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Robust Adaptive Control with Leakage Modification for a Nonlinear Model of Ionic Polymer Metal Composites (IPMC)

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***Abstract*—Ionic Polymer Metal Composites (IPMC) is a smart material used widely in many industrial and medical applications. In this paper, we propose a mathematical nonlinear model for the IPMC by adding the external random disturbances, then we apply the robust adaptive control method with leakage modification to control the position of this material to reduce the tracking error, the overshoot, and the steady state of the IPMC. In addition, a controller is designed to ensure that the IPMC's displacement response is stable and robust in the presence of different external random disturbances.**

Keywords: Leakage modification, nonlinear model, normalized estimation error, normalizing signal, IPMC.

I. INTRODUCTION

A. Motivation

IPMC, one type of electro-active polymers, has many advantages, such as fast and significant bending, mechanical flexibility, low excitation voltage,, ease of fabrication [1], [2], [3], [4] for applications of robots [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], artificial muscles [7], actuators, and transducers [15], etc. Basically, the IPMC is constructed by [16]: Nafion 117, Au or Pt, [Pt(NH3)4]Cl2 or [Pt(NH3)6]Cl4, NaBH4, NH2NH2- 1.5H2O, NH2OH-HCl, NH4OH HCl, and deionized water. Figure 1 shows an SEM (Scanning Electron Microscope) image of Au sputtered the IPMC cross section [14]. Figure.2 shows the experimental setup with

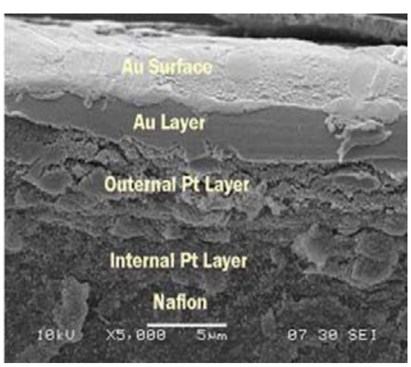

Fig. 1. The structure of the IPMC.

a simple power generator to generate adjustable voltage in

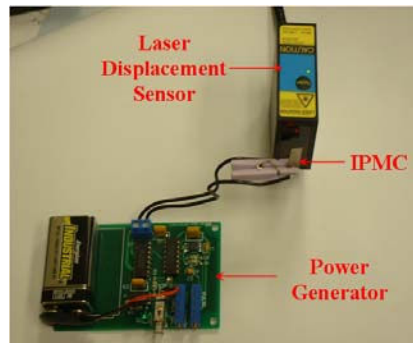

Fig. 2. Experimental setup for checking the actuation of the IPMC.

range -3V to 3V, and also the adjustable frequency and displacement laser sensor, model AR200-50 (from Acuity company)[17] to check the actuation of the IPMC.

The main motivation of this paper is to build the nonlinear model of the IPMC containing all its nonlinear capabilities. This demonstrates its structure and parameters which will be changed in the harsh environments such as for applications in the harsh space environments where there are 1 Torr of pressure and very low temperature [7]. Based on this nonlinear model, we apply the robust adaptive control method with leakage modification to design a new nonlinear controller for its position control so that the IPMC's displacement response is stable and robust in the presence of random disturbances.

B. Related Work

Generally, there are many types of mathematical IPMC model developed in the last decade, but most of them are mathematical linear models [14], [18], [19], [20], [21], [22], [23], [24], [16], [25], [26], [27]. These models can make it easy to design a controller for controlling the IPMC's position and force. The results in these publications are very good in term of small tracking errors, small overshoot, and eliminated steady state, but all of these results are done in ordinary environments with no disturbances, or these models do not include the unstable factors in the IPMC when it works in the varying environment conditions. For example, the imbalanced charge density, the distributed surface resistance [3], the RH (Relative Humidity) factor [25], the relationship between the electrochemical response and mechanical response [28], and the nonlinearity of the absorbed current [29], etc can be changed. Moreover, the external noises under very high or low temperatures can also affect the IPMC material negatively.

