Influence of Desynchronization of Clocks on the Data Congruence of a Real Time Control System

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Abstract. *This paper studies the influence of desynchronization of clocks on the data congruence of a real time control system. In this study two independent computers were chosen, where each computer has its own clock but they could work synchronously. One computer clock was chosen as the reference. This application has two independent control loops where the dynamic system is a DC motor and the control law is calculated by a PID controller, for each loop. The clocks were modeled by two-state variables, phase and frequency, to study the effects of the desynchronization between the clocks in the schedulers of tasks of the computers. To solve the desynchronization problem, this application used the Kalman filter technique to estimate and synchronize the clocks of the computers. This study shows that the desynchronization of clocks degrades the similarity of the responses of the system. The similarity of the systems was improved by the Kalman filter estimation method. All of these results were done by simulations with the help of the TrueTime toolbox to the Matlab/Simulink environmen).*

Keywords*: Clock Synchronization, Real Time, Data Congruence, Kalman Filter, Control System.*

1. INTRODUCTION

A large tendency in real time applications is to integrate the communication, computation and control in different levels of operation. The systems are becoming more complex or highly integrated, distributed control systems, with a large number of sensors and actuators, and the distribution of control tasks among several processors. The space station, artificial satellites, aircrafts, automobiles, are examples where these integrations are present under the form of distributed architectures. Consequently, there is a lot of concern about the reliability of the computation and communication systems used in control systems of these applications.

The distributed architecture allows us the decomposition of the system into subsystems, hoping that the characteristics of a subsystem should not be altered when it forms part of a larger system. In real time systems, the predictability is required in the logical domain and in the temporal domain.

The temporal requirements of real time systems are very strict, and so, this creates the need to work with clocks of high precision and synchronized among them. Most of the modern digital communication systems transmit data with the use of clocks. With that, the distributed architecture of our interest possesses a clock in each node. The inclusion of a clock in each node, can bring a lot of benefits, but can also bring some problems for the system, mainly when the clocks are desynchronized.

The desynchronization of clocks causes damages to the systems when the system has a distributed operation and also when the system has a parallel operation. In our case we have two control systems working together in parallel. Their clocks need the synchronization among them, or the response of system does not have data congruence.

In this study two independent computers were chosen, where each computer has its own clock but they need to work synchronously. One computer clock was chosen as the reference. This application has two independent control loops where the dynamic system is a DC motor and the control law is calculated by a PID controller, for each loop. The clocks were modeled by two-state variables, phase and frequency, to study the effects of the desynchronization between the clocks in the schedulers of tasks of the computers. To solve the desynchronization problem, this application uses the Kalman filter technique to estimate and synchronize the clocks of the computers. This study shows that the desynchronization of clocks degrades the similarity of the responses of the system; and that the similarity of the systems was improved by the Kalman filter estimation method.

The Kalman filter is an optimum linear estimator that will provide the best possible prediction under the linear circumstances. We used the True Time MatLab Toolbox to help acquiring data of time in the real-time computer system. The True Time is a simulator based on the Matlab/Simulink for real-time control systems, with and without a communication network. The computer of True Time works with a virtual time and utilizing the time of Simulink as reference. We have chosen the two state model which is the simplest one to represent the physical clock, based on Varnum et al. [1]. The states are the phase and frequency and we used the Kalman filter to estimate the difference data between a local clock and a reference clock. The reference clock is assumed perfect and the local clock is assumed perturbed.

This paper studies the influence of desynchronization of clocks on the data congruence of a real time control system and we are proposing an internal synchronization based on the Kalman Filter technique, where the virtual time of the real time computer of True Time is synchronized with the time of the reference, utilizing the True Time toolbox, to estimate the states of the clock. In our case the reference clock is the same of the Simulink clock,

2. PROBLEM DESCRIPTION

We chose two independent computers, where each computer has its own clock but they need to work synchronously. One computer clock is chosen as the reference. This application has two independent control loops where the dynamic system is a DC motor and the control law is calculated by PID controller, for each loop. The clocks were modeled by two-state variables, phase and frequency, and study the effects of the desynchronization between the clocks in the schedulers of tasks of the computers. In Figure 1, we can observe our system.

