CHEMICAL ENGINEERING TRANSACTIONS

VOL. 67, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Valerio Cozzani, Bruno Fabiano, Davide Manca

ISBN 978-88-95608-64-8; **ISSN** 2283-9216

DOI: 10.3303/CET1867009

Improving Safety of Process Plants, through Smart Systems for Critical Equipment Monitoring

Paolo Bragatto, Silvia Maria Ansaldi, Canio Mennuti

INAIL- Dipartimento Innovazioni Tecnologiche e Sicurezza degli Impianti, Prodotti e Insediamenti Antropici – Centro Ricerche - Via di Fontana Candida, 1 – 00078 Monteporzio Catone (RM), Italy
Paolo.bragatto@inail.it

In the last years there has been a considerable development of wireless sensors based on technologies that allow machine-to-machine communication, thus to talk about the "Internet of Things" IoT and "smart systems". Many industries, such as manufacturing and construction, are adopting smart technologies for improving all the production activities, including safety. The research laboratories have developed many Smart Safety System SSS. Many Commercial provider are already selling SSS even though the actual benefits are not yet so clear. The paper focuses on the establishments that handle hazardous chemical materials and fall under the Directive 2012/18/EU Seveso III, which requires a quantitative assessment of the risk. The goal of the paper is to assess how the use of SSS applied to critical equipment can improve the safety, reducing the likelihood of incidents occurrence or mitigating the consequences related to the loss of containment of hazardous substances. The paper proposes a method, based on some primary criteria, useful for the stakeholders to address the choice of the SSS and to assess the benefits for risk reduction. Several examples, described in the paper, show solutions of smart systems able to monitor critical equipment on more frequent mechanisms of damage, including corrosion, erosion, thinning, structural defects, and vibration anomalies. The SSS provide the operators with a huge amount of data, which may be integrated with adequate information and sound knowledge, so that to make possible a dynamic management of the risk.

1. Introduction

The adoption of the SSS (Smart Safety System) at workplace may be very useful, but a careful evaluation of the potential benefits as well as of the limits and drawbacks. At the Seveso sites, the risk analysis must be quantitative, despite the other occupational contexts, where just a qualitative risk assessment is required. Thus, the operator of a Seveso establishment must investigate the potential of the new SSS, evaluate in a quantitative way the expected benefits and eventually adopt them to control the hazard of major accident.
The control bodies must evaluate the risk analysis proposed by the managers and eventually prescribe additional systems, considering also innovative solutions, such as the SSS. The control bodies, moreover, periodically visit the sites, to see if the SMS (Safety Management System) is adequate to control the major accident hazard and if there is room for improvement. Even in these situations, it is important to understand whether the SMS takes advantage of the adopted SSS. Thus, the evaluation of the SSS is important for managers and regulators. The authors made a first attempt to classify SSS (Ansaldi et al. 2017). In the present article the method has been definitely revised and different systems has been included in the sample set. The article is divided into four sections, dedicated respectively to the objectives, the evaluation criteria, to the description of some relevant monitoring systems, to the integration of the monitoring systems within the risk management.

2. Objectives

The research is aimed at understanding whether and how the use of the "smart safety systems" SSS can prevent the loss of dangerous substances or mitigate their consequences. The inventors, developers and sellers argue, of course, that SSS systems bring dynamism into safety management, reducing the possibility of human error, warn of dangerous situations in advance and increase efficiency in the emergency. We do not

Please cite this article as: Bragatto P., Ansaldi S.M., Mennuti C., 2018, Improving safety of process plants, through smart systems for critical equipment monitoring, Chemical Engineering Transactions, 67, 49-54 DOI: 10.3303/CET1867009

intend to disprove this optimism, since, however, we are talking about the danger of a major accident, caution is a “must” and we need to reason always in a quantitative way.
To meet the need to be "quantitative", we must answer to two essential research question:
1) How select an SSS and integrate it in the SMS.
2) How take into account of an SSS in the quantitative risk assessment, according to the common practice of the Seveso Directive.

3. Criteria

To assess the impact of adopting Smart Safety Systems (SSS), in order to reduce risks or mitigate the consequences, two basic criteria have been identified: applicability and reliability. Each criterion establishes four levels in ascending order from 1 to 4.

