On the Use of CEP in Safety-critical Systems

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Keywords: Safety-critical, CEP, Systems, Event Processing.

Abstract: Safety-critical systems have to continuously manage risks, in order to handle hazardous situations and still be able to fulfil their purpose. While being composed by a variety of software, as well as hardware components, it is necessary for each part of these systems, alone and as a whole, to exhibit a required set of characteristics, necessary to ensure the correct system functioning. Complex Event Processing (CEP) systems have been used in a diversity of applications and, while they focus on fast data gathering and processing as well as in providing intelligence to their users, there is incomplete information about how they are adequate to integrate safety-critical systems. In this paper we investigate if the mainstream off-the-shelf CEP systems are suitable for safety-critical applications. We describe the use of complex event processing engines in safety-critical systems and how some authors enhance those to better correspond to the critical system requirements. We demonstrate that, although dependability is well handled in most CEP systems, the same cannot be assumed about security and safety attributes.

1 INTRODUCTION

Safety-critical systems are projected and designed to be used in avionics, medical devices, automotive braking systems, nuclear power plant management, flight management systems, chemical processes, nuclear power plants and other potentially life threatening systems, when failure in the system endangers human lives directly or indirectly. Therefore, these systems should be able to provide the required safety functions and overall system integrity (Knight, 2002). In order to be able to mitigate the potential impact of hazardous situations, safety-critical systems must be certified by a regulatory agency to ensure their correct operation. Consequently, it is important that systems in use are reliable while it is possible to detect design and functional problems. Also, those should be able to meet some of the most important quality attributes, such as dependability, reliability, safety and security (Malm et al., 2011). It is important to mention that those are complex systems, which are mostly build using different operational modules and systems combined together, such as Complex Event Processing (CEP) systems. CEP systems have been around for quite some time and have been constantly tested, improved and developed (Mendes et al., 2009). Due to the wide range of possible application domains, CEP system capabilities have been constantly improving over the past years. Figure 1 presents an example of a CEP system architecture – ESPER.

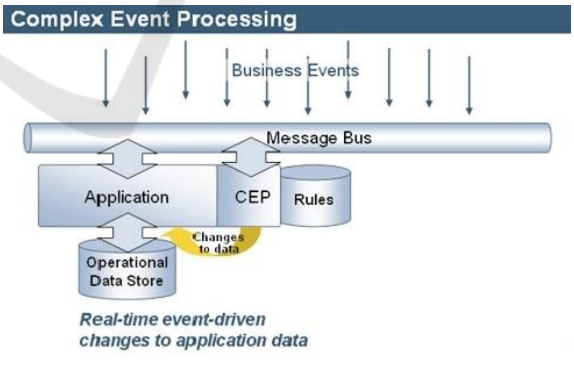

Figure 1: ESPER architecture (Esper, 2016).

Currently they are used in a variety of software systems as a customizable tool for data processing and analysis. These systems have the ability to completely adapt to the desired system purpose and be able to process and present most important data, based on previously defined rules. Therefore, traditionally, CEP systems are part of more complex systems, inside which they are used to process

Abramova, V., Bernardino, J. and Cabral, B.
On the Use of CEP in Safety-critical Systems.
DOI: 10.5220/0006308401020109
In *Proceedings of the 2nd International Conference on Complexity, Future Information Systems and Risk (COMPLEXIS 2017)*, pages 102-109
ISBN: 978-989-758-244-8

incoming information, create alerts based on a collection of rules, and posteriorly provide filtered and summarized data to the final user (Eckert and Bry, 2009). Consequently, those systems are focused on information extraction and processing of important data in real-time environments.

We investigate if current off-the-shelf CEP systems are suitable for usage in safety-critical applications, and are capable of performing designed operations in the required (acceptable) time. As our main contribution, we study some critical systems that use CEP engines, as well the improvements that were made to these CEP engines by some of the authors. We start by identifying the key quality attributes of safety-critical systems and use these to study how some of the available systems manage those requirements. This analysis allowed us to identify different characteristics of CEP systems that require more research.

The remainder of the paper is structured as follows: section 2 presents the state of the art and some of the application areas of CEP systems. Section 3 describes some of the most important quality attributes for safety-critical systems. Section 4 studies the usage of CEP in safety-critical applications and Section 5 evaluates if those quality attributes were considered by the authors and describes possible gaps of usage of CEP in safety-critical systems in some of the existent studies. Finally, Section 6 presents our conclusions and proposes some future research directions.

