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Discrete Time State-Space Modeling of A Wireless Control System With MATLAB

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Abstract—This work has been carried out to demonstrate the performances of two different state space models of a process simulator that was used for the wireless control. Wireless input/output data obtained from the Cussons P3005 type process control simulator which three different temperatures (T2, T3 and T4) were selected as the controlled variables while the heater capacity was chosen as the manipulated variable. Wireless temperature experiments were achieved by using MATLAB/Simulink program and wireless data transfer during the experiments were carried out with radio waves at a frequency of 2.4 GHz. The state space models of the process simulator were developed with the aid of System Identification Toolbox of MATLAB using the data acquired from a unit step change between % 10-80 values on the heater capacity of the process simulator. The model orders used for the estimation of the model coefficients were determined with the aid MATLAB. The comparison between the experimental and two different state space model simulated temperatures of T2, T3 and T4 temperatures on the process simulator have revealed that the *n4sid* state space model can be used to represent the this wireless control system. Compared to the *pem* model investigated, the best step responses without any oscillations, fastest rise time and response time and higher calculated fit values obtained from *n4sid* model showed that it had the good performance.

Keywords—State-Space Modeling (SSM), System identification, MATLAB/Simulink, wireless measurement and control, discrete time

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I. INTRODUCTION

State space models have been reported to be superior to other multivariate statistical methods for the modelling, control and monitoring of dynamic processes. A standard way of constructing control-models is using the state-space representation that is flexible and compact, can include continuous and/or discrete time variables, facilitate the modeling of uncertainty and mode-switching dynamics of hybrid systems, and provide clarity and insight about the effect of different system parameter inputs. State-space models for buildings can be formulated according to the building system under consideration, including linear time invariant or variant, bilinear, nonlinear representations, etc [1].

The state-space approach for the generalized representation of chemical process networks was initially reported to the context of modeling distillation networks [2]. The state space modeling was subsequently used to explore a number of other systems, including time-varying processes [3], seismic signal analysis [4], nonlinear systems [5], fuel cell and power systems [6-7], metabolic networks [8-9], control of reactive distillation column [10]. The state space modeling has been applied into many different areas, such as computer science, econometrics, and statistics [11-14].

Wireless technology makes measurement and control systems to be low cost, easy to installation, use and maintenance and has more broad potential applications. Wireless measurements can reduce noise problems in addition to installation costs by the elimination of wiring problems and electromagnetic interference. Specific requirements of wireless measurement and control applications bring new challenges to wireless networks, specifically regarding the more strict and deterministic performance of real-time and reliability, the dynamic adaptability of the environment, low cost, and low power consumption according to wiring measurement and control [15-16].

In this study, coefficients of two state space models are determined for process simulator which wireless temperature experiments achieved in this work using the System Identification Toolbox of MATLAB (MathWorks 2011). Wireless temperature experiments were achieved by using MATLAB/Simulink program and wireless data transfer during the experiments were carried out using radio waves at a frequency of 2.4 GHz. Two discrete time state space model coefficients determined with MATLAB and state space model performances are compared with the calculated fit values and simulation results of three different temperature points on this wireless control system.

II. EXPERIMENTAL SYSTEM AND PROCEDURE

1) Process Description

The process control simulator consists of two main units, an instrument console and a framework carrying the process equipment which is shown in Figure 1. The instrument console contains the electronic flow, level, temperature controllers and electrical switchgear. It is connected to the process equipment by several cable assemblies. The process equipment consists of a water tank, water circulating pump, electrical water heater, two vessels, two electrically positioned control valves and a heat exchanger. In process control simulator, twelve manual valves are available for different process experiment loops. In the process simulator, temperature measurement and control can be made at four different points which are first tank (T1), heater output (T2), second tank input (T3) and second tank output (T4).

The wireless system developed for transferring data between the computer and the control panel. To achieve the data transfer between computer in Process Control Laboratory and the process simulator in Unit Operations Laboratory, by using the two antennas are found in the laboratory connected to the computer and outside connected to the process simulator. Control valves outputs are connected to the modules, the necessary calibrations are made. The water is pumped via the electrical heater into the reactor up to a certain level. The water then flows back to the sump tank via the cooler. Heat is fed to the water by the heater and residual heat removed by the cooler so as to return the sump tank water temperature to a suitable base level. Heater which is connected on-line to the computer is used as a manipulated variable [16].

Wireless temperature experiments were achieved by using MATLAB/Simulink program and wireless data transfer during the experiments were carried out using radio waves at a frequency of 2.4 GHz. MATLAB/Simulink block diagram was used for the on-line wireless temperature experiments with a computer in the office. There have four moduls, wireless on/off block for the wire or wireless experiments, numerical or graphical display blocks of process parameters, blocks of giving numerical values of valve openness, blocks of stored errors on the MATLAB/Simulink block diagram shown in Figure 2.