3.1 Applicability criterion

With this criterion we want to answer two questions:

1. The system is certainly innovative, but how much is consolidated so that to be able to trust?
2. How much the management system is able to incorporate this innovation?

Technological and commercial availability of smart solutions and the ability of organizations to exploit them must be seen together. The more dynamic is an organization, the more it is ready to accept innovative solutions. For technological availability, three levels have been identified: industrial prototype, innovative commercial product, consolidated commercial product.
Although the SMS are mandatory in the Seveso establishments, their characteristics vary according to the organization. Three levels of SMS have been identified: only basic procedures, compliant systems (or certificates) according to recognized standards, dynamic SMS that can react in real time the information acquired by the SSS. This implies a deep renewal of the SMS, from a document system to a dynamic management system of information and knowledge. There are no standard definitions for "smart" SMS yet, but systems based on risk analysis, adopted in industry for specific purposes (e.g. risk based inspection or maintenance), are good examples of "intelligent systems". They are built on a solid knowledge of a complex physical and chemical mechanism, continually tuned through the measurement data, according to a Bayesian approach. In the end, an SMS is considered "intelligent" if it has the capacity to collect and discriminate huge amounts of data and to update data in information, possibly assisted by soft computing techniques. Table 1 illustrates the levels as a combination of the two factors, the technological levels and the capacities of the SGS.

Table 1 Applicability Criterion. The score ranges from 1 to 4. The higher the better.

SSS readiness	3 consolidated commercial	2	3	4
	2 innovative commercial	1	2	3
	1 industrial prototype	0	1	2
		1 basic	2 certified	3 dynamic
		SMS Dynamism		

3.2 Reliability Criteria

The reliability criterion answers two questions

1. How long will the system work without failures?
2. Will the system really provide the requested service?

A generic SSS is featuring a few electronic components or subsystems, which provide services for identification, transmission, reception and processing of data. The failure of an individual electronic component is, of course, possible. Even more important is the ability to provide the required services.
As in the context of industrial applications, a lot of space is given to SSS for monitoring the integrity and functionality of critical equipment, including vessels, pipes and rotating machines, so we deal with these systems in more detail. In this case the required service is to detect, characterize and discriminate defects by type and size. We must therefore also consider the occurrence that significant defects are not detected.
The Probability of Detection PoD varies according to the size of the defect. The ideal control technique is that which allows to discriminate all the larger defects of a given value defined a priori as the minimum detectable defect a_{NDE}, ignoring the smaller ones. A selective capacity of this type is absolutely ideal and no real system makes it possible to obtain such a clear distinction, which means that the characteristic trend of a PoD curve is continuous, of the type indicated in fig.1. Generally, the minimum detectable defect is considered to be the

one corresponding to a probability of detection of 90%. Measurements taken with smart systems provide indirect measures, this means that the positive signals could also be unequivocally correlated to defects but be generated by non-relevant factors such as the geometric variations of the piece, the surface state, the intergranular structure, etc. These signals constitute the so-called background noise characteristic of any Non Destructive Technique NDT, which uses electronic, optical, or other systems.
A monitoring system is considered reliable when it can operate without failures and intercept the relevant defects. In other words we must consider the probability of electronic failure PoF and the probability of detection PoD. The overall reliability of the SSS, understood as the probability of success in the assigned mission is

$$R = (1- PoF) * PoD \quad (1)$$

The PoF is related to the redundancy, to the need of human intervention as well as to the quality standard and certification adopted by the producer.

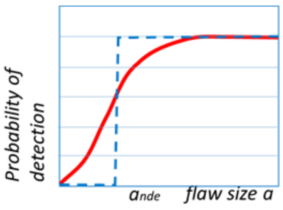

Figure 1: POD curve

In order to select the SSS, the Reliability has been classified according the Table 2.

Table 2 Reliability Level. The score Ranges from 1 to 4. The Higher the Better.

4	All defects are detected long before becoming dangerous
3	All defects are detected before becoming dangerous
2	Most defects are detected before they become dangerous
1	A good number of defects are detected before they become dangerous

4. Smart systems for monitoring: some examples

In this section a few examples of SSS relevant for equipment monitoring and accident prevention are discussed.

