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Design and analysis of control strategies for a cyber physical system

Amjad Gawanmeh[1,2,*], Abdullah Abu Omar[1] and Alain April[3]

[1] *Department of Electrical and Computer Engineering, Khalifa University, Abu Dhabi, 127788, UAE.*
[2] *Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada.*
[3] *Department of Software Engineering, Université du Québec, École de Technologie Supérieure, Canada.*

Cyber Physical Systems (CPS) use emerging computing, communication, and control methods to monitor and control geographically dispersed critical system components to allow a high level of confidence about their operation. Simulation methods are frequently used in testing such critical system components, however, it might not be adequate to show the absence of errors given the complexity of the system components under test. Failure in detecting errors in safety critical systems can lead to a catastrophic situation. In this paper we propose an approach, based on simulation and formal analysis, for the reliability analysis of CPS. We illustrate this approach on a well-known industrial case study, the four tank process, demonstrating several challenging features in the design and implementation of CPS. The contributions of this research include presenting control strategies for distributed CPS and the proposal of a novel approach for reliability analysis of CPS. Experimental results obtained show that the proposed approach is efficiently used in order to test and verify the four tanks process system, where simulation results show the validity of approximation and abstraction of the system, and formal analysis is used to validate that several design requirements were satisfied in the control strategies proposed.

Keywords: Control Strategies, Formal Analysis, Model Checking, Cyber Physical Systems, CPS, Multi-Tank Process

AMS: 14D15, 68Q60, 03B70, 60J20, 93C40, 49J27

1. INTRODUCTION

New paradigms and advances in computing, communications and control have provided and supported a wide range of applications in all aspects of life. In particular, bridging the gap between physical components and cyberspace leading to a growing interest in Cyber Physical Systems (CPS) [17]. CPS aims at the use of recent computing, communication, and control methods to design and operate intelligent and autonomous systems. This requires the use of emerging computing techniques for sensing, processing and analysis of the data. This also allows the resulting information to be used for predicting and acting on this data allowing better communication of resources for interaction, mediation, and interface management, and finally providing advanced control for systems so that they can inter-operate, evolve, and operate in a stable evidence-based environment. CPS has great potential in several industrial domains since it is expected that the complexity of interconnected components and their interactions will continue to increase due to the integration of a growing number of cyber components with physical and industrial systems in the internet of things (IOT).

A collection of several controls, communications, and computing paradigms are used to provide current CPS central host and its operators with a number of services, for example: terminal applications, support for the communications systems, and monitoring and control that are mainly remotely located field data interface devices. Therefore, verifying that CPS actually achieves the desired controls and monitoring objectives is not an easy task, and this for many reasons. First, because of the inherent complexity of interconnected CPS components and systems.

*Corresponding Author: E-mail: amjad.gawanmeh@kustar.ac.ae

Second, because there are many unconstrained behaviors of these systems being monitored. Finally, because of this complexity, there could be many ambiguities about the many interactions between CPS components. This often arise because of the informal description of these systems in their specification. CPS are widely used in power systems control and operations. Power systems require a high level of reliability. They require efficient means to detect any problems in their operation and in the integration between the physical world and the cyber world. Failure of the any component of a power system can result in severe and costly consequences. Monitoring and control of power grids and other similar complex power generation plants is often conducted using SCADA based systems. Even with these solutions we still observe many major power-system blackouts. These can affect millions of people, such as the three major blackouts that took place in 2003, in the USA, and Canada, Italy, Sweden-Denmark, followed by another recent blackout that occurred in Brazil and Paraguay in 2009 and, finally in India in 2012 [10].

This paper presents design and analysis of control strategies for CPS that could be used to improve the situation. It proposes a practical method for modeling and verification of CPS systems process using simulation and formal methods. This research is based on the use of a systematic process that uses mathematical reasoning to verify that design specifications include certain design requirements to improve reliability analysis. This includes the use of simulation as well as formal methods to enhance the validation and verification in allowing the detection of defects and errors during the design and operation of such systems. This approach has already been successfully used for the precise analysis of a variety of complex systems in the past [3]. While simulation method is implemented in this work, we intend to provide formal analysis in future work.

