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CYBER PHYSICAL SYSTEMS FOR OCCUPATIONAL SAFETY AT INDUSTRIAL SITES: OPPORTUNITIES AND CHALLENGES

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Abstract

In last decade, many Cyber Physical Systems CPSs for occupational safety have been developed within research programs funded by national and transnational bodies. Many of them are now ready for the market. The paper focuses on the industrial sectors, where the safety of the worker and the safety of machines, equipment and processes are linked each other. The papers proposes to safety managers criteria and suggestions for choosing appropriate CPS for seizing the great opportunities for safety improvement. The paper discusses a few issues, including cybersecurity and privacy, which are critical for a successful implementation of the CPSs in occupational safety. Safety Management System SMS, in particular, must be adequate to collect the amount of data generated by many sensors distributed in work ambient and worn by workers.

Keywords: Cyber Physical Systems, Occupational Safety, Industrial Safety

1. INTRODUCTION

A Cyber Physical Systems CPS is generally defined as a system that integrates sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other. CPSs were born to exploit the potential of enabling technologies of Industry 4.0, including pervasive sensors, identification systems, communication protocols and cloud computing. A large number of CPSs have been developed in the last decade, aimed at the workplace safety. They are able to prevent the situations of immediate danger and to improve the performances of the personal protection equipment PPE. In recent years, the CPS have attracted many research funds for job safety, both from

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national and transnational bodies and, after a while, it is important to understand if these efforts have been really useful to have safer workplaces.

Through the developed CPSs, safety takes full advantage of Industry 4.0 technologies. Thus, the Safety based on CPS solution is briefly called “Safety 4.0”. The term is very effective, because it brings together two well-defined ideas, that of Safety and that of Industry 4.0, but the idea that it is sufficient a certain number of CPSs to have a safer workplace is a little misleading. That could be an illusion, as discussed in the detail in the present paper, because safety is not simply a technical issue, but, as it has been recognized for decades, it requires an integrated management of technical, human and social factors.

The scope of the paper is just industrial working environment, including both process and manufacturing sectors. Section 2 discusses a few examples of CPSs oriented directly to the workers’ safety. Section 3 discusses, instead, a couple of examples of CPSs for the safety of machines and plants. Section 4 discusses main factors that can threaten the application of CPSs, including a number of regulatory issues. The last session discusses detail how the Safety Management System could be definitely improved, thanks to the adoption of CPSs.

2. CPS TO PROTECT WORKERS

The very first CPS applications were aimed just at remembering when PPE had to be worn, entering a delimited dangerous areas or before to operate hazardous machinery. From a technological point of view, the solutions were based on intelligent tag on the single piece of equipment (helmet, shoe, mask, etc.) and basic position sensors. These systems were born initially for the construction sector, which in many countries has one of the highest frequency of accidents (Ko, 2009).

2.1. Using appropriate PPE

The first solutions developed for construction were soon transferred even into manufacturing industries. Gnoni et al. (2016) presented a good example of CPS developed, in order to protect workers from an assembly machine, which required specific PPE to be worn to prevent both chemical exposure and physical contacts. The system was connected to the control unit so that to block the machine, until the worker wears all the required protective equipment.

2.2. Avoiding interferences

In manufacturing industries, many CPSs have been developed, to protect workers from moving machines (e.g. forklift, crane). The different solutions, are dependent on the type and complexity of machinery, as well as on the congestion in a very restricted area of machines, structures and workers. A few industrial solutions for safer forklift trucks operation inside warehouses were already possible a decade ago, as discussed by Bragatto et al. (2014).

In the framework of machinery, cranes are a significant category, present in many different industries. Many accidents in crane operation are reported, related to errors of the operators. Thus, a number of CPSs was developed aiming to reduce common human errors, which cause interference, loss of load or sagging. Many proposed solutions, unfortunately, have been disappointing, because the approach was too simplistic: just and electronic widget to warn the operator.

