New Smith Predictor Structure Used for the Control of the Quanser SRV-02 Plant

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Abstract: This paper presents the Quanser SRV-02 plant controlled with a new Smith predictor structure combined with PID controllers. The new Smith predictor enhances the system robustness and minimizes the disturbance influence. The structure also achieves Smith dynamic prediction compensations for the delays of the network. The Smith predictor structure used in the control process hides the predictor model of the network delay into the transmission process thus making the network delay measuring or estimation irrelevant. The new Smith predictor structure is ideal for processes characterized by stochastic delays.

Keywords: networked control systems, network delay, Smith predictor.

1. INTRODUCTION

The Quanser SRV-02 series is ideal for introducing fundamental control principles and theories. The plant contains a MicroMo Coreless DC Motor encapsulated in a strong aluminium frame. This model is a high efficiency low inductance motor resulting in a much faster response than a conventional DC motor. The motor is equipped with a gearbox that drives external gears. The motor connection is a 4-pin DIN connector configured to be driven by a Quanser Universal Power Module. All the models in the series include a potentiometer used for measuring the output or loading the angular position. The kit is completed with high-resolution optical encoders and tachometers.

Fig.1. The Quanser SRV-02 plant

For the Quanser SRV-02 plant, two speed configurations are available: “low gear ratio” and “high gear ratio”.

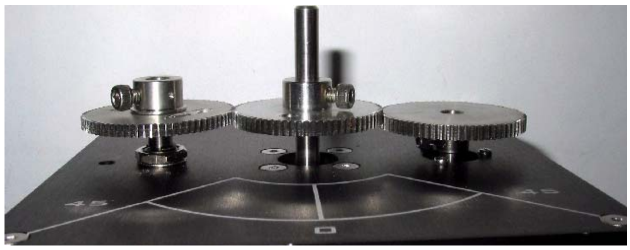

Fig.2. Low gear ratio

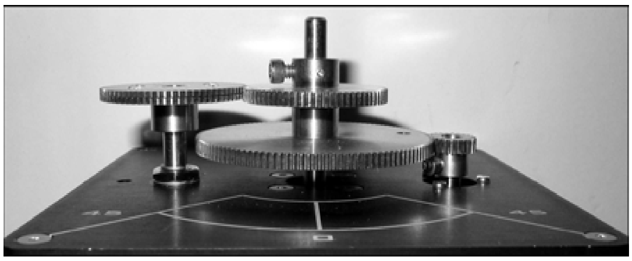

Fig. 3. High gear ratio

Attached to the system is the encoder that measures 1024x4 impulses in a complete rotation. This means that 360 degrees are equivalent to 1024x4=4096 impulses. The resolution of the encoder counter is 360/4096=0.0878906250 degrees. The model used during the experiments is a US Digital Optical Encoder kit.

The tachometer supplies an analogical signal and generates 1,5V every 1000 RPM. For the Quanser SRV-02 plant, the tachometer is attached directly to the motor and there are no response delays and the speed of the motor is accurately measured.

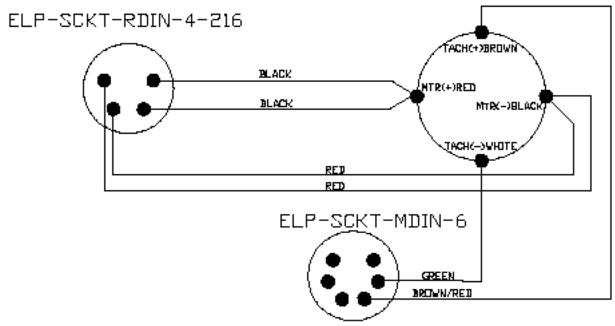

Fig. 4 Tachometer wiring

The potentiometer supplies an analogical signal proportional with the rotation angle. The model used in the experiments is Vshay Spectral model 132. This is a 10kΩ sensor which measures 352 degrees expressed in voltages ranging from +5V to -5V. The difference between the potentiometer and the encoder is that the latter can measure several complete rotations as the potentiometer can only measure 360 degrees and back.