The proposed method is illustrated on the four tank problem, which is a multivariable control process that includes several challenging problems. We first apply linear approximation on the model of the process under analysis, which is a common practice in the design of several control systems. Then we identify a set of design requirement to be met. For instance, stability is one of the fundamental requirement that a control process must satisfy. In order to formally analyze this CPS system, abstractions must be made, which means representing the system at a level that can be comprehended by an analysis tool. For instance, when a model checking technique is used, the system must first be represented as a state based model for this technique to be used. Then a model for the process can be derived, and the set of requirements can be verified against this model. In order to validate the equivalence between the derived model and the real one, simulation is used in order to show that the linearized model behave in similar manner to the original specification.

Few research publications exist on formal analysis of industrial CPS systems. The work in sanwal2013formal presented a formalization of the solutions of second-order homogeneous linear differential equations illustrated on a cyber physical system example. Zhang et. Al proposed a method for test case generation applied to CPS. The authors in [20] proposed a method in order to reduce the infinite set of test parameters in a finite set for testing CPS. Model checking methods were also used for verifying specific CPS aspects such as insecure interactions between all possible behaviors of the given CPS [1] and functional requirements in [4]. A statistical model checker has also been recently proposed to analyze some aspects of CPS [7]. The work in [11] used probabilistic analysis of cyber-physical transportation systems.

On the other hand, interesting works have been done on analysis of distributed systems similar to the case presented here. The authors in [18, 5] presented a distributed estimation problem in relay assisted wireless sensor networks. Its main contribution was weighted rigid graph-based topology optimization scheme used to reduce the redundancy of communication links required between nodes, which in turn results in reducing the energy consumption in the relay assisted WSN. The work in [19] addressed the problem of stability in distributed formation control problem for multi-slave Teleoperating Cyber-Physical Systems (TCPS). The authors showed that the topology optimization can reduce the redundancy of communication links in slave site at the expense of increased convergence time, while the formation controllers guarantee the stability of the CPS. The work in [15] addressed the issue of simulation and analysis of distributed algorithms that are intended for control of CPS like problems. The work in [2] studied the set agreement problem in message passing systems in crash-recovery asynchronous systems. The work presented interesting case that can be useful for design and analysis of control systems in CPSs. The work in [8] addressed the performance evaluation problem in distributed real-time and embedded systems. They presented an Open-source Architecture for Software Instrumentation of Systems (OASIS) framework, that can be used for the analysis of distributed real-time and embedded systems in order to minimize impact on end-to-end response time. The work in [14] presented an Executable Time-Triggered Model (E-TTM) that supports can provide a time domain deterministic modeling framework based on SystemC. The authors used it for early functional, temporal and dependability assessments with illustration on two CPS case studies: simulated fault injection of an odometry safety-critical embedded system, and the design and simulation of a real-time control-system integrated with a SystemC-AMS model of the plant. These methods show the challenges in addressed the problem of designing control algorithms for distributed CPSs. This paper, presents design and analysis of control strategies for CPSs illustrated on the four-tank process. This research result is a first step in creating a novel method that could be used for the reliability analysis of all types of CPS systems.

2. CPS PROPOSED ANALYSIS METHODOLOGY

CPSs are considered complex due to distributive, real time, and their heterogenous characteristics. Therefore, the design and analysis of these systems should undergo different types of analysis in order to provide a high level of assurance, which in turn reduces the presence of defects resulting in errors in their operation. Conducting different types of reliability analysis, on a model representation of the system, is not feasible without transforming the set of equations that describes its operation into a form that can fit into the reliability analysis method used. Consequently, a system mode must be implemented in the simulation language or formal analysis framework in order to be used [13].