2) Wireless Data Generation

The wireless data generated by operating the process simulator described above and shown in Figure 1. Wireless data were used for the development of the models of the three temperatures at different points on the process simulator using Process Identification Technique. The state space model parameters were estimated with the aid of System Identification Toolbox of MATLAB program. Wireless temperature experiments were carried out on process simulator during the 1500s time period. First 300s the heater operated % 10 heating capacity for the temperature is expected to become at steady-state. The fluid flow was obtained by running the pump when the level control valve was % 35 opening. The cooling water was opened after liquid level was fixed value. The heater output temperature was expected to become at steady-state while % heating capacity was on. A step change effect was performed as input signal which apply the heater capacity between % 10-80 values and T2, T3 and T4 temperature changes with time as output signal which selected as the controlled variables while the heater capacity was chosen as the manipulated variable. These effects were given to the heater and output temperatures taken with MATLAB/Simulink during the experiments shown in Figure 2 [16].

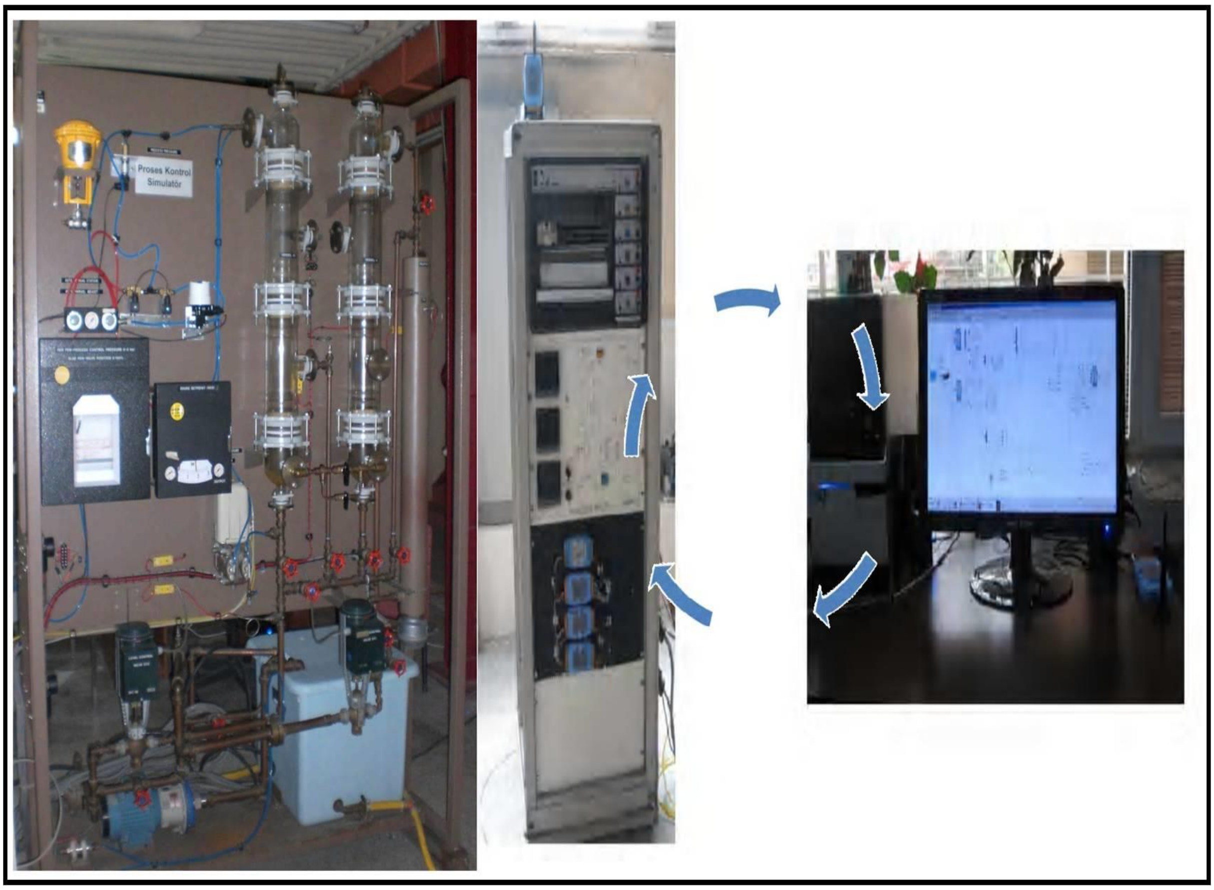

Figure 1. Experimental system: Process simulator, control panel and computer on-line connected to the process simulator with wireless technology [16]