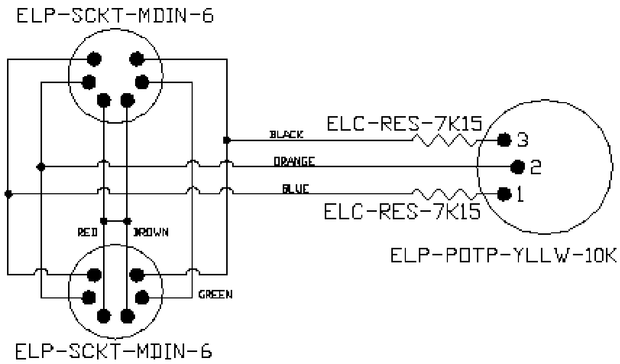

Fig. 5. Potentiometer wiring

The closed loop transfer function is:

$$H_1(s) = \frac{\theta_0(s)}{V_i(s)} = \frac{\dfrac{\eta k_m k_g}{R_a J_{eq}}}{s + \dfrac{B_{eq}}{J_{eq}} + \dfrac{\eta k_m^2 k_g^2}{R_a J_{eq}}} \qquad (1)$$

$$H_1(s) = \frac{\theta_0(s)}{V_i(s)} = \frac{a_m}{s(s+b_m)} \qquad (2)$$

where $a_m = \dfrac{\eta k_m k_g}{R_a J_{eq}}$ and $b_m = \dfrac{B_{eq}}{J_{eq}} + \dfrac{\eta k_m^2 k_g^2}{R_a J_{eq}}$.

The transfer function of the plant with the output $\theta_0(s)$ is:

$$H_2(s) = \frac{\theta_0(s)}{V_i(s)} = \frac{\dfrac{\eta k_m k_g}{R_a J_{eq}}}{s(s + \dfrac{B_{eq}}{J_{eq}} + \dfrac{\eta k_m^2 k_g^2}{R_a J_{eq}})} \qquad (3)$$

$$H_{21}(s) = \frac{\theta_0(s)}{V_i(s)} = \frac{a_m}{s(s+b_m)} \qquad (4)$$

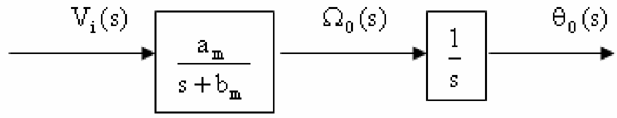

Fig. 6. The transfer function of the plant

The step response is:

$$\theta_0(s) = \frac{a_m}{s(s+b_m)} \frac{1}{s} \qquad (5)$$

The final value of the response is :

$$\lim_{\theta \to \infty} \theta_0(t) = \lim_{s \to 0} s\theta_0(s) = \infty \qquad (6)$$

The response is infinite.

2. THE NEW SMITH PREDICTOR STRUCTURE USED

In 1957, Smith introduced a new technique dealing with the instability issues that occur in control systems, also experimenting with delays. The main idea of this technique is to substitute the conventional controller C(s) with a new design $C^*(s)$ in such a way that closed loop control of the process dynamics without delay can be achieved. Given a process, with a delay of τ seconds, Smith proposed that a new controller $C^*(s)$ be introduced in the closed loop with the delayed process $G(s)e^{-\tau s}$ as seen in figure 7a.

The effect of the Smith controller $C^*(s)$ is to eliminate the delay from the control loop as can be seen in figure 7 b. and to effectively realize the control of the non-delayed process dynamics $G(s)$ using a conventional controller $C(s)$, Aström (1994).

Many slow processes can be described through models of the following form:

$$H(s) = G(s)e^{-\tau s} \qquad (7)$$

where $G(s)$ is rational and strictly proper and τ is the delay (dead time). A conventional control structure like in figure 1a induces an infinity of poles in the system. Thus, $H_0(s)$ is:

$$H_0(s) = \frac{C(s)G(s)e^{-\tau s}}{1 + C(s)G(s)e^{-\tau s}} \qquad (8)$$

In order to eliminate the unwanted effect of the delay from the process model, a separation of the delay inside the model is attempted and also the use of variable $y(t)$ instead of $y(t-\tau)$ is realized. The structure of the control system, in this case, is the one presented in figure 7b with the following transfer function:

