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Reliability modeling and evaluation of cyber-physical system (CPS) considering communication failures☆

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Abstract

In this paper, a new evaluation method of reliability and security in cyber-physical system (CPS) considering communication failures is proposed based on instantaneous availability (IA) model and its fluctuation analysis. In this new method, IA model of CPS is established using the *Markov* process principle, and three types of system states, namely, working state, repairing state and delay-repairing state, are discussed from the perspective of reliability and security. On the basis of the locking error, the numerical solution of the model is solved by the fourth order *Runge–Kutta* method, and the instantaneous availability of the CPS is proved to be fluctuating. Finally, the impact of different parameters on the instantaneous availability of fluctuations and the ways to suppress fluctuations and improve the CPS reliability are obtained by analyzing the instantaneous availability of different parameters.

1. Introduction

As the critical technologies for the development of the information industry in the past decades, computing, communication and control technologies have promoted significant change in our everyday life [1]. However, there is still a lack of effective interaction and

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cooperation between human beings and machines. and cyber-physical system (CPS) is coined under this urgent demand, whose nature is a unified complex system framework that exploits multi-scale dynamic and ubiquitous interconnection technologies to achieve the coordination and control of mass, energy, and information [2], and to promote the further integration of industrialization and informatization.

In recent years, the CPS as a leader in new round of revolution of technology and lifestyle, which is an integration of computing, communication, control technologies and physical processes, plays an extremely important role in smart power grid [3,4], intelligent manufacturing [5,6], healthcare system [7–9], and other critical infrastructure application domains. More specifically, the key characteristic of CPS is integration [10], which not only includes the integration of cyber space and physical space, but also includes the integration of communication, control, and other traditional technologies with distributed computing [11], deep learning [12,13], and other new technologies, as well as the integration of scheduling methods, such as the combination of expert knowledge decision and artificial intelligence decision [14] in medical CPS. Consequently, the CPS is a typical dynamic complex system whose cyber elements and physical elements have tight interactions. When the system is to be random or malicious attacks, the failure will spread in accordance with the predetermined system rules and the coupling of the elements, resulting in the large-scale cascading failures and even the breakdown of the entire system [15,16]. The security and reliability of CPS cannot be neglected because of its vulnerability and application domains involving national security and social stability, such as energy, transportation, aeronautics and astronautics [17]. The reliability evaluation technology of CPS based on system engineering theory, control theory and risk theory is of great significance for improving system security and defense against attacks from adversaries.

The communication system is a key component which connects cyber system and physical system in CPS by exchange of information and data [18], realizing real-time analysis and accurate execution of the cyber system on the physical system [19]. With the wide application of CPS in system of systems (SoS) level, the cyber system is usually far away from the physical system and remote monitoring and control is realized through the communication system. The quality of transmission of information and data in CPS is completely dependent on the reliability of the communication system [20,21]. So, the communication system is the vulnerability of the entire system and attack target of adversaries. By attacking the communication system, the attacker can intercept the user's personal information, or destroy the cyber system or even the physical system by injecting false or malicious information. For example, adversary invaded the power grid monitoring and control system (cyber system) through communication system, remotely shut down the physical power generation system, and caused large-scale blackout accident in Ukraine in 2015 [22].

The functional elements of CPS can enter or leave the system at any time according to certain rules and interface requirements, which are completely different from traditional reliability research objects. The time-varying quantity functional elements, the dynamic system configuration, and the fuzzy system boundaries pose great challenges for the study of CPS reliability [23,24]. In addition, there are many factors affecting reliability of communication system in CPS because of its complex operating environment and longer transmission distance, which need to be analyzed by comprehensive indexes. Instantaneous availability (IA) represents the probability that the system can be available at any time during the use of the system, which is an important reliability indicator to characterize the dynamic and complex

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process of the system [25–28]. The reliability modeling and evaluation in this paper is based on the instantaneous availability of the CPS.

In this paper, instead of focusing on the details of CPS, we aim at the vulnerabilities of CPS in communication system and establish a reliability model of the CPS considering communication system failure or attack, which simplify the research process of the reliability characteristics and mechanism of the CPS. The remaining part of the organization is as follows: Section 2 is preliminary of instantaneous availability in complex system. We establish the reliability model of CPS based on *Markov* process theory and obtain numerical solution in Section 3. Fluctuation analysis and suppression method of instantaneous availability in CPS are given in Section 4.

Notation: Let $P(X)$ denote to *Probability* of event X occurred. Let $o(\Delta t)$ denote high order infinitesimals of Δt. Let F denote to the space of all state. We suppose F to be finite, with $F = \{1, \ldots, N\}$, where $N \in Z^+$. Let E to the working state space. We suppose E to be finite, with $E = \{1, \ldots, S\}$, where $S \in Z^+, S \leq N$. Let $P_{ij}(t)$ denote to the probability that the system transfer from the state i to the state j at the time of t. Let $P_i(t)$ denote to the probability that the system stays in state i at the time of t. Let $v = (v_1, \ldots, v_i)^T$ denote to the vector and define $v'(t) = (v_1'(t), \ldots, v_i'(t))^T$, where $v_i'(t)$ represents the derivative and v^T represents transpose of a vector.