Figure 1 illustrates our proposed novel method for reliability analysis of CPS systems, where the behavior of the given system is described using a set of differential equations. The system is designed based on solutions of the given system of equations, which currently can be exact or approximated. In order to conduct formal reliability analysis of such a system, we first apply linear approximation in order to simplify the system behavior. This results in a linear model of the system with a set of system requirement to be satisfied. It shall be noted here that system approximation is not intended to be used for design purposes, but only for the transformation of the system into a model that can be formally analyzed. Concurrently, it will be shown that the approximation of the system will result in minimum errors in two ways: 1) the behavior of the resulting model is similar to the original model, and 2) errors are minimized.

In order to show that the formally analyzed model is equivalent in behavior to the given model, we provide an implementation for the approximated model in C++ language, and then conduct simulation which will show that the behavior of the approximated model is analogous to the behavior of the original model. In addition, formal specifications can be used in order to derive an abstract model for the given system, which is then implemented using the underlying verification tool. A number of formal properties are then derived from the system requirements, these properties will be later verified on the abstract model. For formal analysis, a model checker such as NuSMV [6] can be used. NuSMV has the ability to conduct automatic verification, and the availability of techniques that allow handling big models. In the next section, we demonstrate the proposed approach on a practical case study that was previously implemented in a CPS system. The example chosen contains different characteristics of a complex CPS system and is representative of several challenges in the design, operation, analysis and verification of CPS systems.

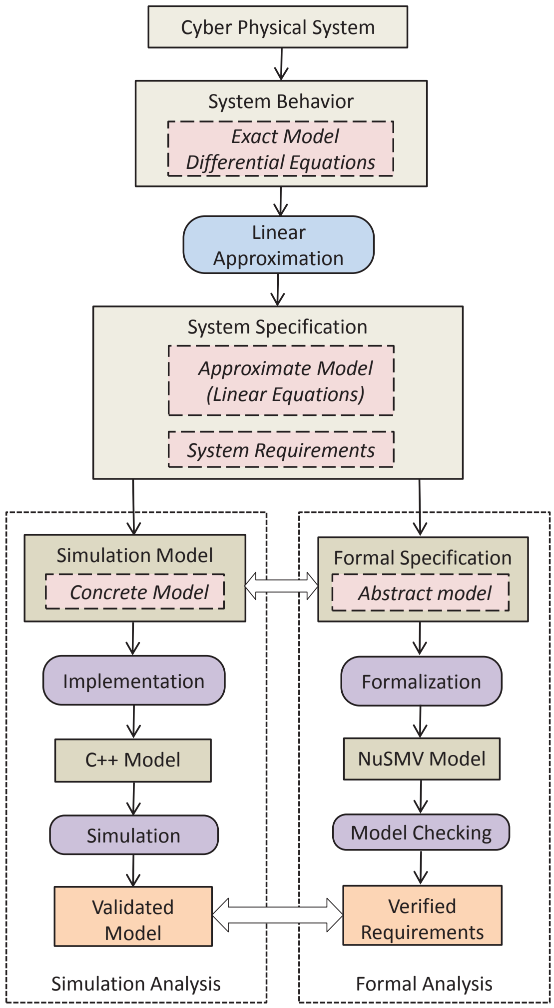

Figure 1 Proposed CPS System Analysis Methodology

3. CASE STUDY: FOUR-TANK CONTROL SYSTEM PROCESS SPECIFICATIONS AND APPROXIMATION

The four tank process was originally proposed in [9] as a multivariable control process, and since then it has been implemented using different control strategies [12]. It was also implemented in the SCADA environment [16]. The four tank process has several interesting characteristics and challenging aspects. Also no similar control process has been formally modeled or analyzed in the literature to date. In this section, we first describe the four tank process, then we apply our proposed methodology where first the model is approximated into a linear system, then simulation is used to validate the approximation, and finally a formal analysis is used to prove several design requirements.