In addition, there are also many types of physical linear IPMC model [30], [19], [29], [28], [31], [32]. All of these models try to describe physical phenomena of the IPMC using equivalent circuits. These models are very useful for checking current and voltage responses of the IPMC, but they may be difficult to be applied in mathematical control laws to control precise position or force of the IPMC. Moreover, although there are many linear controllers for the IPMC, we still do not have any nonlinear controller for the nonlinear model of the IPMC which considers both external and internal disturbances.

The rest of this paper is organized as follows. In the next section we propose a new nonlinear model for the IPMC. Section III presents the existing control methods used to control the IPMC, and then we present a control method called robust adaptive control with leakage modification. Section IV presents the simulation results. Finally, Section V shows the conclusion and the future work of this paper.

II. A NONLINEAR MODEL OF THE IPMC

Although the nonlinear models of the IPMC have been conducted in [29], [33], they do not take into account the external disturbances, for example the temperature, or the internal disturbances of the IPMC such as the imbalanced charge density, the RH, the absorbed current and voltage, etc which can change the structure and parameters of mathematical IMPC model when the IPMC is applied to work in changing environments or harsh environments. Therefore, in this paper we expect to model IPMC with all its nonlinear capabilities by adding disturbance factors from outside coming into the IPMC based on the linear model of the IPMC created by other authors. Based on this, the model of the IPMC in [21] can be rewritten as follows:

$$G(s) = \frac{d_2a_3s^3 + a_2s^3 + a_1s + a_0}{b_4s^4 + b_3s^3 + b_2s^2 + b_1s + b_0} = \frac{c_0}{s^2 + d_1 + d_0} + \frac{q_1s + q_0}{s^2 + k_1s + k_0} \tag{1}$$

Where a_3, a_2, a_1, a_0 and b_4, b_3, b_2, b_1, b_0 are known as follows: $a_3 \in [1.207,\ 7.208]$, $a_2 \in [1906,\ 2299]$, $a_1 \in [2.04e+5,\ 9.816e+5]$, $a_0 \in [4.32e+5,\ 1.355e+7]$, $b_4 = 1$, $b_3 \in [22.66,\ 500.3]$, $b_2 \in [2.068e+5,\ 6.805e+5]$, $b_1 \in [1.932e+6,\ 1.602e+7]$, and $b_0 \in [5.109e+5,\ 3.266e+7]$. Hence, we can easily find out parameters c_0, d_2, d_1, d_0, q_1, q_0, k_1, k_0. We suppose that $G_0(s)$ is the transfer function of the IPMC with no disturbance (the ideal model) and demonstrates the dynamics of viscoelastic beam in the polymer layer of the IPMC, and assume that $G(s)$ and $G_0(s)$ are related by [34]:

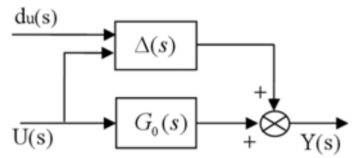

Fig. 3. The model of the IPMC with disturbance $d_u(s)$.

$$G(s) = G_0(s) + \Delta(s) \tag{2}$$

Where $\Delta(s)$ is an additive plant perturbation or uncertainty to demonstrate the electrodynamic of two electrode layers which contain the nonlinear factor such as the effect of distributed surface resistance, the imbalanced charge density, and the absorbed current, etc. From (1) and (2), we have:

$$G_0(s) = \frac{c_0}{d_2s^2 + d_1 + d_0} \tag{3}$$

$$\Delta(s) = \frac{q_1s + q_0}{s^2 + k_1s + k_0} \tag{4}$$

Here $G_0(s)$ is called the linear approximate model to cover the principle characteristics [33].