2. Preliminary

In this section, we will introduce some basic knowledge of reliability math, prepare for the establishment of a reliability evaluation model of CPS afterwards.

First, in order to analyze the fluctuation, we need to introduce the concept of fluctuation as following:

Definition 1. [27] A continuous function $A(t)$ has fluctuation if there exist three points t_0, t_1, t_2 in domain and $t_0 < t_1 < t_2$, which makes the inequality $(A(t_0) - A(t_1))(A(t_1) - A(t_2)) < 0$ hold. Taking $\sin(x)$ for an example, it is clear for us that there exist three points satisfying Definition 1 in Fig. 1.

Then, in order to establish the *Markov* model, we introduced the following three definitions:

Definition 2. [29] A random variable $(r.v)$ X possesses the memoryless property if $P\{X > 0\} = 1$, (i.e. X is a positive $r.v$) and for every $x \geq 0$ and $t \geq 0$,

$$P\{X > x + t\} = P\{X > x\}P\{X > t\}. \tag{1}$$

Definition 3. [30] Define $N(t)$ as a $r.v$ represented the number of breakdowns before time t. $\{N(t),\ t \geq 0\}$ is said to be a *Counting Process*, if it satisfies four properties:

(1) $N(t) \geq 0$, (2) $N(t) - N(s) \geq 0, \forall 0 < s < t$.

Definition 4. [31] *A renewal process* is an arrival process for which the sequence of inter-arrival times is a sequence of independent and identically distributed (*i.i.d.*) *r.vs*.

Definition 5. [32] *A Poisson process* is a *renewal process* in which the inter-arrival intervals have an exponential distribution function; i.e., for some real $\lambda > 0$, each X_i has the density $f_{X_i}(x) = \lambda \exp(-\lambda x)$ *for* $x \geq 0$.

With the above definition, we can introduce the following two lemmas:

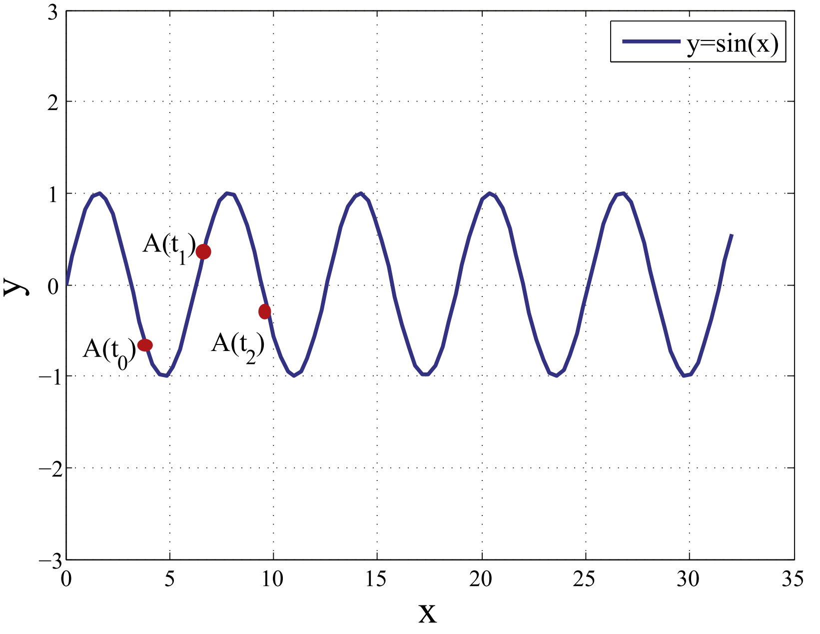

Fig. 1. Fluctuation function.

Lemma 1. *The necessary and sufficient condition for a Counting Process {N(t), t≥0} is a Poisson process with the parameter* λ *is that the* $T_k, k = 1, 2, \ldots$ *are i.i.d., and are subject to the exponential distribution with parameter* λ*. Where let* τ_k *denote to the moment of the kth event occurred and define* T_n *as the elapsed time between adjacent events, that is* $T_n = \tau_n - \tau_{n-1}$.

Lemma 2. *A Poisson process,* $\forall$ *t and sufficient of short time* $\triangle t \geq 0$*, we have*

$$\begin{cases} P(N(t+\Delta t) - N(t) = 1) = \lambda \Delta t + o(\Delta t), \\ P(N(t+\Delta t) - N(t) \geq 2) = o(\Delta t). \end{cases} \tag{2}$$

3. Related work

The advanced reliability theory and technology has realized state evaluation and failure prediction for various systems, such as power, traffic, and energy system, which provide support for the normal work of the system with safety and stable conditions. As an important branch of the theory of reliability, availability theory is used to comprehensively evaluate the performance of systems or components through availability indicators, such as steady state availability, instantaneous availability, interval availability, and so on. Among them, the instantaneous availability can reflect the availability of the system in real time, so it is usually used to evaluate the reliability of complex systems.

