Global Journal of Computer Science and Technology
Network, Web & Security
Volume 12 Issue 11 Version 1.0 June 2012
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 0975-4172 & Print ISSN: 0975-4350

Wave Prediction and Delay Modeling for Teleoperation Via Internet

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Abstract - This paper propose a novel approach for modeling the end-to-end time delay dynamics of the internet using system identification, and use it for controlling real-time internet-based telerobotic operations. When a single model is used, it needs to adapt to the operating conditions before an appropriate control mechanism can be applied. Slow adaptation may result in large transient errors. As an alternative, we propose to use an adaptive multiple model framework, and determine the best model for the current operating conditions to activate the corresponding controller. We employ multivariable wave prediction method to achieve this objective.

GJCST-E Classification: *b.4.m*

Wave Prediction and Delay Modeling for Teleoperation Via Internet

Ehsan Kamrani $^{\alpha}$ & Mohamad Sawan $^{\alpha}$

Abstract - This paper propose a novel approach for modeling the end-to-end time delay dynamics of the internet using system identification, and use it for controlling real-time internet-based telerobotic operations. When a single model is used, it needs to adapt to the operating conditions before an appropriate control mechanism can be applied. Slow adaptation may result in large transient errors. As an alternative, we propose to use an adaptive multiple model framework, and determine the best model for the current operating conditions to activate the corresponding controller. We employ multivariable wave prediction method to achieve this objective.

I. INTRODUCTION

The concept of teleoperation has been around for awhile. It involves remote control of a plant or machine from far distance via a medium environment. The distance can vary from tens of centimeters (micromanipulation) to millions of kilometers (space applications). Teleoperation takes several forms and can be done via any communication medium. Recently, the main focus has been on teleoperation via the Internet. Motivated by the availability, widespread access, and low cost of the Internet, many researchers have focused on the Internet-based teleoperation.

Since the Internet introduces random communication delays, several challenges and difficulties, such as loss of transparency and synchronization in real-time closed-loop telerobotic systems, may arise. In order to meet these challenges, a general and efficient modeling and analysis tool for the Internet delay needs to be developed. Several techniques have been proposed to compensate for this effect, such as a time forward observer developed for a supervisory control over the Internet by Brady and Tarn [1]-[3], a position-based force-feedback scheme implemented by Oboe and Fiorini [4], and a wave variable based technique developed by Niemeyer and Slotine [5].

The methods in [1] and [4] require knowledge of the remote plant, but the method in [5] does not. Due to possible uncertainties on the remote plant, the methods that require the knowledge of remote plant may not be applicable in all cases. The stability of such techniques may depend on the accuracy of knowledge on the remote plant. As such, the wave-based method has an advantage from this point of view, but may suffer from poor performance for delays significantly longer than the time constant(s) of the system. Wave variables were first introduced by Anderson and Spong [6]-[7], and were later presented in a more intuitive, physically motivated, passivity-based formalism by Niemeyer and Slotine [5]-[8]. Later the use of wave variables was extended to variable delay [9]-[10], as is the case for the Internet. Nevertheless, performance degradation for prolonged time delays is still a serious issue. In order to overcome these shortcomings, we propose a multimodel adaptive controller to choose the optimum controller.

Multi-model adaptive control schemes have been used in several applications [17]-[20]. In [21], we have used it in teleoperation control systems to maintain stability in the presence of time-varying or fluctuating delays. In this paper, we study the behavior of multi-model adaptive control systems in conjunction with wave prediction method for variable time delays. Furthermore, here we employ the ARX to model the time delays associated with the communications links, and identify its parameters using a system identification approach to be used in our proposed control system.

The rest of this paper is organized as follows. In Section 2 we propose an approach for modeling the time delay dynamics of the Internet. In Section 3, we explain the wave variable method as well as the Smith predictor. In Section 4, the multivariable Smith predictor is presented. In Section 5, we introduce a combination of wave variable and Smith predictor by adding the observer and the regulator block with a view to improving the performance. The adaptive control method for teleoperation systems is discussed in Section 6. In Section 7, we propose our control scheme which uses a multi-model adaptive controller for selecting the optimal controller. Section 8 contains the results and conclusions.

