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Experimental Comparison of STR and PI Controllers on a Nonlinear Liquid-Level Networked Control System

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***Abstract*—This paper discusses the design, practical implementation, and comparison of the adaptive controller using the indirect self-tuning regulator (STR) method and PI controller for a liquid-level networked control system. The system model is identified by using the least squares (LS) method and design a PI controller tuned by Ziegler-Nichols method. Also, the system parameters are estimated online, using the recursive least squares (RLS) method to implement the indirect STR adaptive controller. With the help of the estimated parameters, the STR controller should be designed through pole placement. To compare the performance of the controllers, the dynamics of the liquid-level control system have been changed by placing an external heterogeneous object inside the tank. Adaptive controllers are used in systems with variable parameters to detect dynamic changes and control the system appropriately. The results show that the indirect STR adaptive controller performs better than the PI controller in both transient and steady-state responses.**

Keywords—STR Adaptive Controller, LS and RLS Method, PI Controller, Liquid-Level Control System.

I. INTRODUCTION

Most control system design approaches are based on knowledge of the system and the environment. Modeling is the process of formulating a mathematical description of the system. No matter how detailed, a model is only a partially accurate representation of an actual physical system and just an approximation of the physical reality of the system dynamics. So, modeling causes uncertainty. Uncertainty refers to the errors and differences between a real system and its model. On the other hand, the information for modeling in many cases is unavailable, or the system is nonlinear and time-varying. Also, there are unknown noises and disturbances in most systems. Different possibilities exist to overcome these difficulties.

Proportional, Integral, and derivative controllers are the most common controllers which are used in industrial processes because of their robustness, easy implementation, and simplicity. The compensation ability of the PID family controllers is used for industrial plants and led them to wide approval in industrial applications. There are different methods to design a PI controller e.g., Parr, McAvoy and Jackson, Ziegler-Nichols, and, Tyreus Luyben.[1] In this article, Ziegler-Nichols method have been chosen to design a PI controller for the system.

Adaptive control is an approach to design controllers that deals with nonlinear time-varying (NLTV) systems with a wide range of variation and difficulty of uncertainty modeling. As defined in [2], this type of controller is a controller with adjustable parameters and a mechanism for parameter adjusting. In this approach, the controller can modify its behavior automatically to the variation of system dynamics and disturbances. In [3-5], various examples of different adaptive control methods are implemented and simulated.

The adaptive control system includes two closed loops. One of them is a typical feedback control loop, and the other is a parameter-adjusting loop. There are different mechanisms for adjusting controller parameters. Some well-known methods of adaptive control are self-tuning regulators (STR), model reference adaptive control (MRAC), gain scheduling, switching control, and multiple model control that is mentioned in [6,7].

STR controllers are one of the most famous and widely used methods in designing adaptive controllers. STR controllers are implemented in indirect and direct approaches. This paper uses the indirect STR method to control a liquid-level system. In this approach, the parameter estimation and the control mechanism operate separately. The recursive least squares (RLS) algorithm estimates the system parameters and sends them to the control mechanism. Fig. 1 shows the block diagram of the indirect STR adaptive controller.

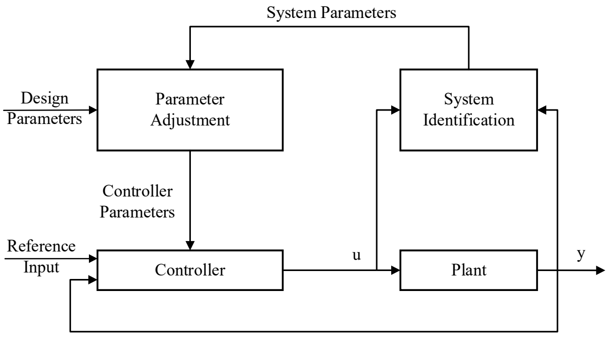

Fig. 1. Indirect STR adaptive control system block diagram.[2]

This article discusses the design of a PI controller using the Ziegler-Nichols method and the adaptive controller using the STR method. The PI and STR controllers are implemented and compared on a liquid-level networked control system with LTI and NTI system dynamics to evaluate the designed controllers' performance. The control objective is setpoint tracking and unvarying transient response characteristics of the system, such as overshoot and settling time for different reference input values in both LTI and NTI systems.

II. SYSTEM INTRODUCTION

Desired control algorithms were implemented on a liquid-level control system. This process has a cylindrical tank with a maximum height of 40 cm and a radius of 4.5 cm. Also, this process has a pump to transfer the liquid to the tank with a variable rate for the input voltage of 0.4 V to 2.5 V. Also, the process has an adjustable valve to drain the liquid from the tank. A physical interface panel communicates between the liquid-level control system and its data logger. The data logger uses a Wi-Fi module to establish communication between the system and the computer. The data logger includes two digital-to-analog converters (DAC), four analog-to-digital converters (ADC), eight digital inputs, and eight digital outputs. Fig. 2 shows these parts of the system.