In this paper, the reliability evaluation model of cyber-physical system is established based on instantaneous availability. Now, the work related to instantaneous availability will be introduced.

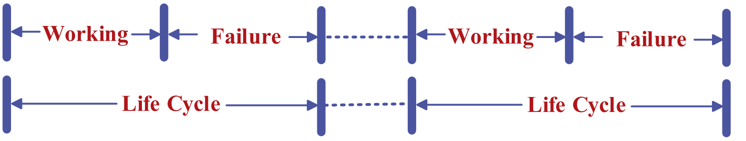

Fig. 2. The renewal process of the one-unit two-state system.

3.1. Instantaneous availability research on different systems

For one-unit repairable systems, in [33], the characteristics and the analytical expression of instantaneous availability are given by the first order auto-regressive and moving average (ARMA) model. At the same time, the limitations of failure time and repair time obeying the exponential distribution are overcome. The instantaneous availability of the two-unit repair delay model is studied using renewal process theory in [34], which is a generalization of the one-unit three-state model.

For multi-unit systems, the value of instantaneous availability was calculated by probability theory based on the modeling of network warfare environment in [35]. The multi-unit parallel repairable systems under different conditions in [36] are modeled by *Markov* process and renewal process, and the expression of reliability is given. In [37], the state of the multi-unit redundant system is simulated by the birth–death process in *Markov* theory, and the instantaneous availability of the system is estimated effectively.

For complex systems, the instantaneous availability model of the complex repairable system is established by neural network in [38]. Since the instantaneous availability is difficult to solve in large-scale systems, the relationship between the peak of instantaneous unavailability and the failure rate is discussed in [39] using the renewal process.

When the analytical expression of instantaneous availability is difficult to solve, there are some numerical algorithms used to calculate approximate solutions. In [28], for the renewal theoretical model, the compound trapezoidal formula is used to transform renewal process equation into the series and approximate solution is obtained. In [40], the failure rate function is estimated through the empirical data, and the approximate time-varying failure rate function can roughly judge the variation range of the instantaneous availability.

3.2. Instantaneous availability research on modeling

3.2.1. Renewal process model

The renewal process represents the random periodic replacement of the system state in time series [41]. Fig. 2 shows the renewal process of the one-unit two-state system. The renewal model describes the renewal process by modeling the related random variables. According to the definition of instantaneous availability, the renewal equation is derived by full probability formula, and the analytical expressions of related physical quantities can be obtained using Laplace transform and Laplace inverse transform.

3.2.2. Renewal process model

The *Markov* process is one of the most important stochastic processes which original model is the *Markov* chain [42]. The *Markov* property can be described that the future evolution of the system does not depend on its past states. Fig. 3 shows the state transition

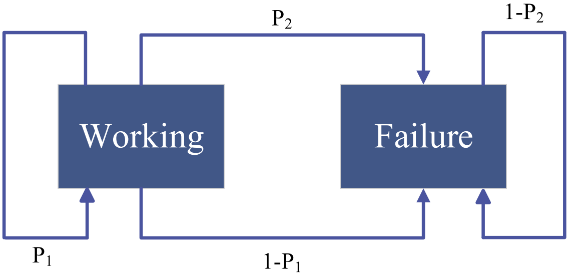

Fig. 3. The state transition model of one-unit two-state system constructed by *Markov* process.

model constructed by *Markov* process. The *Markov* model describes the stochastic process of variables through the ordinary differential equations composed of state transition matrices, but the random variables are required to obey the exponential distribution. The analytical expressions of related physical quantities can be solved by ordinary differential equations. In addition, *Markov* process has good application in many fields, which makes the model have better fit [43–45].

According to the related work above, the research on instantaneous availability is mostly aimed at the theoretical system of single component or multi component, which is relatively scarce for the actual complex system. From the perspective of research methods, the model is established mainly by the renewal or *Markov* theory, and approximate solutions are also obtained by numerical calculation in the case that the analytical solutions are difficult to solve. In addition, many systems like CPS are mixed with continuous time and discrete time with the development of information and communication technology in real life, and the current instantaneous availability model with characteristic of discrete time is not applicable to CPS and other complex systems.

In summary, it is necessary to reestablish instantaneous availability model of complex system and find the reliability and failure mechanism with to realize the reliability evaluation. In this paper, aiming at the frequent communication failures in CPS, we establish the instantaneous availability model combining renewal process as well as *Markov* theory, and give a comprehensive reliability analysis in the later sections.