First, we follow the specifications and the mathematical model of the four tank system as it was presented in [12]. Figure 2 below illustrates the four tank process and how it is connected to a data acquisition computer. The process is called the quadruple-tank process and consists of four interconnected water tanks and two pumps. There are two sensors that provide water level for the two main tanks: sensor 1 and sensor 2. As illustrated in Figure 2, Pump01 extracts water from the bottom reservoir and feeds into Tank 1 and Tank 4 via a three-way valve (Valve 1), while Pump 2 feeds Tank 2 and Tank 3 via another three-way valve (Valve 2). The voltages to the two valves are manipulated such that they determine the proportion of the flow that goes into the tanks. The proportion of the output flow into the tanks is determined and controlled by the valves position, as any change in the valve position will alter the quantity (or proportion) of flow into the tanks. The regulation of this process is designed using different types of controllers, however, it has been concluded based on several researches that the splitting of water flow from the pump into all the four tanks causes process interactions and control loop interactions [12].

The process controller implemented in [16] receives two input voltages that represents water levels of lower tanks, Tank 1 and Tank 4, and outputs four voltages that derive the two pumps and the two valves. This process can illustrate several interesting multivariable phenomena. The linearized model of the quadruple-tank process has a multivariable zero, which can be located in either the left or the right half-plane by simply changing a valve. Both the location and the direction of a multivariable zero are important for control design. They have direct physical interpretations for the quadruple-tank process, which make the process suitable to use in control education [9].

The mathematical model for the four-tank process, presented

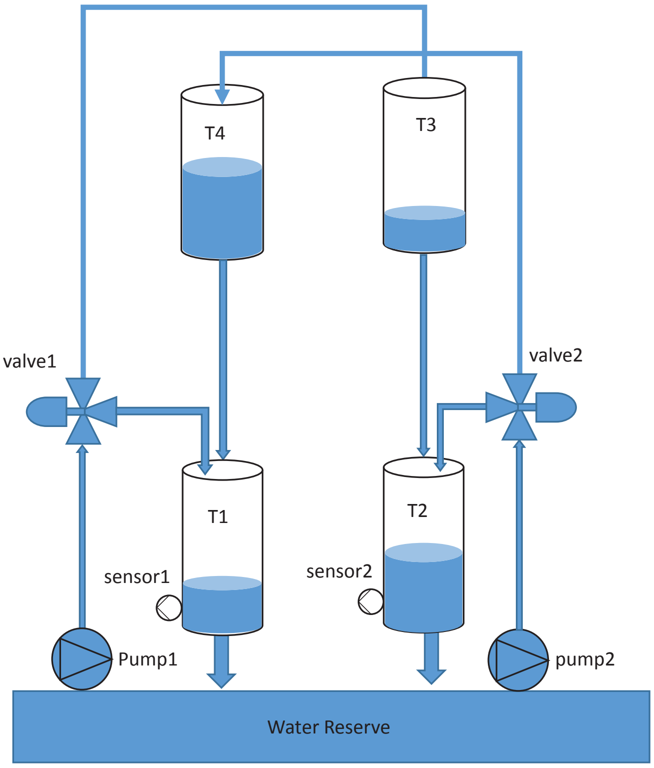

Figure 2 Diagrammatic representation of the four-tank process

in [9], was derived by applying the mass balance and Bernoulli theorem to each tank and can be described using the following non-linear differential equations:

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_4}{A_4}\sqrt{2gh_4} + \frac{\gamma_1 k_1}{A_1}v_1 \quad (1)$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_3}{A_3}\sqrt{2gh_3} + \frac{\gamma_2 k_2}{A_2}v_2 \quad (2)$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}v_2 \quad (3)$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}v_1 \quad (4)$$

In these equations, the parameters used above include A_i for cross-sectional area of Tank i, a_i cross-sectional area of the outlet of the tank, h_i the water level in Tank i, v_i the voltage applied to pump i, $k_i v_i$ the flow from pump i, and g acceleration due to gravity.

