G(1 - M_s) \\ \delta(\theta) &:= \|\Delta(\theta)\|_\infty \end{aligned} \tag{30}$$

Lemma 4[16]: The controller $K(\theta)$ stabilizes the plant G if

- $\Delta(\theta)$ is stable.
- $\exists\delta_N \in [0, 1]$, **such that** $\delta(\theta) \le \delta_N$

Thus follows from the small-gain theorem and Lemma 4, the robust stability condition is

$$\begin{aligned} |K_0\tilde{G}| &< 1 \\ \|RQ\| &\le \delta_N \end{aligned} \tag{31}$$

V. Simulation

In this section, some simulation examples are used to verify our proposed control algorithm.

The system to be controlled is given by a Wiener model [17], which is depicted as

$$\begin{aligned} x(k) &= 1.5714x(k-1) + 0.6873x(k-2) \\ &+0.0616u(k-1) + 0.0543u(k-2) \\ y(k) &= \frac{x(k)}{\sqrt{0.1+0.9x^2(k)}} \end{aligned} \tag{32}$$

The control input is voltage and output is speed of a motor. This model used to produce input and output data and it is without any relation to the controller design. The target closed-loop transfer function is given by

$$M(z) = \frac{z^{-3}(1-\alpha)^2}{(1-az^{-1})^2}, \alpha = e^{-T_s\omega} \tag{33}$$

where ω=10rad/s, T_s=0.01s is the sample time.

For nominal controller, the initial value of parameters are: $n_y = 1, n_u = 2, \eta = 0.2, \lambda = 1, \phi(1) = 1$.

For robust controller, Q is defined as:

$$Q(z;\theta) = \frac{\theta_0 + \theta_1 z^{-1} + \theta_2 z^{-2}}{1 - z^{-1}} \tag{34}$$

The value of the parameters are selected as: $\theta_1 = 0.264, \theta_2 = 0.112, \theta_3 = -0.33$.

From Fig.5 to Fig. 8, X-axis is simulation time and unit is 10ms, Y-axis are speed of motor and unit is rad/s. Control results with different white noise are shown in Fig. 5. The red solid line and blue dot line represent the situation that noise power is 0.5 and 1, respectively. The black dot line is setpoint.

Control results with impact disturbance is shown in Fig. 6. The impact disturbance is added in the half of simulation time and amplitude of disturbance is 10. Disturbance is added in the initial part and adjust to smooth and steady in the follow part.

Control results and tracking error with different parameters are shown in Fig.7 and Fig.8, respectively. The red

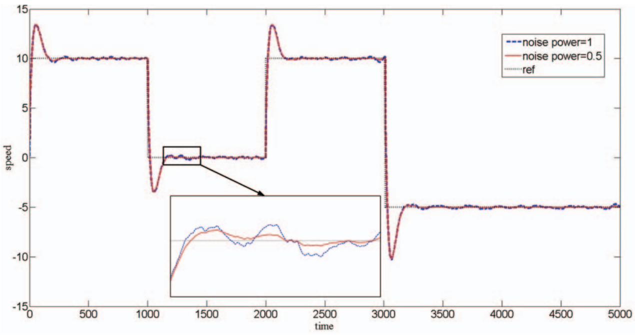

Fig. 5. Control results with different white noise

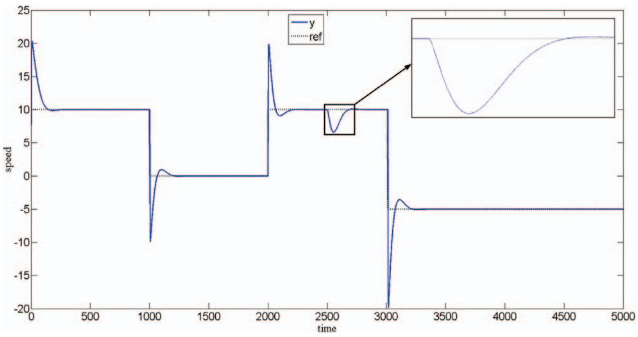

Fig. 6. Control results with impact disturbance

solid line and blue dot line are represented by $\lambda = 0.1$ and $\lambda = 1$. It is obvious that tracking performance of proposed approach is well and tracking error be close to zero in the end.

