Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Towards Intelligent Maintenance Systems: Rescuing Human Operator and Context Factors

Silvia S. C. Botelho*, Achim Rettberg, Nelson Duarte Filho*, Bernd Hellingrath****, Marcos Amaral* , Danúbia Espíndola*, Carlos Eduardo Pereira***, Ann-Kristin Cordes****, Renato Ventura ***, Enzo Frazzon*******

* Federal University of Rio Grande, FURG, RS, Brazil
(Tel: +55 53 32336875; e-mail: silviacb, dmtnldf, danubiaespindola@furg.br)
**University Oldenburg, Oldenburg, Germany (e-mail: achim.rettberg@offis.de)
***Federal Universiy of Rio Grande do Sul, UFRGS, RS, Brazil
(e-mail:cpereira, rventura@ece.ufrgs.br)
****University of Muenster, Muenster, Germany
(email: hellingrath@ercis.uni-muenster.de, ann-kristin.cordes@wi.uni-muenster.de)
*****Federal University of Santa Catarina, Florianópolis, Brazil
(email: enzo@deps.ufsc.br)

Abstract: Current technologies have used embedded devices for degradation monitoring based on Condition-Based Maintenance (CBM) paradigm for critical parts of equipments. Intelligent Maintenance Systems (IMS) have been proposed in order to autonomously provide failure predictions through data acquisition from sensors. This paper intends to discuss how to capture the operator skill and environment conditions into the IMS. We have adapted the data flow in CBM classical architecture in order to consider the resultant information from maintenance operations associated with the technical teams and their contexts. For this purpose was used a Cyber-Physical Systems (CPS) approach to consider human and context factors. Considering the CPS as system that combines and coordinates physical and computational elements, the CPS incorporates the ability to act in the physical world with the intelligence from cyber or virtual world. In this paper, we propose to use a CPS for taking account human/context factors applied maintenance strategies. The proposed tool, called Toogle-IMS, aims at developing an advanced Human-Computer Interaction (HCI) applied to Intelligent Maintenance System (IMS). We have applied the Toogle-IMS in two case studies associated with: *i.* mobile robots in maintenance and *ii.* mobile trucks in shipyards.

Keywords: Intelligent Maintenance System, Condition-Based Maintenance, Human-Computer Interaction, Cyber-Physical System.

1. INTRODUCTION

The *Condition-Based Maintenance systems* (CBM) apply predictive techniques to avoid unforeseen breakdown of equipments. This kind of systems predicts where, when and why the failure will occurs Qiang, Li. CBM systems are often used in equipments which breakdown impacts directly the production line. *Intelligent Maintenance Systems* (IMS) combines signal processing in sensors data for equipment condition analysis. This shift from the traditional systems based on corrective and preventive maintenance to predictive systems is indicated to critical component/parts of machines (Muller et al (2007), You et al (2011)).

Critical components are considered those parts requiring to be monitored by IMS, otherwise the machines responsible by production break unexpectedly. So, the role of sensor networks and computational forecasting systems are constantly monitoring the equipments, providing support to repair and maintenance decisions before the failure happens (Peysson et al (2007)).

On the other hand the maintenance technicians still holds many of the information associated with the operation of the equipment. The manner in which they perform repair activities may result in different future demands for maintenance. Intrinsic human factors and extrinsic environment context are determining factors in activities of repair and diagnostic for future maintenance.

Thus the rescue of the operator role and the addition of context information to the monitoring, intelligent diagnosis and prediction can contribute to improve the CBM approaches, enhancing the requirements of cost, time and quality of the processes.

In this context the challenge is to combine digital and numerical information from monitored equipments (virtual components) with qualitative and subjective perceptions from users and context (real components). What factors should be perceived? How to perceive them? How to integrate these real impressions to the system? These are some open questions.

In recent years technological advances are leading to new relationships between humans and machines. New digitally supported environments arise allowing different agents (real and virtual) to interact in a way previously unimaginable. In this new scenario there are new theories, methodologies, techniques and tools from different areas related to Human-Computer Interaction that should be urgently be designed in order to insert the human/context as a living sensor in industrial operating systems.

In this sense different objects equipped with embedded computing can interact each other. They can sense and adapt to the environment in a transparent manner, making the *Human-machine interface* (HMI) simpler (Chattopadhyay, D.; Dasgupta, R., 2012).