Previous proposals used different linearization methods in order to implement controllers for such systems. In order to enhance proficient stability analysis and controller design, it is necessary to linearize the model such a way that approximates the original non-linear model [16], [9], [12]. The non-linear model of equations was linearized around the chosen working point given by the level in the tanks. Consequently, in our analysis, we follow a similar approach, where, an approximate model will be provided around the working point of the tank level with an accepted margin of error. In fact, this approximation will not be used in actual implementation of the controller, but in the development of an equivalent model that will be formally analyzed.

In order to conduct a formal analysis of this process it is necessary to linearize the model in such a way that approximates the original non-linear model (similar to the one adopted in [12], which was successfully used for the design of different controllers for the tank). This can be achieved for the above equations by using simple linear approximations and working around a relatively small Δt around the chosen working point given by the level in the tanks, h_i^t. Let us assume that the term:

$\frac{dT_i}{dt} = \frac{a_i}{A_i}\sqrt{2gh_i^t}$ represents the flow out from $Tanki$, then, for any time t, at which the level of Tank i is h^t, and time interval Δt, we can approximate $\frac{dT_i}{dt}$ as follows:

$\frac{dT_i}{dt} \approx \frac{\Delta T_i}{\Delta t} \approx f_i(h_i)$, where $f(h_i) = \frac{a_i}{A_i}\sqrt{2gh_i}$.

Applying linear approximation on f_i yields to

$\hat{f}_i(h_i^t) = f(h_i^t) + f_i'(h_i^t)(h_i - h_i^t)$, which yields to

$\hat{f}_i(h_i) = \frac{a_i}{A_i}\sqrt{2gh_i^t} + \frac{a_i}{A_i}\sqrt{\frac{g}{2h_i^t}}(h_i - h_i^t)$.

Given this equation, it will be possible to calculate the amount of flow from or into each tank at any time interval during the analysis.

4. CONTROL STRATEGIES FOR FOUR TANK PROCESS

Based on above linearization method, we propose the following control strategy as illustrated in 1 that can be applied to control water level in the tank. The objective is that the main two tanks reach a specific target level of water. Then the system remains in a stable situation, where the control voltages for valves and pumps remain in this steady state. In order to achieve this using traditional control systems, the initial value s for the system parameters must be known. Therefore, any given solution will be stable only under these initial conditions.

The control strategies presented here will reach stable state for any initial values. This will be demonstrated by simulation results. First, using various initial values and then by a formal proof. The algorithm takes current water level in this tank and the other tank, and then it updates the valve and pump voltages in order to reach the given target level. Algorithm 1 is used to control the water level in a given tank based on two variables parameters, and three fixed values: water level in the tank itself, which is acquired through water level sensor in the tank itself and water level in the other tank in the process, which is transmitted to the current tank. In addition, three fixed value parameters are used: water target level in the tanks, valve voltage, and pump voltage. The control strategy for the tank then decides to adjust the voltages for the valve and pump based on the current situation.

In order to use the control strategy defined above to control water level in the four tank system, we present algorithm 2 for the four tanks process system in Figure 2 above. The algorithm is added to algorithm 1 described above. Every tank uses its current paramors and water level, which is received from the other tank, in order to adjust its control variables: valve and pump voltages. The tank will then transmit its current level to the other tank. The second tank performs the same operation. The algorithm iterates until both tanks reach the required water