II. DYNAMICS OF THE INTERNET

a) QoS Parameters

The following four parameters describe the network QoS (Fig. 1): a) Time Delay, b) Jitter, c) Bandwidth, and d) Packet Loss. To improve the performance, the time delays need to be minimized. The impact of other parameters in Fig. 1 can be reduced using existing methods, which usually involve a tradeoff with the time delay. Therefore, QoS improvement in general involves minimization of the time delay, which is our focus in this paper.

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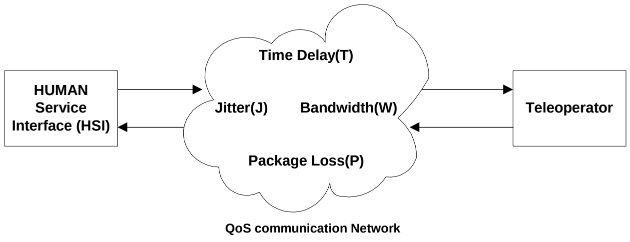


Fig. 1: Block diagram of teleoperation system in a QoS network

III. INTERNET DELAY MEASUREMENT

a) Delay Dynamics of Internet in Iran

We have measured the delay for a number of Internet nodes in different geographical locations in Iran as well as another international node for different time intervals. Statistical results are shown in Table 1. Fig. 2 shows the variations in the delay during a 24 hour period with sampling at 1 min intervals.

Table 1: Characteristics of the measured delay in some Internet nodes

Minimum delay(ms)	Maximum delay(ms)	Std. deviation(ms)	Average delay(ms)	Place
639	1381	38.6454	846.01035	Sistan Univ.
723	1931	94.2156	930.7525	Tabriz Univ.
691	2831	83.0866	1911.55	T.M.U Univ.
86	337	61.0934	189.2639	www.yahoo.com

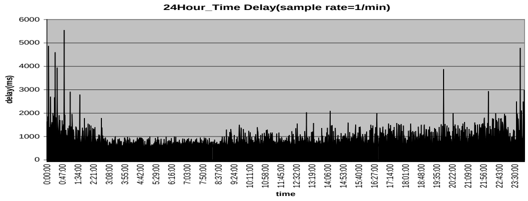


Fig. 2: Time delay in 24 hour with sampling interval of 1 min

IV. BLACK-BOX MODEL OF INTERNET DELAY

The end-to-end packet delay dynamics is modeled as a SISO (Single-Input-Single-Output) system. The input is the inter-departure times between packets leaving the source, and the output is an end-to-end packet delay measured at the destination. We use the Auto-Regressive eXogenous (ARX) model and determine its coefficients using system identification approach (Fig. 3). Since the ARX is a linear time-invariant model, it cannot rigorously capture the non-linearity of the packet delay dynamics. Nevertheless, the ARX model is applied in many control engineering problems, because non-linearity around a stable operating point can be well approximated by a linear system.

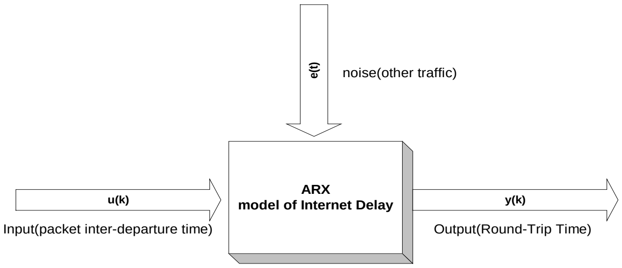
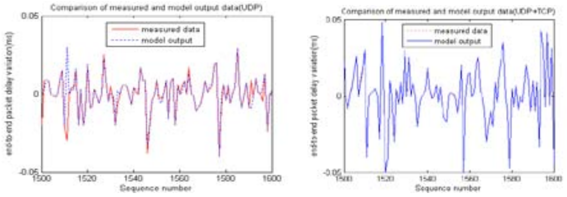


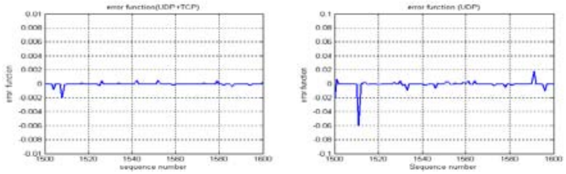
Fig. 3 : The ARX model for the end-to- end packet delay dynamics

Fig. 4 compares the measured data (solid line) and the model output (dotted line) in the UDP case, and the UDP+TCP case, respectively. It is evident that in both cases, the model output $\hat{y}(k\,|\,\theta)$ and the measured output $y(k)$ roughly coincide but slightly differ. This is because the measured end-to-end packet delay variation is disturbed by other unknown traffic not included in the model output $\hat{y}(k)$. According to the Fig. 5, the error of modeling is very low and so the model is acceptable.



