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PREDICTIVE RELIABILITY ASSESSMENT FOR AN AUTOMOTIVE SPEED SENSOR USING HIERARCHICAL TIMED COLOURED PETRI NET

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Abstract

For a manufacturer, a good component is one that fails one day after the warranty expires. For a user, a good component means a component that never fails. To predict reliability of a single component produced by a manufacturer, is to attempt to answer an all-important question: when wills the component breakdown? In this paper we will attempt to answer this question by exploring the application of timed hierarchical coloured petri nets to estimate predictive reliability of a regenerative braking system's electronic component using a stochastic process. The proposed approach is tested on the example of an automotive speed sensor. This approach appears to be efficient for evaluation of stochastic MTBF indicator. Since Monte Carlo simulations are used to provide data for analysis, the present study is not restricted by the Markovian hypothesis.

Keywords: Predictive reliability, Physical model, logical model, hybrid systems, and timed hierarchical colored Petri net.

INTRODUCTION

Nowadays, the automotive industry has embarked on an innovative path. Manufacturers are now offering in-vehicle electronic solutions to build intelligent vehicles that "think" and act for their drivers and occupants. The design of these elements, comprising an advanced integration of components from different technologies, requires a harmonious collaboration between them from the beginning of the study in such a way as to achieve a competitive and high-quality industrial product. Any change in the level of this complexity introduces emerging issues whose nature and importance will depend on the depth of the integration process and the increased functionality of the final product. To obtain systems in which users place a high confidence, dependability studies, and in particular reliability studies, must be carried out throughout the system's development or life cycle: from specification to validation and putting into operation (Misra, & Ljubojevic,1973). The methods of estimating the reliability of such systems are very different from each other. In fact, hybrid systems have been the subject of numerous works. They mainly consisted in suggesting functional and/or dysfunctional models to measure the performance of a given architecture (Dionysiou, Bolbot, & Theotokatos, 2022), (Lakhoua, & Karoui, 2019). We can distinguish two categories: static model and dynamic ones. The fault tree (Khare, Nema, & Baredar, 2019) is the most used to describe malfunction or failure scenarios. However, this model does not allow to model correctly real-time and/or reconfigurable systems (possibility of operation in degraded mode. Dynamic model: Stochastic Petri Nets (Elusakin & Shafiee, 2020) and Markov chains (Ye, Grossmann, Pinto, & Ramaswamy, 2019) are the most used to describe the functional or/and dysfunctional aspects

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of hybrid systems. The studies carried out mainly use the assumption of constant failure rate to characterize a transition to a place characterizing a failure state. Within the scope of this work, a predictive reliability evaluation of an automotive speed sensor based on hierarchical timed coloured Petri nets will be presented. Initially, it is pivotal to work out the reliability and Hierarchical timed coloured petri net definition. Then we will investigate an automotive speed sensor under the umbrella of the proposed methodology. Finally, some conclusions and an outlook on further research needs to complete this work will be conducted.

RELIABILITY AND TIMED HIERARCHICAL COLOURED PETRI NET

Reliability

According to IEC 50 (191): Reliability is the entity's aptitude to perform the requested function in fixed conditions during a fixed time (Rausand, & Øien, 1996). Very early on, large companies showed a great interest in reliability: General Motors, since the 1940s, NASA, the Department of Defense in the United States, since the 1950s, Airbus, Air Force, Bell Telephone Laboratories, since the 1960s, Thomson, Philips, Kodak, Citroën, since the 1970s (Denson, 1998) . The quest to reduce the cost of operational failures has led to an increase in system reliability requirements. For example, in 1995, General Electric estimated that the costs of unreliability amounted to $8 to $12 billion and decided to increase the quality level of its products within the scope of the Six Sigma policy (Claudio, 2001).

Mastering the reliability of a system represents an important economic challenge for any business. The measurement of this parameter is an essential first step towards its control. The "quality" of the product, in terms of reliability, is given by a set of performance indicators or measures which are presented in this section.

a. Distribution function, probability density

We consider a system that can experience different states. This set of states, noted E, is broken down into two subsets forming a partition: the subset M of the operating states and the subset D of the failure states. Let us consider T the random variable that represents the time elapsed between the start-up of an entity and the first observed failure. Reliability at time t is the probability that an entity E is non-failed over time [0, t].