Algorithm 1 Tank Control Strategy

procedure Tank_Control($T_l, T_d, L_T, v_l,\ \gamma_l, L_T$)
  Input: $T_l, T_d, L_T, v_l,\ \gamma_l$.
  Output: $v_l,\ \gamma_l$.
  • T_l and T_d are obtained from sensors
  • update valves and pumps
   if $T_l < L_T - \delta$ **then**
    if $T_d < L_T - \delta$ **then**
      $v_l = v_l + 3 \times DP$
      $\gamma_l = \gamma_l + 2 \times DV$
    else if $T_d > L_T + \delta$ **then**
      $v_l = v_l + 1 \times DP$
      $\gamma_l = \gamma_l + 2 \times DV$
    else
      $v_l = v_l + 1 \times DP$
      $\gamma_l = \gamma_l + 1 \times DV$
      endif
     endif
   else
   if $T_l > L_T + \delta$ **then**
    if $T_d < L_T - \delta$ **then**
      $v_l = v_l - 1 \times DP$
      $\gamma_l = \gamma_l - 2 \times DV$
    else if $T_d > L_T + \delta$ **then**
      $v_l = v_l - 3 \times DP$
      $\gamma_l = \gamma_l - 2 \times DV$
    else
      $v_l = v_l - 1 \times DP$
      $\gamma_l = \gamma_l - 1 \times DV$
      endif
     endif
   else
   if $T_l > L_T + \delta$ **then**
    if $T_d < L_T - \delta$ **then**
      $v_l = v_l + 1 \times DP$
      $\gamma_l = \gamma_l - 1 \times DV$
    else if $T_d > L_T + \delta$ **then**
      $v_l = v_l - 1 \times DP$
      $\gamma_l = \gamma_l + 1 \times DV$
    else
      $v_l = v_l$
      $\gamma_l = \gamma_l$
      endif
     endif
   endif

end procedure

Algorithm 2 Four Tanks

procedure Four_Tanks_Control
  Input: L_T.
  Output: T_1, T_2.
  REPEAT
  • Tank 1 reads T_1 from sensor.
  • Tank 1 sends T_1 to Tank 2.
  • Tank 2 receives T_1 from Tank 1.
  • Tank 2 reads T_2 from sensor.
  • Tank 2 sends T_2 to Tank 1.
  • Tank 1 receives T_1 from Tank 1.
  • Tank 1 calls $Tank\_Control(T_1, T_2, v_1,\ \gamma_1, L_T)$.
  • $v_1,\ \gamma_1$ are updated.
  • Tank 2 calls $Tank\_Control(T_2, T_1, v_2,\ \gamma_2, L_T)$.
  • $v_2,\ \gamma_2$ are updated.
  UNTIL $(L_T - \delta < T_1 < L_T + \delta)$ and $(L_T - \delta < T_2 < L_T + \delta)$
  END
end procedure

level. The system should reach a stable state after executing a specific number of steps. It can be observed that the proposed controls strategy is independent of the initial values of the system (i.e. including pumps and valves).

5. SIMULATION BASED ANALYSIS

We used simulation parameters for the above system as $A_i = 2800$, $a_i = 16, 16, 13, 13$, pump proportionality constant $k_1 = k_2 = 0.67$, and Gravitational constant $g = 981$. These parameters were proposed and used in [12]. We then run simulations for different types of settings for initial value of water level in the tanks, and also for pumps and valves. In the first scenario, we consider the initial values for pump voltages as $v_1 = 4V, v_2 = 1.5V$, where the pump operates on a voltage of scale between $0 - 5\ V$. We also set the valve initial values to $\gamma_1 = 0.4, and \gamma_2 = 0.4$, then we run the simulation for eight different cases of initial value for the four tanks, where we set the target stable level for tanks 1 and at at 1500 units, with min at 1490 and max at 1510 units. We used an incremental value for the pump of $DP = 0.05V$ and for the valve $DV = 0.01$. Figure s3 and 4 illustrate the water level in the four tanks, where the x-axis represents the simulations steps in time units, and the y-axis represents the water level for the given four tanks. We then repeat the same experiment with different setting for the initial values of the pumps and the valves as follows: $v_1 = 0.6V, v_2 = 4V$, and $\gamma_1 = 0.9$, and $\gamma_2 = 0.2$.