4. Reliability and security evaluation model of CPS

In this section, we will begin to conduct a detailed analysis of the instantaneous availability modeling of the CPS considering communication failures. The cyber-physical system consisting of physical nodes, sink nodes, communication links, the Internet, and information processing terminals realizes the deep integration and collaborative work of cyber and physical space, as shown in Fig. 4. As mentioned above, communication process is the vulnerability of the CPS. In our model, there are two parallel communication systems working simultaneously from the perspective of CPS reliability design [46], which cannot only guarantee the accuracy and real-time of information exchange, but also the other system can maintain the normal communication to avoid the failure of the entire system in the condition of one of the communication systems fail or be attacked. To this end, it is assumed that the communication system in CPS contains two parallel subsystems, and each with three states during the life

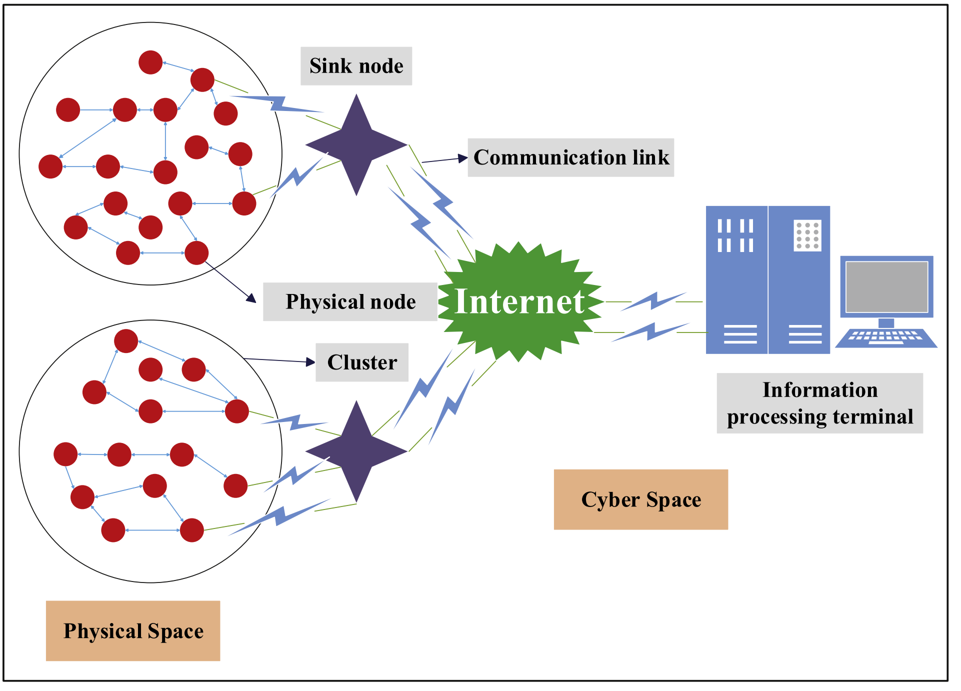

Fig. 4. The structure of CPS.

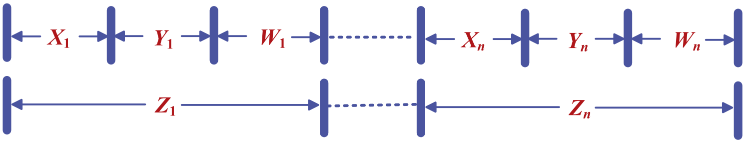

Fig. 5. The renewal process of system with three states.

cycle, namely, working, delay-repairing and repairing in our model. The normal work of communication system represents the normal work of CPS without considering other reliability factors.

4.1. Model introduction

In the following, the figure of a renewal process is shown. In Fig. 5, X_i, Y_i, W_i represent failure time, delay-repair time, repair time of *subsystem i*, respectively, then Z_i represent a life cycle.

Then, for each subsystem, we can get the following states including working state, delay-repairing state and repairing state. Obviously, we will get the following states respectively after the combination of any two states:

$$state1: \ subsystem1 - working, \ \ subsystem2 - working.$$

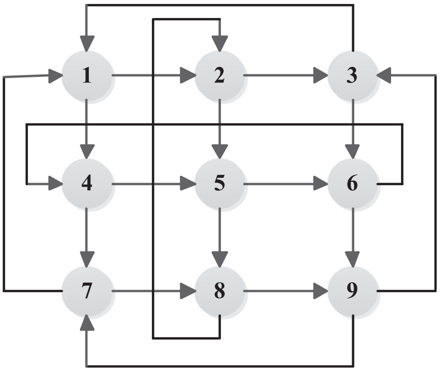

Fig. 6. State transition diagram.

$$state2:\ \ subsystem1-working,\ \ subsystem2-delay-repairing.$$
$$state3:\ \ subsystem1-working,\ \ subsystem2-repairing.$$
$$state4:\ \ subsystem1-delay-repairing,\ \ subsystem2-working.$$
$$state5:\ \ subsystem1-delay-repairing,\ \ subsystem2-delay-repairing.$$
$$state6:\ \ subsystem1-delay-repairing,\ \ subsystem2-repairing.$$
$$state7:\ \ subsystem1-repairing,\ \ subsystem2-working.$$
$$state8:\ \ subsystem1-repairing,\ \ subsystem2-delay-repairing.$$
$$state9:\ \ subsystem1-repairing,\ \ subsystem2-working.$$