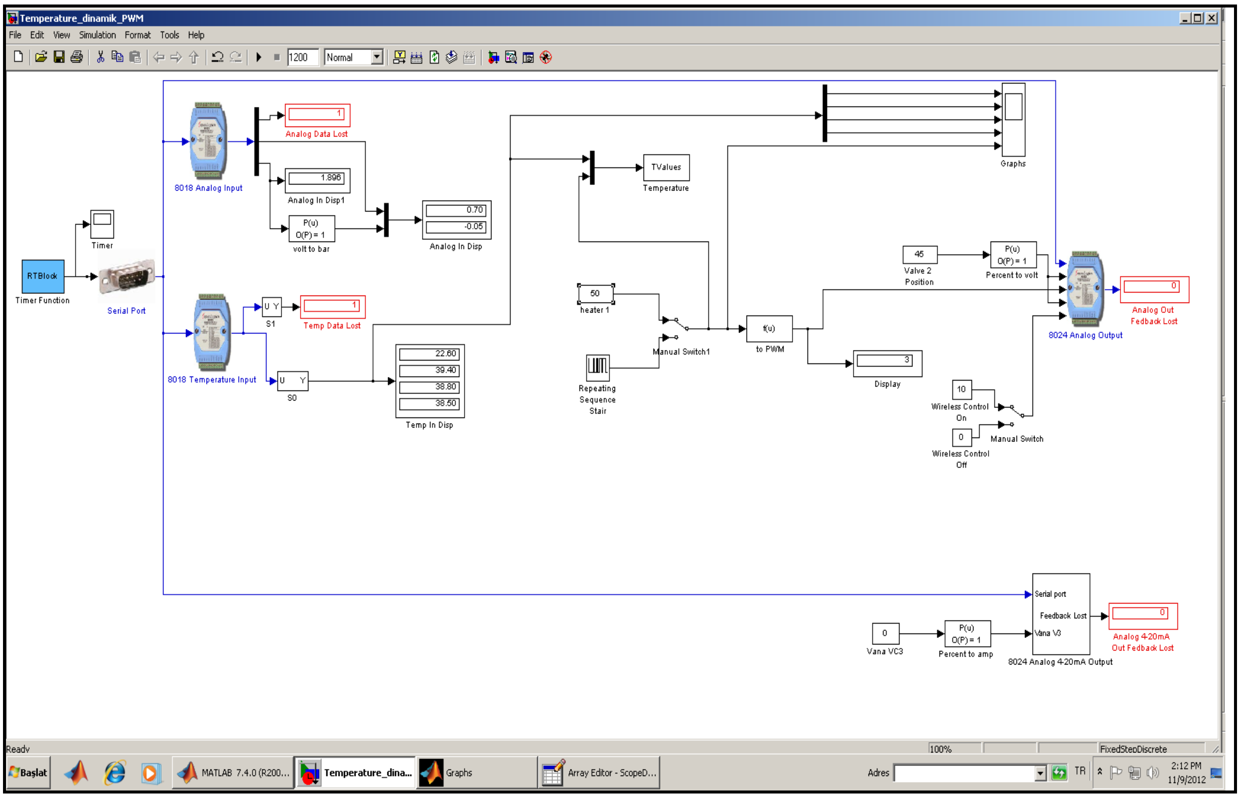

Figure 2. MATLAB/Simulink block diyagram for wireless temperature experiments [16]

3) State-Space Formulation

The state–space model is a set of differential or difference equations and an observation equation to describe the relationship between the input and output of a dynamic system. The state space representation of systems has several advantages over input–output representation. State space models convey much knowledge about the internal relations of systems. The discrete time state space representation of a system is given by Eq. (1),

$$\left.\begin{aligned} x(t+Ts) &= Ax(t)+Bu(t)+Ke(t) \\ y(t) &= Cx(t)+Du(t)+e(t) \end{aligned}\right\} \tag{1}$$

where *x* is the state vector of system, *u* is the vector of inputs and *y* is the vector of outputs. A, B, C, D and K are the state space matrices used to express the process dynamics. They (A, B, C, D and K) can be regarded as the model coefficients and thus be called matrix model coefficients. Discrete-time type models were developed using the ***pem*** and ***n4sid*** commands of MATLAB R2011a. The notations used to denote the models were derived from their MATLAB commands. Given the process simulator which has, apart from the disturbance e, the capacity of heater capacity (R) input variable and the three temperatures (T2-T3-T4) as the output variables respectively [16],

III. RESULTS AND DISCUSSION

The wireless data acquired from the experiment carried out in the process simulator are as shown in Figure 3. It can be observed from Figure 3 that a change in the heater capacity between % 10-80 values to a step effect resulted in a change in the temperatures of the T2, T3 and T4. The polynomial coefficients estimated are as outlined given in Table 2-4-6 for ***pem*** and Table 3-5-7 for ***n4sid*** models, respectively.