(a) (b)

Fig. 4 : Comparison between measured data $y(k)$ and model output $\hat{y}(k)$ for (a) UDP case, and (b) UDP+TCP case



(a) (b)

Fig. 5: Error between measured data $y(k)$ and model output $\hat{y}(k)$ for (a) UDP case, and (b) UDP+TCP case

V. WAVE VARIABLES

a) Definition of Wave Variables

Wave variables were proposed in [6]-[7] for teleoperators with time delays, and is based on a more general framework of passivity for scattered operators. The basic mathematical formulations for wave variables can be described by power flow as

$$P = X_m F = U_t^T U_t - V_t^T V_t \tag{1}$$

Where *F* and *X* denote force and velocity, and *U* and *V* are incidental and reflected wave variables in

Fig. 6. We obtain *U* and *V* from power parameters *X* and *F* by

$$U = \frac{bX + F}{\sqrt{2b}}, \quad V = \frac{bX - F}{\sqrt{2b}} \tag{2}$$

Where *b* is a positive constant that depends on the communication link's parameters. In the bilateral control of force reflected systems, the transmission process is

$$U_s(t) = U_m(t-T), \quad V_m(t) = V_s(t-T) \tag{3}$$

Where *m* and *s* represent the corresponding side of the waves (master side or slave side) respectively, and *T* is a constant time delay. The stability of the system is preserved for any time delay, but performance is degraded proportionate to the actual delay.

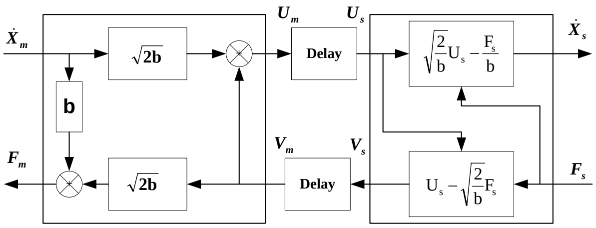


Fig. 6 : Transformation from power parameters to wave variables [5]

b) *Passivity*

Transformation of power parameters into wave variables affects the passivity of the system. The power inflow into the communication block at any time is given by (1). If we use (3) in (1) and assume that the initial energy is zero, the total energy in the communications link during the signal transmission between the master and the slave is

$$\begin{aligned} E &= \int_0^t P_{in}\, d\tau = \int_0^t (\dot{X}_{md} F_m - \dot{X}_{sd} F_s)\, d\tau \\ &= \frac{1}{2}\int_0^t (U_m^T U_m - V_m^T V_m + \dot{V}_s^T V_s - U_s^T U_s)\, d\tau \\ &= \frac{1}{2}\int_0^t (U_m^T U_m + \dot{V}_s^T V_s)\, d\tau \geq 0 \end{aligned} \tag{4}$$

Where, X_{md} and X_{sd} are the desired velocities of the master and the slave, respectively. The system is passive independent of the delay *T*, meaning that this transformation makes wave variables robust to constant time delays. This is achieved at the cost of significant performance degradation for long delays. Recently, in [11] it was shown that incorporating a predictor or an observer in the communication channel can enhance the performance significantly in the presence of prolonged or variable delays over the Internet.

VI. SMITH PREDICTOR

a) *Structure of Smith Predictor*

A very effective time delay compensation method is to use the Smith Predictor [12]-[14] as shown in Fig. 7, in which *C(s)* is the controller, *P(s)* is the plant that includes communication delay, $\hat{P}(s)$ is the plant model, and $\underline{\hat{P}}(s)$ is the plant model without the time delay. Since the control signal is delayed, the same delay is accounted for in the controller to coordinate the feedback with system dynamics. The Smith Predictor works poorly unless the delay is precisely known [15].