Then according to the relationship between the above 9 states, we can get the following state transition as Fig. 6 shown:

We assume that the failure time X, delay-repair time Y and repair time W obey exponential distribution. The reasons for choosing the exponential distribution are as follows. On the one hand, the exponential distribution is perhaps the most widely applied statistical distribution for problems in reliability research [47]. On the other hand, CPS is a complex system characterized by information and networking, which has no obvious aging characteristics, so the change of failure rate and repair rate with time can be can be approximately ignored. Therefore, an exponential distribution with no memory properties is applied to CPS model in this paper.

In order to explore three-state two-subsystem parallel system under exponential distribution, we let $F(t)$, $W(t)$, $G(t)$ denote to distribution functions of X, Y and W, respectively. where

$$\begin{aligned} F_i(t) =& 1-e^{-\lambda_i t}, G_i(t) = 1-e^{-\mu_i t}, \\ W_i(t) =& 1-e^{-\theta_i t}, (i=1,2). \end{aligned} \tag{3}$$

Theorem 1. *Let a r.v X obey the exponential distribution, then* $\forall s,\ t>0$, *we have*

$$P\{X > s+t | X > s\} = P\{X > t\}. \tag{4}$$

Proof.

$$P\{X > s+t|X > t\} = \frac{P\{(X > s+t)\cap(X > s)\}}{P\{X > s\}} = \frac{P\{X > s+t\}}{P\{X > s\}} = \frac{1-F(s+t)}{1-F(s)} = \frac{e^{-\lambda(s+t)}}{e^{-\lambda s}} = e^{-\lambda t} = P\{X > t\}. \quad (5)$$

□

The following theorem will tell us how to get $P_{ij}(\Delta t)$:

Theorem 2. *Let r.v X obey to the exponential distribution with parameter λ. in a sufficiently small time* Δt*, it satisfies*

$$P_{ij}(\Delta t) = \lambda\Delta t + o(\Delta t). \quad (6)$$

Proof. During the proof process, we let i represents state i, j represents state j. Then according to *memoryless property*, we have

$$\begin{aligned} P_{ij}(\Delta t) &= P\{i\ to\ j\ once\ in\ \Delta t\ time|Initially\ in\ i\} \\ &= P\{i\ to\ j\ at\ least\ once\ in\ \Delta t\ time|Initially\ in\ i\} \\ &= P\{X \le \Delta t\} = \lambda\Delta t + o(\Delta t). \end{aligned}$$

□

Finally, Theorem : 3 tells us how to establish the instantaneous availability of the *Markov* model.

Lemma 3. *[10] When the initial state* $P_0(0), \ldots, P_N(0)$ *is given. Then the instantaneous availability of the system is given as following:*

$$A(t) = \sum_{j\in E} P_j(t), \quad (7)$$

where

$$P_j(t),\ j \in E.$$

And A(t) is the solution of the following differential equations:

$$\begin{cases} P_i'(t) = \sum_{k\in F} P_k(t)a_{ki}, \\ initial\ state\ P_0(0), P_1(0), \ldots, P_N(0), \end{cases} \quad (8)$$

where

$$a_{ki} = \lim_{\Delta t\to 0}\frac{P_{ki}(\Delta t)}{\Delta t}, a_{ii} = 1 - \sum_{k\in F\ \ k\neq i} a_{ki}.$$

According to Lemma 2, there is only one transition of state in Δt time. Let *r.vs* X_i, Y_i, Z_i be subject to the following distribution functions. According to the theoretical analysis of the

Markov process, we can calculate the probability of transfer between each state as following:

$$\begin{cases} p_{11} = 1 - 2\lambda\Delta t + o(\Delta t), \; p_{12} = \lambda\Delta t + o(\Delta t), \\ p_{14} = \lambda\Delta t + o(\Delta t). \\ p_{22} = 1 - (\lambda+\mu)\Delta t + o(\Delta t), \; p_{23} = \mu\Delta t + o(\Delta t), \\ p_{25} = \lambda\Delta t + o(\Delta t). \\ p_{31} = \lambda\Delta t + o(\Delta t), \; p_{33} = 1 - (\lambda+\theta)\Delta t + o(\Delta t), \\ p_{36} = \lambda\Delta t + o(\Delta t). \\ p_{44} = 1 - (\lambda+\mu)\Delta t + o(\Delta t), \; p_{45} = \lambda\Delta t + o(\Delta t), \\ p_{47} = \mu\Delta t + o(\Delta t). \\ p_{55} = 1 - 2\mu\Delta t + o(\Delta t), \; p_{56} = \mu\Delta t + o(\Delta t), \\ p_{58} = \mu\Delta t + o(\Delta t). \\ p_{64} = \theta\Delta t + o(\Delta t), \; p_{66} = 1 - (\mu+\theta)\Delta t + o(\Delta t), \\ p_{69} = \mu\Delta t + o(\Delta t). \\ p_{71} = \theta\Delta t + o(\Delta t), \; p_{77} = 1 - (\lambda+\theta)\Delta t + o(\Delta t), \\ p_{78} = \lambda\Delta t + o(\Delta t). \\ p_{82} = \theta\Delta t + o(\Delta t), \; p_{88} = 1 - (\mu+\theta)\Delta t + o(\Delta t), \\ p_{89} = \mu\Delta t + o(\Delta t). \\ p_{93} = \theta\Delta t + o(\Delta t), \; p_{97} = \theta\Delta t + o(\Delta t), \\ p_{99} = 1 - 2\theta\Delta t + o(\Delta t). \end{cases} \tag{9}$$

Then, according to Lemma 3, we will get a differential equations of instantaneous availability as follows:

$$\begin{cases} P'(t)^T = P(t)^T A, \\ P(0) = (1, 0, \ldots, 0, 0)^T. \end{cases} \tag{10}$$

where

$$A = \begin{bmatrix} -2\lambda & \lambda & 0 & \lambda & 0 & 0 & 0 & 0 & 0 \\ 0 & -(\lambda+\mu) & \mu & 0 & \lambda & 0 & 0 & 0 & 0 \\ \theta & 0 & -(\lambda+\theta) & 0 & 0 & \lambda & 0 & 0 & 0 \\ 0 & 0 & 0 & -(\lambda+\mu) & \lambda & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & -2\mu & \mu & 0 & \mu & 0 \\ 0 & 0 & 0 & \theta & 0 & -(\mu+\theta) & 0 & 0 & \mu \\ \theta & 0 & 0 & 0 & 0 & 0 & -(\lambda+\theta) & \lambda & 0 \\ 0 & \theta & 0 & 0 & 0 & 0 & 0 & -(\mu+\theta) & \mu \\ 0 & 0 & \theta & 0 & 0 & 0 & \theta & 0 & -2\theta \end{bmatrix} \tag{11}$$

Then we will perform the numerical solution of the differential equation because of the difficulty of obtaining analytical solution.

4.2. Numerical solution of the IA model

For the system, through the use of fourth-order *Runge–Kutta* method [48], the problem is described as following:

$$P'(t)^T = P(t)^T A, \; P(0) = (1, 0, \ldots, 0, 0)^T. \tag{12}$$

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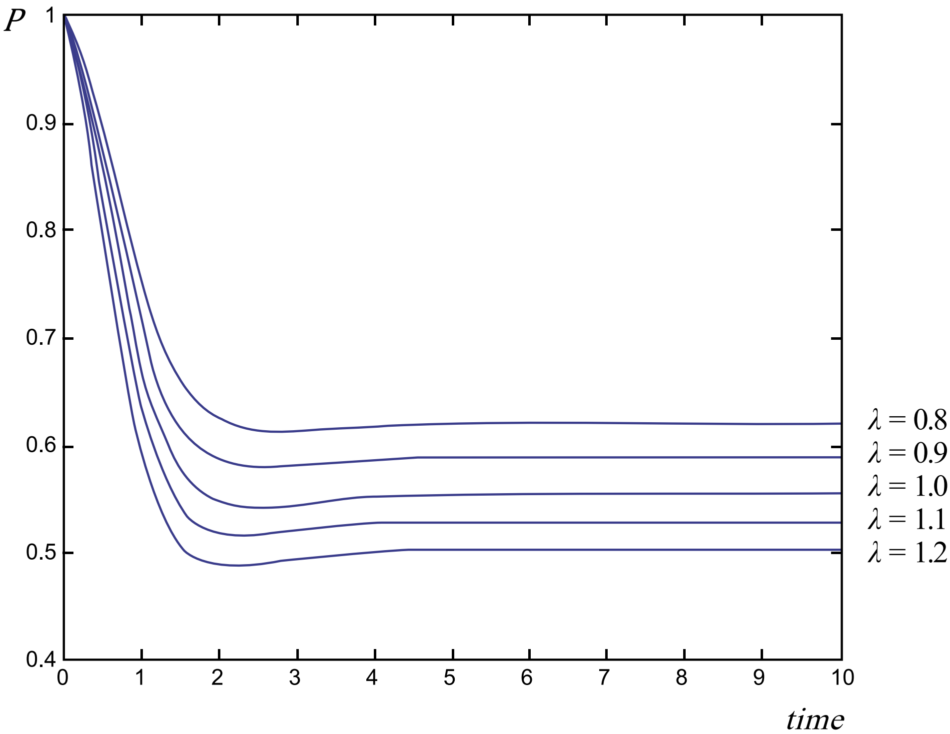

Fig. 7. Trends in instantaneous availability under different λ parametric.