Fig. 2. Liquid-level control system, the interface panel and, data logger.

A piezoelectric pressure sensor is used to measure the liquid level inside the tank, as shown in Fig. 3. This piezoelectric sensor converts the liquid level pressure caused by the level of the liquid into voltage. Increasing the level of the liquid increases the output voltage of the sensor. The output of the piezoelectric sensor is from -10 V to 10 V, but a range of 0 to 10 V is used.

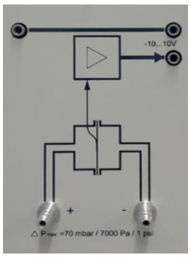

Fig. 3. Piezoelectric sensor.

III. EXPERIMENT DESIGN AND IMPLEMENTATION OF DESIRED CONTROL ALGORITHMS

Controlling the level of the liquid is our experimental target. Two separate experiments are conducted to compare the performance of the PI controller designed by Ziegler-Nichols method and the indirect STR controller. First, the designed controllers are implemented on the linear time-invariant (LTI) liquid-level control system. Then, to investigate the performance of two controllers on a nonlinear time-invariant (NTI) system, an external heterogeneous object is placed inside the liquid tank to change the system dynamics. Due to the presence of this heterogeneous rigid object in the tank at different liquid levels, different liquid volumes are needed to change the liquid level, which indicates the change in system dynamics in different level intervals.

0.6 V input voltage is applied to the system pump in both LTI and NTI systems to show the differences and make a comparison between mentioned systems in open loop mode. The liquid level and its changes are assessed to illustrate the differences between LTI and NTI systems. Fig. 4. shows the output of the LTI and NTI systems in open loop mode. As can be seen, in the NTI system, due to the presence of the heterogeneous object inside the tank, the liquid reaches the level of 15 cm faster when the liquid inflow is more than the liquid outflow. Also, liquid drains faster when the liquid outflow is more than the liquid inflow. Furthermore, the liquid level in the LTI system changes at a constant rate, but the liquid level in the NTI system does not have a constant rate and has different slopes at different points.

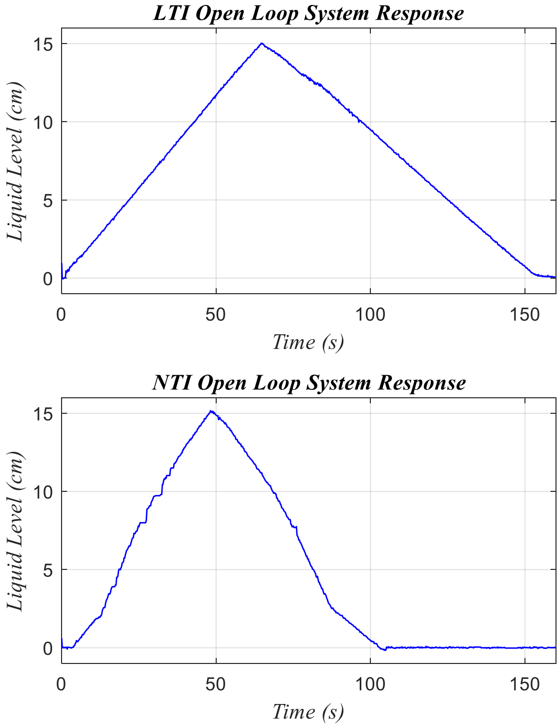

Fig. 4. LTI and NTI open loop system responses.

A networked control system has been used to control the liquid-level system. Networked control systems (NCSs) are a general class of control systems. In this type of control system, the control loop is closed through a serial communication network.[8] The data in NCSs are encoded in the data packets and then transmitted via a network. In general, NCSs are divided into two different structures: the direct structure and the hierarchical structure.[9] the direct structure NCSs is used for controlling the system.

In the control feedback loop, the analog output of the piezoelectric sensor is converted to digital values with the help of an analog-to-digital converter (ADC). The digital values are sent to a computer through a Wi-Fi network. After executing the control algorithm, the calculated control signal is sent to the data logger through the Wi-Fi network. For applying the control signal to the pump, a digital-to-analog converter (DAC) is used to convert the digital control signal to analog values. MATLAB/Simulink is used to implement the desired control algorithms. With the help of the real-time synchronization block, the algorithms were executed in real-time. The codes needed to execute the algorithm are also written in the MATLAB S-Function block. The results are obtained and analyzed for LTI and NTI system dynamics. Fig.5. shows the designed block diagram of the indirect STR adaptive controller using MATLAB/Simulink.

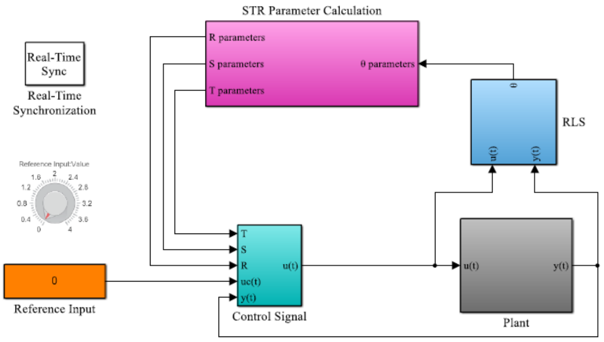

Fig. 5. Block diagram of the designed indirect STR adaptive controller using MATLAB/Simulink.