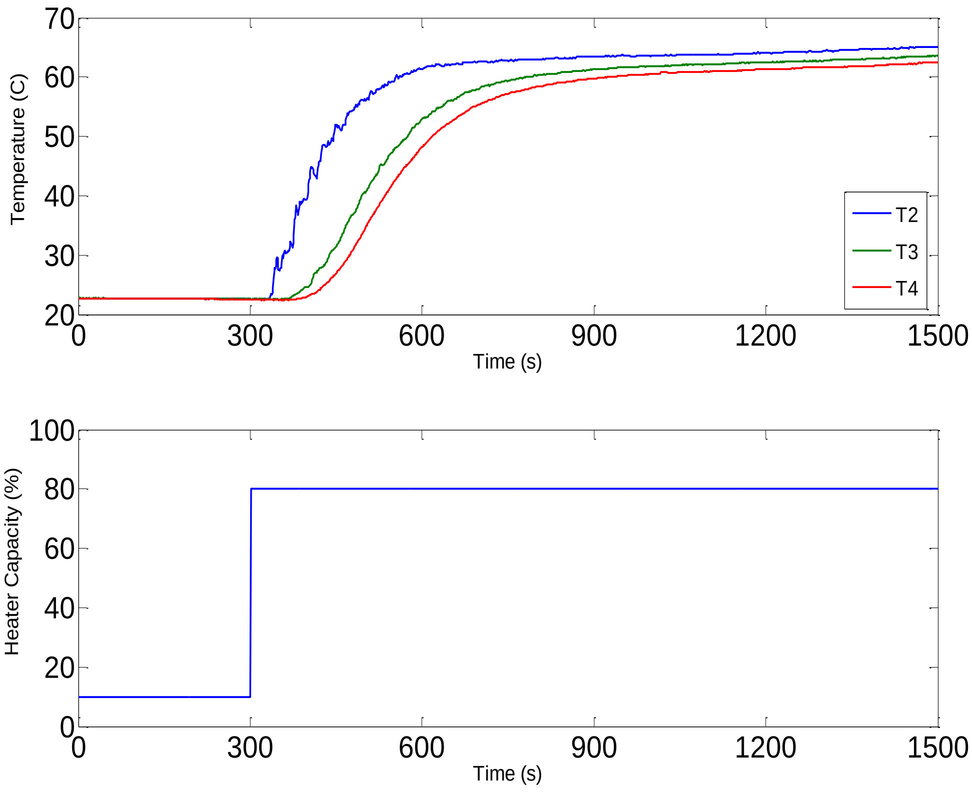

Figure 3. T2, T3 and T4 temperature changes to given a step effect to the heater capacity between % 10-80 values

The developed two state space models were then simulated and their simulated results were compared to the T2, T3 and T4 temperatures on the simulator. Simulated temperatures were compared with each other by calculating their fit values (using the expression given in Eq. (2)). The calculated fit values are as shown in Table 1 below.

$$Fit\ Value\ (\%) = \frac{1 - norm(Ts - Te)}{norm(Te - mean(Te))} * 100 \qquad (2)$$

1) State Space Modeling (SSM) Studies

Shown in Figure 4-6 were the comparison between the experimental and the simulated ***pem*** and ***n4sid*** models temperature outputs for T2-T3-T4 temperatures of the process simulator, respectively. As can be seen from Figure 4 there was a good agreement between the experimental and ***n4sid*** model simulated T2 temperature while there was a low agreement between the experimental and ***pem*** model. From the Figure 4, ***pem*** model is expected to show a very large oscillations until it reaches the steady state but ***n4sid*** model was reaches steady state rapidly without any oscillations. From the Figure 5, the simulated ***pem*** and ***n4sid*** model temperature profiles of T3 were similiar to each other and two profiles are reaches steady state rapidly without any oscillations. From the Figure 6 there is a good agreement between the experimental and ***pem*** model simulated T4 temperature while there was a low agreement between the experimental and ***n4sid*** model. From the Figure 6, ***n4sid*** model is expected to show a very large oscillations until it reaches the steady state but ***pem*** model is reaches steady state rapidly without any oscillations. In Figure 5-6 there were not any agreement between experimental and simulated ***pem*** and ***n4sid*** models temperature profiles in first 300s.