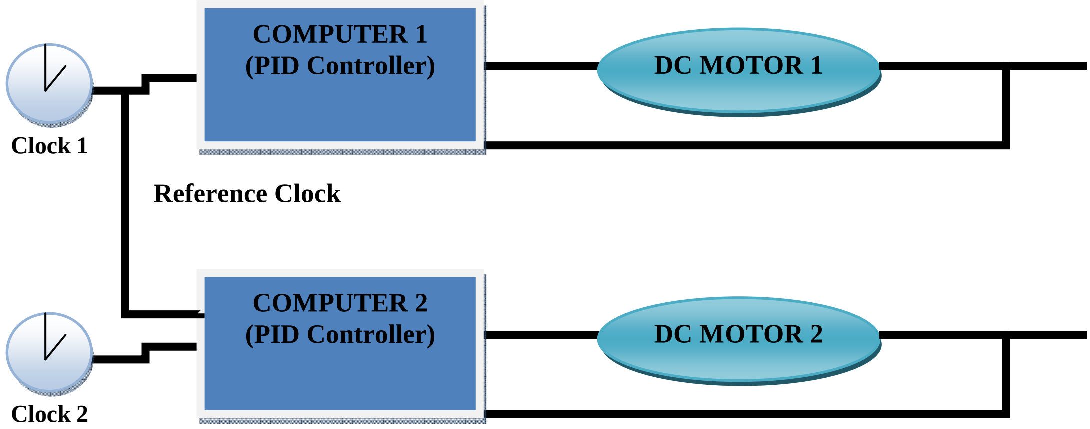

Figure 1. Parallel Control System.

The problem that we found in the Figure 1 is when the clock 1 and clock 2 are desynchronized. This desynchronized problem cause an error in a similarity of response of system. In many systems, for instance in Fly-by-wire system the similarity is very important to the system operate correctly and non-cause a catastrophe. The dissimilarity, caused by the desynchronization, increases a stress in the mechanical controls of the aircraft that can cause damages in the aircraft. Other systems can need the similarity for its time of answer, as in opening of panels in artificial satellites and other operations. For that we selected a general case, where we have a control PID with a motor DC for us to use as starting point to investigate the effects that the imperfections of the clock cause in the similarity of data of systems of real time.

In the sequence, we described how we uses the Kalman Filter technique to synchronize the clocks and reduce the dissimilarity in the response time.

2.1 CLOCK MODEL

The model to represent the physical clock is the simplest one, and the clock variables are phase and frequency, based on Varnum et al. The phase is described as the time difference between the local clock and the reference clock, commonly called offset error. The offset denotes the instantaneously time difference between two clocks. The frequency is described as when the local clock starts ticking faster (or slower) than the reference clock, commonly called drift error. The jitter is the fluctuation on the measurement of the clock. In Figure 2 we can observe the offset error and the drift error in the physical clock.

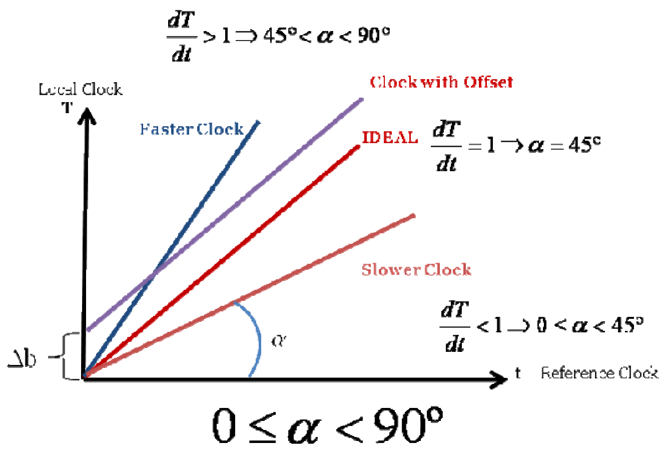

Figure 2. Clock Model.

In Equation 1, we have an equation of states of the physical clock, where T represents an offset and D represents a drift and a w1 and w2 are the associated white Gaussian process noise.

$$\begin{bmatrix} \dot{T} \\ \dot{D} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} T \\ D \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \quad (1)$$

Kopetz et al. described the offset and a drift, respectively, given by:

$$T_k = t_k^2 - t_k^1 \quad (2)$$

$$D_k = \frac{t_k^2 - t_{k-1}^2}{t_k^1 - t_{k-1}^1} - 1 \quad (3)$$

Where t_k^2 is the time at time tk in the local clock and the t_k^1 is the time at time tk in the reference clock. More details about the model of the clock are detailed in the sequence.