4.1 Erosion Acoustic Monitoring

The problem of erosion in oil industry is growing due to both the characteristics of the crude (suspended sand, salinity) and the characteristics of carbon steel (carbon steel), adopted in the pipelines for cost savings, which is vulnerable to salt water. Non-intrusive Sand Monitoring Technologies use Acoustic sensors. These systems measure the noise impacts, noise and the number of particles present both for crude oil and for gas. These solutions have already been installed in off-shore installations and in refineries (Wold and Carugo 2017). The problem of erosion is also present for other fluids, linked both to the presence of particulate material and to the phenomena of turbulence. However, these are now accepted and consolidated solutions, available at acceptable costs.

4.2 UT for Thickness Monitoring

Thinning is one of the most common effects of many corrosion phenomena. The thickness of pressure equipment, including pipes, reactors and heat exchangers, must be periodically inspected to prevent loss of containment and to predict the remaining useful life of the equipment. Techniques based on the ultrasonic (UT) method can be used to monitor the wall thickness at certain critical points of an equipment. The monitoring systems that adopt this technique are essentially composed of high frequency ultrasound emitter (generally 1 ÷ 10 MHz), a localization device and a wireless communication system. Signals are analyzed by specialized software and displayed on the remote control room. Some advanced companies are already providing oil & gas companies with wireless monitoring systems based on UT technologies. Many refineries worldwide had already put into service these systems for the most critical units (Cegla & al. 2017). Monitoring systems are used in pipelines that operate in areas that cannot be frequently checked, due to the dangers of the personnel who carry out the inspections or access costs. These systems have been tested on many different materials and are in service in many critical locations, such as the walls of columns and towers, the inputs and outputs of pumps, heat exchangers and ovens. The ultrasonic sensors may be embedded in a thin dielectric film that can be integrated with the pipe, so that to control progress of corrosion damage (Bergman & al. 2016). The performance of monitoring systems based on UT technologies surpasses those of traditional systems for thinning monitoring, such as probes or software systems based on process variables. If the thinning is punctual, the positioning of the sensor can be critical. It should be stressed that monitoring always requires a certain number of sensors in the network in all critical units, so redundancy helps to increase the overall reliability of the solution. Monitoring of equipment also allows more time to take appropriate actions. That significantly reduces the likelihood of breakages and major failures. UT monitoring reduces, furthermore, the uncertainty on the corrosion rate. The considerable amount of measurement data available may be useful for recalculating corrosion rate and ultimately having a more credible risk assessment. To summarize the reliability score R of UT based SSS, depend on adequateness of installation.

4.3 Asymmetry defects Monitoring

Guided Wave GW is a global non-destructive test method, based on the propagation of low-frequency ultrasonic elastic waves (generally up to 100 kHz), aimed at detecting variations in the cross-section of the equipment investigated through the measurement of variations in acoustic impedance. It is a method used primarily as a screening of the state of pipe integrity (Weihnacht & al. 2017). The smart system, based on GW technologies, uses a ring of transducers positioned around the tube, the emitted waves are sent along the tube in both directions of the ring. GW technology, which can detect defects within the pipeline or equipment, is already used for periodic inspections. Smart systems, based on GW, are innovative because they are wireless, they can be installed in hard-to-reach places, they are equipped with memory and specific software for data processing. An advantage is the ability to monitor the evolution of damage, as well as the utility of calculating the corrosion rate and determining the residual useful life of the equipment. These types of systems are already commercially available and even the PoD is higher. They, obviously, apply only to objects with axial symmetry, in practice to the piping system.

4.4 Acoustic Emission Monitoring

Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of the stress state in a material. When a structure is subjected to an external stimulus (change in pressure, load or temperature), the localized sources trigger the release of energy, in the form of tension waves, which propagate to the surface and are recorded by the piezoelectric sensors array. The AE examination is a non-destructive method used for several decades to identify defects (e.g. cracks and micro cracks) in structures and components, both in civil and industrial engineering. The technology is particularly suitable to build a network of sensors across large structures. The system consists of a digital signal processor, standardized data transfer ports, reconfigurable logic and specific software (Augugliaro & al. 2017). The use of AE techniques with a wireless sensor network still presents considerable problems to solve, such as synchronization of the arrival times of the signals and the consequent localization of the AE source, the power supply of the sensors at the installation site, the modes signal transmission, just to name a few. Experimental tests carried out in the laboratory have shown encouraging results, however further research and pilot tests are needed.