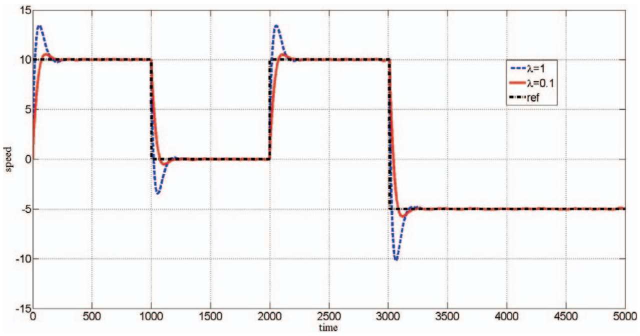

Fig. 7. Control results with different parameters

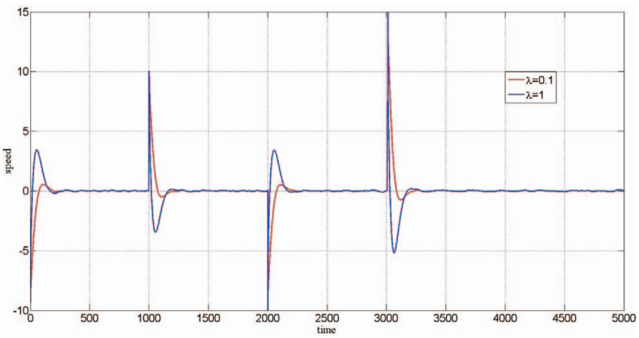

Fig. 8. Tracking error with different parameters

VI. Conclusion

In this paper, a novel model free adaptive robust control (MFARC) algorithm is proposed for nonlinear discrete system. Using online I/O data of system, the control strategy is proposed directly so that nominal performance and robustness are both achieved. Although there are some oscillations in the beginning, the tracking error is small and converge to zero finally.

However, since the stability of controlled system is considered, the stability conditions are dependent on the quality of the data. It is not same to the situation of model based control and some sufficient conditions are essential to confirm advanced in next work. Meanwhile, for lack of the mechanism acknowledge of system, the initial value of parameters are difficult to determine. It is needed to add some criterions to determine those value in the future work.

Appendix

Proof of Lemma 1.

The system is described as (1) and the change of $y(k+1)$ can be obtained

$$\begin{aligned}
\Delta y(k+1) &= y(k+1) - y(k) \\
&= f(y(k)+n(k),\dots,y(k-l_y)+n(k-l_y), \\
&\quad u(k),\dots,u(k-l_u)) + d(k) \\
&\quad -f(y(k-1)+n(k-1),\dots,y(k-l_y-1)+n(k-l_y-1), \\
&\quad u(k-1),\dots,u(k-l_u-1)) - d(k) \\
&= f(y(k)+n(k),\dots,y(k-l_y)+n(k-l_y), \\
&\quad u(k),\dots,u(k-l_u)) \\
&\quad -f(y(k)+n(k),\dots,y(k-l_y)+n(k-l_y), \\
&\quad u(k-1),u(k-1),\dots,u(k-l_u)) \\
&\quad +f(y(k)+n(k),\dots,y(k-l_y)+n(k-l_y), \\
&\quad u(k-1),u(k-1),\dots,u(k-l_u)) \\
&\quad -f(y(k-1)+n(k-1),\dots,y(k-l_y-1)+n(k-l_y-1), \\
&\quad u(k-1),\dots,u(k-l_u-1))
\end{aligned} \tag{35}$$

Define

$$\begin{aligned}
\Pi(k) &= f(y(k)+n(k),\dots,y(k-l_y)+n(k-l_y), \\
&\quad u(k-1),u(k-1),\dots,u(k-l_u)) \\
&\quad -f(y(k-1)+n(k-1),\dots,y(k-l_y-1)+n(k-l_y-1), \\
&\quad u(k-1),\dots,u(k-l_u-1))
\end{aligned} \tag{36}$$

Using the Cauchy differential mean value theorem, we can obtain

$$\Delta y(k+1) = \frac{\partial f}{\partial u(k)}\Delta u(k) + \Pi(k) \tag{37}$$

where, $\frac{\partial f}{\partial u(k)}$ denote the partial derivative operation of f with respect to $u(k)$. For a fixed time index k, there exist a proper $\delta(k)$ that

$$\Pi(k) = \delta(k)\Delta u(k) \tag{38}$$

If we let

$$\phi(k) = \delta(k) + \frac{\partial f}{\partial u(k)} \tag{39}$$

(35) can be written as

$$\Delta y(k+1) = \phi(k)\Delta u(k) \tag{40}$$

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