IV. PI CONTROLLER DESIGN BY ZIEGLER-NICHOLS METHOD

A. *System identification using the least squares method*

To design a PI controller based on Ziegler-Nichols method, the least squares method is used to identify the model of the system. The least squares (LS) method is widely used in system identification. Based on this method, mathematical model unknown parameters should be specified to minimize the sum of squares of the difference between the observed values and the values calculated from the model. Consider the process model with $e(t)$ white noise.

$$\begin{gathered} A(z^{-1})y(t) = z^{-d_0}B(z^{-1})(u(t)+e(t)) \\ A(z^{-1}) = 1 + a_1 z^{-1} + \cdots + a_n z^{-n} \\ B(z^{-1}) = b_0 + b_1 z^{-1} + \cdots + b_m z^{-m} \end{gathered} \tag{1}$$

Where d_0 is the system delay and must be non-zero. The process model can be rewritten in vector form as

$$\begin{gathered} \hat{y}(t) = -a_1 y(t-1) - \cdots - a_n y(t-n) \\ +b_0 u(t-d_0) + \cdots + b_m u(t-d_0-m), \\ \varphi(t) = [-y(t-1) \quad \cdots \quad -y(t-n) \\ u(t-d_0) \cdots \quad u(t-d_0-m)]^T, \\ \theta = [a_1 \quad \ldots \quad a_n \quad b_0 \quad \ldots \quad b_m]^T, \\ \Phi = [\varphi(1) \quad \varphi(2) \quad \cdots \quad \varphi(N)]^T, \\ Y = [y(1) \quad y(2) \quad \cdots \quad y(N)]^T, \\ \varepsilon(t) = y(t) - \varphi^T(t)\theta, \\ E = [\varepsilon(1) \quad \varepsilon(2) \quad \cdots \quad \varepsilon(N)]^T = Y - \Phi\theta \\ V(\theta) = \frac{1}{2}E^T E \end{gathered} \tag{2}$$

By minimizing $V(\theta)$, the unknown parameters of the system can be obtained.[10]

$$\hat{\theta} = (\Phi^T \Phi)^{-1} \Phi^T Y \tag{3}$$

A discrete Second-Order plus Time-Delay (SOPTD) model is identified for the system using the LS method. Generally, the liquid-level control system is a first-order system. However, the output flow rate in our system is limited and low, so the system behaves like an integrator. As a result, another pole is considered for the system, so that the model can better match actual system dynamics. Also, the delay is considered for the model due to the inherent characteristics of the system (delay of pipes connecting the pump to the tank and the computer Wi-Fi connection to the data logger). It should be mentioned that the time delay in networked control systems is variable and uncertain, but the communication network used in this article is a local network, so this time delay is small and can be ignored compared to the inherent delay of the system (delay of pipes connecting the pump to the tank). descending consecutive steps are used as a suitable input to excite all system dynamics. So, the identified discrete transfer function of the system with sample time Ts=0.2 second is as follows.

$$G_1(z^{-1}) = \frac{0.03217z^{-5}}{1 - 0.9z^{-1} - 0.09z^{-2}} \tag{4}$$

B. *PI Controller Design Using Ziegler-Nichols Method*

PI controller is selected for the sake of simplicity. Controller parameters (proportional and integral gains) were chosen by Ziegler-Nichols Method. A general form of a PI controller can be described by

$$C(s) = K_p + \frac{K_i}{s} \tag{5}$$

First, the identified discrete-time transfer function is converted to continuous time transfer function. Then, Ziegler-Nichols method is used for designing the PI controller. The controller coefficients are obtained according to Table I.

TABLE I. PI CONTROLLER COEFFICIENTS BY ZIEGLER-NICHOLS METHOD.

Controller Type	**Ziegler-Nichols Method**	
	K_p	K_i
PI	$0.45K_u$	$0.54\ K_u\ /\ T_u$

$K_p = 10.4$ and $K_i = 3.4$ were calculated, so

$$C(s) = 10.4 + \frac{3.4}{s} \tag{6}$$

And the discrete-time transfer function of the PI controller is equal to

$$C(z) = K_p + K_i \frac{Ts}{z-1} = 10.4 + 3.4\frac{0.2}{z-1} = \frac{10.4z - 9.72}{z-1} \tag{7}$$

The designed PI controller discrete transfer function (7) is implemented in MATLAB/Simulink for controlling the system.