From the Table 1, it was observed that the fit values of the ***n4sid*** model which was calculated for T2, T3 and T4 were higher than that of the ***pem*** model. It has been revealed from Table 1 that, even though the differences of the fit values were not too much between the T2, T3 and T4 temperatures for ***pem*** model. According to the Table 1, fit values of the ***n4sid*** model decreased while fit values of the ***pem*** model increased from the T2 to T4. The highest and the lowest fit values are calculated for T2 with ***n4sid*** and ***pem*** model, respectively.

Table 1. Fit values (%) of the state space models for T2, T3 and T4 temperatures

Model	**T2**	**T3**	**T4**
n4sid	**85.56**	**77.63**	**75.78**
pem	**70.59**	**72.96**	**73.25**

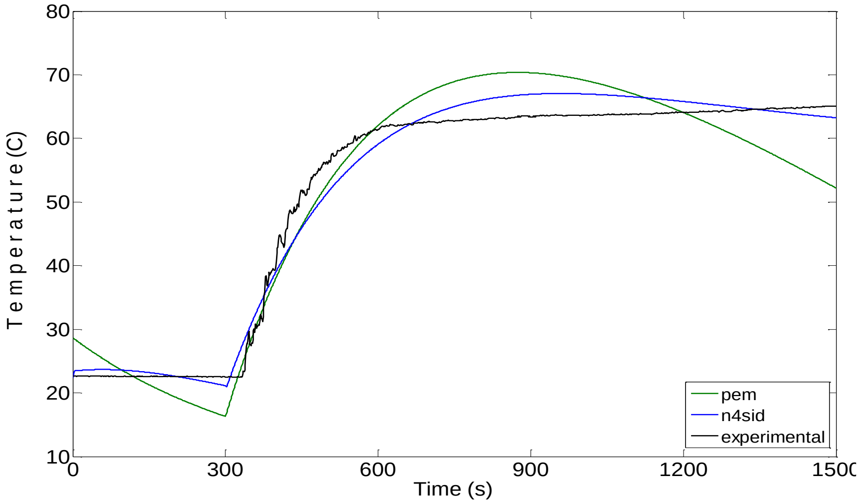

Figure 4. Comparison of experimental and two state space model outputs for T2

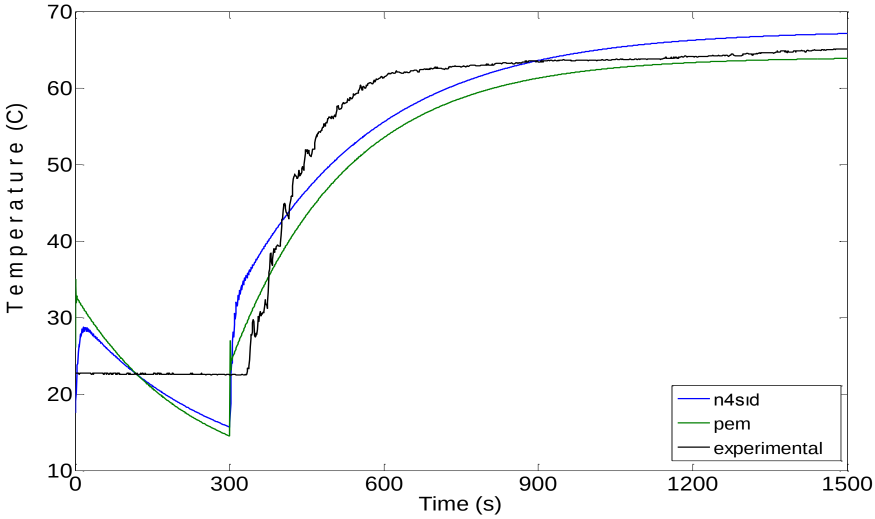

Figure 5. Comparison of experimental and two state space model outputs for T3

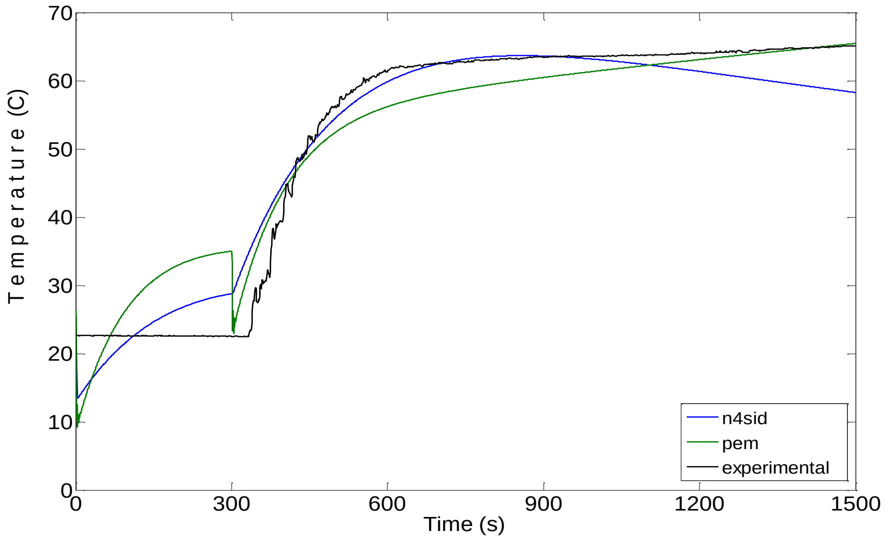

Figure 6. Comparison of experimental and two state space model outputs for T4

Table 2. Model coefficients of pem state space model for T2 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	0.99724	0.00133	0.00475	0.00070
	x2	0.00787	0.43009	0.40678	1.63910
	x3	-0.00100	-0.69332	-0.19409	0.65565
	x4	0.00177	0.14288	-0.51469	0.25565
B		**u1**	**u2**	**u3**	**u4**
	x1	3.8862E-06	0.0001	0.0001	0.0001
	x2	-0.00426	0.0001	0.0001	0.0001
	x3	-0.00227	0.0001	0.0001	0.0001
	x4	0.00149	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	516.5700	-0.5860	1.6160	0.6350
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	-9.660E-05	0.0001	0.0001	0.0001
	x2	-1.42900	0.0001	0.0001	0.0001
	x3	0.40856	0.0001	0.0001	0.0001
	x4	-0.67451	0.0001	0.0001	0.0001

Table 3. Model coefficients of n4sid state space model for T2 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	0.99896	-0.00218	-0.00099	-0.00117