In [33] the nonlinear characteristics of the IPMC were identified by the Hammerstein model, or we also do that with other models such as Wiener model, NARMAX model, etc. Based on these results, we clearly see that the IPMC is a nonlinear object. Therefore, we must build its model by considering nonlinear characteristics to achieve an appropriate model in large range. To demonstrate the nonlinear factors of the IPMC we can build a nonlinear model for the IPMC by adding the external disturbance into $\Delta(s)$ as Figure 4. This figure shows a nonlinear IPMC model with an external disturbance affecting the IPMC where $d_u(s)$ is a bounded random disturbance. It demonstrates the internal nonlinear factors of the IPMC such as the asymmetric charge distribution, the RH factor, the electrochemical response and mechanical response, and the nonlinearity of the absorbed current, etc, and also the external disturbances such as the very high or very low temperatures of the working environments of the IPMC. Therefore, we obtain the mathematical nonlinear model for the IPMC to be:

$$Y_p(s) = [G_0(s) + \Delta(s)]U_p(s) + \Delta(s)d_u(s) \tag{5}$$

Where $Y_p(s)$ is the position response, and $U_p(s)$ is the control voltage applied to the IPMC. Hence, with this nonlinear IPMC model when the disturbance $d_u(s)$ is applied to it, all parameters q_1, q_0, k_1, k_0, and structure of $\Delta(s)$ will be changed. Now, our mission is to design a robust adaptive controller to reduce the impact of disturbances and ensure that the position response of the IPMC is stable and robust in the presence of changed parameter and structure.

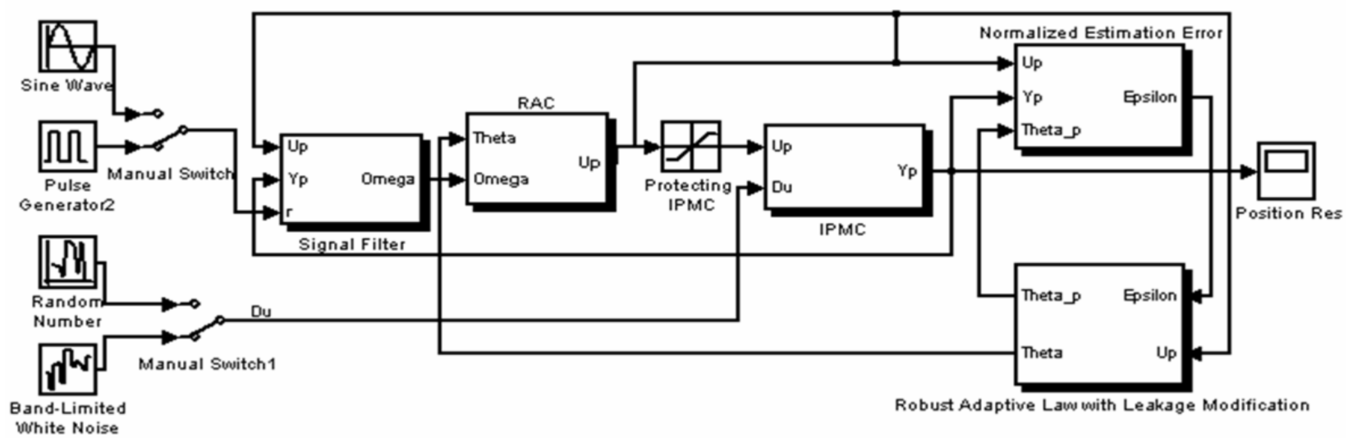

Fig. 4. The adaptive robust control scheme with leakage modification for controlling the IPMC's position.

III. DESIGN OF CONTROLLER

In the last decade, many control methods have been applied to design a controller for the linear model of the IPMC, such as the feedback control method [26], the digital lead-lag compensators [20], [23], [16], PID (Proportional-Integral-Derivative) [22], PID with LQR (Linear-Quadratic-Regulator) [21], MRAC (Model Reference Adaptive Control) with a genetic algorithm [24], Anti-windup scheme [35], Adaptive intelligent control [27], H-infinity control to deal with uncertanties [36], Robust adaptive control to deal with Conjugated Polymer Actuators [37], and Fuzzy control [25]. The results of the tracking error, the overshoot, and the eliminated steady state of these control methods are satisfying. However, there are a few nonlinear controllers for the nonlinear models of the IPMC. To control a nonlinear object as IPMC, adaptation of controller is desirable for it because its actuation behaviors can vary remarkable over time. There are various adaptive and robust controllers can be designed [34] and [38]. Therefore, in this paper, we first build the nonlinear model, and then apply a control method called the robust adaptive control with leakage modification to control its position.