2.2 KALMAN FILTER DESIGN

The Kalman Filter is a set of mathematical equations that provides an optimal computational recursive linear solution for the problem of linear state estimation. In this paper, linear and continuous dynamical model are considered for the clocks; and the measurements are assumed discrete in time.

The measurements model at time t_k is given by:

$$y_k = H_k x_k + v_k \quad (4)$$

With:

$$v = N(0, R_k(t)) \quad (5)$$

Where yk is the m-measurements vector, Hk is the mxn observation matrix, xk is the n-state vector of the system, vk is the m-white Gaussian measurement noise and Rk is the mxm observation noise covariance matrix, all terms at time tk.

The proposed model is given by:

$$x_k = \begin{bmatrix} T_k \\ D_k \end{bmatrix} \quad (6)$$

$$H_k = \begin{bmatrix} 1 & \Delta t \end{bmatrix} \quad (7)$$

Therefore the equation (4) is:

$$y_k = \begin{bmatrix} 1 & \Delta t \end{bmatrix} \begin{bmatrix} T_k \\ D_k \end{bmatrix} + v_k \tag{8}$$

where Δt is elapsed time since epoch.
The dynamic model for the state is defined as:

$$\dot{x} = Ax + Gw \tag{9}$$

With:

$$w = N(0, Q(t)) \tag{10}$$

Where the x is the time variant continuous state, A is the nxn matrix, G is the nxm process noise transformation matrix, w is the white Gaussian process noise and Q is the nxn process noise covariance matrix.
The time update equations of the Kalman filter are summarized as:

$$\dot{x} = A\bar{x} \tag{11}$$

$$\dot{\bar{P}} = A\bar{P} + \bar{P}A + GQG^t \tag{12}$$

Where P is the covariance matrix and the initial conditions are coming from the measurement update cycle of the Kalman filter:

$$\bar{x}_k = \hat{x}_k \tag{13}$$

$$\bar{P}_k = \hat{P}_k \tag{14}$$

The equation (12) is referred as the matrix Riccati equation.
The transition matrix of the clock model in (1) is given by:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{15}$$

$$\emptyset_{k+1,k} = e^{A\Delta t} \cong I + A\Delta t + \frac{1}{2!}A^2\Delta t^2 + \cdots \frac{1}{n!}A^n\Delta t^n \tag{16}$$

$$\emptyset_{k+1,k} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & t_k - t_{k-1} \\ 0 & 1 \end{bmatrix} \tag{17}$$

The solution of (1) describes the evolution of the modeled states with time. The value of the states at any time, tk is:

$$\begin{bmatrix} T_k \\ D_k \end{bmatrix} = \emptyset_{k+1,k} \begin{bmatrix} T_{k-1} \\ D_{k-1} \end{bmatrix} \tag{18}$$

The solution of the non-deterministic part of the clock model is the solution of the matrix Riccati equation in (12). For this paper:

$$\bar{P}_k = \emptyset_{k+1,k}\hat{P}_{k-1}\emptyset_{k+1,k}^t + \int_k^{k+1} \emptyset_{\tau,k}G(\tau)Q(\tau)G^t(\tau)\emptyset_{\tau,k}d\tau \tag{19}$$

The equation (19) presents the matrix G and matrix Q constant with time. Therefore the solution of the equation (19) for all time intervals is:

$$\bar{P}_k = \emptyset_{k+1,k}\hat{P}_{k-1}\emptyset_{k+1,k}^t + \begin{bmatrix} 1 & \frac{\Delta t}{2} \\ 0 & 1 \end{bmatrix} Q \begin{bmatrix} 1 & \frac{\Delta t}{2} \\ 0 & 1 \end{bmatrix} \Delta t \tag{20}$$

Where Q is given by:

$$Q = \begin{bmatrix} \sigma^2 & 0 \\ 0 & \sigma^2 \end{bmatrix} \quad (21)$$

The covariance matrix, P, of the solution to the random part of the clock model specifies the uncertainty in the clock's output due to the white noise sources incorporated in the model. The matrix Q specifies the amount of process noise to be incorporated for each filter state.