$$H_0^*(s) = \frac{C^*(s)G(s)e^{-\tau s}}{1 + C^*(s)G(s)e^{-\tau s}} \tag{9}$$

Imposing the condition that the structures have the same input-output behaviour, we obtain:

$$H_0(s) = H_0^*(s) \tag{10}$$

The predictive control algorithm (Smith predictor) will be defined by the following transfer function:

$$C^*(s) = \frac{C(s)}{1 + C(s)G(s)\left(1 - e^{-\tau s}\right)} \tag{11}$$

For the design of the control system any known method for non-delayed systems can be used in order to determine $C^*(s)$, Veronesi (2003).

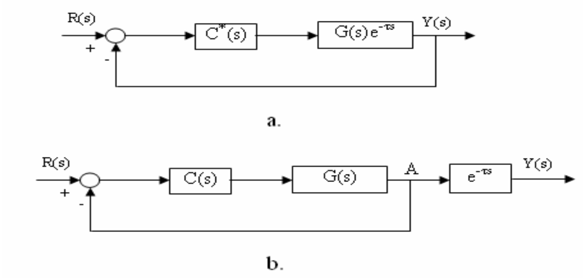

Fig.7. The Smith controller and its equivalent conventional controller

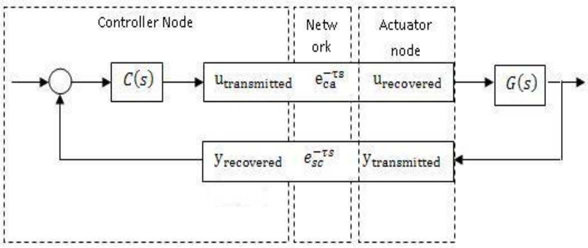

Fig. 8. The control loop with network communication delays

In figure 8, τ_{sc} and τ_{ca} are the network delays, τ_{sc} is the delay from the sensor to the actuator and τ_{ca} is the delay from the controller to the motor. The total network delay $\tau = \tau_{sc} + \tau_{ca}$ is greater than 1.

The closed loop transfer function is:

$$\frac{Y(s)}{R(s)} = \frac{C(s)e^{-\tau_{ca}s}G(s)}{1 + C(s)e^{-\tau_{ca}s}G(s)e^{-\tau_{sc}s}} \tag{12}$$

From (12), it can be seen that $e^{-\tau_{ca}s}$ and $e^{-\tau_{sc}s}$ are included in the denominator of the transfer function. They can decrease overall performance and may constitute a source of instability of the system, Feng (2009).

The solution for this situation is the introduction of a Smith predictor structure presented below:

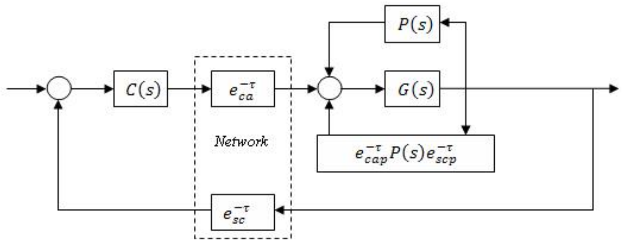

Fig.9. The control loop using the P(s) Smith predictor

τ_{scp} and τ_{cap} are the predicted values of the network delays τ_{sc} and τ_{ca}. The closed loop transfer function is (13):

$$\frac{Y(s)}{R(s)} = \left[C(s)e^{-\tau_{ca}s}G(s)\right] / \left[1 + C(s)e^{-\tau_{ca}s}G(s)e^{-\tau_{sc}s} + G(s)P(s) - C(s)e^{-\tau_{cap}s}P(s)e^{-\tau_{scp}s}\right] \tag{13}$$

If $\tau_{scp} = \tau_{sc}$, $\tau_{cap} = \tau_{ca}$ and $C(s) = P(s)$, then the prediction models can accurately describe the real models.

$$\frac{Y(s)}{R(s)} = \frac{C(s)e^{-\tau_{ca}s}G(s)}{1 + C(s)G(s)} \tag{14}$$

Through the Smith predictor the τ_{sc} delay can be eliminated from the feedback by eliminating the τ_{ca} delay from the direct path, thus making the delays fully compensated when the prediction models can accurately approximate the real models.