The control scheme is shown in Figure 5 disigned for the given model of IPMC in (7). This control scheme contains six blocks. The saturation block with the goal limits output voltage of the controller in the range from -3V to 3V for protecting the IPMC. The filter Ω synthesizes and filters the output feedback signal Y_p and the control signal U_p. The Epsilon block is normalized to create the smallest error between the parameter vector Y_p and the online estimated parameter vector θ_p . The robust adaptive control law with leakage modification block creates the adaptive law based on receiving the signals U_p and ε to estimate parameters for the controller. The controller combines Ω vector and θ vector to generate a control voltage to control the position of the IPMC.

A. Signal Filter

The goal of the filter is to avoid the presence of derivatives of signals in the parametric model. Hence, we design vector Ω as a filter to process signals U_p and Y_p before they come to the controller.

$$\Omega = [\omega_1,\ \omega_2,\ \omega_3,\ \omega_4] = [\frac{1}{\Lambda_1(s)}U_p(s),\ \frac{1}{\Lambda_1(s)}Y_p(s),\ Y_p(s),\ r(s)] \tag{6}$$

where $r(s)$ is a reference input, and $\Lambda_1(s)$ is a filter.

$$\Lambda_1(s) = \lambda_1 s + 1 \tag{7}$$

Here constant $\lambda_1 > 0$, and by substituting $\Lambda_1(s)$ from (7) into (6), we get

$$\Omega = [\frac{1}{\lambda_1 s+1}U_p(s),\ \frac{1}{\lambda_1 s+1}Y_p(s),\ Y_p(s),\ r(s)] \tag{8}$$

B. Normalized Estimation Error

We have to use the normalized signal in the normalized estimation error block to ensure that the estimation error $\varepsilon(s)$ goes to zero as soon as possible, and it is designed as follows:

$$\varepsilon(s) = \frac{1}{m^2(s)}(z(s) - \hat{z}(s)) \tag{9}$$

Where $m(s)$ is the dynamic normalized signal computed as

$$m^2(s) = 1 + n^2(s) \tag{10}$$

$$n^2(s) = \int (U_p^2(s) + Y_p^2(s) + \delta_0)ds \tag{11}$$

Here δ_0 is positive constant. Substitute (11) into (12) we have

$$m^2(s) = 1 + \int (U_p^2(s) + Y_p^2(s) + \delta_0)ds \tag{12}$$

The parametric model $z(s)$ is designed as follows:

$$z(s) = \frac{s^2}{\Lambda_2(s)}Y_p(s) \tag{13}$$

The estimation of parametric model $\hat{z}(s)$ is established as follows:

$$\hat{z}(s) = \Phi\theta_p^T \tag{14}$$

here vectors θ_p and Φ are designed as

$$\theta_p = [\hat{q}_1,\ \hat{q}_0,\ \hat{k}_1,\ \hat{k}_0] \tag{15}$$

$$\Phi = [-\frac{d}{ds}(\frac{Y_p(s)}{\Lambda_2(s)}),\ -\frac{Y_p(s)}{\Lambda_2(s)},\ \frac{d}{ds}(\frac{U_p(s)}{\Lambda_2(s)}),\ \frac{U_p(s)}{\Lambda_2(s)}] \tag{16}$$

where $\Lambda_2(s)$ is a filter to avoid a direct differentiation of signals.

$$\Lambda_2(s) = \lambda_2 s^2 + \lambda_3 s + 1 \tag{17}$$

here constants $\lambda_2 > 0$ and $\lambda_3 > 0$.