The development of a successful CPS, instead, must start from an adequate modelling of Human Factors, including perception of information, cognitive resources and strategic formulation. Just in that way, it is possible a real reduction of human errors in using cranes, as well as other machines. The understanding of the human factors is, for instance, underlying the Visual Guidance System (VGS) developed by the SPRINCE project, funded by SAF€RA partnership (Spasojević-Brkić et al., 2015). As discussed by Milazzo et al. (2021), the limited view of the working area for crane operators was identified as a major cause of errors and the smart uses of stereo images allowed a quick understanding of the scenario, so that to avoid collision between load, structure and moving workers. Interference is also a basic issue for unmanned vehicles, robots and similar systems, which are not discussed in the detail in the present paper, as they are not directly aimed at the safety improvement.

2.3. From wearable sensors to smart textile

Many CPS are based on wearable sensors that alert the worker to various situations helping them to avoid errors and reduce exposure to risks. At first, these systems were a bit intrusive: bulky boxes hanging from belts or inside pockets. The evolution has been to develop more easily wearable and usable objects with the commitment of design experts, accustomed to always considering the issue of ergonomics. The use of personal protective equipment (PPE) is the main way to protect workers; but its use is highly sparse. Currently, products and systems embedded with wearable technologies are able to protect, motivate and educate users. Wearable technology can be persuasive and elicit a conscious behaviour towards the use of the PPEs by consequently improving their health condition. A successful implementation of this approach may be found in the Project named POD and funded by SAF€RA partnership provide a possible example of how to use wearable technology as a useful tool to influence behavioural change (Ferraro et al., 2018).

In the near future the safety sensors will be even woven into the clothes. Smart textile have been developed for sports but in the next future they will provide solutions for safety at work. This a very new area of research, which poses many scientific challenges. A recent research project funded by INAIL (Italian Workers' Compensation Authority) faced many basic issues, essential to develop this very new field (Marra et al., 2021).

2.4. Protecting workers in difficult areas

In process industries, a number of CPS applications are aimed at the protection of lonely workers in hostile environment. Hazard are related to the congestion of plants and the structure, the presence of hazardous material, including toxic, asphyxiant or flammable gases and so on. In this case CPS should include a number of smart sensors disseminated in the working ambient to monitor environmental parameters, including, for instance, temperature, noise, toxic or flammable concentration in ambient air, dust and smoke, oxygen percentage, and so on. The worker, in turn, is wearing a number of sensors, aiming at monitoring the position.

The monitoring of position is highly improved by gyroscopic sensors. That allowed also to send to the control room an immediate signal in the event of a fall. Further worn sensors may include, if relevant, physiological parameters, such as pressure and heartbeat. In a nutshell it can be said that there are sensors worn and sensors distributed in the environment. Intelligent tags identifies the sources of dangers and first aids. Alert is send directly to the worker, using smartwatches or ad hoc gadgets worn by the workers. The signal is replicated to the supervisor in control room, to arrange interventions in case of need (De Cillis et al., 2016).

On the basis of this general model, many applications have been developed, encountering and overcoming various difficulties. First of all, the presence of large metal masses, typical of many industrial environments, which hinder the use of medium-range communication systems, such as *wifi*. That forced researchers to think about short-range communications for workers entering the most congested areas, to be sent to the control room if necessary (Bragatto et al., 2018).

2.5. Leakage Detection

A lot of work has also been done in recent years on chemical sensors. Chemical sensors have a much longer history, starting with the electronic "nose", available for decades and strategically placed to detect gas leaks in factories. From this starting point, many steps have been made, developing sensors with different levels of reliability and precision, as well as low energy consumption and small dimensions. This fact is also evident from the large availability of commercial products specifically designed to increase the safety of workers in refineries, chemical or Oil and Gas plants. There are simple wearable battery powered gas detectors, that can generate acoustic and vibration local alarms or more sophisticated devices that may be connected to a proprietary centralized monitoring software. These devices can cover different application environments where different constraints such as battery lifetime, sensors lifetime, device physical dimensions or the need to be connected to a central monitoring station. In the research prototype CP-SEC funded by INAIL, a smart solution is proposed combining electrochemical sensors, for the detection of oxygen and toxic compounds in air and catalytic sensors for Hydrocarbon detection. Details about CP-SEC project may be found in Tamang et al. (2022). For the purpose of the present paper, it is important to stress that Consumption for these sensors may be a critical issue, which may be solved by implementing an adequate powering strategy balancing measurement accuracy, sampling time and energy requirements. The chemical sensors are integrated with position sensors, as outlined in previous paragraph.