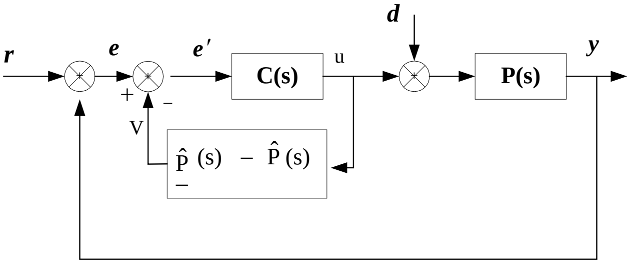


Fig. 7 : Smith Predictor block diagram

b) *Multivariable Smith Predictor*

The Smith Predictor is typically used for Single-Input-Single-Output (SISO) systems. However, if $P(s)$ and $\hat{P}(s)$ are transfer matrices then

$$P(s) = e^{-Ts}\begin{bmatrix} P_{11}(s)e^{-T_{11}S} & P_{12}(s)e^{-T_{12}S} \\ P_{21}(s)e^{-T_{21}S} & P_{22}(s)e^{-T_{22}S} \end{bmatrix}, \quad \hat{P}(s) = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \tag{5}$$

Now, it is easy to show that the closed loop system is

$$P_{cl}(s) = PC(I + \hat{P}C)^{-1} \tag{6}$$

Thus we can remove the delay from the loop, similar to the SISO case.

VII. NONLINEAR ADAPTIVE CONTROL

A typical teleoperation system consists of a local master manipulator (master site) and a remote slave manipulator (slave site). The human operator controls the local master manipulator to drive the slave in order to perform a given task remotely. The system must be completely "transparent" so that the human operator could feel as if he/she is able to directly manipulate the remote environment. Instead of perfect force tracking, the overall teleoperation system should behave as a free-floating mass plus linear damper specified by the control and scaling parameters.

Hung, Marikiyo and Tuan in [16] used the concept of a virtual manipulator to design a nonlinear control scheme that guarantees the asymptotic motion (velocity/position) tracking and has a reasonable force tracking performance even in when the acceleration, the values of dynamic parameters of manipulators as well as the models for human operator and the environment are not available. In the absence of friction and other disturbances, dynamic models of the master and the slave manipulators are

$$
\begin{aligned}
F_{am} + F_{mam} &= M_{xm}(q_m)\,\dot{X}_m + C_{xm}(q_m, \dot{q}_m)\,\dot{X}_m + g_{xm}(q_m) \\
F_{as} + F_{ext} &= M_{xs}(q_s)\,\ddot{X}_s + C_{xs}(q_s, \dot{q}_s)\,\dot{X}_s + g_{xs}(q_s)
\end{aligned}
\tag{7}
$$

If the followings are achieved

$$X_m(t) = X_s(t), \quad F_{as} = -F_{ext} \tag{8}$$

Then the system is said to be “transparent” to human-task interface. This requires knowledge of the manipulator acceleration, which in practice, is difficult to obtain. Moreover, there is a trade-off between motion tracking performance, force tracking performance, and system stability for a master-slave teleoperation system. In order to improve the performance, we increase the degree of freedom of the control system by utilizing a “virtual master manipulator.” This manipulator is described by the following dynamic model

$$F_d = M_d\,\ddot{X}_d + K_d\,\dot{X}_d + K_p\,\ddot{X}_d \tag{9}$$

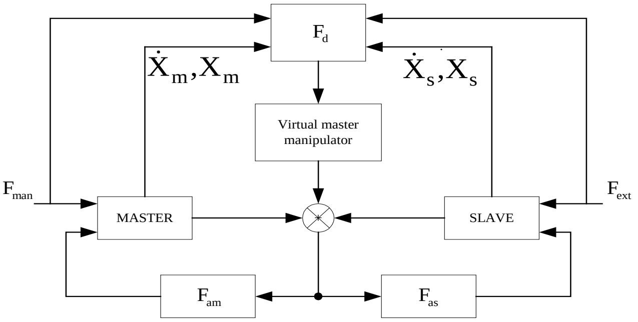


Fig.8 : Block diagram of the adaptive control system

Fig.8 shows the block diagram of the overall teleoperation system using the virtual master manipulator.

VIII. THE PROPOSED CONTROL SYSTEM

A switched system is utilized when there are abrupt changes in the structures and parameters of the dynamic system, which can be caused by component failures, repairs, environment changes, disturbances or changes in subsystems interconnections [17]-[18], and may result in improving the performance[19]-[20].