2 STATE OF THE ART

CEP systems have been used in a large number of systems for data processing and alarm triggering. Although our focus is on safety-critical applications, in this section, to correctly assess the state-of-the-art, we will also consider works reporting on the application of complex event processing in other areas.

For example, (Aidi, 2006) describes some of the most common areas of application of complex event processing systems, where these engines are capable of exploring their full potential. The author presents some of the key benefits brought by those systems. A more focused study is performed by (Oracle, 2012) and (Aidi et al., 2006), who emphasize their approach on financial area and propose solutions using CEP engines. All of the authors state that CEP systems have a high potential for processing data when it arrives and are capable of providing data of interest in a satisfactory amount of time. Since the main goal of CEP is to be agile and efficient in data presentation to the end user, (Cockburn, 2016), (Schmidt et al., 2012) and (Ammon et al., 2009) investigate the efficiency of those systems in alarm triggering and alert management. These authors present the advantages of CEP systems in those cases and describe how those can be tuned to be able to provide all the required information. Those systems may be focused on alarms in dangerous environments as well as noncritical businesses that completely rely on getting information in time. Therefore, (Daum et al., 2012) focused mainly on BPM - Business Process Management Systems and describe if CEP are capable of satisfying all the requirements of those systems.

Healthcare is another highly important area that could potentially take advantages of CEP systems. (Wang et al., 2010) describe real-time healthcare applications and state that CEP engines can efficiently monitor patient behaviour and control medical regulations. Similarly, (Foley and Churcher, 2009) and (Naqishbandi et al., 2015) propose architecture solutions and required characteristics of the systems using complex event processing in healthcare domain. Authors state that CEP engines are highly useful for large and critical data processing and are capable of improving medical systems.

Our work presents some of the available solutions and studies, performed by other authors, which focus on application of CEP engines in safety-critical systems. We attempt describing some of the systems developed by them and some of the authors' conclusions.

3 SAFETY-CRITICAL REQUIREMENTS

While developing a safety-critical system there is a wide range of standards that must be followed as well as system requirements (Bowen and Stavridou, 2002). Those requirements may be also translated into system quality attributes and define the system characteristics without getting deep inside into its functionalities. Currently software systems present, in most cases, a long list of quality attributes (Laranjeiro et al., 2015) and, therefore, we decided to consider in this work the most general ones, which are fundamental in safety-critical systems (see Figure 2).

Figure 2: Quality attributes.

We based our choice on the available standards and attributes presented by (Barbacci et al., 1995), (Sommerville, 2004), (Atoum and Bong, 2015). Therefore, the considered quality attributes are:

- **Dependability.** Can be directly translated into trustworthiness of the developed system and represents the confidence in the correct functioning of its functions. One of the dimensions of dependability is fault tolerance that states that failure in a part of the system cannot compromise the whole system. Also, should be considered the repair capability of the designed system, which describes if the system is capable of recovering without any intervention, as expected.
- **Security.** Ensure that extracted, stored and processed by the system data is not easily intersected or corrupted. There should not be intentional disruption by the third parties. Authentication mechanism is also a requisite since it allows user identification and extends up to the possibility of the system to recognize the configured devices and treat them as trusted. The collected data will be recognized as viable modifications and not by others. System vulnerability should be reduced as much as possible in order to prevent possible harm by attackers and important data exposure.
- **Reliability.** Describes the probability of the system of performing designed operations in expected time. This attribute is tightened with the availability of the system that states that the system should have the ability to work with limited amount of data when it cannot be collected. There should be available backup data collectors that would gather at least part of the necessary data. Therefore, reliability considers not only software but hardware and firmware modules that are required for correct system functioning.
- **Safety.** This is another quality attribute highly related to the reliability. Thus, safety reflects the system's ability to operate, normally or abnormally, without danger of causing human injury or death and without damage to the system's environment. Some of related safety terms are: hazard, damage and risk. All of those are considered by the standards and usually are described as a prevention list of measures instead of qualities.

We believe that, among others, those are some of the most important requirements of critical software. Also, chosen attributes enclose other vital software system characteristics, for example, performance, resilience, availability, etc.