Researches on ubiquitous computing seek models for the interconnection of "things" (objects, computers, animals, people, etc.) in a network, similar to the devices today already interconnected through Internet (Huang, Y. and Li, G., (2010), Koshizuka, N. and Sakamura, K. (2010), Koshizuka, N. and Sakamura, K. (2010)).

More recently a new approach has emerged, coining the term *Cyber-Physical Systems* (CPS) (Lee, E. (2008)). A CPS is a system that combines and coordinates physical and computational elements (Ying, M. (2010)). The CPS integrates the ability to act in the physical world and the intelligence from cyber world (virtual), adding a new HCI and resources to real world systems (Shunqing Y., et al (2012)). Among several possible applications of CPS systems are the medical, education, industrial areas. (Jianhua, S (2011)).

Considering the perspective where the maintenance tasks have technical and human features, this work focuses in the human features. Human factors associated with the maintenance management play an important role in improving the efficiency and effectiveness of maintenance processes. The operator teams have lots of knowledge about the system to be repaired which cannot be obtained solely through data analysis of sensors (Pophaley, M. and Vyas, R. (2013)), (Choi, B. and Kim, B. (2000)).

We propose a HCI interface for IMS focusing on how CPS can (re)introduce the human and context factors in maintenance activities. The human factors role in maintenance activities need to be clarified to ensure better understanding and integration of the individual knowledge and capabilities of the service personnel. This can lead to an IMS in which this information might be acquired and used for the planning of maintenance processes and forecasting the demand for spare parts in factory floor.

The idea is to integrate knowledge and ability of the service personnel into the IMS. For this it was developed an user interface that is suitable for meeting the integration requirements between human/context and IMS. The idea aims to explore the CPS concepts and how the human knowledge and ability can be integrated into the IMS in order to support the planning and the collaboration between the different actors for maximize the responsiveness and the skills of the IMS.

Advanced techniques in Virtual Reality and Sensor Networks were used to allow taking into account human factors in the maintenance activities. The proposed CPS for Human-Computer Interaction is based on a so-called *Toogle* platform that has four main sub-systems: (i) Middleware and Components; (ii) Editor Module; (iii) Decision Module; (iv) Browser Module.

We use the Editor to create and edit the different components (real and virtual) of the maintenance scenario, which is called *hyper-environment* with its components interconnected through the Middleware. The Intelligent Decision module gathers a set of applications related to the prediction maintenance. At last the Browser module allows visualization of different multi-modal information in the system.

The paper structure is organized in five sections: after the introduction we identity which modules of CBM architecture have connection with human operators (section 2). Section 3 presents the proposed system implementation to integrate both issues (IMS and human/context factors by CPS). Some experiments with the proposed system (section 4) and the conclusions of the paper (section 5) are finally presented.

2. CONDITION-BASED MAINTENANCE

The system development for *Condition-Based Maintenance* (CBM) should include the integration of a wide variety of hardware and software components.

The *Open System Architecure* for Condition-Based Maintenance, which provides a framework for systems implementation based on working condition of equipments [Lebold (2001)] was enhanced by Machinery Information Management Open Standards Alliance called MIMOSA. This alliance standard the CBM processes in following way:

- Data acquisition: converts an output from the transducer into a digital parameter;
- Data manipulation: performs the signal analysis, calculates significant descriptors and provides the virtual sensor readings from the measurements obtained;
- Condition monitor/state detection: provides normal "profiles", search for abnormalities whenever new data is acquired, and determines to which area of abnormality, if applicable, the data belong;
- Health assessment: provides fault diagnosis and rates of current health of the equipment or process, considering all state information;
- Prognostic assessment: determines future health states and failure modes based on the current assessment of health and use estimation of future demand for equipment and/or process, as well as the remaining useful life;
- Automatic decision reasoning/advice generation: provides practical information on maintaining.

Our concerning is about the interaction issues of OSA-CBM which, it means that data provision by HCI can not be apply directly to condition monitor module, for instance. In this paper we intended to develop a solution for implantation of a system that can rescue and add human and context factors in all architecture modules. The next section discusses the requirements for this purpose.

3. FUNCTIONAL REQUIREMENT

In order to take into account the human factors in IMS approaches, technical and social issues must to be treated. For instance, how to schedule functions among service personnel is an important question. Another key issue is how to design a human-oriented software system or HCI to capitalize on and capture human skills in perception, attention and cognition, while minimizing the effects of human error. The decision support for operator should be designed such that operations are skill-based commands and some are rule-based commands.