	x2	0.00446	0.99387	-0.19518	-0.29337
	x3	0.00108	-0.01133	-0.80243	0.22734
	x4	-0.00158	-0.00873	-0.16894	0.84245
B		**u1**	**u2**	**u3**	**u4**
	x1	4.5081E-08	0.0001	0.0001	0.0001
	x2	7.7716E-06	0.0001	0.0001	0.0001
	x3	-6.211E-05	0.0001	0.0001	0.0001
	x4	3.518E-06	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	505.9100	0.11422	0.47811	0.18936
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	0.00166	0.0001	0.0001	0.0001
	x2	-0.21351	0.0001	0.0001	0.0001
	x3	-0.02734	0.0001	0.0001	0.0001
	x4	0.02605	0.0001	0.0001	0.0001

Table 4. Model coefficients of pem state space model for T3 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	0.99743	-0.00013	-0.00598	0.01737
	x2	0.01679	1.01520	0.29825	0.04409
	x3	-0.00887	-0.01331	0,28833	0.81942
	x4	0.00122	-0.04141	0.21121	-0.11809
B		**u1**	**u2**	**u3**	**u4**
	x1	3.1153E-06	0.0001	0.0001	0.0001
	x2	0.00022	0.0001	0.0001	0.0001
	x3	-0.00027	0.0001	0.0001	0.0001
	x4	-0.00033	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	588.1800	-0.63085	-0.23477	0.36390
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	0.00163	0.0001	0.0001	0.0001
	x2	-0.06792	0.0001	0.0001	0.0001
	x3	0.06592	0.0001	0.0001	0.0001
	x4	-0.02626	0.0001	0.0001	0.0001

Table 5. Model coefficients of n4sid state space model for T3 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	0.99994	-0.00320	0.00687	0.00520
	x2	-0.00051	0.93294	0.60310	-0.10623
	x3	-0.00172	-0.23967	0.74316	-0.89517
	x4	0.00073	-0.01772	-0.13715	-0.05299
B		**u1**	**u2**	**u3**	**u4**
	x1	4.9144E-06	0.0001	0.0001	0.0001
	x2	0.00013	0.0001	0.0001	0.0001
	x3	-0.00056	0.0001	0.0001	0.0001
	x4	-0.00056	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	521.9900	0.18446	-0.19836	0.43443
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	0.00302	0.0001	0.0001	0.0001
	x2	0.00462	0.0001	0.0001	0.0001
	x3	0.04857	0.0001	0.0001	0.0001
	x4	0.02094	0.0001	0.0001	0.0001