Therefore, the time update of the Kalman filter is given by Equations (18) and (20). Now we will show the measurement-update of the filter in the sequence.

The measurement-update cycle is summarized as:

$$K_k = \overline{P_k} H_k^T (H_k \overline{P_k} H_k^T + R_k)^{-1} \quad (22)$$

$$\hat{x}_k = \bar{x}_k + K_k (y_k - H_k \bar{x}_k) \quad (23)$$

$$\hat{P}_k = (I - K_k H_k) \overline{P}_k \quad (24)$$

Where K_k is the Kalman gain, $\hat{P}_k$ is the updated *nxn* error covariance matrix estimate and $\hat{x}_k$ is the updated state vector estimate.

2.3 COMPUTER SCHEDULER

The computer scheduler is a set of rules that define how the task should be processing with the computer. We know like this tasks interacting with the system. In our study, we interest in hard real time systems whose control tasks need to satisfy the strict timing requirements. In the Figure 3, we can observe one example of the tasks.

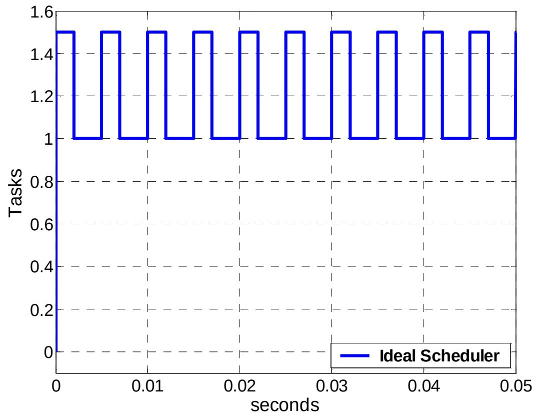

Figure 3. Computer Scheduler.

The scheduler define the properties these tasks, like the period. In the Figure 3, the period of tasks has 5 ms and the computation time has a 2 ms. If the clock has not a present imperfections, the pulse of train has this form. In the sequence, we can observe, when the scheduler is affect by an imperfections of clock and damage a response of time.

3. RESULTS

We show case where the computer presents a clock error and how those errors influence the computer scheduler and consequently the data congruence of the system. Tasks are of periodic and non-periodic nature and in our case we are working with one periodic control task to control the system. But, to synchronize the system, we need adding one more task, where we call the sync task.

The test case analyzed is the general case, when the local clock possesses all errors working together. The errors are the drift case, when the local clock has a drift with respect to a reference clock, the offset case, when the local clock has an offset with respect to a reference clock and the jitter case, when the local clock has a variance on measurements of the clock. The case has as reference the clock of the Computer 1. We consider that the Computer 1 is an ideal case. More details about these cases are described in the sequence.

3.1 IDEAL CASE

In this case we suppose that the clocks are perfect be not presenting errors in both local clock and reference clock operation. The local time is the virtual time given by the clock of the virtual computer 2 of the True Time toolbox. The reference time is the virtual time given by the clock of the virtual computer 1. Utilizing the True Time Toolbox we can observe in Figure 4 the scheduler, in the left, and its timeline, in the right.

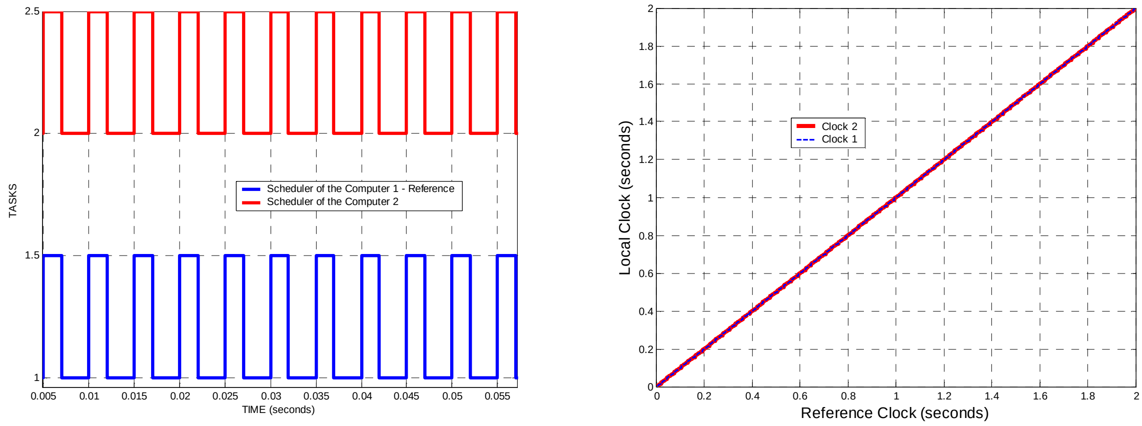

Figure 4. Drift of the Computer Scheduler and Drift Timeline of the Scheduler.