From the IMS and HCI specification, a set of functional requirements for this human-centered IMS may be identified as follows:

- Responsiveness;
- Knowledge and resources sharing with other agents/users;
- Access to existing information;
- Results dissemination;
- Development a creative environment for generates and introduces new information to the system from the skill of service personal.

Some input and output data can be classified as:

- Location of the technical system;
- Product ID;
- Bill of material;
- Damaged part(s) identified in the bill of material and/or in the HCI visualization via mobile device;
- Required skills and equipment;
- Description of the problem;
- Failure reasons caused by environment;
- Breakdown probability date (estimated).

The HCI-IMS proposed here might be informally defined as a "cyberspace structure for planning, control and communication to support human decision-making via monitoring and simulation of maintenance condition through modeling of all activities and resources in a physical maintenance system". The CPS for HCI-IMS works as a design tool or as an operational tool once that is possible setting the scenario intended. As design tool, the function is prototype Virtual Manufacturing Systems (VMS) and this module can be called *Editor HCI-IMS*; as operational tool, the function will be to simulate and control Manufacturing Systems by VMS and the module can be called *Operational HCI-IMS*.

In order to capture the environment context, this approach will use advanced computational technologies associated with the intelligent environments concept. These technologies are distributed on sensors-actuators through heterogeneous systems including: multimedia presentation services, automation and control components, intelligent physical objects, nodes of wireless sensor network, nomadic operator, shared devices, and many other systems and entities in a CPS.

This way, it was implemented the CPS concept through the *Toogle* tool, which supports the merge between various technological elements and their virtual representation, giving to designers and developers the necessary support for the creation of intelligent environments.

4. TOOGLE PLATFORM

The *Toogle* platform was proposed as a technological architecture for HCI-IMS applications. It uses ROS (Robot Operating System) (Morgan, Q. et al (2009)) for communication between real devices and virtual world. Moreover, it uses Blender 3D rendering software (Roosendaal, T. (2004)) as object visualization tool for virtual-real environment of industry. The Figure 1 shows the modules that compose the platform architecture.

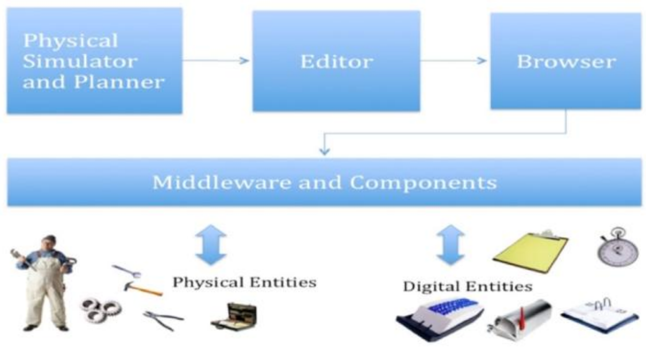

Fig. 1. Toogle platform architecture.

4.1 Middleware and Components

An IMS scenario is composed by real and virtual elements that can be grouped on the following categories:

- Physical Entities: workers, equipments, tools, etc. It can be accessed by *devices* (sensors, actuators and tags); and
- Digital Entities: a set of *services* associated with logs, scheduling, digital applications, etc.

The *Toogle* Components abstract the physical and virtual entities resulting in an *identifier* with a set of associated *properties* and *resources* available. Physical entities that have some embedded processing are called *Smart Objects*. The *Toggle* Middleware is responsible by communication between the components. It is composed by the ROS system. The ROS has a set of drivers for different sensors and equipments. In order to describe the CPS for HCI-IMS we embedded some sensors in the physical components. This way, each *Smart Object* and *Digital Entity* was represented by computing process, which can run in different machines. The Middleware allows synchronous and asynchronous communication.

4.2 Toogle Editor

The *Toogle* Editor allows building and editing cyber-physical environments, providing navigability and interaction with the information provided by *smart objects* and *digital entities*. The module allows adding and removing components (i.e smart objects and digital entities). Moreover it is possible to edit the features of these components, i.e, their properties, resources (devices and services) and 3D representation. For 3D representation the *Toogle* Editor uses the Blender tool that is an open source and multiplatform system. Figure 2 show a screenshot of the *Toogle* Editor.

Fig. 2. Toogle Editor.