An improved version of the control loop is presented below:

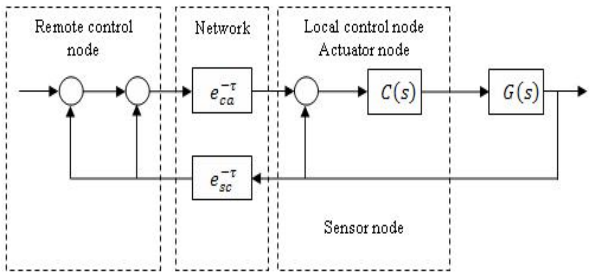

Fig. 10. The control loop using the improved P(s) Smith predictor

The closed loop transfer function is:

$$\frac{Y(s)}{R(s)} = \frac{e^{-\tau_{ca}s}C(s)G(s)}{1 + C(s)G(s)} \tag{15}$$

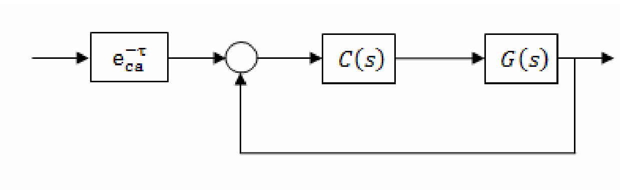

Fig. 11. The equivalent control loop

3. EXPERIMENTS USING THE NEW SMITH PREDICTOR STRUCTURE

The following Simulink control scheme is proposed using a PI controller: $K_p = 6.8$, $T_i = 0.1$.

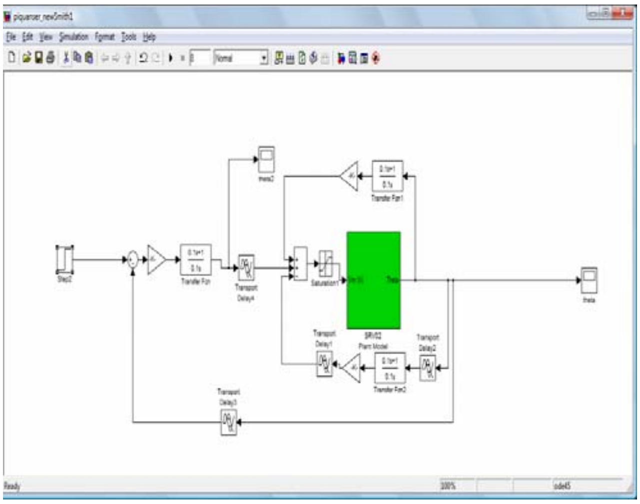

Fig. 12. Smith predictor control loop

In this first simulation a PI controller is used and the process delay is fixed.