Table 6. Model coefficients of pem state space model for T4 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	0.99755	-0.00277	2.348E-05	0.00019
	x2	0.00403	0.99699	-0.13322	0.03583
	x3	-0.00010	-0.00612	-1.09900	0.26944
	x4	0.00074	0.00097	-0.22936	-0.38446
B		**u1**	**u2**	**u3**	**u4**
	x1	-8.2988E-07	0.0001	0.0001	0.0001
	x2	9.1441E-05	0.0001	0.0001	0.0001
	x3	0.00567	0.0001	0.0001	0.0001
	x4	0.01837	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	600.8100	0.52279	0.18936	-0.02494
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	0.00092	0.0001	0.0001	0.0001
	x2	-0.03877	0.0001	0.0001	0.0001
	x3	-0.16703	0.0001	0.0001	0.0001
	x4	-0.00782	0.0001	0.0001	0.0001

Table 7. Model coefficients of n4sid state space model for T4 temperatures

A		**x1**	**x2**	**x3**	**x4**
	x1	1.00010	-0.00207	0.00171	0.00136
	x2	0.00219	0.99478	0.62597	0.60797
	x3	-0.00091	-0.00847	1.14090	0.79804
	x4	-0.00256	-0.00156	0.19247	-1.15650
B		**u1**	**u2**	**u3**	**u4**
	x1	1.9838E-05	0.0001	0.0001	0.0001
	x2	0.00063	0.0001	0.0001	0.0001
	x3	0.00097	0.0001	0.0001	0.0001
	x4	-0.00277	0.0001	0.0001	0.0001
C		**x1**	**x2**	**x3**	**x4**
	y1	537.1600	0.43459	-0.62629	-0.41342
	y2,3,4	0	0	0	0
D		**u1**	**u2**	**u3**	**u4**
	y1,2,3,4	0	0	0	0
K		**y1**	**y2**	**y3**	**y4**
	x1	0.00237	0.0001	0.0001	0.0001
	x2	-0.87289	0.0001	0.0001	0.0001
	x3	-0.45410	0.0001	0.0001	0.0001
	x4	0.52087	0.0001	0.0001	0.0001

As can be observed from the model coefficients shown in the tables (Table 2, 3, 4, 5, 6 and 7) above, while some of the coefficients were positive, others were negative and some of coefficients were constant for both the two state space models. The sign changes in the coefficients of the wireless control system could be attributed to the complex nature of the this process. Apart from that, between the discrete models (developed with ***pem*** and ***n4sid*** MATLAB commands), some coefficients of the ***pem*** state space models were found to be close to each other than to that of the ***n4sid*** model. This was the main reason why the dynamic behaviors of the ***pem*** and that of ***n4sid*** state space models were discovered to be similar in the simulation studies.

2) State Space Simulation Studies

In order to have ideas about the dynamics of the developed models, the two state space models were simulated with the aid of MATLAB by applying a step effect to each of them and their dynamic responses were recorded. The obtained dynamic responses for the ***pem*** and ***n4sid*** models are as shown in Figures 7, 8 and 9 for temperatures T2, T3, and T4, respectively. From Figure 7, 8 and 9 for temperature T2, T3 and T4 ***n4sid*** models step response results were stable because they were able to the steady state succesfully. ***n4sid*** model simulation results from Figure 7, 8 and 9 for temperature T2, T3 and T4 were stable because they were able to the steady state rapidly while ***pem*** simulation results were able to the steady state slowly and in Figure 9 ***pem*** model result have big oscillations. Based on the simulation results, ***n4sid*** models were discovered to be better than ***pem*** models due to fastest rise time and fastest response time than ***pem*** models in getting to the steady-state and without any oscillations for this wireless control system.

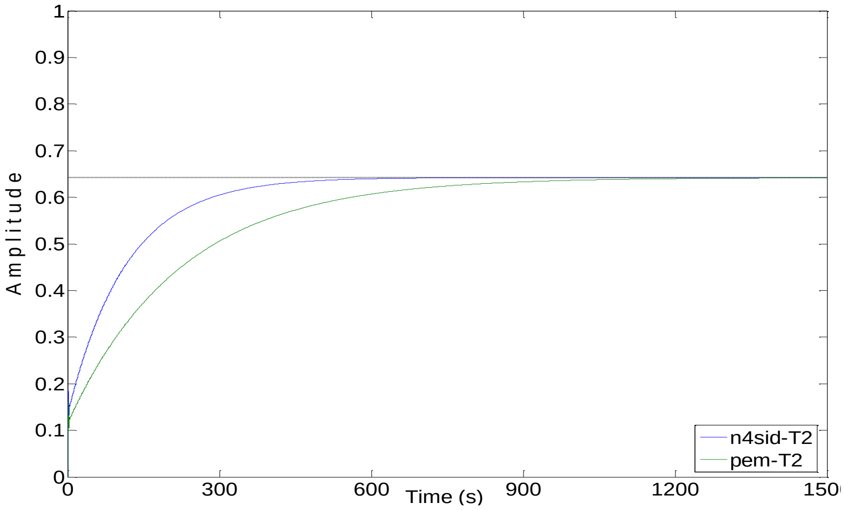

Figure 7. Comparison of the step responses of pem and n4sid models for T2 temperature