The Ideal case is when the local clock no present errors with respect to a reference clock. We can observe the Figure 4 the scheduler. The blue line is the reference, and the red line is a local scheduler. We observe that the timeline no presents error and the clocks are synchronized. Therefore, the data congruence of the system is not affect as we can observe in the Figure 5.

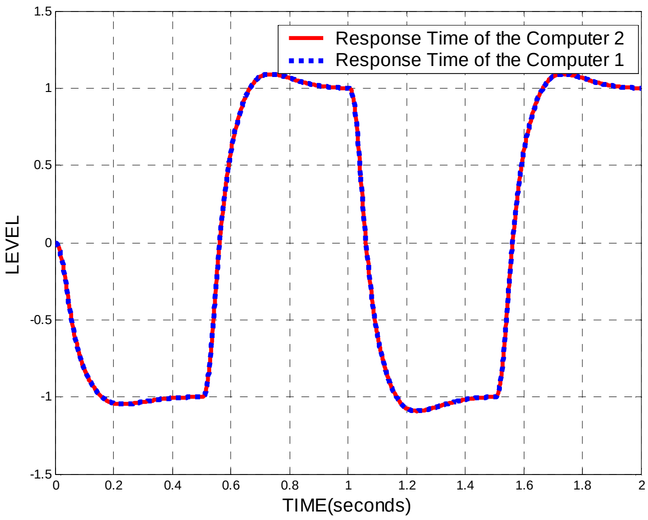

Figure 5. Response Time of the Computers.

We can observe in the Figure 5 two lines. The red line is a line of response time of the Computer 2, and the blue line is a line of the response time of the Computer 1. In this case, when the clocks are perfectly synchronized the data congruence is not affected. The objective is to utilize the Kalman Filter technique to estimate the imperfections of the clock 2 utilizing the clock 1 with your reference, and to go correcting the value of the clock 2.

3.2 GENERAL CASE

In this case the local clock presents all errors working together. These errors are a jitter, offset and drift errors with respect to a reference clock. In our case, the jitter is 40% of a reference task period. The reference task period is 5ms and this means that the fluctuation is between -2 ms and 2 ms in the activated control tasks; the local clock presents an offset error of 0.03 seconds; and the local clock presents 30% of drift, which is the local clock (clock 2) tick 30% faster than the reference clock (clock 1). To synchronize the systems we need add the one more task in the computer 2. This task defines with 7 ms of period with the 1 ms of the computation.

In the Figure 6, we observe the scheduler of the computer 1 in compare of the computer 2. The red line is the scheduler of the computer 2 and the blue line is the scheduler of the computer 1.

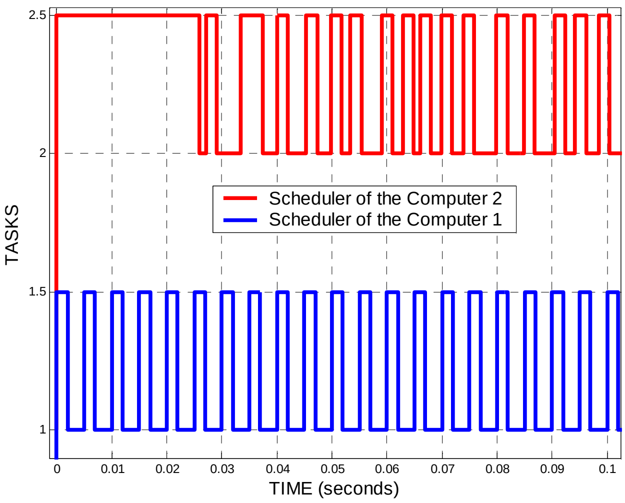

Figure 6. Schedulers of the Computers.