C. Robust Adaptive Law with Leakage Modification

In this paper leakage modifiacation is applied to obtain a robust mechanism for the controller. From the nonlinear model of IPMC in (5), and expressions of parameters in (3, and 4), and from knowledge of only parameters of $\Delta(s)$ which are changed when the disturbance is added in it as shown in Figure 4. Hence we need update positive parameters q_0, q_1, k_0, and k_1 of $\Delta(s)$ by design the estimation vector θ_p as shown in (15). In addition, these parameters are bounded by a small constant $M_1 > 0$ and an upper bound $M_2 > 0$. These constants are chosen based on the given parameters of IPMC in (1). Therefore the leakage modification is designed as follows:

$$\frac{d\theta_{p_i}(t)}{dt} = \begin{cases} 0 & if \quad |\theta_{p_i}(t)| < M_1 \\ \sigma_0(\frac{|\theta_{p_i}(t)|}{M_1} - 1) & if \quad M_1 \le |\theta_{p_i}(t)| \le M_2 \\ \sigma_0 & if \quad |\theta_{p_i}(t)| \ge M_2 \end{cases} \tag{18}$$

where $\sigma_0 > 0$ is the design constant.

D. Robust Adaptive Controller (RAC)

The main task of the controller is to control the IPMC's position precisely, and ensure that the displacement responses closely follow the reference. In addition, these responses must be stable and robust in the presence of any random disturbance in a certain range. Hence, the controller is designed by combining the Omega vector which receives the output feedback position response and reference response and the theta vector which is updated online by a robust adaptive law with leakage modification algorithm. This controller generates the control voltage law as

$$U_p(s) = \Omega\theta^T \tag{19}$$

Where $\theta = [\theta_1,\ \theta_2,\ \theta_3,\ \theta_4] = [0,\ 0,\ \theta_3,\ \theta_4]$ with $\theta_3 = -\theta_{p_3}^2/2\theta_{p_2}^2$ and $\theta_4 = \theta_{p_4}^2/2\theta_{p_1}^2$, and Ω is computed as (6). Hence we obtain the control law as follows:

$$U_p(s) = -\frac{\theta_{p_3}^2}{2\theta_{p_2}^2} Y_p(s) + \frac{\theta_{p_4}^2}{2\theta_{p_1}^2} r(s) \tag{20}$$

IV. Simulation Results

In this section we check the output position response y_p, the average tracking error e_t between simulated position response and reference response, and the normalized estimation error $\varepsilon(t)$. The average tracking error:

$$e_t = \frac{\int_t^{t+T} |r(t) - y_p(t)| dt}{\int_t^{t+T} |r(t)| dt} \tag{21}$$

Parameters used in this simulation are specified as follows: $\lambda_1 = \lambda_2 = 1,\ \lambda_3 = 2,\ \delta_0 = 1,\ \sigma_0 = 0.2,\ M_1 = 0.02$, and $M_1 = 10^8$. To demonstrate the disturbances inside the IPMC or from outside affected to the IPMC, we use the Band-Limited White Noise block in Matlab/Simulink software to generate normally distributed the random numbers. The parameters of this block are randomly chosen in bounded ranges with the power of noise equal to 0.1, sample time equal to 0.1, and seed equal to [2 3 3 4 1]. In addition, another disturbance is also added in this simulation. This is the random number disturbance block. This block generates a normally (Gaussian) distributed random signal which is repeatable for a given seed. Also, the parameters of this block are randomly chosen in bounded ranges with mean equal to zero, variance equal to 1.5, initial seed equal to 0.5, and sample time equal to 0.4. These disturbances are put in the IPMC model block as shown in Figure 5. The simulation results in the presence of white noises are shown in Figure 6. All the simulated displacement responses are very close to reference responses with the average tracking error e_t less than 10%, and the normalized estimation error go to zero with the average time of 4 seconds.

In addition, the simulation results in the presence of random number disturbance are shown in Figure 7. Also, all simulated displacement responses are very close to the reference with the average tracking error e_t less than 7%, and the normalized estimation error goes to zero in 4 seconds on average. Although we have changed the shape of reference responses such as the sine wave response and the other step responses, and the different disturbance types, the simulated position responses of the IPMC still closely follow the reference and are stable.