V. INDIRECT STR CONTROLLER DESIGN

A. *Recursive Least Squares Methods*

In adaptive control systems, the observations are attained sequentially in real-time. So, a recursive estimation algorithm is desired for online estimation of the system parameters. Using the results attained at time *t-1* to get the estimates at time *t* saves calculation time. Hence, the recursive least-square (RLS) estimation method is used. The RLS estimator for (1) is given by [2]

$$\begin{gathered}\varphi(t)=[-y(t-1) \quad \cdots \quad -y(t-n) \quad u(t-d_0) \quad \cdots \quad u(t-d_0-m)]^T \\ \theta=[a_1 \quad \cdots \quad a_n \quad b_0 \quad \cdots \quad b_m]^T \\ \hat{\theta}(t)=\hat{\theta}(t-1)+K(t)(y(t)-\varphi^T(t)\hat{\theta}(t-1)) \\ K(t)=P(t-1)\varphi(t)(I+\varphi^T(t)P(t-1)\varphi(t))^{-1} \\ P(t)=(1-k(t)\varphi^T(t))P(t-1)\end{gathered} \tag{8}$$

Intuitive interpretations can be made of the RLS algorithm above. The expression $y(t)-\varphi^T(t)\hat{\theta}(t-1)$ as a prediction error term is weighted by $K(t)$ and added to the former estimate $\hat{\theta}(t-1)$ for obtaining the new estimate $\hat{\theta}(t)$. Based on the previous estimates $\hat{\theta}(t-1)$, the expression $\varphi^T(t)\hat{\theta}(t-1)$ is considered as a prediction of $y(t)$.[2]

Depending on the application, various modified versions of the RLS estimation algorithm are available. An exponential forgetting algorithm, for example, can be used to estimate slow-changing parameters in RLS. By using this approach, data are weighed based on time. A weight of one is applied to the most recent data, while a weight of λ^n is applied to data which is n time units older. (λ is named the forgetting factor, and $0<\lambda<1$). This weighting is because time-varying information should be valued differently based on its time of arrival. Following is a description of this algorithm. [2]

$$\begin{gathered}\hat{\theta}(t)=\hat{\theta}(t-1)+K(t)(y(t)-\varphi^T(t)\hat{\theta}(t-1)) \\ K(t)=P(t-1)\varphi(t)(\lambda+\varphi^T(t)P(t-1)\varphi(t))^{-1} \\ P(t)=(1-k(t)\varphi^T(t))P(t-1)/\lambda\end{gathered} \tag{9}$$

B. Pole Placement Design

A general linear STR controller can be described by

$$R(z^{-1})u(t)=T(z^{-1})u_c(t)-S(z^{-1})y(t) \tag{10}$$

This controller consists of feedback with $S(z^{-1})/R(z^{-1})$ transfer function and a feed-forward with $T(z^{-1})/R(z^{-1})$ transfer function. Thus, the controller has two degrees of freedom.

$$u(t)=-\frac{S(z^{-1})}{R(z^{-1})}y(t)+\frac{T(z^{-1})}{R(z^{-1})}u_c(t) \tag{11}$$

For having a causal control law in the discrete-time case, the following conditions must be imposed upon the polynomials in the control law.

$$\begin{gathered}\deg S(z^{-1}) \le \deg R(z^{-1}) \\ \deg T(z^{-1}) \le \deg R(z^{-1})\end{gathered} \tag{12}$$

The closed-loop system block diagram with the STR controller is shown in Fig. 6.

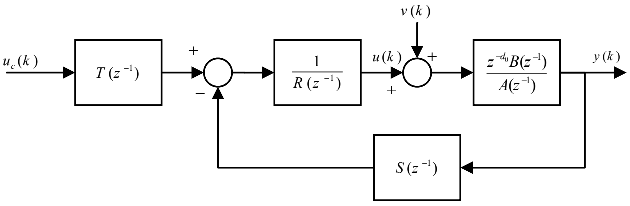

Fig. 6. Closed-loop system block diagram using the STR controller.

The closed-loop system transfer function is as follows.

$$\begin{aligned}y(t)=&\frac{z^{-d_0}B(z^{-1})T(z^{-1})}{A(z^{-1})R(z^{-1})+z^{-d_0}B(z^{-1})S(z^{-1})}u_c(t) \\ &+\frac{z^{-d_0}B(z^{-1})R(z^{-1})}{A(z^{-1})R(z^{-1})+z^{-d_0}B(z^{-1})S(z^{-1})}v(t)\end{aligned} \tag{13}$$

Therefore, the characteristic polynomial of the closed-loop system is [2]

$$A(z^{-1})R(z^{-1})+z^{-d_0}B(z^{-1})S(z^{-1})=A_c(z^{-1})=A_m(z^{-1})A_o(z^{-1}) \tag{14}$$