The offset error causes a delay of 30 ms in the whole pulse train. We see that before 0.03 seconds the control tasks are being executed because when the computer starts its operation the computer identify that there are delayed control tasks. On the other hand, the drift and jitter affects the period of tasks. The drift affects 30% relative to the reference scheduler, due to the local clock ticking 30% faster. The jitter causes an uncertainty in the period of tasks, as the jitter presents a fluctuation of 40% compared to the activated control tasks, and it could mean interferences amongst tasks. These accumulated errors cause a drift larger than other cases in the timeline.

Figure 7 depicts the errors behavior. It is seen that the errors of the clock cause an error in the timeline. These errors are the final result having contributions of an offset, drift and jitter, altogether. In the Figure 7, in the right, we can observe the errors of the clock 1 and the clock 2. This error growing with the time and the system need a synchronization to minimize this problem.

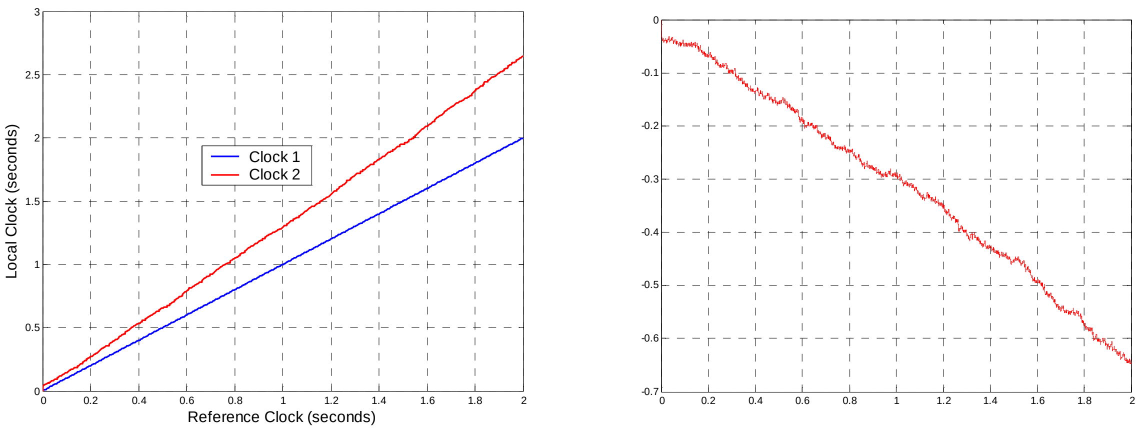

Figure 7. Timeline with errors of clocks and the Errors of the clocks.

In the Figure 8, in the left, we see the response of the system of the Computer 1 and the Computer 2. These responses need the equal, but because of the clock errors in the clock of the computer 2 the responses are different as we see in the Figure 8. In the right, we can see the error in the data congruence of the system. This error is the difference of Response of Computer System 1 and the Response of Computer System 2.

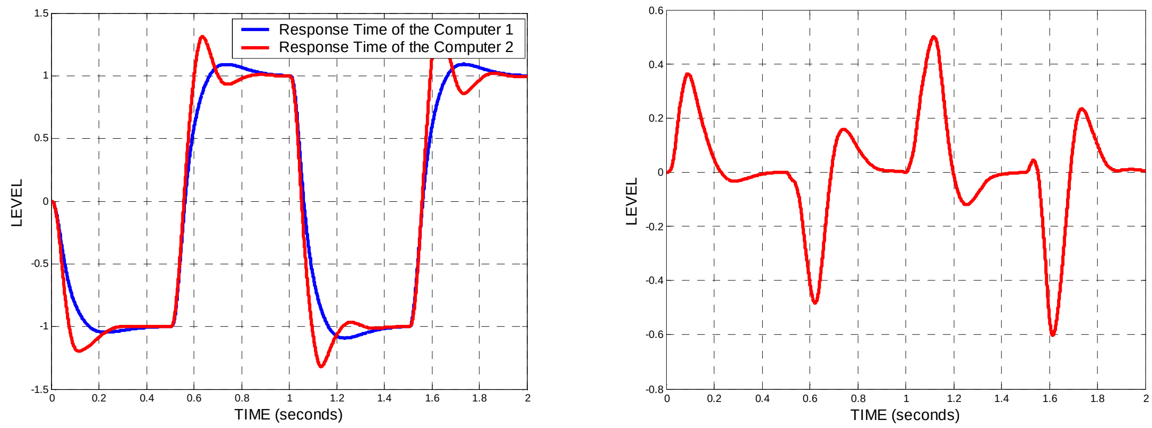

Figure 8. Response Time of the Computers and the errors in the response times.