V. Conclusion and Future Work

In this paper we propose a nonlinear model of the IPMC by adding the random disturbances which are bounded in a certain range, and apply the robust adaptive control method with leakage modification to control the position of the IPMC. The simulation results show that the average tracking error e_t is less than 10%, and the overshoot and the steady state are both eliminated. In addition, the normalized estimation error for robust adaptive block goes to zero very fast within 4 seconds. We have tested with different disturbances, and we obtain the similar results. Hence, we can conclude that the robust adaptive controller with leakage modification is the stable and robust controller for controlling the position of the IPMC. In future work, we expect to implement this control method to check the actual displacement responses of the IPMC in considering the actual noises affecting on it.

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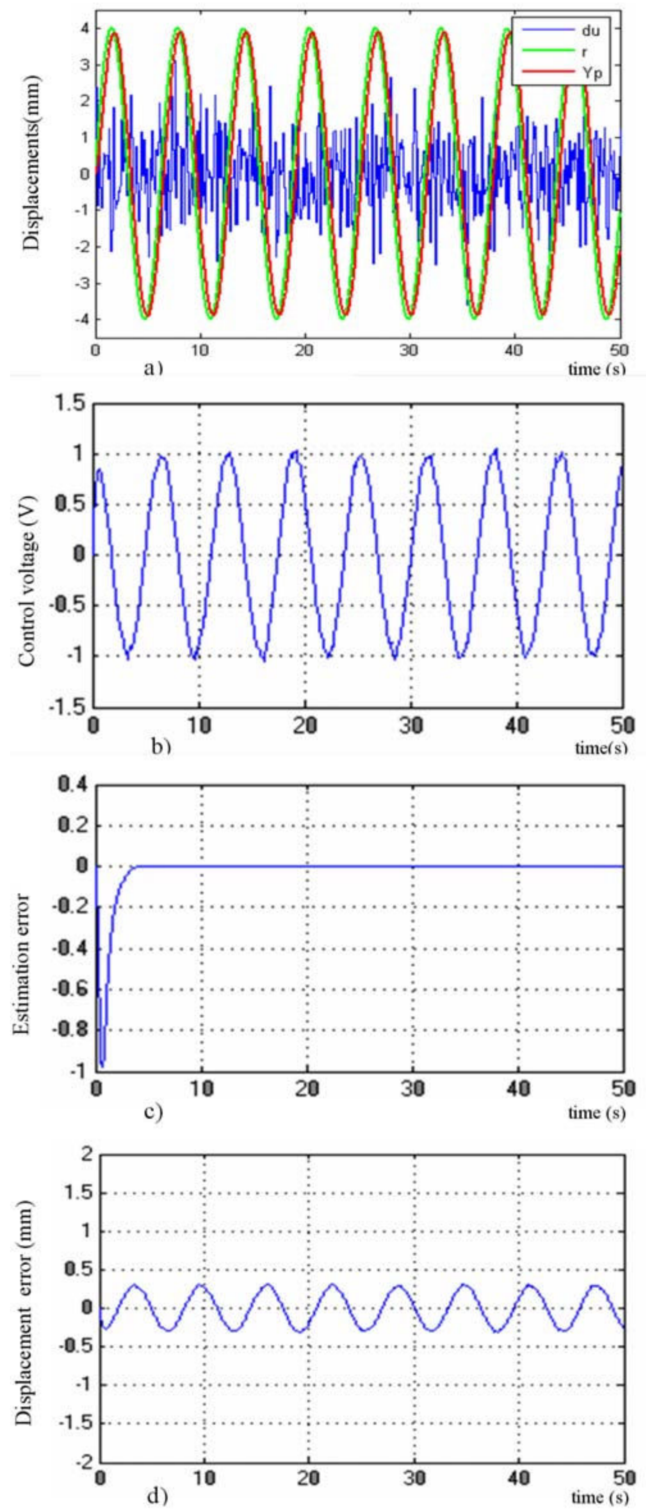

Fig. 5. a) The simulated displacement response Y_p (green color), and the sine wave reference r (red color) in the presence of disturbance d_u (blue color) applied to the IPMC. b) The control voltage law of controller after the saturation block. c) The normalized estimation error goes to zero after 3 seconds. d) The displacement error between Y_p and r.