4 CEP IN SAFETY-CRITICAL SYSTEMS

(Baldoni et al., 2015) proposed a solution that combines Complex Event Processing (CEP) and Hidden Markov Models (HMM) to analyse system failures and their symptoms considering specifically defined metrics. The anomalies conditions are detected using the defined rules and creating alert events. CEP provides all the necessary data as well as performance metrics while HMM are used for system state specification and recognition. Authors state that it is important to be able to detect faults in system components in order to be able to prevent the entire system to be compromised. Hence, this work proposes a failure prediction architecture, focused on the traffic control systems, named CASPER. Authors state that CASPER exhibits pretty good accuracy and it is able to generate predictions with a margin of time that allows recovery actions to mitigate the upcoming occurrence of a failure of the system.

Considering usage of CEP in different domains and with increased interest in CEP systems, (Zappia et al., 2012) describe the design and the implementation of a lightweight and extensible Complex Event Processing engine, called LiSEP. During the system design specification, authors were driven by the principle of minimizing dependency on external software components and, therefore, LiSEP depends solely on the Java Standard Edition libraries, thus minimizing deployment requirements. Moreover, the LiSEP logic is strictly focused on core event processing, consequently resulting in a lightweight and minimal implementation. The proposed solution is complemented by the specification of the Event Processing Language, based on the SQL syntax. As a proof of the architecture, authors propose experimenting the use of the LiSEP engine in a case study on dangerous goods monitoring during maritime transport as a part of Italian Ministry for Economic Development research project, called SITMAR - Integrated system for goods maritime transport in multi-modal scenarios. More data-focused approach is presented by (Evchina and Lastra, 2016). This work aims aiding end users of monitoring systems by delivering selected information to each user based on their role in the system. The proposed approach combines Semantic Web (SW) technologies and Complex Event Processing (CEP) for configuration purposes and run-time data processing and analysing. Authors state that final developed solution should be able to provide ways to deal with multiple devices and multiple users of the system; should be reconfigurable to reflect changes in the environment and/or user information needs; and finally, the device updates should be delivered to users within reasonable amount of time. Considering those requirements, the developed approach provides two major advantages. Firstly, the behaviour of the system could be easily changed by configuring only underlying ontology and, secondly, CEP usage at runtime makes system event-driven and reactive to frequent changes in the environment.

(Itria et al., 2014) present an approach for critical situation detection that uses CEP architecture for real time event analysis as well as event correlation. While event analysis consists of data processing, event correlation corresponds to establishing a relation between input events that were gathered from various sources, for detecting patterns and situations of interest in the emergency management context. This solution describes the engine, developed in the context of the Secure! Project (Secure, 2016). That solution has two main requirements: the correlation module has to be adaptable to the possible changes of the source environment, and it has to process available historical data in order to evaluate the actual events considering also what has happened before. After submitting the system for testing, authors state that their approach can be easily used and maintained. It is also extensible to other scenarios where the application requires nearly real-time correlation, like intrusion detection system (Ficco and Romano, 2011) and monitoring of critical infrastructures.

Solution for power grid monitoring using CEP is presented by (Cerullo et al., 2014). Authors claim to be able to provide a detailed treatment of the security issues resulting from the adoption of Wireless Sensor Networks and QoS-enabled IP connections. The proposed solution attempts enhancing current information security and event management technology, by improving its capability of detecting and mitigating attacks targeting the heterogeneous network infrastructure. As an example, in power grid scenario, the attacker may prevent some nodes from sending events to the connected collector, thus hiding changes in the power grid conditions. The WSN security probe generates alarms based on the analysis of the network and periodically calculates the package generation rate at every node and the developed engine is capable of correlating those alarms to protect the visualization server. (Wang and Kuang, 2015) propose a traffic prediction method based on Predictive Complex Event Processing (PreCEP) and Bayesian networks to improve the prediction accuracy. The prediction model is trained with historical data and it is used to predict future events based on the recent output of basic CEP engine. Authors address the prediction problem for moving objects that can be vehicles or even pedestrian and conclude that the performance of PreCEP still needs to be improved. Currently the parallel method only works when learning the structure of models and training models for different context.