$A_m(z^{-1})$ is the polynomial corresponding to the desired poles of the closed-loop system. Also, $A_o(z^{-1})$ is the observer polynomial. After choosing the desired poles of the polynomials $A_m(z^{-1})$ and $A_o(z^{-1})$ and solving (14), which is known as the Diophantine equation, the coefficients of the polynomials $S(z^{-1})$ and $R(z^{-1})$ will be obtained $T(z^{-1})$ coefficients can be calculated by

$$T(z^{-1})=\beta A_o(z^{-1}) \tag{15}$$

where β is equal to

$$\beta=\frac{A_m(1)}{B(1)} \tag{16}$$

According to the model considered for the system (4), the degree of polynomials $A(z^{-1})$, $B(z^{-1})$, $R(z^{-1})$, and $S(z^{-1})$ will be as follows. The degree of $R(z^{-1})$ and $S(z^{-1})$ polynomials must be chosen so that the order of the polynomials on both sides of the Diophantine equation is equal. Due to the inherent delay of the system, it should be mentioned that it is not possible to reduce the STR controller order.

$$\begin{gathered}A(z^{-1})=1+a_1z^{-1}+a_2z^{-2} \\ z^{-d_0}B(z^{-1})=b_0z^{-5} \\ S(z^{-1})=s_0+s_1z^{-1} \\ R(z^{-1})=1+r_1z^{-1}+r_2z^{-2}+r_3z^{-3}+r_4z^{-4}\end{gathered} \tag{17}$$

$z=0.2$ and $z=0.8$ are chosen as desired poles of the closed-loop system. Also, to equalize the polynomials on the sides of the Diophantine equation, a fourth order observer polynomial have been chosen with fast poles $z=0.01$. Therefore, the Diophantine equation required to design the system controller using the STR method is as follows.

$$\begin{aligned}&(1+a_1z^{-1}+a_2z^{-2})(1+r_1z^{-1}+r_2z^{-2}+r_3z^{-3}+r_4z^{-4}) \\ &\quad+(b_0z^{-5})(s_0+s_1z^{-1}) \\ &=(1-0.8z^{-1})(1-0.2z^{-1})(1-0.01z^{-1})^4\end{aligned} \tag{18}$$

During the algorithm execution in MATLAB/Simulink, the polynomial $A(z^{-1})$ and $B(z^{-1})$ parameters are estimated using the RLS method. The estimated parameters are transferred to the $R(z^{-1})$, $S(z^{-1})$, and $T(z^{-1})$ parameter calculation block, and the $R(z^{-1})$, $S(z^{-1})$, and $T(z^{-1})$ polynomial coefficients are obtained using the corresponding equations. Then, the control signal is calculated and sent to the data logger through the Wi-Fi network for controlling the system.

VI. EXPERIMENTAL RESULTS

A. *PI Controller*

The results of controlling the linear system with the PI controller are shown in Fig. 7. As can be seen, due to the LTI system dynamics, the transient response characteristics of the system, such as overshoot and settling time for different values of the reference input, are unchanged. Also, the control signal peak amplitudes are constant during the time with the reference input changes.

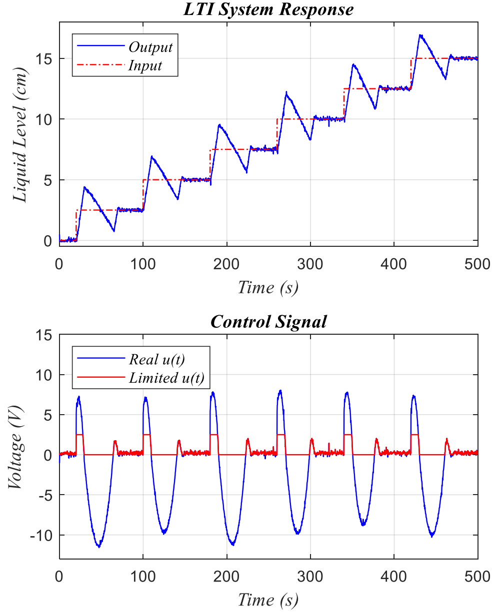

Fig. 7. Liquid level and control signal of LTI system with robust PI controller.

Fig. 8 shows the results of controlling the nonlinear system with the PI controller. As can be seen, the system remains stable with changes in system dynamics, and achieve good setpoint tracking due to the design of a PI controller. However, the transient response characteristics of the system, such as overshoot and settling time for different values of the reference input, are changed. Also, the control signal peak amplitudes vary during the time with the reference input changes.

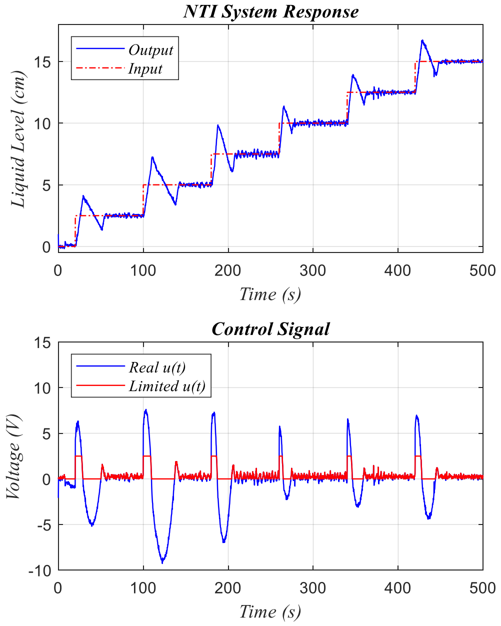

Fig. 8. Liquid level and control signal of NTI system with robust PI controller.