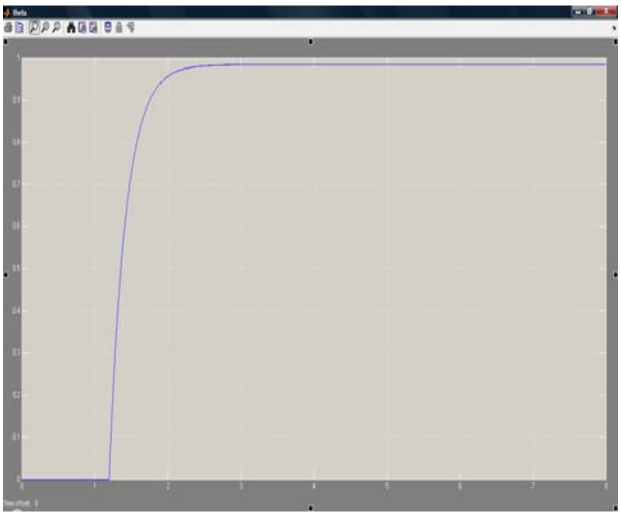

Fig. 13. The step response for the first simulation

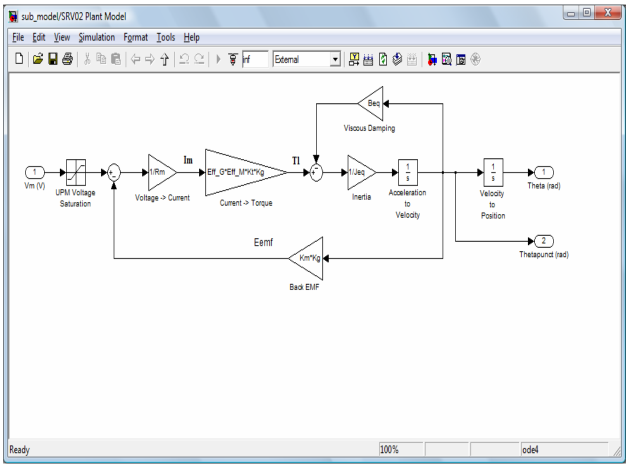

Fig. 14. Quanser SRV-02 model

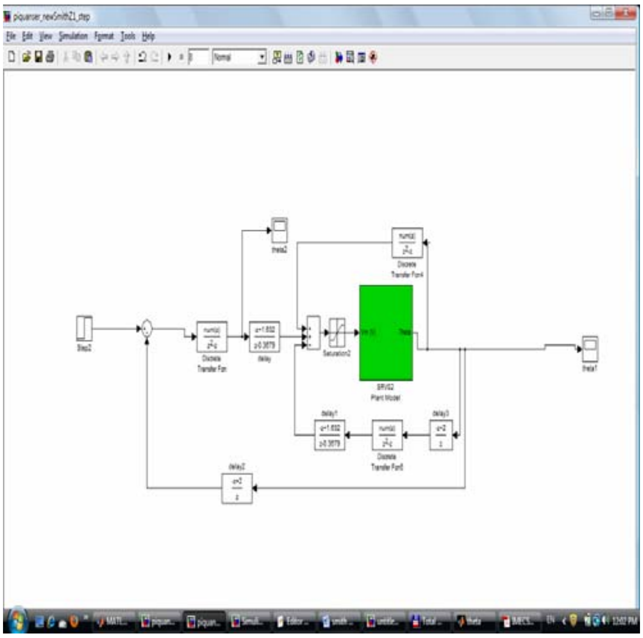

Fig. 15. The second simulation of the new Smith predictor structure

This second simulation uses a discrete model of an ideal PID controller and the process delays are approximated through a Pade first order approximation. The ideal PID controller discrete model is obtained by approximating the integral through a sum of square and the derivative components through backward differences.

The Pade first order approximations of the process delays are calculated and a discrete model is obtained by using the c2d function in Matlab.

Pade approximant is the "best" approximation of a function by a rational function of given order - under this technique, the approximant's power series agrees with the power series of the function it is approximating.

The Pade approximant often gives better approximation of the function than truncating its Taylor series and it may still work where the Taylor series does not converge.