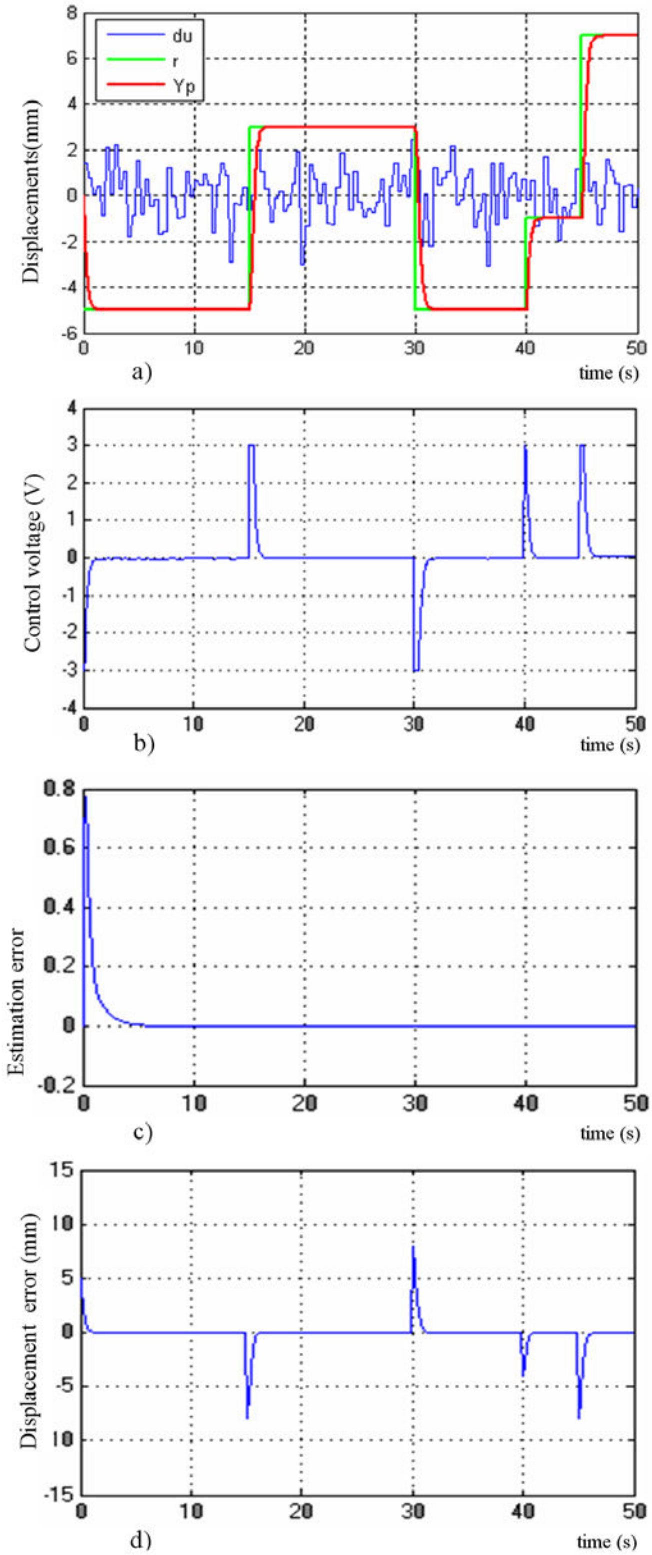

Fig. 6. a) The simulated displacement response Y_p (red color), and other step reference r (green color) in the presence of disturbance d_u (blue color) applied to the IPMC. b) The control voltage law of controller after the saturation block. c) The normalized estimation error goes to zero after 5 seconds. d) The displacement error between Y_p and r.

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