Figures 5 and 6 illustrate the water level in the four tanks for the second simulation of the experiment. It can be concluded, from these simulation results, that the approximation of the system yielded a stable level of water for the two tanks for different simulation scenarios. In addition, simulation results show that the control strategy algorithm presented above guarantee that the system reaches stable state within a reasonable number of steps.

The simulation results presented in Figures 3 and 5 show that the behavior of the resulting model is similar to the original model where the tanks water level reach the steady state target value after around 300 simulation steps. On the other hand, the errors in the resulted water level is calculated using $e = \frac{|R-T|}{T} \times 100\%$, where R is the real value of the tank, T is the target value of the tank. The average error for tank T1 was about 0.092% and for T2 was about 0.32%. This shows that the errors are minimized even while using the linearizing method.

On the other hand, comparing simulation results to the ones in [12] shows that steady state water level is reached in around 200 steps, and with up to 300 steps with very small error. While, the work in [12] shows around 500 steps until steady state, and in other scenarios, only one tank would reach steady state while the other will be deviating from it.

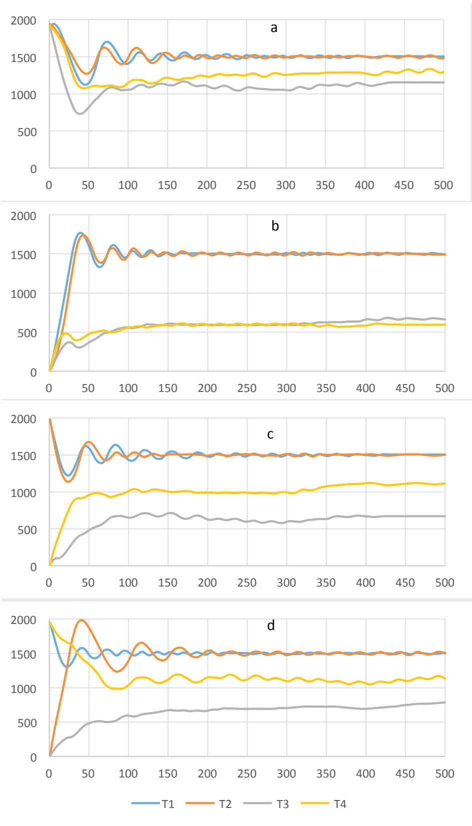

Figure 3 Simulation results for the first scenario (part 1)

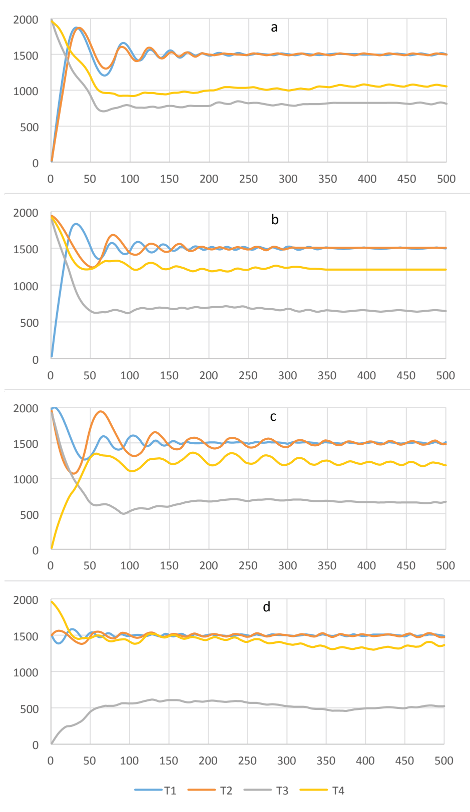

Figure 4 Simulation results for the first scenario (part 2)