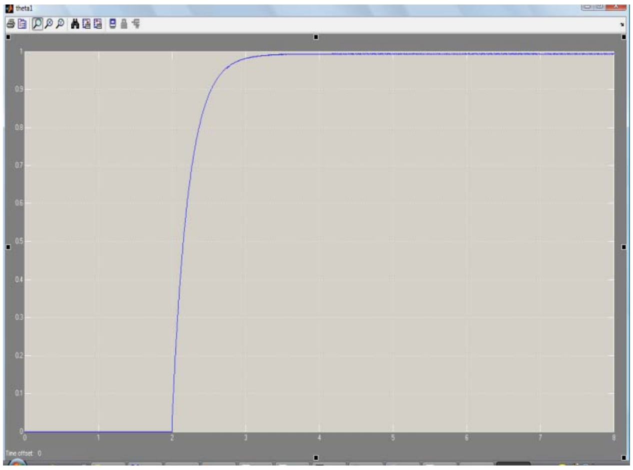

Fig. 16. The step response for the previous simulation

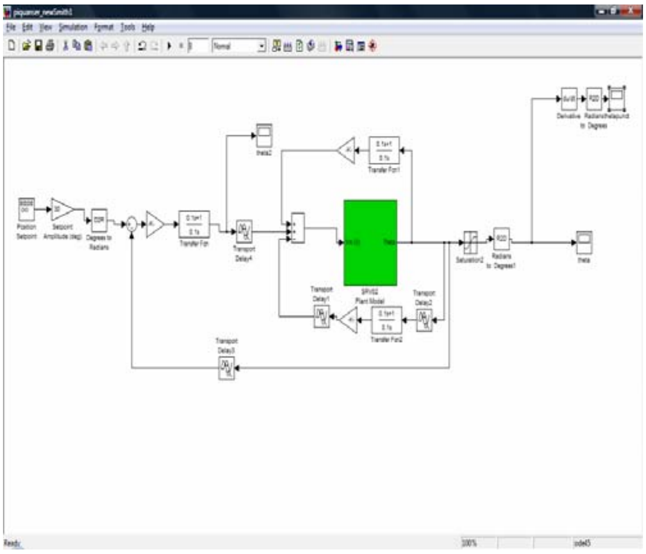

Fig. 17. Remote position control for the Quanser SRV-02 plant using the new Smith predictor configuration

The simulation presented above is meant for the remote control of the Quanser SRV-02 experiment. In other words, we aim to control the theta movement angle. The reference in this case is set to 30 degrees. The controller is of PI type and the delay is fixed.

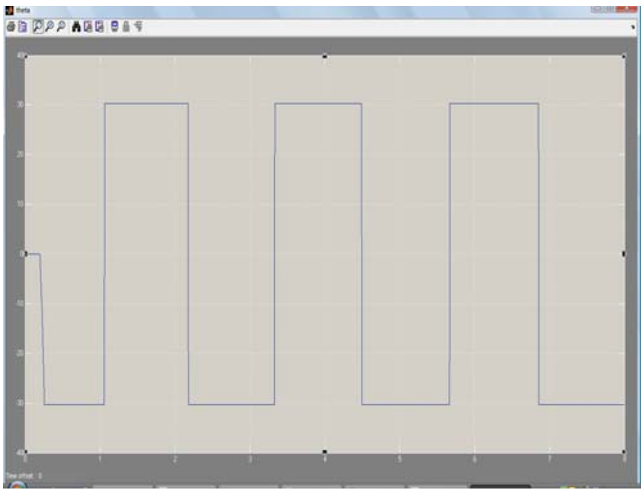

Fig. 18. θ angle –movement angle

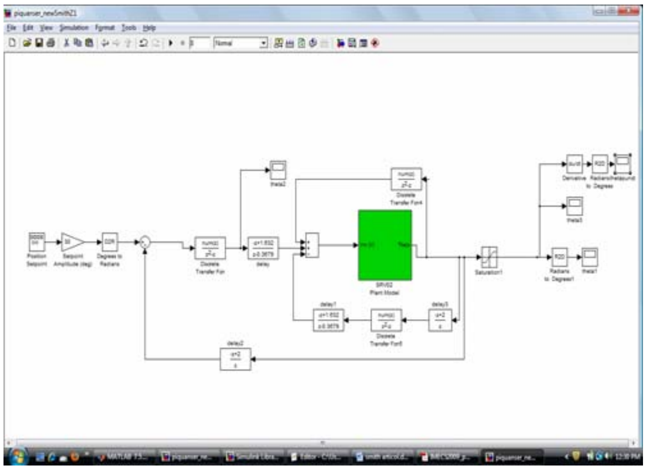

Fig. 19. Control loop with a Smith predictor and a PID discrete model controller is used

The b0, b1, b2 coefficients are determined by obtaining a discrete-time model of an ideal PID controller by approximating the derivative component through backward differences and the integral through a sum of squares.