2.6. Virtual Reality for Training

Immersive virtual reality VR systems allow realistic simulations in which the user can learn the use of dangerous machinery through structured paths and actively learn how to manage dangerous situations in total safety. The use of VR for training of industrial equipment while not new is not as widespread due to the cost of creating and adapting it to address various equipment and situations. To overcome this limitation, a recent project named PITSTOP and funded by INAIL proposed a VR simulator for training steam generator operators and verifiers focusing on the easy of customizing the VR system to suit new learning paths and different equipment while reducing the implementation effort (Giannini et al., 2022).

2.7. Augmented Reality in Operation

Whilst in VR the user receives the visual input just from an artificial system, in Augmented Reality AR the artificial input is mixed with normal vision. Despite VR applications, which are basically for training, AR applications are more versatile.

Other two INAIL project, named SISOM and ARTEMYS, used AR to provide in real time the operators in different industrial contexts, with the appropriate pieces of information coming from machines visual manuals (Vignali et al., 2019). The effort underlying these projects is understand what piece of information is really needed at any time by operators, possibly exploiting even the potential of AI technologies, as discussed by Di Donato (2018). The ultimate proposal in this field is delivering learning content in the form of short educational games by using a common technological platform based on virtual, interactive and immersive reality, as discussed by Longo et al. (2021).

2.8. Near Miss

In the framework of safety management, the attention to the issue of near miss NM were considered important just is a few industries, requiring a higher reliability level (e.g. aviation, nuclear). NMs have, by definition, no consequences, but are much more frequent than accidents and, consequently, may be a larger source of knowledge and help to prevent accidents. A recent paper (Elia et al., 2022) has reviewed a few CPSs developed to promote and possibly automate the reporting of anomalies, near misses and other minor events.

3. CPS TO PROTECT PLANTS

The present section discusses a few advanced sensors, based on non-destructive testing techniques, which have been demonstrated suitable to automatically monitor the integrity of the industrial assets, including equipment and machinery. In process industries, asset integrity is a major concern of plant managers and many CPSs are already in service.

3.1. Integrity Monitoring

A generic monitoring system is featuring sensors and electronic components or subsystems, which provide services for identification, transmission, and processing of data. These systems can be used in many different contexts of process industry for monitoring critical equipment, including vessels, pipes and rotating machinery. The sensors suitable for monitoring system must be low cost, non-invasive, flexible, scalable and possibly easy to connect. They include, for instance, Vibration Monitoring and Ultrasound Thickness. The first ones are early as possible damages that could lead to failures. The second ones are installed in critical position along pipelines and pressure vessels to monitor the loss of material due to corrosion or erosion and prevent ruptures.

The current practice of most refineries and petrochemical plants already include the remote control of rotating machinery through vibration sensors connected to the control room. At those establishments, before the adoption of automated solutions, a lot of resources were consumed to check each pump one by one and a lot of time went from one inspection to another (Goyal et al., 2018). The benefits are really great, defects are detected much earlier and there is a significant risk reduction for workers, who no longer have to go around looking for pumps in difficult areas. Automated thickness monitoring is, instead, is newer and it is not yet popular and implementation is difficult, although a few refineries adopt it, with clear benefits (Cegla & Allin, 2015).

In order to have an effective CPS, the above mentioned sensors must be connected each other to have a pervasive network adequate to sensitize every item of equipment and every area of and industrial plant. That allow a detection of minor defects much earlier than damages, failures or accidents happen. To do that is essential to have a perfect identification of any critical items, through a smart tagging system. In order to have a complete and effective response it's essential to have also a software, adequate to merge the measurement from sensors and information from the smart tag, so that to have a prognostic of the "health" condition of critical items and assure the safe extension of plants' lifetime. The software should include a platform for communication, database and user interface. The prognostic module may uses a more or less sophisticated algorithm (e.g. Bayesian Network) to forecast the evolution of the plant, so that to support operation, inspection and maintenance, as discussed by Bragatto et al. (2020). There is a great interest in these systems have multiple benefits, protecting assets and workers. it also helps to avoid more major accidents with consequences on the environment.