An IMS scenario is composed by a set of components. Digital Entities (technical reports, tutorials, datalogs, prediction, planning) and smart objects (workers, tools, equipments) compose a hyper-environment that can define the maintenance goals (optional). Toogle uses a STRIPS-like formalism to describe properties, resources and goals in hyper-environments (Fikes, R (1972)).

4.3 Toogle Intelligent Decision Module

This module provides intelligent decision-making for IMS. We can add different tools and services to allow prediction and diagnostic of maintenance.

Currently the *Toogle* provides two distinct services:

- *Toogle* Physics Simulation: it allows realism and high performance for physical simulations, through updating of smart object properties. It module uses Bullet open source library, which uses OpenGL for real time rendering[1]; It has mechanisms for collision detection and rigid body dynamics. The physical simulator makes it possible to simulate objects that can fall, roll and collide with other objects, all with a realistic appearance. Aspects of scene lighting make use of GLSL and Pixel Shaders techniques;
- *Toogle* Planning: a strips planning is used to achieve the hyper-environments goals.

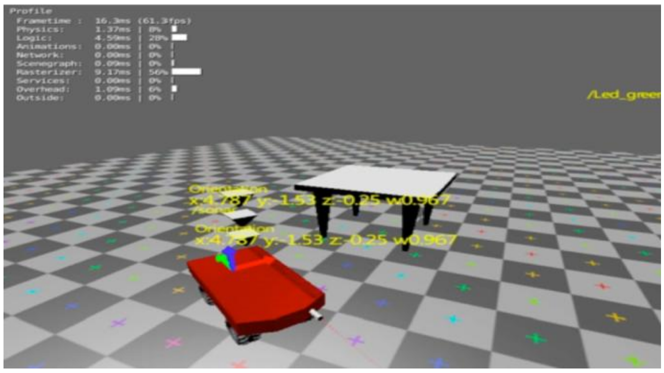

Fig. 3. Physical Simulator.

4.4 Toogle Browser

The *Toogle* browser allows the distributed and remote access and the data visualization that has been created by the *Toogle* Editor. It is possible browser for hyper-environments – their smart objects and digital entities. The *Toogle* Browser is a multi-modal viewer with a 3D scenario where a replica of a real world scenario can be seen, according to the connections created in Editor. An multi-projection interface in a CAVE device is also available. This interface allows an immersive visualization of hyper-environments. The Figure 4 shows a screenshot of Browser running in CAVE.

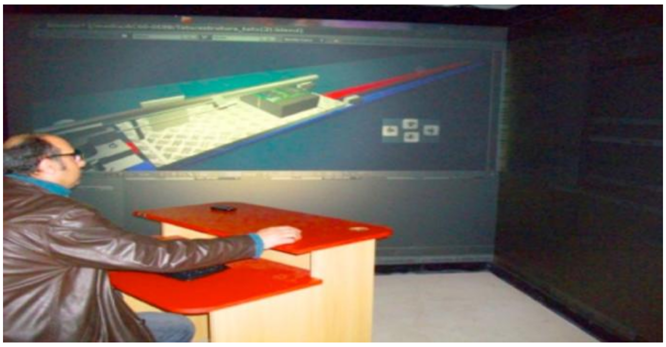

Fig. 4. Toogle Browser.

The *Toogle* proposal explicitly considers the possibility of co-existence of virtual and real worlds for advanced HCI, focusing on the study of a large device scalability crossing/interfacing between them. The architecture model and implementation of *Toogle* as well as their autonomy and intelligence are being tested and validated in different scenarios involving heterogeneous devices for high scalability.

The HCI-IMS implementation intends to combine technologies and techniques in order to exploit and enhance

[1] Bullet Physics Library. http://www.bulletphysics.com.

the human-knowledge and capabilities of the service personnel. The service personnel and technicians have available multi-modal interface, 3D immersive experiences in mixed physical-virtual worlds, including interaction with large surface displays, smart mobile devices, and wearable computers. As result, the human/context interaction for IMS will become significantly more natural, intuitive, and spontaneous than it is today.

5. TESTS AND RESULTS

The platform has been tested and validated in two case studies. Real and virtual components compose the hyper-environment associated with the perception and integration of human and context factors to monitoring, diagnosis and prognosis of equipment maintenance. The next sub-sections present each experiment.

5.1 Mobile Robot Maintenance

In this experiment we adopt as equipment to be repaired a mobile robot. This robot is considered a complex system for achievement maintenance activity. The equipment is fitted with several sensors and actuators. It was test a collaborative task of maintenance with a team of technicians to repair the robot.