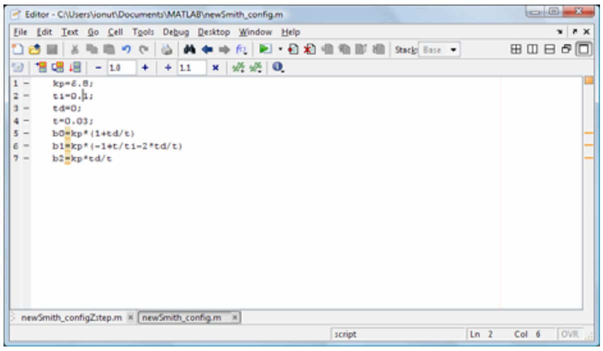

Fig. 20. The coefficient m-file for the controller used in the Smith predictor configuration

The transfer function for the discrete time controller is:

$$C(z)=\frac{Y(s)}{U(s)}=\frac{b_2 z^2+b_1 z+b_0}{z^2-z} \qquad (16)$$

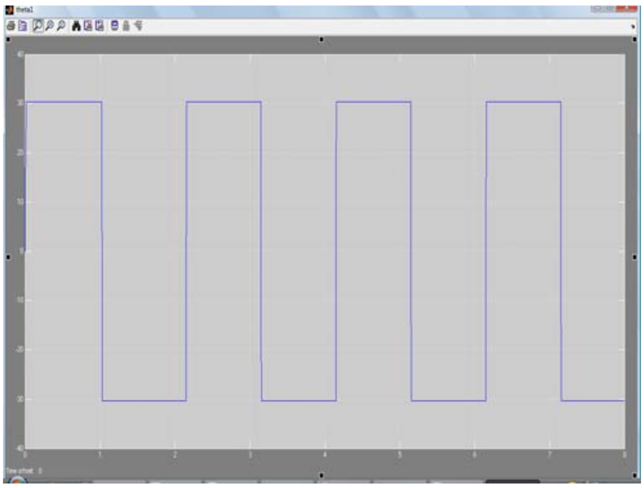

Fig. 21. θ angle which varies from -30^0 to 30^0

For the network delays the following experimentally approximated values were used $\tau_{sc} = 0.02$ and $\tau_{ca} = 0.2$. For these values, a model of the network delays was obtained using the Pade first order approximation:

$$
\begin{aligned}
e^{-\tau_{sc}s} &= (-z + 1.632)/(z - 0.3679) \\
e^{-\tau_{sc}s} &= (-z + 2)/z
\end{aligned}
\tag{17}
$$

The Simulink model using a variable delay:

