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Reinaldo Squillante Jr[1], Diolino J. Santos Fo[1], Jeferson A. L.de Souza[1], Fabrício Junqueira[1], Paulo E. Miyagi[1]

[1]University of São Paulo, São Paulo, Brazil
{reinaldo.squillante, diolinos, jeferson.souza, fabri, pemiyagi}@usp.br

Abstract. Recent studies show the designs of automated systems are becoming increasingly complex to meet the global competitive market. Additionally, organizations have focused on policies to achieve people's safety and health, environmental management system, and controlling of risks, based on standards. In this context, any industrial system in the event of a fault that is not diagnosed and treated correctly could be considered to pose a serious risk to people's health, to the environment and to the industrial equipment. According to experts, the concept of Safety Instrumented Systems (SIS) is a practical solution to these types of issues. They strongly recommend layers for risk reduction based on control systems organized hierarchically in order to manage risks, preventing or mitigating faults, or to bringing the process to a safe state. Additionally, the concept of Risk and Hazard Control can be applied to accomplish the required functionalities. It is based on problem solving components and considers a cooperative way to find a control solution. In this context, the software architecture can be based on a service-oriented architecture (SOA) approach. This paper initially proposes a new architecture for design of safety control systems for critical systems, based on Safety Supervisory Control Architecture, in accordance with standards IEC 61508 and IEC 61511. Furthermore, a method is also proposed for design the control layer of risk prevention within Safety Supervisory Control Architecture.

Keywords: Safety Supervisory Control Architecture, Safety Instrumented System, Critical Fault diagnosis, Critical Fault Treatment, Service-oriented architecture.

1 Introduction

Recent studies show that automation is highly influenced by the advance of technologies such as mechatronics and Internet, moreover, the design of automated systems are becoming increasingly complex to meet the global competitive market. Industrial processes must considerer an increasing number of functionalities associated with customized products and concepts such as design for manufacturing, design for quality, etc. and their control solutions must frequently consider contradictory specifications. Additionally, organizations have focused on policies to achieve people's safety and health, environmental management system, and

controlling of risks, based on standards like Occupational Health and Safety Assessment Services – OSHAS 18001[1], and ISO14001[2], respectively.
In this context, any industrial system in the event of a fault that is not diagnosed and treated correctly could be considered to pose a serious risk to people's health, to the environment and to the industrial equipment [3].Thus, several approaches for fault-tolerant reconfigurable control system have been proposed [4].However, although the development of techniques for diagnosis and treatment of faults exists, accidents still occur. These issues are fully explained because there is no zero risk in industrial processes since: (i) physical devices do not have zero risk of failure; (ii) human operators do not have zero risk of error; and (iii) there is no control programs developed that can predict all the possibilities. Thus, studies that aim to diagnose and treat faults rely on restricting its state space for the control and treatment of a particular class of faults.
According to experts, the concept of Safety Instrumented Systems (SIS) is a practical solution to these types of issues. They strongly recommend layers for risk reduction based on control systems organized hierarchically in order to manage risks, preventing or mitigating failures, or bringing the process to a safe state. In this sense, some safety standards such as IEC 61508 [5], IEC 61511 [6], among others, guide different activities related to a SIS Safety Life Cycle (SLC),such as design, installation, operation, maintenance, tests and others [7].
The term "risk" defines a metric for quantifying injury, environmental damage and economic losses; in reference to both probability of a fault occurrence and magnitude of the injury or loss [8]. According to IEC 61508 [5], the term "fault" is defined as an abnormal condition that can cause a reduction or loss of the ability of a functional unit. In this work, faults are classified into two groups: (a) non-critical faults that define risks to be tolerated and therefore automatically recovered by the Basic Process Control System (BPCS); and (b) critical faults that define unacceptable magnitude of risks and must be either prevented or mitigated in order to avoid a catastrophic scenario. The principal is that industrial processes should always be placed into a safe state via the degeneration of the processes by layers of risk reduction of SIS.
One of the challenges is the development of safety control systems, based on SIS. The initials basic questions are: (a) how to design safety control systems based on Safety Supervisory Control Architecture (SSCA) in accordance with standards IEC 61508 and IEC 61511; (b) how to design a layer of risk prevention based on control system, which will be incorporated in the SSCA, according to standards. Therefore, this paper initially proposes the design of safety control systems, based on Safety Supervisory Control Architecture (SSCA), as shown in Fig. 1, in accordance with standards IEC 61508 and IEC 61511. The functions for each layer of both risk prevention and mitigation control systems consider safety programmable controllers with their respective safety sensors and actuators, safety programs based on analysis, validation and verification of mathematical models for diagnosis, treatment and mitigation of critical faults and integration of these layers in a cooperative way by a Risk and Hazard Supervisory Control using service-oriented architecture (SOA).