In this case one proposes to apply the Kalman filter to estimate the states of the local clock, and then to approximate the tick of local clock with the tick of the reference clock reducing the errors caused by bad clock operation due to the jitter error, the drift error and the offset error. Like this, synchronizing the clocks the error reduces in the Figure 7 and Figure 10. We observe the overall Kalman filter performance in Figure 10 and Figure 11.

In the Figure 9, we can observe the new scheduler with the new task in computer 2. This task is the sync task, that has 7 ms of the period. In the red line we have a scheduler of the computer 2 and in the blue line we have scheduler of the computer 1.

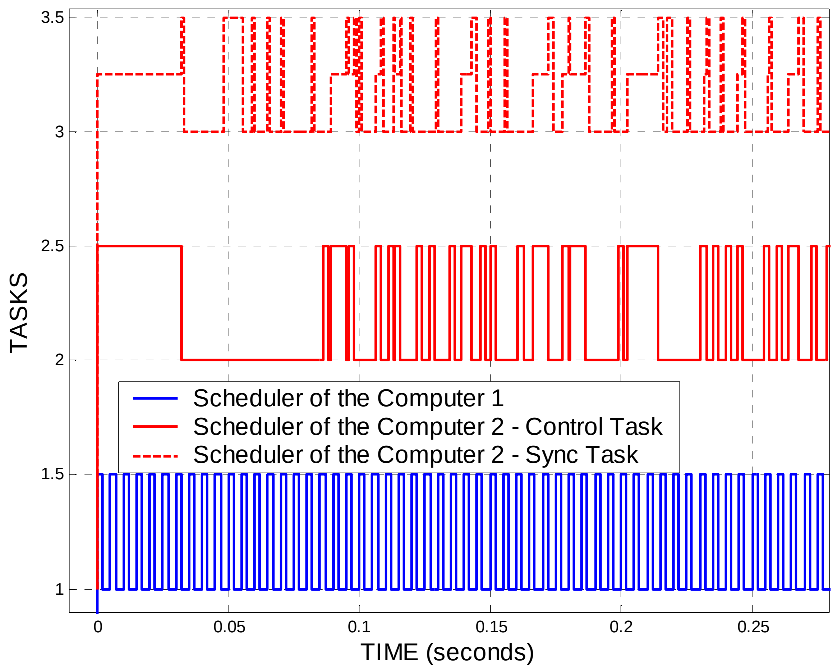

Figure 9. Schedulers Estimated .

In the Figure 10, in the right, we can observe the timeline estimated in compare with the ideal timeline, and in the left, we can see the error of the estimate. We can see that the error in the clocks when we applied the Kalman Filter Technique converge is around 10 ms.

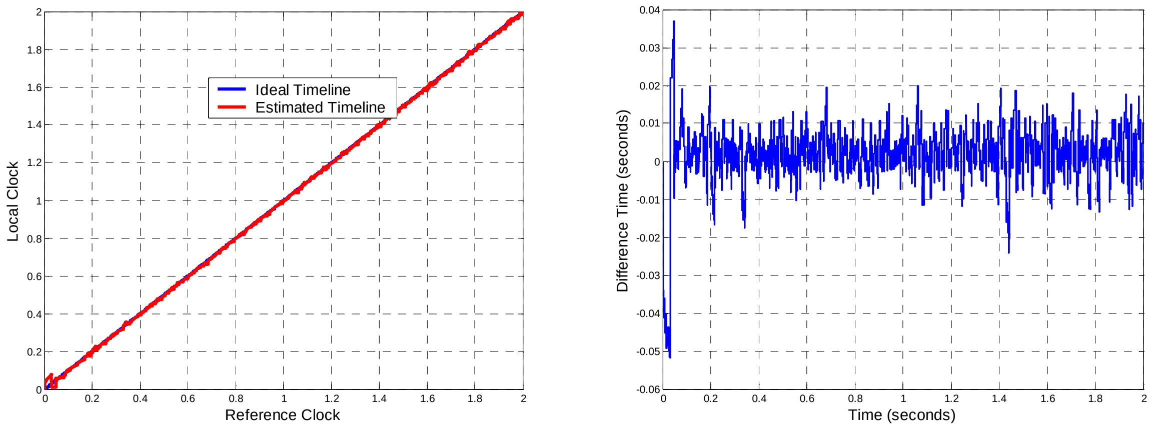

Figure 10. Timeline Estimated and the Error in the Estimate.