Transient response characteristics of the system and the maximum control signal of the PI controller for both LTI and NTI system dynamics are shown in Table II. Although the PI controller ensures the stability of the system when the system dynamics are variable, the transient response characteristics of the system are changed and undesirable. However, due to the integrator part, the closed-loop system achieves good setpoint tracking.

TABLE II. SYSTEM TRANSIENT RESPONSE CHARACTERISTICS AND MAXIMUM CONTROL SIGNAL OF THE PI CONTROLLER.

System Dynamics And characteristics		**Liquid Level (cm)**					
		2.5	5	7.5	10	12.5	15
LTI	Overshoot (%)	76.91	78.52	82.7	80.74	81.41	77.88
	SettlingTime 5% (s)	46.2	44.2	45.2	42.9	44.6	43.8
	Max Control Signal (v)	7.31	7.39	7.54	7.85	7.48	7.42
NTI	Overshoot (%)	65.4	90.16	94.34	54.43	57.68	69.58
	SettlingTime 5% (s)	34.2	41.2	27.2	15.6	20.8	26.4
	Max Control Signal (v)	6.35	7.61	7.12	5.13	6.58	6.98

B. *Indirect Adaptive STR Controller*

The results of controlling the linear system with the Indirect STR adaptive controller are shown in Fig. 9 and 10. Fig. 9 shows the linear system response to reference input and corresponding control signal. The transient response characteristics of the system, such as settling time for different values of the reference input, are unchanged because of the LTI system dynamics. Furthermore, the control signal peak amplitudes are unchanged during the time with the reference input changes.

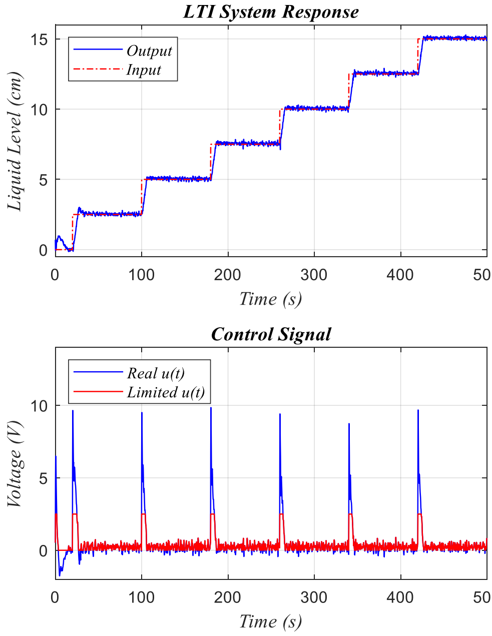

Fig. 9. Liquid level and control signal of LTI system with Indirect STR adaptive controller.

Fig. 10 show the linear system parameters estimated by the RLS method and STR controller parameters ($R(z^{-1})$, $S(z^{-1})$, and $T(z^{-1})$ polynomials) over time. The convergence of parameters can be seen.