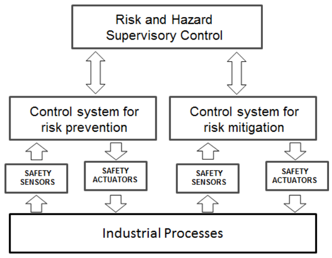


Fig.1. Safety Supervisory Control Architecture (SSCA)

Additionally it is proposed a method for modeling and validating the control layer of risk prevention within SSCA, in compliance to IEC 61508 and IEC 61511 standards. This method considers diagnostic and treatment for each Safety Instrumented Function (SIF) including hazard and operability (HAZOP) studies of the equipment or system under control. For modeling critical faults diagnosis, approaches based on Artificial Intelligent (AI), such as Fuzzy Logic, Neural networks, and Bayesian Network (BN) has the potential to solve them [3, 12]. In this method BN and Interpreted Petri Net(IPN) are used.

IPN is also used for modeling critical faults treatment, since this technique is proper for treat dynamic system behavior oriented by the occurrence of instantaneous events and discrete states, i.e., dynamic discrete event systems (DEDS). Additionally, a coordination model based on IPN is used to link each fault treatment model to a corresponding diagnostic model. The mathematical models generated enable the validation of the control program by using a computational resource ensuring that the Safety Integration Level (SIL) is achieved. Finally, these models can be translated to a control program in any language defined by IEC 61131-3 in accordance to IEC 61511 standard [5] and implemented in a safety Programmable Logic Controller (PLC) as a layer of prevention control within SSCA.

This paper is organized as follows: Section 1 presents the introduction and proposes the design of safety control systems, based on Safety Supervisory Control Architecture (SSCA). Section 2 presents its relationship to Internet of Things. Section 3 presents the fundamental concepts for BN, and IPN. Section 4, presents the proposal of a risk prevention control system layer. Section 5 presents the example of application. Section 6 presents the conclusion. Finally references are presented.

2 Relationship to Internet of Things

According to [9], the Internet infrastructure will retain its vital role as global backbone for worldwide information sharing and diffusion, interconnecting a wide range of services and technologies, such as RFIDs, sensors/actuators, machine-to-machine communication devices, etc. In the context of service-oriented architecture (SOA)-based automation systems, the communication among components in a cooperative way is completely based on open standards, and the components can be easily rearranged. This saves down-times and costs when a system needs to be reconfigured or extended [10]. Furthermore, it is possible the distribution of the control logic as independent software-blocks is possible. Therefore, the concept of SSCA can be applied considering a cooperative way to find a control solution by using SOA-based automation system. Works adopted SOA, in which Web Service (WS) is a popular instance of this architecture [11].Finally, SOA architecture approach will be used to allow Risk and Hazard Supervisory Control to obtain information from risk prevention and mitigation control systems in order to generate a data repository that will be used as input for Artificial Intelligence (AI) algorithms and also for continuous improvement of safety control systems [12].

3 Fundamental Concepts

This section introduces fundamental concepts of Bayesian Network (BN) and interpreted Petri net (IPN) for critical faults diagnosis. Moreover, it introduces IPN for coordination and treatment of critical faults.

3.1 Bayesian network (BN)

The BN provides a method to represent partial beliefs under conditions of uncertainty [13]. Its graphical structure models relationships of probabilistic dependence of cause-effect considering a group of variables. Bayesian networks have been extensively applied for fault diagnosis [14]. BN allow the combination of human expert knowledge of the process under observation and probability theory for building a diagnostic structure, based on algorithms, like *K2* [15].