Also known as reliability, the associated probability R (t) defined by (Birolini, 2013) (Ascher, 1989):

$$R(t) = P(t < T)$$

To complete the theoretical approach of reliability, it is necessary to also define the following concepts, which are derived from the probability theory. The function F (t) stands for the distribution function of the random variable T. It is the "unreliability" R (t) (the system failure probability) or the probability complementary to 1 of the reliability R (t) defined by (Birolini, 2013) (Ascher, 1989):

$$F(t) = P(t \geq T) = 1 - R(t)$$

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The function f (t) is the probability density of t and is given by:

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt}$$

b. Instantaneous failure rate:

The instantaneous failure rate, λ (t), is one of the key reliability measures. The value λ (t) dt represents the conditional probability of experiencing a failure in the time interval [t; t + dt], knowing that there was no failure in the time interval [0; t] (Birolini, 2013) (Ascher, 1989):

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{1}{R(t)}.\frac{dR(t)}{dt}$$

Therefore, it can be deduced that:

$$R(t) = \exp\left[-\int_0^t \lambda(u)du\right]$$

Hierarchical Timed coloured Petri Net

In distinction to the place-transition Petri nets, it is possible to have tokens of different nature in the same place. If a place represents a stock, with coloured Petri nets it is possible to put in this place two tokens of different natures representing different products whereas with simple Petri nets this is not possible because it will be impossible to differentiate the two tokens. In an industrial system, the products can be of different nature, therefore the use of coloured Petri nets is deemed necessary. Furthermore, the colours of a Petri net can represent any type of data (real, integer, string, structure etc.) This means that we can integrate any type of information within our models.

We start by defining a coloured Petri net module which is a four-tuple:

$$CPN_M = (CPN, T_{sub}, P_{port}, PT)$$

Where (Jensen, & Kristensen, 2009):

- P: is a finite state of places.
- T: is a finite state of transitions such that P ∩ T = ∅
- A ⊆ P × T ∪ T × P is a set of directed arcs.
- S: is a finite set of non-empty colour sets.
- V: V is a finite set of typed variables such that Type[v] ∈ S for all variables v ∈ V.
- C: P → S is a colour set function that assigns a colour set to each place. A place p is timed if C (p) is timed, otherwise p is untimed.
- G: T → EXPR is a guard function that assigns a guard to each transition such that Type [G (t)] = Bool.

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- E: A → EXPRv is an arc expression function that assigns an arc expression to each arc a such that:
    - Type [E (a)] =C (p) MS where p is the place connected to the arc a.
- I: P → EXPR∅ is an initialization function that assigns an initialization expression to each place p such that:
    - Type [I (p)] =C (p) MS.
- T sub ⊆ T is a set of substitution transitions.
- P port ⊆ P is a set of port places.
- PT: Pport → IN, OUT, I/O is a port type function that assigns a port type to each port place.

A hierarchical CPN model consists of a finite set S of modules. Each module s ∈ S is defined according to module definition ((Jensen, & Kristensen, 2009) :

$$s = (CPN^S, P^S_{Port}, T^S_{sub}, PT_s)$$

With:

$$CPN^S = (P^S, T^S, A^S, S^S, V^S, C^S, G^S, E^S, I^S)$$

Hierarchical coloured Petri nets (HCPN) provide the possibility of modelling every part with a substitution transition which is an abstraction of another model. Hierarchy is used to subdivide a model into different parts which allow a modular modelling (Farah, Chabir & Abdelkrim, 2019).

Timed coloured petri nets are:

$$CPN_T = (CPN, T1, T2, T3)$$

Where CPN stand for coloured petri net, and T1, T2 and T3 are, respectively, time delays assigned to net places, arcs, and transitions.

CPN TOOLS:

CPN Tools is a tool package supporting the use of CPN. It consists of four integrated tools for modelling and simulation (Ratzer, & Al, 2003):

- An editor for construction, modification, and syntax check of models,
- a simulator for interactive and automatic simulation,
- A graph tool for construction and analysis of occurrence graphs and
- A performance tool for simulation based on performance analysis.

CPN Tools (Jensen, Kristensen, & Wells, 2007) supports CPN models with complex data types (colour sets) and data manipulations (arc expressions and guards) - both specified in the functional programming language Standard ML (Harper, Mac Queen, & Milner, 1986).

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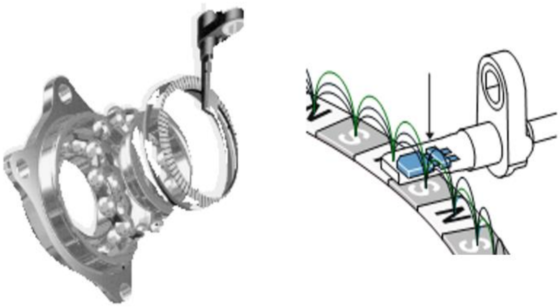
The package also supports hierarchical CPNs, so it's possible to model a set of separate modules (subnets) with well-defined interfaces.