We see in the figure 8 the response of the system of the Computer 1 and the Computer 2 when the clocks are desynchronized. When we applied the Kalman Filter Technique to synchronize the system, we see in the Figure 11, in the right, the new response of the system. In the left, we see the error in the data congruence. When we synchronized the system the error reduces in relationship when the clocks are desynchronized.

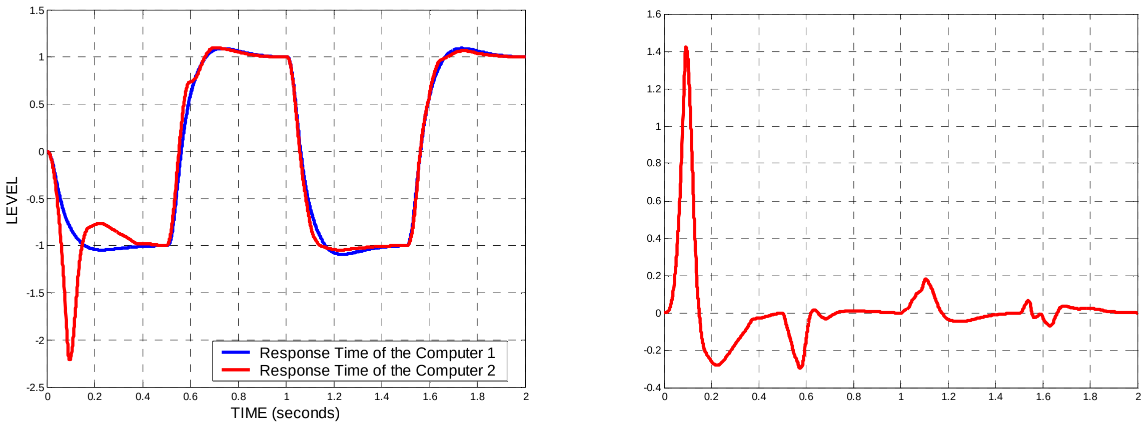

Figure 11. Timeline Estimated and the Error in the Estimate.

The Kalman Filter in this case is efficient to reduce the error in the clocks and in the data congruence. The error in the clocks converge around 10 ms. In the scheduler, we have now two tasks in the computer 2. The sync task is interfered by the control task. The dissimilarity of data of the response system reduces.

4. CONCLUSIONS

In the hard real-time computer systems, where specific timing requirements are present, the notion of time is fundamental to correct timing operation of the system. These possibilities motivated the development of an investigation about the effects of the desynchronization on the data congruence of Real Time control Systems. All of these results shown here were accomplished by computer simulations with the help of TrueTime toolbox within the Matlab/Simulink environment. The simulation considered two virtual computers of True Time with a two virtual clocks called local clock 1 and clock 2; the clock 1 is called reference clock.

We see that the schedulers are perturbed when the local clock operates with errors. The error is a drift when the local clock ticks faster (or slower) than the reference; an offset when the local clock has a time difference with respect to reference; and a jitter when the control tasks have a fluctuation in its activation. This perturbation affected the data congruence of the system.

One approach to synchronize the virtual clocks of the computers using the Kalman filtering technique was presented, with the Kalman filter estimating the states representing the clock.

The simulation results show that when the clocks present errors between them, the scheduler is affected as compared to the reference, which in our case is supposed ideal. When the scheduler is affected the similarity of the data in the response time is affected too. The Kalman filter converges neatly. We can say that the Kalman Filter has good performance to synchronize the system, where the errors converged to 10 ms level. And when we synchronize the clocks the similarity of data in the system reduce.

The Kalman filter should make an optimum estimate that thus would provide the best possible clocks error prediction under the circumstances. The method of synchronization applying Kalman filter would provide the good prediction of the states of clocks.

5. ACKNOWLEDGEMENTS

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