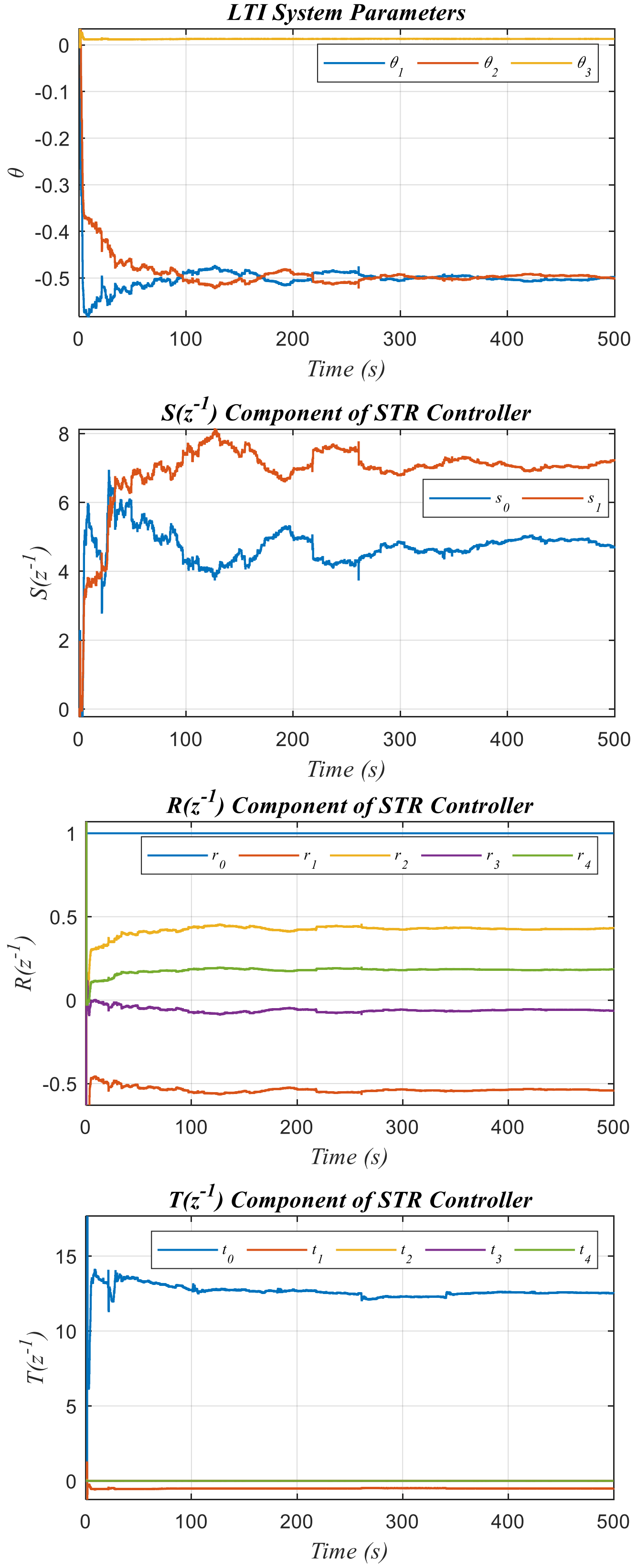

Fig. 10. The estimated parameters of LTI system and STR controller parameters.

Fig. 11 and 12 show the results of controlling the nonlinear system with the indirect STR adaptive controller. Fig. 11 shows the nonlinear system response to reference input and corresponding control signal. Unlike the PI controller, the transient response characteristics of the system, such as settling time for different reference input values, are almost unchanged. Also, the control signal peak amplitudes are nearly unchanged during the time with the reference input changes. By comparing the control signals of Fig. 9. and Fig. 11. As is evident, the NTI system has smaller peaks of the control signal than the LTI system due to the external heterogeneous object. Unlike the PI controller, the indirect STR adaptive controller detected the presence of the external object.

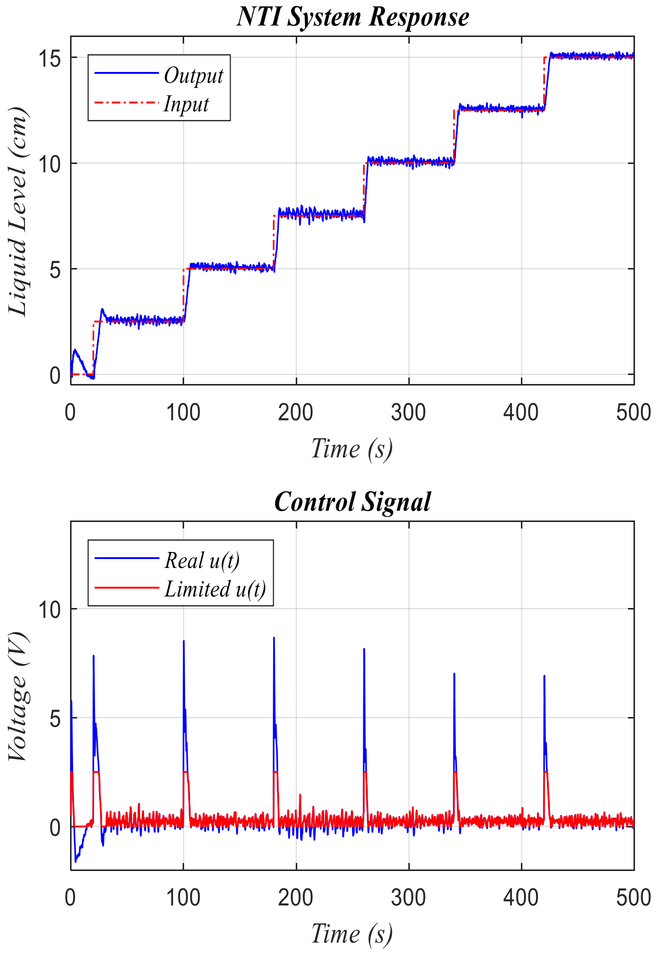

Fig. 11. Liquid level and control signal of NTI system with Indirect STR adaptive controller.

Fig. 12 shows the nonlinear system parameters estimated by the RLS method and STR controller parameters ($R(z^{-1})$, $S(z^{-1})$, and $T(z^{-1})$ polynomials) over time. According to the changes in system dynamics over time, the values of $R(z^{-1})$, $S(z^{-1})$, and $T(z^{-1})$ parameters have changed, which indicates the change in the estimated parameters of the system.