APPLICATION

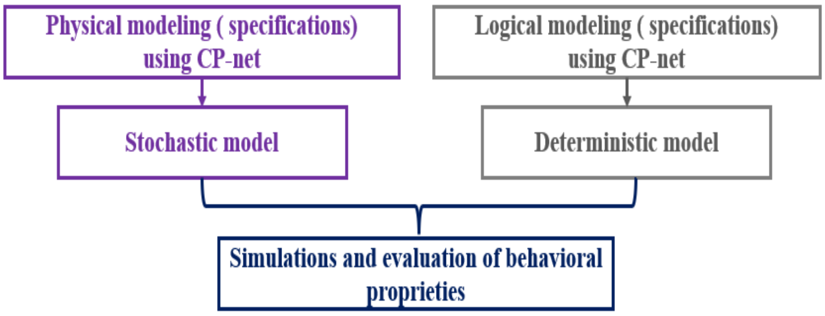
The system under examination is the wheel's speed sensor of a regenerative braking system Fig.5 The wheel speed sensors measure the speed of the vehicle's wheels, and the speed signals are transmitted via cables to the vehicle's regenerative braking system control unit, which controls the braking force on each individual wheel. This control loop prevents the wheels from locking up:

Figure 1 : Wheel's speed sensor



The proposed approach in this paper, is the one highlighted in the perspectives of the work (Mehdi, & Boudi, 2021):

Figure 2 : Proposed Approach



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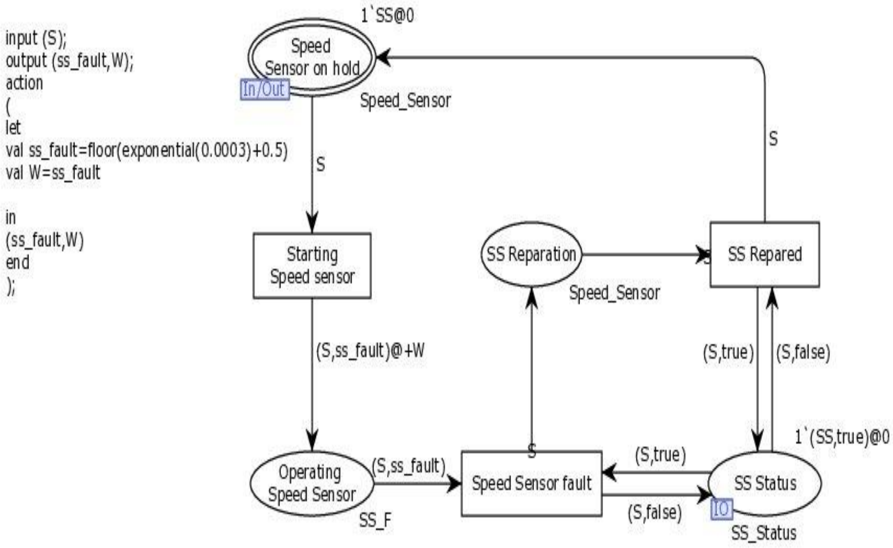
Physical Model

In this section, physical model of a speed sensor is defined:

Figure 3 : Physical Model -Speed sensor



We observe that at the place: Speed Sensor on hold, a token is presented: SS at the initial time. The variable S is involved in picking up the token SS, from the place: Speed Sensor on hold to the transition: Starting Speed sensor. The output of the transition is a complex timed token, with two different values. The actions executed in the Starting Speed Sensor are random. The failure time's ss-fault is taken randomly from the exponential distribution. A time value @W is associated with the token. The underlying logic is that the speed sensor is running and after the @W time, the failure transition is activated. The output token corresponds to the speed sensor, and the speed sensor's failure time. These times are used to activate the following transitions.

The Speed Sensor Fault transition is activated if a fault occurs. The operations performed in the transitions have the same meaning as in the Start speed sensor transition. An important place is the SS status place. This place is the bridge between the physical and control speed sensor 'models. Its working is very simple, it has 2 tokens of type SS_Status = SS, BOOL: when the SS is ok the token value is true, when the SS is broken the Boolean value is false.

Logical model

In this second section the logical model is defined:

- The logical model is deterministic.
- It should follow the provided specification.
- The logical model stores all the information in order to carry out the performance analysis.