Cloud platform monitoring system, JTangCMS - JTang Cloud Monitoring System, is proposed by (Lu et al., 2016). Authors claim that proposed solution can deal with the flexibility, scalability, efficiency and performance challenges of cloud monitoring. The system gathers all the data using dissemination framework that allows transferring huge amount of runtime information with high throughput and low latency using DDS - Data Distribution Service which partitions the input into smaller parts. After transferring all the data, it has to be analysed and, therefore, was developed a decision-making support system using CEP, named JTangCMS. Performed evaluations of the implemented algorithm and DDS-based data delivery system state that JTangCMS is efficient solution and does support intelligent decision making. In (Li et al., 2013) authors propose the overall structure and workflow for a CEP-based monitoring system, which can be applied to a private cloud to alert system failures.

(Bruns et al., 2014) proposed ambulance coordination architecture that provides real-time data processing and deliver comprehensive data to the end users. The developed architecture consists of two core components: CEP and FSM- Finite State Machines. CEP focuses on gathering and analysis of the sensor data streams, emitted by the ambulance in order to automatically detect changes of the operational states defined in the FSM. Authors defend that efficient and fast patient care requires reliable and up to date information and, therefore, present an approach that determines the actual state of all ambulances as well as possible relevant mission incidents. Presented solution attempts completing research of (Brotcorne et al., 2003), (Li et al., 2011), (Ciampolini et al., 2004). (Zappia et al., 2014) also present patient related data and usage of CEP systems in healthcare area. The goal is to use RFID technology to be able to support clinical management of the patients. Proposed solution is focused mainly on the following scenarios: patient identification and tracking, and drug administration. The proposed distributed system is based on event abstraction, event aggregation and event transformation, and uses those to offer a hierarchical and distributed data processing architecture where CEP used data is provided by different processing nodes. Overall, the projected solution, based on CEP and RFID technologies, is used to support clinical risk management by means of detecting possibly dangerous patient conditions as well as patient take care. Solution for critical situation detection in elderly daily life is proposed by (Xu et al., 2014). Authors focus their study on personal assistance as well as possible risks and identification of the required assistance situations. These situations are detected by analysing data received from the sensors. This study is focused on ALL – Ambient Assisted Living technologies and uses sensors to monitor welfare parameters and environmental conditions as described by (Wolf et al., 2009).

Another RFID solution is proposed by (Yao et al., 2011). Authors propose an RFID framework, using CEP, for managing hospital data, gathered from different sources, and try detecting patterns and medically significant events. Therefore, authors created prototypes that attempt showing that CEP has the ability of providing alerts to the healthcare professionals as well as increasing quality of healthcare and patient safety. One of the main goals consists of identifying the patient and tracking all the necessary procedures since there may be mistakes from part of the hospital staff. Also, the use of the system provides all the necessary historical data for emergency handling as well as for health problems and medication identification and response. All of those characteristics show that this approach may reduce errors as well as provide faster and more efficient risk management.

CEP scaling solution for processing CPS - Cyber-Physical System data (Ollesch, 2016) uses elevator example to describe the challenges of CEP technology in a CPS context. One of the main aspects is the calculation of the floor, since it may be calculated wrongly as well as the sensors themselves are subject to errors and can be disturbed (in the example was considered the use of Kinect sensor) since, for example, passengers would obstruct the Kinect sensor. CEP systems are based on rules and using this example was possible to proof that some parts of the system design should be adjusted. Considering Esper system (Esper, 2016) as example, its rules are embedded inside program code and cannot be externalized. Consequently, each change affects the source code of the CEP application. In particular, (Wang et al., 2014) also study Esper as example and define the event process functions, like event attribution extraction and composition determination. Authors investigate the challenges in designing a CEP method for Cyber-Physical System, and propose a semantic enhancement CPS event model. (Balogh et al., 2016) propose a conceptual architecture for system monitoring that ensures the correct behaviour of the system considering a set of different monitoring rules. It was developed a prototype using the VIATRA-CEP Event Processing Language (Viatra, 2016). Posteriorly monitoring rules are distributed over the nodes. System evaluation was based on development and monitoring of safety-critical embedded systems in the railway domain.