3.2 Interpreted Petri net (IPN)

Presented in 1962 by Carl A. Petri, the Petri net (PN) is a powerful tool for modeling, analysis and design of DEDS. PN can represent processes with synchronism, concurrent, causality, conflict, share resources and normal situations in DEDS. It is especially useful in applications in which security is a relevant factor. As mentioned in section 1, the proposal of this work is to use PN as a tool for modeling coordination and treatment of critical faults in a SSCA design. Interpreted Petri net (IPN) is defined as a tool which is associated with either an interpretation or meaning to their places and transitions; representing something real which aims to modeling (i.e.: safety sensors and safety actuators).

4 Proposal of risk prevention Control System Layer

The proposal of a method for modeling and validating control programs is based on BN, and IPN. The initial idea was introduced in [16], and is presented in Fig.2.

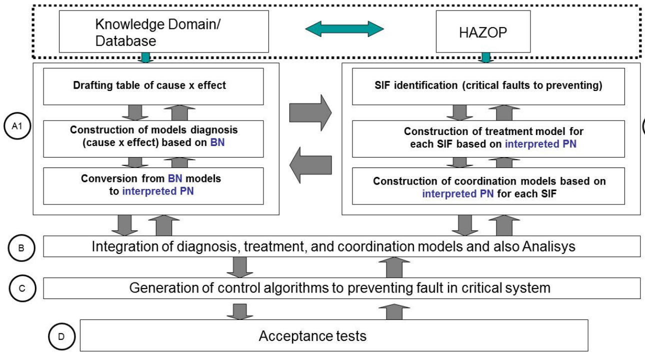


Fig.2. Method for modeling and validating control programs for preventing risks in SSCA projects

This method defines four steps: (A) modeling, (B) integration and analysis of models, (C) generation of control programs for preventing faults in critical system and (D) acceptance tests. The modeling step is divided in the stages: (A1) diagnosis of critical fault and (A2) critical fault treatment and coordination. The Step (B) is performed to: (i) verify if some PN properties are met and; (ii) validate integrated models in compliance with specification. The Step (C) is performed to convert verified models into a language recommended by standard IEC 61131-3 [17] and accepted by IEC 61511 [6] for implementation in a Safety PLC. Finally, Step (D) is performed for validating if a control program for each SIF complies with the specifications.

4.1 Description of the proposed mathematical method

A1 - Critical Fault Diagnostic modeling

Step 1 - Drafting table of cause x effect:
In this step, it is build a table that lists the causes (critical faults) defined for each SIF, and effects that are observed by sensors when these critical faults occur. The criteria for the building of this table can be: (a) based on domain knowledge about the system and / or (b) based on database obtained from either field experiments or historical data.

Step 2 - Construction of models for diagnosis (cause x effect) based on BN
The cause x effect table obtained is used for building the BN model for diagnosis of faults. Additionally, it is strongly recommended to apply some restrictions from knowledge to improve the network structured.

Step 3 - Conversion from BN models to IPN
In the diagnostic reasoning, causes should be diagnosed based on the monitored effects, in other words, the relationship *effect x cause* must be established. Furthermore, these diagnosis models must be converted into IPN to make its possible. Finally, IPN model should be transcribed into IEC languages [18] to be implemented into a Safety PLC.

A2 - Critical Fault Treatment and Coordination modeling

Step 1 - SIF identification
From HAZOP studies, SIF and SIL are identified. For each SIF, that represent critical fault to prevent, important data are obtained as SIL; that includes initialization events (sensors) and actions(actuators) to be performed by SSCA to prevent such critical faults.

Step 2 - Construction of Treatment Model for each SIF
An IPN model is built based on information obtained from each SIF, as shown in the previous step. It ensures that the Safety PLC takes appropriate actions to prevent undesirable risks in the critical system. The aim of each SIF is verified based on dynamic behavior of IPN models at the end of this step.