A. Components and Middleware

The experiment consists of the following components (equipment, humans and context) see Figure 5: (i) Smart objects: mobile robot, operator, toolbox and tools, tablets and computers; (ii) Devices: global and local cameras, GPS, RFID; and (iii) Digital entities: tracking, logs, and scheduler.

Fig. 5. Physical entities of case study: mobile robot, operators, tools, toolbox, tablets and cameras.

B. Editing hyper-environment

We have used the editor to create the components (*smart objects* and *digital entities*) and the context. Each component has a set of *properties* (position, charge level, on/off state, owner, etc) and *resources*. *Resources* describe *devices* (cameras, GPS and RFIDs) and *services* (logs, trackers and scheduling). Strips-like predicates describe the *properties* and main *goals* to be achieved. Strips-like actions describe the *resources*. *Smart object* have a 3D representation.

C. Toogle Intelligent Decision Module

We have used Bullet Physical Simulator to forecast the physical behavior of smart objects. mGTP planner (Bonet, B. (2011)) was used to plan a set of actions to achieve maintenance goals.

D. Toogle Browser

The Figure 6 shows a screenshot multi-modal representation of hyper-environment. The browser allows accessing the different properties on real time. For instance: location of the technical system and team, objects ID, bill of material, images from damaged parts, videos and procedures from used team skills and equipment, description of the problem, maintenance forecast, can be shown by HCI.

Fig. 6. Browsing in a Mobile Robot Maintenance Hyper-environment.

5.2 Monitoring trucks in shipyards

The *Toogle* platform was applied also case study related to the shipping industry. The case study was associated with the monitoring and truck repair in shipyards. We used a methodology similar to that applied in the previous example.

The trucks and workers were tracking with the use of Radio Frequency Identification (RFID). The *Toogle* Editor created the components needed and their properties, resources and 3D representations. The Figure 7 shows a screenshot of the hyper-environment obtained. The prototype was tested and validated, generating a database with the activities performed by all operators of the equipments and the positioning of the equipments and trucks.

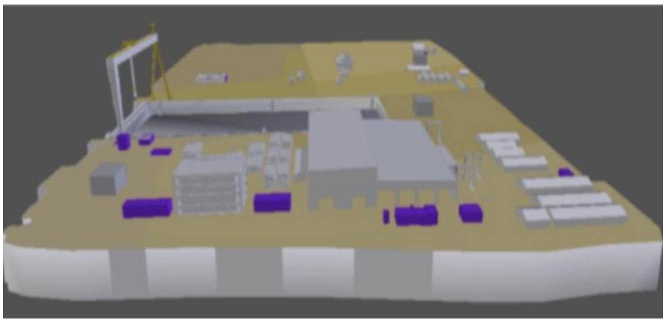

Fig. 7. Shipyard hyper-environment.

In both case studies, the real and virtual components are mixed aiming to improve the topics associated with responsiveness, knowledge and resources sharing with other agents/users, access to existing information, dissemination of results, and providing a creative environment for generate and introduce new information to the system.

6. CONCLUSIONS

This paper presented advanced technologies through CPS for HCI in Intelligent Maintenance Systems. We have proposed a CPS approach for rescuing/adding the operator/context in CBM systems.

We have presented the hyper-environment concept, which is formalism for hybrid world maintenance scenario description. Toggle is a CPS platform to design hyper-environments. It is composed by Middleware and Components (Smart Objects, Digital Entities and ROS); Editor (Multi-modal editor, Blender, STRIP-like description; Intelligent Decision (Physical Simulator and Planner) and Browser (multiplatform, mobile, stereoscopy, multi-projection).

Future works intends to do more tests on IMS scenarios, to treat usability and friendliness issues, and finally to improve the system intelligence through a recognize system for complex events (Younger, S (2012)).

ACKNOWLEDGMENTS

The research leading to these results have received funding from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) in cooperation project, between Brazil and Germany – BRAGECRIM, named Integrating Intelligent Maintenance Systems and Spare Parts Supply Chains (I2MS2C) in the visualization context. These results were achieved between FURG, UFRGS, UFSC and WWU teams in collaboration with University of Oldenburg.

REFERENCES

A.H.C Tsang (1995). *Condition-based maintenance: tools and decision making*, Journal of Quality in Maintenance Engineering 1 (3) (1995), pp-1355–2511.