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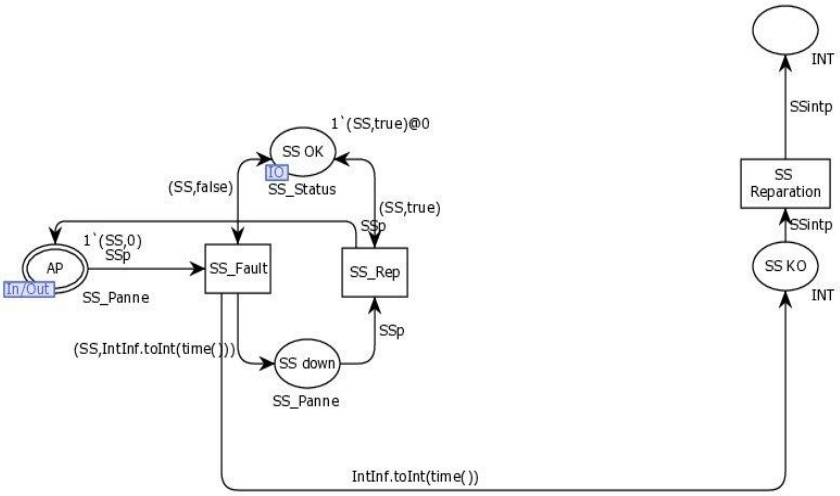
Figure 4 : Logical Model-Speed sensor



The SS OK place is in "read-only" mode, only the SS physical model can change its content. When the SS is broken, the SS OK place has the token (SS, false) which allows the SS_Fault transition to occur but does not change the token of the SS OK place. A first problem presented in this case is that when the SS_Fault instantaneous transition is enabled, the marking of size SS down is infinitely increased. To solve this problem, an Anti-Place A is implemented: a next execution of SS_Fault transition is only enabled if the token with SS is placed by the repair transition SS_Rep. Thus, the SS down place has at most one token.

Top Module:

After building the two modules of our system, it is needed to develop a Top module:

Figure 5: Speed sensor's top module

Interpretation

The final stage of our methodology entails running simulations of the Petri Nets figures 3 and 4, considering the exponential distribution with lambda. Data collector monitor (Wells, 2006) was used to collect all MTBF times. The breakpoint monitor (Gehlot, & Nigro, 2010) stops the simulation after 15000 hours in our case using the function CPN' Replications. Nreplications

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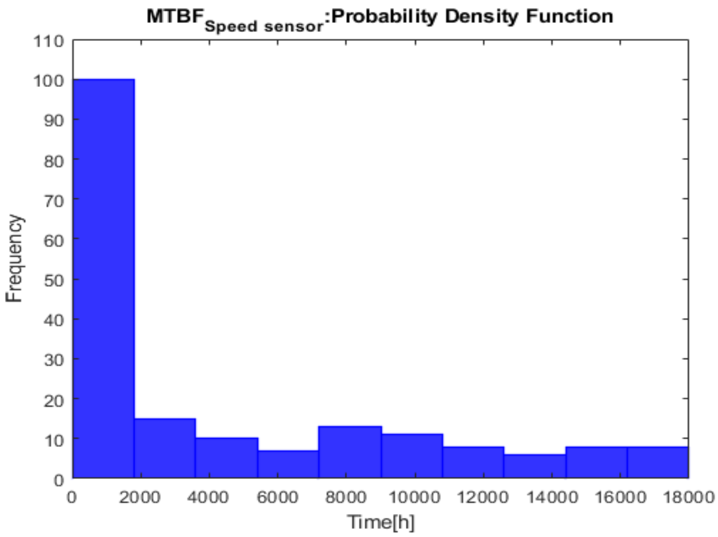
n. To complete the analysis, we loaded all the text with a MATLAB script, evaluated and plotted the results.

Figure 6: MTBF Probability density function using Monte Carlo



The histograms of the Speed sensor MTBF have an exponential distribution form. Intuitively, the speed sensor's failure rate is constant, thus there is no particular time region where the system has the higher probability to fail.

CONCLUSION AND PERSPECTIVES

In this paper, we have presented an approach for estimating the predictive reliability of a wheel speed sensor. The approach is structured around coloured Petri nets which allow to model the physical and logical behavior of the system. The simulation of n systems permits to obtain the failure times and to compute the parameters of the reliability law by the Monte Carlo method. As a perspective, we will extend the predictive reliability analysis to a complete behavioral analysis of the system including availability and maintainability.

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