Step 3 - Construction of Coordination models
A coordination model for each SIF is built based on IPN. Once a critical fault is identified by the diagnose model, the coordinator model is responsible for calling their respective treatment model to be run, taking actions to prevent risks. These models should be designed to be robust against the occurrence of spurious faults that may unduly de-energize final elements and produce unwanted system downtimes.

B – Integration and Analysis of models
In this step, the models of critical fault diagnosis, treatment, and coordination are integrated to compose the SIF general model. The integration is made from logical connections, since no flow of tokens should occur among IPN models. After integration, SIF general model should be simulated based on computational tools (e.g.: HPSim [19]) for validating control programs for each SIF complies with the specifications. For the proceeding of simulation of SIF general models, the models of devices for sensing and actuation are considered to close the control loop.

C – Generation of control programs to prevent fault in critical system
The SIF general model obtained in the previous step should be converted into control program based on the IEC 61131-3 [16] language and accepted by IEC 61511 [6] such as (a) Ladder Diagram, (b) Function Block Diagram and (c) SFC (Sequential Function Chart). Many works have been published about methods for converting PN models into algorithms based on IEC 61131-3 languages. An example is showed in [18].

D – Acceptance tests

In according with the IEC 61508 / IEC 61511 standards, one of the Safety Life Cycle (SLC) steps is related to final testing for commissioning and start-up procedures.

5 Example of Application

A natural gas compression station is presented to illustrate the proposed method. To evaluate this approach, it is considered one SIF, identified as SIF-01; obtained from HAZOP.

5.1 Process Description

The natural gas compression station has at least a natural gas supply line, called suction, from a gas pipeline which transports this natural gas. At the station entrance, natural gas goes through filters before it being compressed by the turbo-compressor machine. A portion of this gas is directed to the utility unit. The utility unit accounts for controlling the gas temperature and pressure for use in the compression station, such as fuel gas for the turbo-compressor machine, gas heaters, and gas power generators. Then it is sent back to the gas pipeline through discharge lines.

5.2 Application of the proposed method

A1 - Critical Fault Diagnostic modeling

Step 1 - Drafting table of cause x effect

This step was based on the knowledge about the system. The cause x effect table is shown in Fig. 3a. All values are binary (e.g.: 0=*off*, 1=*on*); except the first column, which defines the number of knowledge cases for the specific SIF-01. The second column defines the critical fault (e.g.: Very High Pressure on Discharge Header) considered for the SIF-01 under study and the remaining columns represent the states values from sensors observed when the critical fault occurred. PSHH-006A, PSHH-006B, and PSHH-006C states are based on thresholds for very high pressure observed via sensors installed in the discharge lines in the natural gas compression station.

CASE	VERY HIGH PRESSURE ON DISCHARGE HEADER	PSHH-006A	PHSS-006B	PSHH-006C
1	*1*	*0*	*1*	*1*
2	*1*	*1*	*0*	*1*
3	*1*	*1*	*1*	*0*
4	*1*	*1*	*1*	*1*

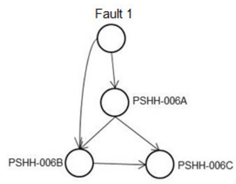


Fig.3. (a) Cause x effect table (b) Resulting BN model for SIF-01 Diagnosis.

Step 2 - Construction of models for diagnosis (cause x effect) based on BN

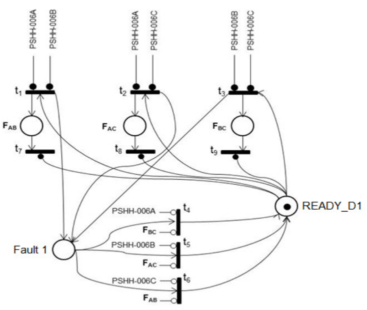
In this work, the learning algorithm K2 (search and score) and also the data from step 1 were used to obtain the initial structure of BN. Furthermore, some restrictions based on human knowledge of relationships between variables were considered. The resulting BN model for SIF-01 diagnosis is shown in Fig.3b.