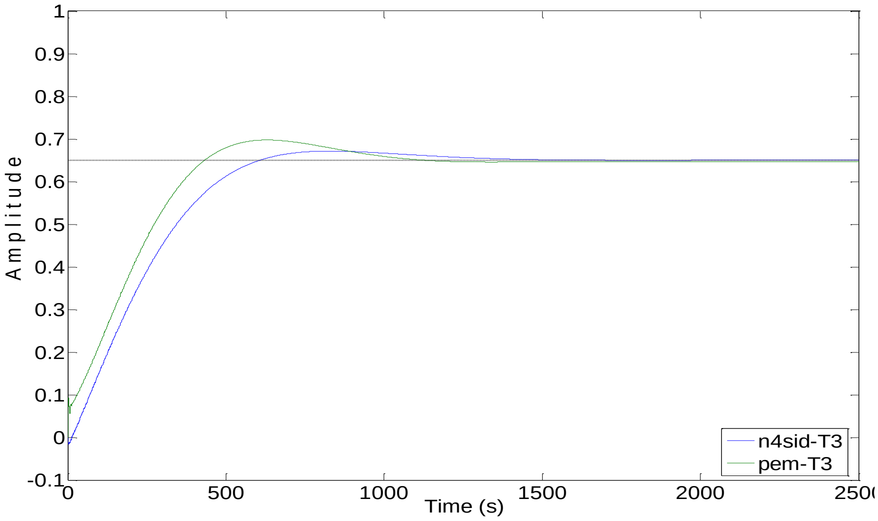

Figure 8. Comparison of the step responses of pem and n4sid models for T3 temperature

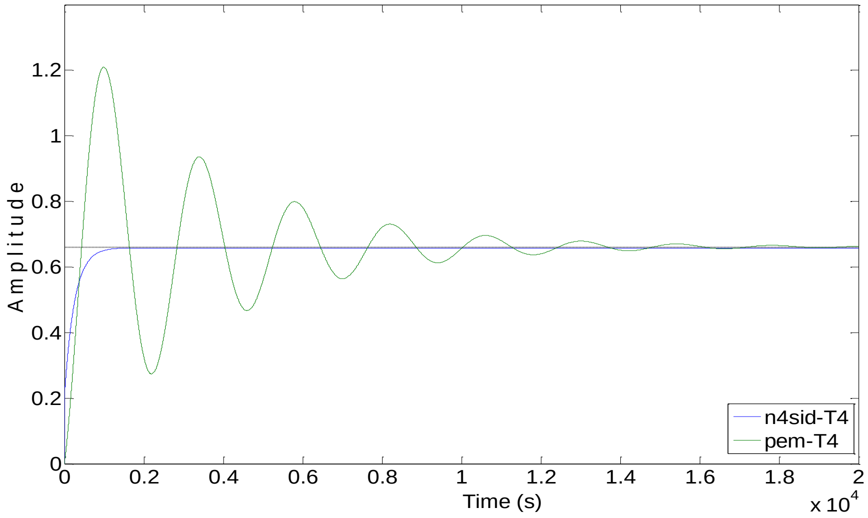

Figure 9. Comparison of the step responses of pem and n4sid models for T4 temperature

IV. CONCLUSION

In this study the development of two state space (***pem*** and ***n4sid***) models for a process simulator has been carried out. Wireless temperature experiments were achieved by using MATLAB/Simulink program and wireless data transfer during the experiments were carried out using radio waves at a frequency of 2.4 GHz. The wireless data used for the models development were generated using a unit step change between % 10-80 values on the heater capacity of the process simulator. The comparisons between the wireless experimental and the simulated values of the temperatures (T2-T3-T4) of the developed ***pem*** and ***n4sid*** models for the process simulator have shown that the ***n4sid*** models can be used to represent the behavior of the this wireless control system. According to the calculated fit values of the ***n4sid*** model decreased while fit values of the ***pem*** model increased from the T2 to T4. The highest and the lowest fit values are calculated for T2 with ***n4sid*** and ***pem*** model, respectively. Based on the simulation results, ***n4sid*** models were discovered to be better than ***pem*** models due to fastest rise time and fastest response time than ***pem*** models in getting to the steady-state and without any oscillations for this wireless control system.

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