4.5 Acoustic monitoring for rotating machines and valves

In process plants there are many rotating machines, such as pumps and compressors, which are critical equipment for major accidents. In the refineries, periodically (for example once a month) the pumps are manually controlled for vibration, but this may not be sufficient to detect any critical issues promptly. Schodowski (2016) illustrates how a wireless monitoring system, associated with appropriate software, allows to identify anomalies in advance and reduce risks. Some wireless anomalous vibration detectors are already commercially available and adopted in refineries. A further application of acoustic sensor technology is the overpressure events monitoring of safety valves (Ma & Lu 2017). The high availability also corresponds to a very good PoD. This type of SSS has to be definitely recommended for all establishments featuring pumps and compressors.

4.6 Safe Cranes for Hazardous Goods

Handling loads in factories at major accident risks can cause containment loss. The interference of paths between containers of hazardous materials and other parts may be the cause of breakage and release of materials into the environment. Systems are proposed, based on augmented vision (Ancione & al. 2017) that allow to identify in advance the potential confrontation and avoid it. These systems are still not widespread.

The PoD is the probability of detect interference in advance. An initial tuning is essential at startup phase; aiming at increasing the PoD and excluding potential confounding elements. Apart from possible startup errors, reliability is higher.

4.7 Identification of critical equipment

QR codes and RFID (Radio Frequency Identification) devices are well-known techniques for identifying people or objects. QR codes are simple and passive tags, with limited memory capacity, require applications with a reader, but can easily be renewed by reprinting. RFID is an active tag, capable of storing small data, but available for bidirectional communications. Identification of critical equipment is an important requirement in chemical plants subject to the Seveso Directive. The equipment, identified as critical for major accident events, must be marked with visible or equivalent signals. While intelligent identification systems are often used in places of everyday life (e.g. smart cities, tourist sites), they are not so popular in Seveso establishments and there is still a need for specific developments. The level of availability is very high and, given the simplicity, even the overall reliability is excellent. However, the system does not directly prevent loss of containment, but facilitates the management of the primary containment system. These are easy to use and low cost solutions, which bring great benefits. Of course the PoD in this case does not make sense. Instead of the missed detection, a misleading identification is possible. Thus, the PoD should be interpreted as probability of correct identification. A simple tuning at startup phase is required and, consequently, a very low likelihood of error is present. Thus, the reliability score is higher. As the solution is mature, it has to be recommended at all.

4.8 Scoring

The Table 3 summarizes the partial scoring of the 7 discussed SSS. The score in real cases depend also on SMS as discussed in section 3. Table 3 is just a sample table, where an adequate SMS is assumed.

Table 3 Applicabilty and Reliabilty of the SSS described in section 3

	A applicability	R reliability
1 Erosion Acoustic	4	3
2 UT Thickness Monitoring	4	3
3 Asymmetry Monitoring	4	4
4 AE Monitoring	2	3
5 Acustic Monitoring	4	4
6 Safe Cranes	2	3
7 Identification of Critical Equipment	4	4

5. Integration with the risk management system

5.1 Reference practices for SMS

The more or less sophisticated solutions described in the previous section are able to improve the safety level of the plant only if they meet the criteria indicated in section 3. The criteria partly relate to the goodness of the proposed innovation and in part to the capacity of the organization of use all measurement data and information that SSS systems make available. This is very challenging. A solid basic knowledge is essential to understand why, how, what, when to measure. If, within the SMS, the technical documentation is well managed throughout the life cycle, there is all the information to take full advantage from the measured data. In particular, data on the integrity and functionality of the equipment, acquired through the monitoring systems, must firstly feed the planning of the inspection and maintenance activities, which will depend on the conditions detected on the equipment and on the forecast models of degradation. For this point, it is important to integrate the SSS with an inspection program based on quantitative risk assessment, such as API 581.

5.2 Maintenance policies and SSS

With the emergence of SSS, data collection from equipment passes from manual, paper-based inspections to automated systems. This improves both data quality and quantity. The monitoring of equipment and systems enabled by SSS also allows you to greatly expand the number and variety of parameters that can be monitored economically. These data, combined with today's most advanced models, allow industrial organizations to implement new and more effective maintenance strategies. To summarize, SSS combined with modeling allows better maintenance strategies with benefits for both safety and business.