Step 3 - Conversion from BN models to IPN

The relationship *cause x effect* is:

Fault 1→ (PSHH-06A ^ PSHH-06B) $_{v}$ (PSHH-06A ^ PSHH-06C) $_{v}$ (PSHH-06B ^ PSHH-06C)

Finally, the model of Fig.4awas constructed including the representation of the additional elements necessary to reset the model after no further fault detection and also considering the possibility of a failure be spurious(eg.: the possibility of the diagnosis do not be effected). The places F_{AB}, F_{AC} and F_{BC} represent transient states that may correspond to spurious failures. If the transitions t_4 or t_5 or t_6 are enabled for firing, it means that the signal from sensor is no longer active and therefore, the fault diagnosis should be aborted, returning the system to the initial state (place READY_D1 marked). BesidesFig.4b describes the interpretations given to the model elements.



Element	Description
Enable Arc associated with "PSHH-006A"	*Very High Pressure Deviation in the discharge detect by sensor PIT-006A.*
Enable Arc associated with "PSHH-006B"	*Very High Pressure Deviation in the discharge detect by sensor PIT-006B.*
"Enable Arc associated with "PSHH-006C"	*Very High Pressure Deviation in the discharge detect by sensor PIT-006C.*
Place "F_{AB}"	*Auxiliary memory that transition t1 was fired.*
Place "F_{AC}"	*Auxiliary memory that transition t2 was fired.*
Place "F_{BC}"	*Auxiliary memory that transition t3 was fired.*
Place "READY_D1"	*Model is ready to re-start in case of pressure deviation in the compression station discharge.*
Place "Fault 1"	*Fault Diagnosis due High Pressure Deviation in the compression station discharge.*

Fig.4. (a) SIF-01Diagnosis model based on IPN (b) Description of model Elements

A2 - Critical Fault Treatment and Coordination modeling

Step 1 - SIF identification (critical faults to prevent)

From the risk analysis report in a real situation, 13 SIF's were obtained [15]. In this work, it is only considered SIF-01.

Step 2 - Construction of Treatment Model for each SIF based on IPN

In this step, the treatment model should represent the action to be taken by the SSCA when the SIF-01 is diagnosed. The action should be close valves XV-001/017/019/020 (suction line), close valves XV-003 / 018 (discharge header),and send the shutdown command for the turbo-compressor.

Step 3 - Construction of Coordination models based on IPN for each SIF, according to [15].

B – Integration and Analysis of models

In this step, the models of critical fault diagnosis, treatment, and coordination were integrated to compose the SIF general model of SSCA. After the integration, the following activities were accomplished: (a) The SIF general model was simulated using HPSim to validate safety requirements for preventing faults and it was also verified that the SIF general model is restartable; (b) The properties of liveness and safety were verified for SIF general model based on PIPE2[20].

C – Generation of control programs to prevent fault in critical system

The models for fault critical diagnosis, coordination, and treatment were converted into a control program based on IEC 61131-3. The language used in this example of application was the Ladder Diagram, although, other languages based on the IEC 61131-3 and accepted by IEC 61511 such as Function Block Diagram and, SFC (Sequential Function Chart) also could be used.

D – Acceptance tests
In the first instance, the control programs were tested on-line in a simulation tool based on Siemens PLC technology (e.g.: Simatic S7-300F, where "F" means Fail Safe), and then they were validated in compliance with technical requirements.

6 Conclusions

In the first, a new architecture for the design of safety control system, based on Supervisory Safety Control Architecture (SSCA), was proposed in accordance with standards IEC 61508 and IEC 61511, concerning cooperative and hierarchical layers of control prevention and mitigation of critical faults. In the second, a method for design the layer of risk prevention control system was presented and validated to an application example of a gas compression station, showing to be an efficient method. Furthermore, SSCA will use SOA [12] to work with the new Risk and Hazard control module responsible for the acquisition and maintenance of data for synthesis needs in safety programmable controllers. Finally, some issues must be solved: (a) how to design a layer of risk mitigation based on control system that will be incorporated in the SSCA; (b) how to proceed the dynamic commissioning to ensure effective tests of safety devices in accordance with SIS SLC of IEC 61508. Research is being developed to address these issues.

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