Bonet, B. and Geffner, H. (2011). *mGPT: A probabilistic planner based on heuristic search*. arXiv preprint arXiv:1109.2153.

Chattopadhyay, D.; Dasgupta, R., (2012). *A novel comprehensive sensor model for cyber physical system: Interoperability for heterogeneous sensor*, Sensing Technology (ICST), 2012 Sixth International Conference on vol., no., pp.179,183.

Choi, B. and Kim, B. (2000). *A Human-Centered VMS Architecture for Next Generation Manufacturing*, Proceedings of 2000 International CIRP Design Seminar (Haifa, Israel, May 16-18, 2000), pp. 169-174.

Fikes, R. E., and Nils J. N. (1972). *STRIPS: A new approach to the application of theorem proving to problem solving*. Artificial intelligence 2.3 (1972): pp- 189-208.

Henderson, S. and Feiner, S. (2010). *Opportunistic Tangible User Interfaces for Augmented Reality*. In IEEE Transactions on Visualization and Computer Graphics, pp. 4-16.

Huang, Y. and Li, G. (2010). *Descriptive models for /internet of things, in Intelligent Control and Information Processing* (ICICIP), 2010 International Conference on, 2010, pp. 483–486.

Koshizuka, N. and Sakamura, K. (2010). *Ubiquitous id: Standards for ubiquitous computing and the internet of things*, Pervasive Computing, IEEE, vol. 9, no. 4, pp. 98 – 101.

Lebold, M. and Thurston, M. (2001). *Open standards for condition-based maintenance and prognostic system*. In: Proceedings of MARCON 2001 – Fifth annual maintenance and reliability conference, Gatlinburg, USA, 2001, pp-6-9.

Lee, E. (2008). *Cyber Physical Systems: Design Challenges*. University of California, Berkeley Technical Report No. UCB/EECS-2008-8. Retrieved 2008-06-07, pp-363-369.

Muller, A and Marquez, A and B. Iung, (2007). *On the concept of e-maintenance:Review and current research*, In Reliability Engineering and System Safety, pp. 1165–1187.

Peysson F. et al. (2007). *New Approach to Prognostic Systems Failures*. In: Proceedings of the 17th IFAC World Congress.

Pophaley, M. and Vyas, R. (2013). *Plant maintenance management practices in automobile industries: A retrospective and literature review*, JIEM, 2010 – 3(3): Online ISSN: 2013-0953 Print ISSN: 2013-8423, pp. 512-541.

Qiang, L., Weijun, Q., Bing, H., Ruicong W., Limin S. (2011). *A case study on REST-style architecture for cyber-physical systems: Restful smart gateway*. Comput. Sci. Inf. Syst 01/2011; 8:1317-1329. pp. 1317-1329.

Quigley, M., Gerkey, B., Conley, K., Faust, J. (2009). *ROS: an open-source Robot Operating System*. Tully Foote, Jeremy Leibs, Eric Berger, Rob Wheeler, Andrew Ng. ICRA Workshop on Open Source Software, 2009.

Roosendaal, T., and Stefano S., (2004). The Official Blender 2.3 guide: *Free 3D creation suite for modeling, animation, and rendering*. Vol. 3. No Starch Press, 2004.

Shi, J.; Wan, J.; Yan, H.; Suo, H. (2011). *A survey of Cyber-Physical Systems*, Wireless Communications and Signal Processing (WCSP), 2011 International Conference on , vol., no., 9-11 Nov. 2011 doi: 10.1109/WCSP.2011.6096958, pp-1-6.

Shunqing Yan, Yongxin Zhu, Qiannan Zhang, Qin Wang, Ming Ni, Guangwei Xie, (2012). *A Case Study of CPNS Intelligence: Provenance Reasoning over Tracing Cross Contamination in Food Supply Chain*, 32nd International Conference on Distributed Computing Systems Workshops, pp. 330-335.

Ying, T., Mehmet, C. Vuran, S.G., Yue, Y., Song, M. and Ren, S. (2010). *A concept lattice-based event model for Cyber-Physical Systems*. In Proceedings of the 1st ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS '10). ACM, New York, NY, USA, pp-50-60.

You, M., Li, L., Meng, G., and Ni, J. (2010). *Cost-Effective Updated Sequential Predictive Maintenance Policy for Continuously Monitored Degrading Systems*. In IEEE Transactions on Automation Science and Engineering. pp. 257-265.