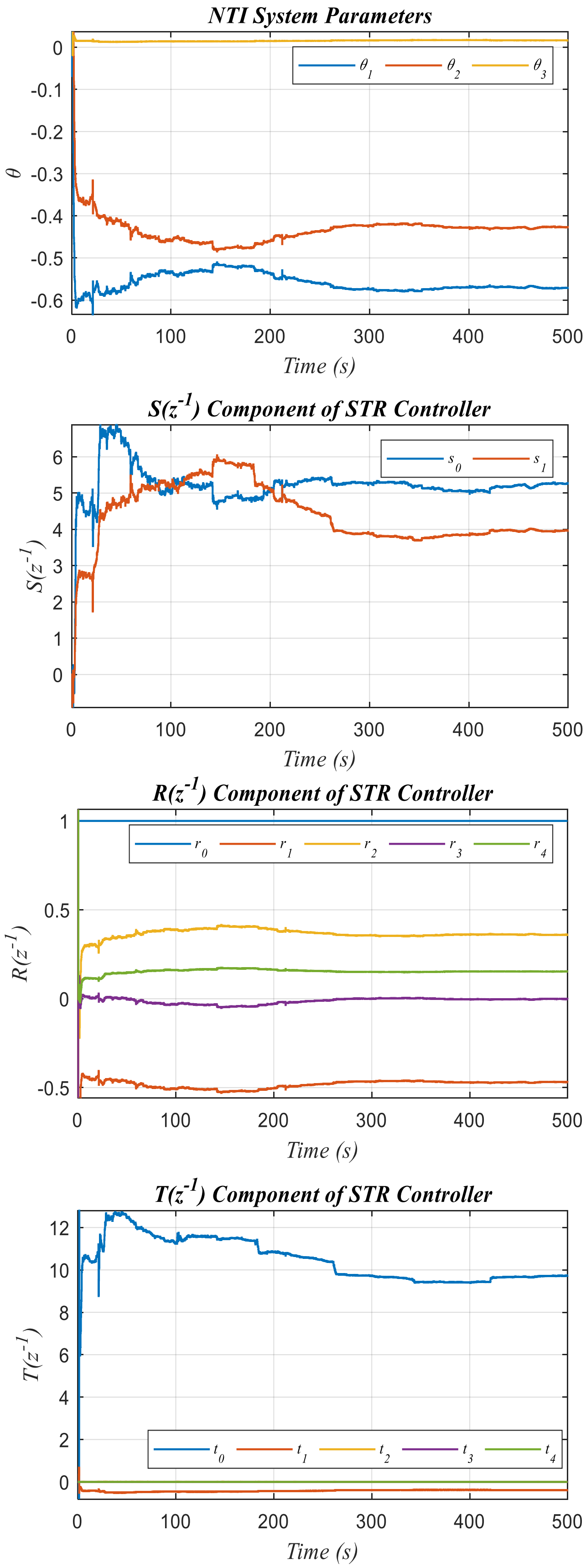

Fig. 12. The estimated parameters of NTI system and STR controller parameters.

System transient response characteristics and the maximum control signal of the indirect STR adaptive for both LTI and NTI system dynamics are shown in Table III. By using the indirect STR adaptive controller and online estimation of parameters with the RLS method, the system transient response characteristics are unchanged and desirable. The changes in system dynamics were detected, and the indirect STR adaptive controller performed well in both transient and steady-state responses.

TABLE III. SYSTEM TRANSIENT RESPONSE CHARACTERISTICS AND MAXIMUM CONTROL SIGNAL OF THE STR CONTROLLER.

System Dynamics And characteristics		**Liquid Level (cm)**					
		2.5	5	7.5	10	12.5	15
LTI	Overshoot (%)	-	-	-	-	-	-
	SettlingTime 5% (s)	11.6	11.2	11.4	11.8	11.5	11.3
	Max Control Signal (v)	9.65	9.51	9.85	9.41	8.74	9.68
NTI	Overshoot (%)	-	-	-	-	-	-
	SettlingTime 5% (s)	11.3	10.9	11.1	11.3	11.5	11.2
	Max Control Signal (v)	7.84	8.52	8.65	8.15	7.07	7.02

To compare the STR controller implemented in this article with other methods used to control the liquid-level system, [11] and [12] are used. In [11] and [12], Fuzzy Logic Controller (FLC) is used to control the liquid-level system. The results of the implementation and simulation in these articles are appropriate. However, it has more calculations and requires more initial knowledge of the system than the STR controller.

VII. CONCLUSION

This paper compared the performance of the indirect STR adaptive and PI controllers by practical implementation on a liquid-level control system. Due to using a PI controller for an NTI system with variable dynamics, the transient response characteristics of the system will be undesirable and variable. To enhance the control efficiency of the process with variable dynamics, using an adaptive controller (in this paper with the indirect STR method), which can estimate system parameters online and update its control parameters, will be a good choice. The indirect STR adaptive controller has achieved better control of the system and appropriate steady-state and transient response characteristics. However, the PI controller is easier to implement and has less online calculation, but the STR adaptive controller performs better.

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