(Beer and Heindl, 2007) overview the state of art in testing dependable event-based systems and identify the challenges that have to be addressed in the future. Authors consider two case studies during their testing: large-scale project for business-unit transportation systems and a small-scale telecommunications project for AIRBUS. Authors' main focus is on testing and they state that it is an important topic and cost reduction of testing may be achieved by developing new and more efficient techniques of requirements tracing as well as test-case design and validation. Authors based part of their work on (Luckham, 2002) who proposed CEP usage for managing multiple events and event causality in order to elicit meaningful events in an event-based information system. This is because CEP can analyse incoming data and transform it into out coming events. (Lang and Capík, 2014) present a procedure for performing predictive analysis of complex events occurrence in time critical complex event processing systems. Similarly, to (Tendick et al., 2016), authors state that using CEP it is possible to identify and apply business intelligence rules over the streams of events and this technology is critical in an environment where time plays an important role, such as, real time decision making. Authors analyse the possibilities and use of the available methods and techniques for classification and

Table 1: Quality attributes.

	Dependability	Reliability	Security	Safety
(Baldoni et al., 2015	X		X	
(Zappia et al., 2012)	X			
(Evchina and Lastra, 2016)	X	X		
(Itria et al., 2014)	X			
(Cerullo et al., 2014)	X		X	
(Wang and Kuang, 2015)		X		
(Lu et al., 2016)	X	X		
(Li et al., 2013)	X	X		
(Bruns et al., 2014)		X		
(Zappia et al., 2014)	X			
(Xu et al., 2014)	X			
(Yao et al., 2011)		X		
(Ollesch, 2016)	X			
(Wang et al., 2014)	X			
(Balogh et al., 2016)	X			
(Beer and Heindl, 2007)				X
(Lang and Capík, 2014)		X		

prediction in complex event processing. For this purpose, it was designed and implemented an application CepPredictiveAnalysis, which uses defined methods for predictions and despite certain limitations, the system gives acceptable accuracy in financially-oriented applications.

Over the next section we present our analysis of the described solutions, concerning previously stated quality attributes.

5 REQUIREMENTS ANALYSIS

After briefly describing the considered quality attributes in Section 2, we consider that it is important to confirm whether described systems and solutions of CEP systems in safety-critical applications consider any of those.

The summary of quality attributes analysis is presented in Table 1. It is important to notice that some of the solutions may have partially addressed some of the quality attributes, but we just consider overall approach and the authors focus and goals in the designed architecture.

The summary of quality attributes analysis is presented in Table 1. It is important to notice that some of the solutions may have partially addressed some of the quality attributes, but we just consider overall approach and the authors focus and goals in the designed architecture.

After analysing the results, we concluded that most of the systems are focused on their performance and operability and do not consider safety neither security. Those quality attributes are often considered less important than assuring system proper functioning or performance. Most of the authors, as expected, consider the proper functioning of their systems and focus on Dependability and Reliability attributes. Those are more functional characteristics and any designed and developed system is expected to work as intended. Some of the authors consider how their system is affected by security attributes and if their data is secure and only one study considers risk and hazardous situations management and system awareness of those. It is important to notice that we performed our analysis of quality attributes based on authors' description and designed system specifications.

Though, some of the described works may provide parts of considered by us quality attributes, but those were not mentioned. Also, although we just have one level analysis, as previously stated, we investigated authors' main focus and what their work was trying to achieve.

6 CONCLUSIONS AND FUTURE DIRECTIONS

Safety-critical systems are necessary to perform critical operations if safe environment that will not endanger any life or property. Thus, those systems should be carefully designed and have a set of qualities and characteristics that would attempt ensuring their proper functioning. In this paper we present some of the most important studies that incorporate the use of CEP engines in software-critical systems. We describe performed studies and some of the authors main goals and conclusions. After considering the main system characteristics and quality attributes we attempt investigate which of those are considered in the selected investigations.

We conclude that there are some characteristics, which are highly important, that are not considered by all the authors. Those may have high impact while dealing with critical data as well when processing received information. Both safety and security are focused on providing correct system data by concerning authenticity of the received information, system components safekeeping. Our goal was to analyse some of the available solutions of application of CEP engines in safety-critical environments and describe some of the most common areas where those are used. We believe that there are still some system characteristics that have not been fully covered by existing works and we presented two of those, namely, safety and security.

After concluding our research and while considering the results, we believe that security and safety are equally important quality attributes and have been neglected by some of the available solutions. Therefore, as our future research direction, we will investigate some of the mechanisms that should be considered in safety-critical systems and that would provide necessary system safety. Currently, there are some protection mechanisms that are already used by most of the developed systems, such as, authentication, data encryption, safe connections, hardware authentication and register, etc. As future work we consider investigating methods from which safety-critical systems could benefit and that would not compromise systems performance.

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