3.2. Safety walk

An example of application of the systems described above, can be that of the "safety walk". Milazzo et al. (2019) presented an innovative solution, developed in SMARTBENCH a project funded INAIL. It features a number of sensors distributed in the plant, an appropriate management software and a simplified modeling. The great novelty is that plant integrity conditions of the plant can be presented to the inspector in the form of AR, exploiting the potential of "smart glasses" technology.

3.3. Remote Inspections

The technology described in previous paragraph was demonstrated valuable during COVID-19 lockdown period: mandatory safety inspection in charge of Italian regulators continued from remote, exploiting the technology developed just one year before. Even though the pandemic crisis in over, Italian regulators allowed to regular use this technology when the activity in presence may be demonstrated too onerous (Giacobbe & Bemporad, 2020).

4. DIFFICULTIES AND CHALLENGES

The offer of CPS for safety is really huge and may be very confusing. Even though a single system is "low cost" by definition, their systematic adoption in complex industrial contexts involves significant direct and indirect costs, as well as impacts on the organizational model. Thus, it is important to retain technology enthusiasts and evaluate the expected benefits in quantitative terms in order to make rational decisions.

4.1. Evaluation Criteria

In search of an evaluation criterion for safety CPS, it's possible refer to the very classic 4X4 risk matrix, where cell are grouped in four risk classes: low, medium, high, very high. A CPS intervenes on a certain work hazard identified in the risk assessment by reducing the probability of occurrence or the severity of the consequences. In this way, risk can moved to a lower risk class. The CPS is effective if for a given hazard, it allows you to drop to a lower cell in matrix risk, very effective if it drops one risk class or more. In more complex industrial sites (e.g. process plants), where formal method are used for quantitative risk analysis (e.g. FTA, LOPA) the potential effect of a safety CPS may be quantified as a factor (less than 1) which is applied to the initial probability of failure. The lower the factor, the better the CPS. An effective system reduce the failure rate by an order of magnitude, a very effective of two orders and so on. In the case of sensors for the early detection of damage or defects, the reduction factor is directly related to the probability of detection POD. The higher the POD, the lower the reduction factor, the higher the efficiency, as discussed by Ansaldi et al. (2018).

4.2. Cybersecurity

Most CPSs are web-based and heavily use resources such as internet and cloud networks. They are, consequently, subject to cyber-attacks This issue is very important but it should not hinder the adoptions of CPS solutions. Rather before to adopt a CPS, digital vulnerability should be considered and it should be included in the company defensive strategies, as any digital items. An effective Cyber Security strategy should, in fact, protect both information technology and operational technology, which include safety CPSs.

4.3. Privacy

The large part of the CPS proposed for occupational safety in the literature have, unfortunately, difficulties to be accepted because they have implicitly mechanism that could be used to monitoring the worker'' activities. With the aim to overcome such drawback, in the context of a project funded by INAIL a fully distributed solution have been proposed, where all the detailed information is managed in order to avoid any possible incorrect abuse of the data. In more detail, the system is able to provide information about the environmental status directly and exclusively to the worker. Only in case of anomalous situation the information is shared in order to better manage the crisis (Faramondi et al., 2020).

4.4. Regulatory Issues

Occupational Safety is matter strictly regulated in most national legislations. PPE, in particular, need specific certifications, according to national and Int. standard. In most countries even machine and equipment safety is strictly ruled by national or supernational regulations (e.g. EU "Machine" Directive). The lack of regulation in many cases could hinder the application of innovative safety systems. Thus it is essential to have a fast update of technical regulation, including standards and recommended practices, so that to follow the evolution of technology. Legislation in turn should be general and independent on the technological details. A positive example come from §3.3, where the application of new technology was encouraged by competent authorities and supported by adequate regulations.

5. SAFETY MANAGEMENT SYSTEM

The safety management system has been for a decade and more a pillar of industrial and occupational safety. In European process plants, it is even mandatory, but in many contexts it is strongly encouraged through soft-law systems. Under the SMS umbrella there all the procedures and operating instructions, which in turn are the basis of many CPS. Sensors distributed pervasively throughout the industrial site and worn by the workers offer a great opportunity to improve and strengthen safety management. On the other hand, it would be unthinkable to get a bunch of data from the CPS without exploiting it in the management system.

The Occupational Health and Safety Management System OHSMS, defined a few years ago by the standard ISO 45001 (ISO 2018) is now popular in many industries. CPSs are truly a great opportunity to drastically improve OHSMS performances. The management system must include the data provided by the multitude of sensors distributed and worn.