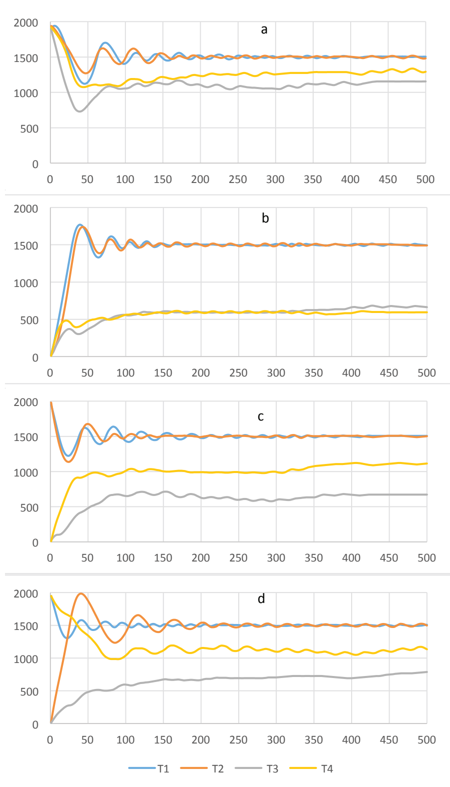

Figure 5 Simulation results for the second scenario (part 1)

6. CONCLUSIONS AND FUTURE WORK

We have presented a novel method of reliable design and analysis approach for CPS systems based on a combination of techniques including linear approximation, abstraction, simulation, and model checking. We used simulation in order to validate the set of control strategies applied on the linearized model that can lead to a stable system under a given set of initial conditions. Next, an abstract model is implemented and verified using model checking technique where the system is proved to be stable and satisfies the design requirement for different sets of initial conditions and for all system states. From this research, we have learned several lessons. First, using a single method for assessing the reliability analysis of industrial CPS systems might not be efficient nor effective in verifying their design requirements. In addition, a single approach alone is often not sufficient to handle the complexity of the system, nor to satisfy the critical design requirement of CPS systems. Second, an appropriate combination of different techniques, such as simulation and formal methods, can significantly improve the reliability analysis of industrial CPS systems. Finally, in order to be able to use such approach, approximation and abstraction techniques must be used. However, system specifications and requirements must still be valid in the approximated design. Hence, it must be proven beforehand that the initial design requirement is still valid in the abstract one.

As future work, we intent to extend this first research result in different directions. First, we intend to use formal analysis in order to demonstrate that the controls strategy presented above

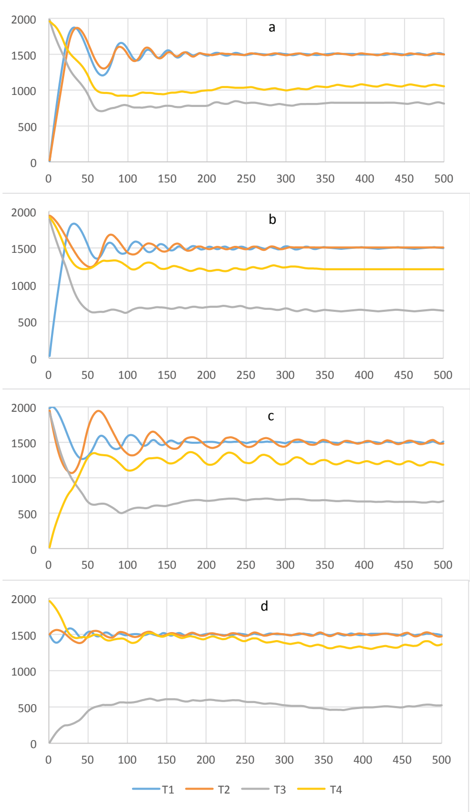

Figure 6 Simulation results for the second scenario (part 2)

are stable for any initial state value. In addition, it will be interesting to consider a more complex scenario that encompasses a larger number of interconnected processes. Such system could also represent a realistic power distribution SCADA system for example. In addition, we intend to consider a collection of distributed process in CPS and conduct formal analysis on such a system. Several new challenges could emerge in such a system, including, the possibility of errors or delays in the feedback from the many distributed processes. As well, in these situations, new challenge arises for developing proper control strategies for distributed processes and manage the increased complexity.

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