Let y_i denotes the dotproduct of $P(t)^T$ and the ith column of the matrix A, and let $y_i(x_n)$ denotes the function value corresponding to x_n, where let $\{x_n\}$ denote to the point sequence. Let $y_i' = f_i(t, y_i(x_n))$ denote to the ith equation. The fourth-order *Runge–Kutta* for the problem is given by the following equation where let $\{t_n\}$ denote to the time sequence:

$$y_i(x_{n+1}) = y_i(x_n) + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4), \tag{13}$$

where

$$k_1 = f_i(t_n, y_i(x_n)), \tag{14}$$

$$k_2 = f_i\left(t_n + \frac{h}{2}, y_i(x_n) + \frac{h}{2}k_1\right), \tag{15}$$

$$k_3 = f_i\left(t_n + \frac{h}{2}, y_i(x_n) + \frac{h}{2}k_2\right), \tag{16}$$

$$k_4 = f_i(t_n + h, y_i(x_n) + hk_3). \tag{17}$$

The fourth order *Runge–Kutta* method, that is, the error of each step is h^5 order, and the total accumulation error is h^{-4}. It should be noted that the formula for the scalar function or vector function is established.

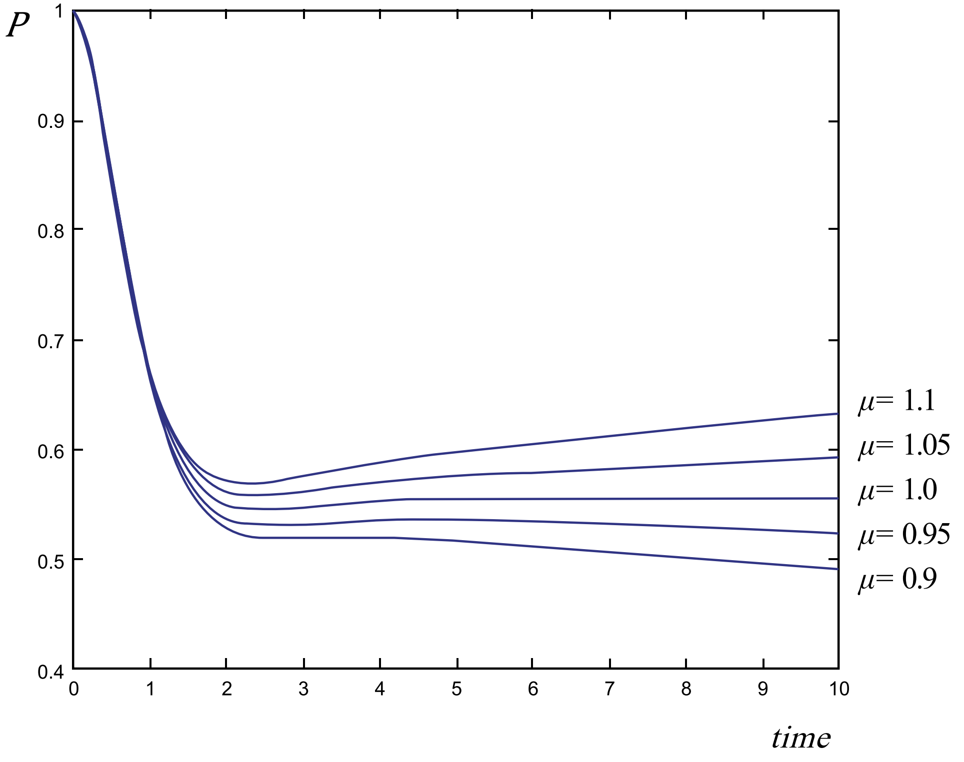

Fig. 8. Trends in instantaneous availability under different μ parameter.

5. CPS reliability analysis and improved method based on the instantaneous availability fluctuation

Using the *Runge–Kutta* method after defining $h = 0.1$ as algorithm steps, the numerical solution of the CPS reliability can be obtained. In the case of two parameters fixed, there will be a detailed analysis of another parameter for the instantaneous availability of fluctuations to reveal the failure mechanism of CPS and propose ways to improve reliability.

5.1. Effect of parameters λ on instantaneous availability fluctuations

As Fig. 7 shown, fixed $\mu = 1, \theta = 1$, we see that when the value of λ gradually approaches 0, the fluctuation of the curve gradually decreases, and the fluctuation appears at about time $t \in (0, 3)$. It proves that the fluctuation of instantaneous availability is decline. According to it, we obtain a way to suppress the fluctuation, that is, in the case of fixing other parameters, by reducing the value of λ (ie failure rate) to reduce the instantaneous availability of fluctuations.