To be effective, OHSMS should be able to adapt quickly to new opportunities in the context. Elements of flexibility and dynamism should be introduced for taking advantage from huge amount of data provided by CPSs. In a recent paper Ansaldi and Bragatto (2022) proposed a new approach, to implement the OHSMS, staying in the standard structure and exploiting the potential of enabling technologies. The paper singles out the levels of the safety management system where it is possible have flexible procedures and instructions, adequate to exploit the potential of the new CPSs.

The Table 1 shows how the functionalities of the CPSs described in the paper should be integrated in a few key points of the SMS. Operative instructions are affected by CPS of workers protection, including those to

Table 1. The CPSs discussed in the paper and the corresponding points of the OHSMS

CPS, according the number of paragraph in the papers	Corresponding clause in the standard ISO45001:2018
2.1 Using appropriate PPE	8.1 Establish Processes to meet requirements
2.2 Avoiding interferences	8.1.2 Establish Processes for Managing Hazard and Risks
2.3 From wearable sensors smart textile	8.1 Establish Processes to meet requirements
2.4 Protecting workers in difficult areas	8.1.2 Establish Processes for Managing Hazard and Risks
2.5 Leakage Detection	8.2 Establish Processes for Emergency Prparedness
2.6 Virtual Reality for Training	7.2 Promoting Competences
2.7 Augmented Reality in Operation	7.5.2 Managing documents and records
2.8 Near Misses	9.1.1 Monitor, Measure, Analyse, and Evaluate
3.1 Integrity Monitoring	6.1.2 Identify Hazard and Assess Risks
3.2 Safety walk	9.1.1 Monitor, Measure, Analyse, and Evaluate
3.3 Remote Inspections	9.1.2 Evaluate Compliance with requirements

work with moving machinery, to avoid interferences. CPSs for monitoring health parameters or workers' positions have effect on both operative instructions and emergency activities. A prompt communication in congested areas and detection of gas leaks provide data and information crucial for emergency. Training of operators for using dangerous machinery or learning working activities can be improved by related CPSs. Finally, CPSs for safety walk and for remote inspections improve, respectively, the review activity of SMS and the integrity inspection.

6. CONCLUSIONS

CPSs are truly a great opportunity to drastically improve occupational safety. To prevent initial enthusiasm from being followed by disappointments, managers must adopt systems that have achieved a high degree of readiness and for which effectiveness has been demonstrated. The management system must include the data provided by the multitude of sensors distributed and worn, also keeping in mind the privacy and cyber security requirements.

The existence of a modern management system, possibly ISO 45001 or equivalent system, is an indispensable prerequisite for the adoption of safety CPSs. It is important that the huge data provided by CPSs goes into the safety management system.

If these criteria will be applied, the safety CPS in a near future will be decisive in many practical cases and the investment made by national and Int. research funding institutions will return as lower costs for injuries compensations, as well as better performances.

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САЈБЕР ФИЗИЧКИ СИСТЕМИ ЗА БЕЗБЕДНОСТ НА РАДУ У ИНДУСТРИЈСКИМ ПОСТРОЈЕЊИМА: МОГУЋНОСТИ И ИЗАЗОВИ

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Извод

У последњој деценији, многи сајбер физички системи (енг. Cyber Physical Systems - CPSs) за безбедност на раду су развијени у оквиру истраживачких програма које финансирају национална и транснационална тела. Многи од њих су сада спремни за тржиште. Рад се фокусира на индустријски сектор, где су безбедност радника и безбедност машина, опреме и процеса међусобно повезане. У раду се руководиоцима безбедности предлажу критеријуми и сугестије за избор одговарајућег CPS-а за коришћење великих могућности за унапређење безбедности. У раду се разматра неколико питања, укључујући сајбер безбедност и приватност, које су критичне за успешну примену CPS-а у заштити на раду. Нарочито, систем управљања безбедношћу (енг. Safety Management System – SMS) мора бити адекватан за прикупљање свих података генерисаних од стране бројних сензора распоређених у радном окружењу, као и оних које носе радници.

Кључне речи: сајбер физички системи, безбедност на раду, индустријска безбедност

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