When a single identification model is used, it will have to adapt itself to the operating condition before appropriate controls can be taken. If the environment changes suddenly, the original model (and hence the controller) is no longer valid. If the adaptation is slow, it may result in a large transient error. However, if different models are available for different operating conditions, then suitable controllers corresponding to each condition can be devised in advance.

The control structure in Fig. 9 determines the best model for the existing operating condition at every instant, and activates the corresponding controller. This structure is based on *N* models which have been developed at various points across the operating range of the process. A controller is designed for each model, using the Diophantine pole–placement algorithm. A supervisor as shown in Fig. 10 compares the output errors for each one of the *N* models. A discrete equivalent of the performance index is given in (10), for the i^{th} model:

$$J_i(k) = \alpha e_i^2(k) + \beta \sum_{j=1}^{M} \exp(-j\lambda_i) e_i^2(k-j) \tag{10}$$

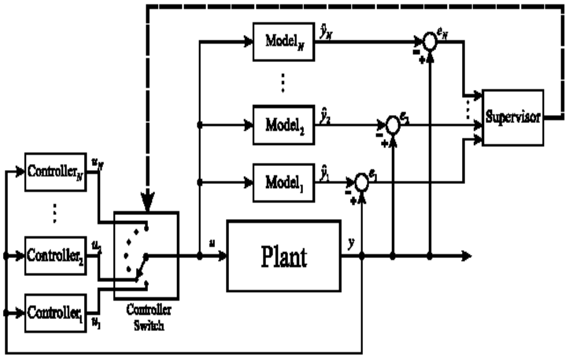


Fig. 9 : Multi-model adaptive control system

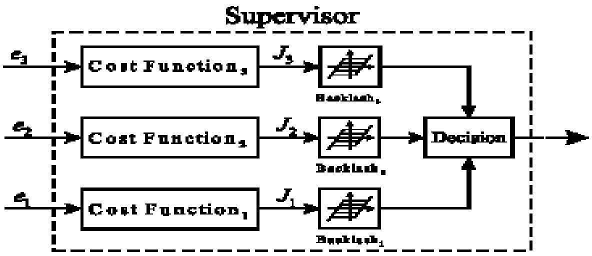


Fig. 10: Supervisor operation

Expansion of this controller for the master-slave teleoperation was proposed in [21], where the best model for the current operating condition is identified and the corresponding controller either in the master or in the slave is activated. The block diagram of this proposed control system is shown in Fig. 11.

Here we have used the ARX model for the communication delay, and obtained its parameters using a system identification approach; and studied its performance under abrupt changes in the time delay using simulation and analysis.

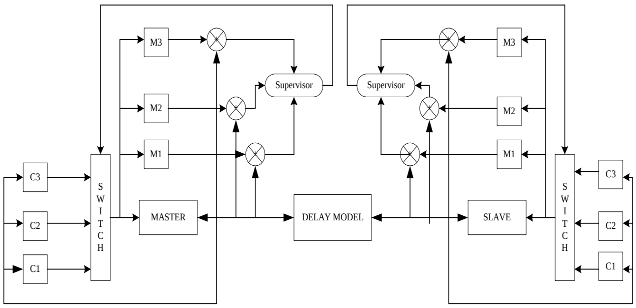


Fig.11 : The proposed master-slave multi-model adaptive control system block diagram for teleoperation via the Internet

IX. Results and Conclusions

We presented a new method for designing a robust stable Internet-based teleoperation system. Our focus is on the robustness against delay and its random nature. We have applied our proposed method to control a simple teleoperation system and studied its behavior for a time varying delay on the communication link between the plant and the controller.

This control scheme was initially proposed and analyzed in [21]. Here we focus on the behavior of the proposed control system under abrupt changes in the time delay. Furthermore, we have replaced the delay block in [21] with a delay model obtained using the ARX model, the parameters of which are obtained using system identification as discussed above.