5.3 Evaluation in quantitative risk analysis

When an SSS is installed to prevent a loss of material or energy it can be treated as a further barrier, according to the well known “bow-tie” model. The monitoring systems described in section 4 are essentially preventive barriers, aimed at reducing the probability of occurrence. Thus, it is required to know much the new SSS is able to reduce the likelihood of a top event. There is no experimental evidence, but we can refer to API 581. It suggests, for on line corrosion, monitoring a reduction factor F ranging from 1 to 20, depending on corrosion type and monitoring techniques. The factor affects the Likelihood of Failure; it does not consider innovative techniques, which could be even more effective in risk reduction. It is essential to stress, anyway, that any SSS is aiming at the control of a prevalent damage mechanism or class of mechanisms. It cannot control all concurrent mechanisms, which are present and contribute to the likelihood of failure. For instance UT techniques (4.2) control corrosion and may be erosion, but not thermal shock or metallurgical embrittlement; Safe cranes (4.6) prevent collisions but not structural failures and so on. For such a reason, the suggestions of API 581 may be good even for most SSS. Thus, the effects of an additional SSS on the likelihood of an event should not exceed one order of magnitude. The factor F has to be related to the factors A and R as defined in § 3.1 and §3.2 respectively. This relationship may be empirically described by eq. 2.

$$F \cong (A \cdot R) \quad (2)$$

6. Conclusions

The various smart safety systems are still at an early stage. In many cases the experiments have been carried out on pilot plants and the products put on the market are little more than prototypes. Only in some cases, there are already systems so mature as to ensure a high degree of reliability through codified systems of design, construction, testing and maintenance. In this innovative phase, in the absence of defined standards, the systems are still very different from each other and often incompatible. An objective of ongoing research is to develop a common communication protocol between smart safety systems so that systems can communicate with each other and especially with the safety management system that should integrate all the various aspects. The availability of numerous, up-to-date and accurate data on the conditions of critical equipment gives the possibility of a dynamic risk assessment, updating those probabilistic assessments made initially on the basis of literature data. That has to potential to improve all the risk management.

Acknowledgement

Research funded by INAIL within program PAR 2016-18 Ob 2.2

References

API 581. 2016. Risk-based inspection methodology. API RP 581. American Petroleum Institute. Vol. 3.

Ancione, G., Kavasidis, I., Milazzo, M.F. Improving Safety of crane-related operations by the support of a real-time computer aided visual guidance system , Safety and Reliability – Theory and Applications – Epin & Briš (Eds) 1787-1792 (2017) Taylor & Francis Group, London

Ansaldi, S.M., Agnello, P., Bragatto, P.A. Smart safety systems: Are they ready to control the hazard of major accidents? (2018) WIT Transactions on the Built Environment, 174, pp. 169-180.

Cegla, F., Allin, J. Ultrasonics, corrosion and SHM - The story of Permasense Ltd. Structural Health Monitoring 2017: Real-Time Material State Awareness and Data-Driven Safety Assurance - Proceedings of the 11th International Workshop on Structural Health Monitoring, IWSHM 2017, 1, pp. 28-36.

Bergman, J., Chung, H., Janapati, V., Li, I., Kumar, A., Kumar-Yadav, S., Chapman, D., Nissan, A., Sarrafi-Nour, R. Evaluation of the real-time active pipeline integrity detection system for corrosion quantification (2016) NACE - International Corrosion Conference Series, 4, pp. 2674-2685.

Augugliaro, G. Mennuti, C. Brini, F. Quaresima, P. Assessment of structural damage to reinforced concrete structures with AE-based techniques Safety and Reliability – Theory and Applications – Epin & Briš (Eds) 2173-2177 (2017) Taylor & Francis Group, London

Weihnacht, B., Klesse, T., Neubeck, R., Schubert, L. Monitoring of hot Pipes at the power plant using guided waves (2013) Proceedings of SPIE - The International Society for Optical Engineering, 8692.

Wold, K., Carugo, M. New perspectives on refinery corrosion, integrity management, communications and optimizing opportunity crudes (2017) AFPM Annual Meeting 2017, pp. 331-34

Ma, J., Lu, J. Application of wireless sensor based on sound localization in safety valve condition monitoring of chemical plant (2017) Chemical Engineering Transactions, 62, pp. 745-750.

Schodowski, E., Wireless sensing improves refinery operations. AFPM Annual Meeting 2016 www.emersonprocess.com. Accessed on: November 2016