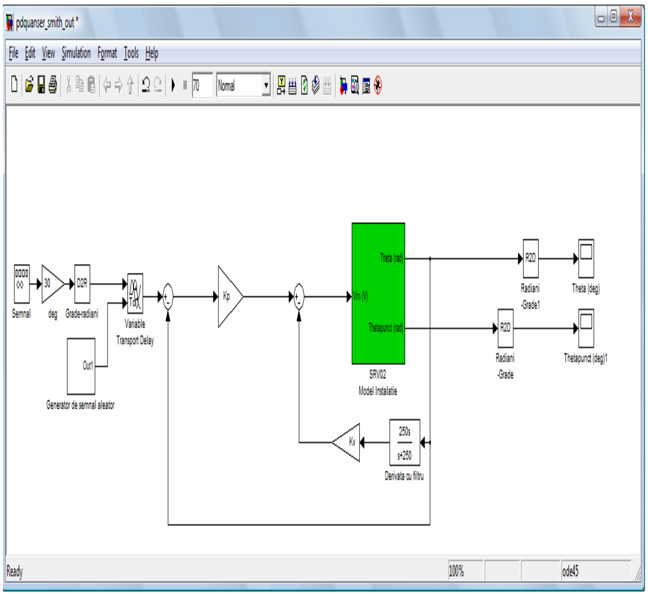

Fig. 22. Control loop using a variable delay

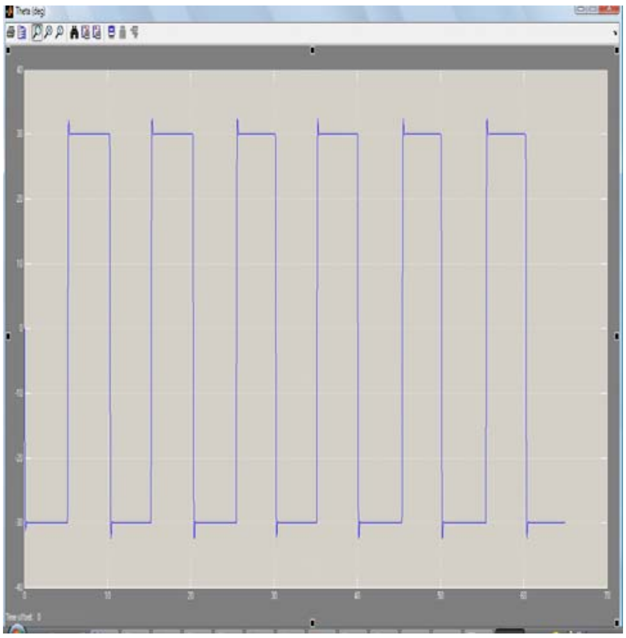

Fig. 23. θ angle which varies from -30^0 to 30^0

Controller, sensor and actuator (the fixed part of the system) are connected through a network, Velagic (2008). Data transfers between the controller and the actuator will induce network delays in addition to the controller processing delay. Network delays in a networked control system can be categorized from the direction of data transfers as the sensor-to-controller delay τ_{sc} and the controller-to-actuator delay τ_{ca}.

The delays are computed as

$$
\begin{aligned}
\tau_{sc} &= t_{sc} - t_{se} \\
\tau_{ca} &= \tau_{rs} - t_{ce}
\end{aligned}
\tag{18}
$$

where t_{se} is the time instant that the actuator encapsulates the measurement to a frame or a packet to be sent, t_{sc} is the time instant that the controller starts processing the measurement in the delivered frame or packet, t_{ce} is the time instant that the main controller encapsulates the control signal to a packet to be sent, and t_{rs} is the time instant that the system starts processing the control signal

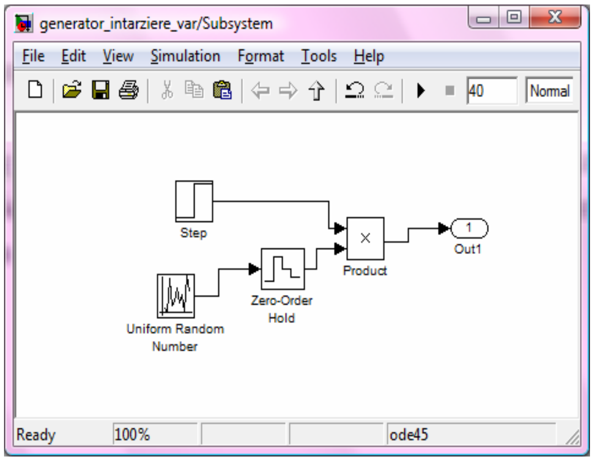

Fig.24. System for generating a uniform distributed random signal

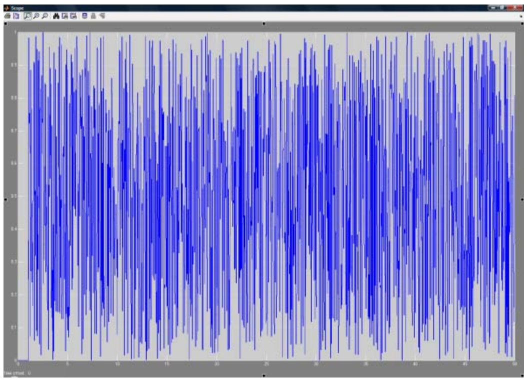

Fig.25. Time distribution of communication delay

6. CONCLUSIONS

The conclusion that derives from this paper is that both delays can be smaller or greater than the sampling rate T. In the first case, the process can be controlled in optimal conditions. In the second case, major process discontinuity issues can occur which may lead to unsatisfactory evolutions or stability loss.

Following extensive laboratory experiments, the following steps are recommended:

- the evaluation of the dynamic characteristics of the controlled process including actuators and sensors
- sampling rate choice in agreement with the stability and performance criteria
- tests performed on the network used in the control process; medium delays and probability of error are observed

If these delays are much smaller than the necessary sampling rate, the process can be controlled by introducing a delay block in the fixed part of the system.

If the delays become comparable in size with the sampling rate, then the use of a Smith predictor is recommended.

If the network induces large delays and the process has small time constants, remote control is possible only through a hierarchical structure.

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