Fig. 12 shows the system output using ordinary wave prediction method. In the output of our proposed method (Fig. 13) we note that the proposed control system is more robust with minim overshoot. Fig. 14 shows the step responses for ordinary and proposed control methods, when time delay changed abruptly from 700 msec to 2100 msec at t=50. We note that the proposed multi-model control strategy has a satisfactory response with small fluctuations. Fig. 15 shows the tracking response without wave prediction. In Figs. 16 and 17, the tracking responses of wave prediction and the proposed control methods are shown. The results indicate the usefulness of our proposed approach particularly for abrupt variations of the environment's parameters.

We can also use this structure together with the wave variable method, the Smith predictor method, and a combination of the two in linear and/or nonlinear controllers, time-based and/or non-time based controllers and other suitable types of controllers, so that the most fitting controller can be utilized depending on the circumstances.

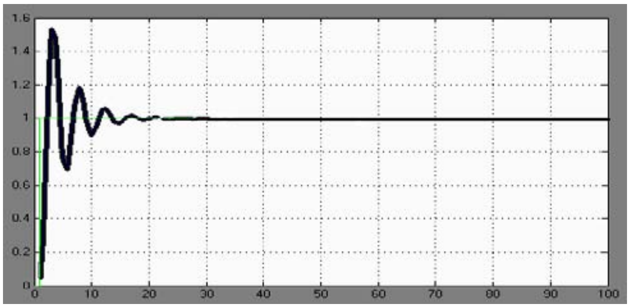


Fig.12 : System response using the ordinary wave-prediction method

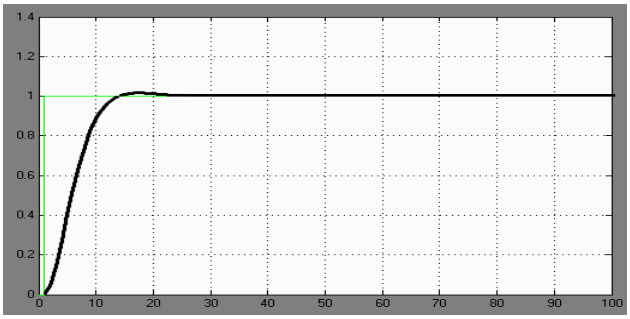


Fig.13: System response using our proposed method

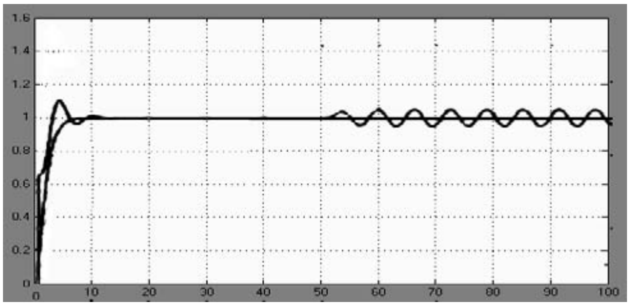


Fig.14: System step responses for the ordinary and the proposed control methods, when time delay changed abruptly

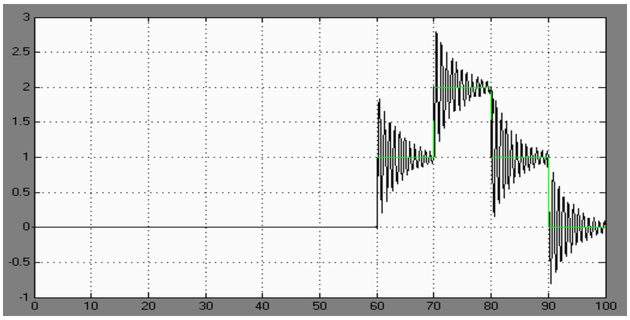


Fig.15: System tracking response without wave prediction

Fig.16: System output tracking response with wave prediction

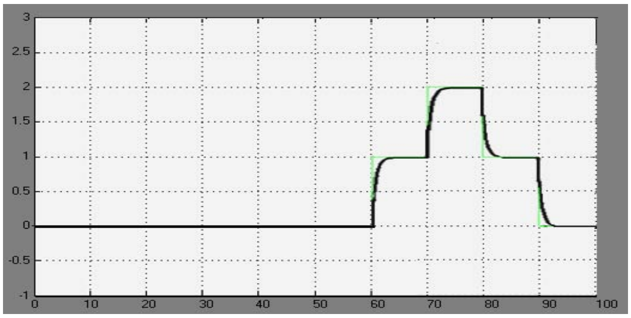


Fig.17: System tracking response with proposed control system

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