5.2. Effect of parameters μ on instantaneous availability fluctuations

As Fig. 8 shown, fixed $\lambda = 1, \theta = 1$, we observe the effect of parameter μ on the fluctuation of instantaneous availability. When the value of μ gradually approaches 0, the fluctuation appears at about time $t \in (0, 3)$ and the fluctuation gradually decreases at time $t \in (1, 2)$. But

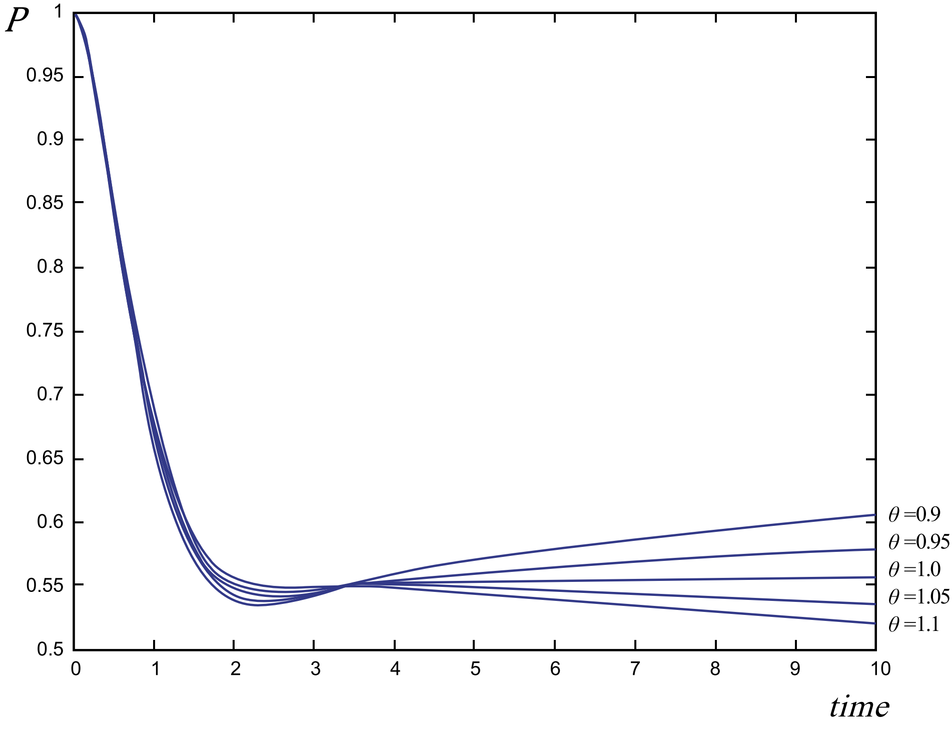

Fig. 9. Trends in instantaneous availability under different θ parameter.

as time goes on, steady availability gradually tend to 0, indicating that although the decrease in μ will reduce the fluctuation of instantaneous availability, at the same time, it will lead to the system cannot be long-term use. According to it, we get a way to suppress the fluctuation, that is, in the case of fixing other parameters, by reducing the value of μ (ie, the delay rate) to reduce the fluctuation of instantaneous availability. At the same time, if the μ delay rate is greatly reduced, The system will become increasingly durable.

5.3. Effect of parameters θ on instantaneous availability fluctuations

As Fig. 9 shown, fixed $\lambda = 1, \mu = 1$, we observe the effect of parameter θ on the fluctuation of the instantaneous availability. When the value of θ gradually approaches 0, the fluctuation appears at about time $t \in (0, 3)$ and the fluctuation of the curve gradually increases. But the steady-state availability will gradually progress to 1 over time, indicating that although the decrease in θ will increase the fluctuation of instantaneous availability in a short time, it will help improve the system. The effect of long-term use. According to it, we obtain a way to suppress the fluctuation, that is, by increasing the other parameters of the conditions, by increasing the value of θ (i.e. repair rate) to reduce the instantaneous availability of fluctuations. But if the increase in θ delay rate, the system life will be extended.

According to the case study above, the proposed reliability evaluation method of CPS has a greater progress than the existing evaluation approaches [49,50]. Firstly, the model analyzes all state transition processes of the system life cycle, which ensures the comprehensiveness and accuracy of the evaluation information. Secondly, the method in this paper can reflect the

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reliability state of the system in real time. In particular, it is possible to find fluctuations of instantaneous availability during the initial operation of the system, which is a problem that is difficult to find when evaluating the reliability of CPS over a period of time.

6. Conclusions

The reliability evaluation model of CPS based on instantaneous availability has been established under the exponential distribution. The main contributions of this paper have made as follows. One has been to establish the reliability evaluation model and obtain the numerical solution of instantaneous availability, the other has been to find the existence of the IA fluctuation and evaluate the reliability of the CPS by analyzing the variation of instantaneous availability over time. We have analyzed the impact of some key parameters such as failure rate and repair rate on CPS reliability by theories and simulations. However, the analytical solutions of IA and application for large-scale CPS have not been studied due to the complexity of the CPS model, which deserve further research work in the future.

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