Promising Technologies and Solutions for Supporting Human Activities in Confined Spaces in Industry

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Abstract: Although there is a growing concern about accidents and illnesses at work, global statistics still reveal alarming data. It is estimated that 2.78 million people die each year worldwide due to labor factors. In this regard, information systems and automation systems applied to occupational health and safety are gaining prominence for accident prevention. One of the high risk activities that have adopted technology as an ally is working in confined spaces. Currently, non-human entry robotic systems have been widely adopted for this purpose. However, these solutions do not always cover all scenarios, still requiring humans to perform tasks in those locations. Thus, it is expected that the new era of work in confined environments will be increasingly guided by hybrid systems of human-computer interaction. Some solutions from this perspective foresee the use of wearable computing, virtual reality and augmented reality to assist at these locations. The challenges in adopting these new technologies still consist in the characteristics of the environments themselves, which are hostile places with natural blockages for traditional communication and data transmission signals.

1 INTRODUCTION

The impacts that technological changes have had in the various sectors of economy are a constant theme in debates about the future of work. Advanced manufacturing raised the industry to a new level of productivity, allowing the creation of more agile machines and processes through the integration of technologies such as robotics, internet of things (IoT) and artificial intelligence.

In the field of Occupational Health and Safety (OHS), industrial conditions and workplaces have also evolved into more ergonomic and safer environments. Since the First Industrial Revolution started in the 18th century, where steam engines reduced manual effort, researchers and engineers from all over the world are increasingly striving to make these environments more accessible and less harmful to human beings.

The massive use of advanced tools, more robust protective equipment and better supervised work practices show a more assertive involvement of employers and workers in solving OHS-related problems in recent years (Badri et al., 2018).

However, the problem is that the technology that increased production efficiency and performance is also the technology that created new job scenarios with adverse risk and hazard conditions for the health and safety of employees. In mining, for example, technological solutions have allowed access to and exploration of deep deposits, where large soil movements place workers in unhealthy and dangerous environments (Cattabriga and Castro, 2014).

To get an idea of the statistics on occupational health and safety, in 2017 a survey estimated that 2.78 million people die worldwide each year due to labor factors (Hämäläinen et al., 2017). Globally, it is estimated that 1,000 deaths per day are caused by direct accidents and 6,500 by work-related illnesses (International Labour Office, 2019). The figures also show a general increase in the total number of deaths: from 2.33 million deaths in 2014 to 2.78 million in 2017 (Hämäläinen et al., 2017).

These changes have a major impact on operational

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health and safety and are expected to continue to do so in the future (International Labour Office, 2019). Thus, the need for new engineering solutions applied to OHS is evident.

Some solutions in this regard foresee the use of wearable computing, virtual reality and augmented reality for human assistance in dangerous and diverse activities. Wearable smart devices are already being used to monitor worker fatigue and fall detection, for example (International Labour Office, 2019).

In this perspective, this paper's main objective is to review and investigate the technologies already used in confined spaces and also to describe some promising solutions to support human activities in these environments, since working in these places is still classified as high risk and harmful to employees' health. Thus, this study is a preliminary investigation for the improvement of these technologies and serves as a theoretical foundation for the development of wearable devices in confined spaces. The work, in current progress by the authors and still in its infancy, proposes to display monitoring data on augmented reality glasses in a more practical and intuitive way for confined workers. An example application under development is the computational coloring of naturally colorless gas concentrations for users of these glasses.

2 CONFINED SPACES

The concept of confined spaces is understood as any area not designed for continuous human occupation that has limited means of entry and exit. According to the US Occupational Safety and Health Administration (OSHA), three characteristics define a confined space: (i) it is large enough and configured so that an employee is able to enter and perform the work, (ii) it has limited entry or exit opening, (iii) and it is not designed for human occupation (OSHA, 1993). Examples of confined spaces include, but are not limited to, silos, ducts, boilers, storage tanks, sewage ditches, chimneys and underground galleries.

When developing a regulatory procedure on work in confined spaces, OSHA estimated, in 1993, that 4.8 million entrances into confined spaces were made annually in the United States and they involved an average of 1.6 million workers and 63 deaths (Burlet-Vienney et al., 2015).

The most common causes of accidents in these places are fires, explosions, spontaneous combustion and contact with extremely high temperatures (Botti et al., 2017). Tasks in confined spaces involve physical, chemical, biological and ergonomic risks to the health of employees, the risk of asphyxiation and intoxication being among the most common (Botti et al., 2018).

These risks are present in several industrial segments. In mining, in non-ferrous metal mining activities, the accumulation of methane gas in coal mines and toxic concentrations of hydrochloric acid are some of the sources of risks and dangers to which workers are exposed in these locations (Dräger, 2015). In the chemical industry, a case study in 2005 reported a fatal accident in the US where two workers at a refinery were asphyxiated inside a confined space filled with nitrogen (CSB, 2005).

Simply put, the most effective risk control measure for working in a confined space is not to enter the confined area (Botti et al., 2018). In this trend, robotic systems and stand-alone operations for work in confined environments have gained prominence. In a systematic review of automated solutions for entering these places, 60 scientific articles that document the use of these tools, produced between 1999 and 2015, were cataloged (Botti et al., 2017).

At first, one can imagine that the future of confined spaces will be dominated by these innovative non-human entry technologies. However, they are still limited to certain industrial operations such as cleaning, inspection and maintenance. Moreover, because they are places with rigid and divergent operational parameters, autonomous solutions for work in confined environments are limited to the activities to which the solutions were initially designed (Botti et al., 2017).

From this perspective, it is certain that research in this area will considerably evolve the flexibility of robots for access in distinct operations, but even so, certain activities will still require human presence in these locations. To remove automatic cleaning residues in naval tanks, for example, human intervention is still required (Botti et al., 2017).

Perhaps the greatest gain obtained from the insertion of robots in confined environments is the reduction in the time that workers remain in these places. Thus, the work done in these environments tends to be guided by hybrid systems of human-computer interaction.

This paradigm shift is observed not only in confined spaces, but also in the industry as a whole. This is what enthusiasts consider the philosophy of the recent Industry 5.0, where humans work together with robots or computer instruments integrated into their bodies to improve their physical, sensory and cognitive capabilities (Longo et al., 2020).

If in Industry 4.0 technology has advanced towards interconnecting machines and cyber-physical systems to the processes, in Industry 5.0 the focus is on collaboration between machines and humans. The Fifth Industrial Revolution will pair men and machines to further utilize intelligence and creativity in order to increase the process efficiency by combining workflows with smart systems (Nahavandi, 2019).

The challenges regarding the adoption of these new technologies still consist in the characteristics of the environments themselves, which are quite hostile, poorly lit, with the presence of water, dust and natural blockages for traditional communication signals.

Finally, it is important to point out that most of the existing confined spaces are considered potentially explosive atmospheres, which requires that the equipment developed specifically for these places be certified by national and international standards.

3 RELATED WORK

The use of technological solutions for accident prevention and occupation of confined spaces is already a reality. With the accelerated digital revolution in recent years, the use of these solutions is increasingly frequent.

When it comes to accident prevention in these environments, today the main contributions of IoT technologies are geared to improve the flow of information between all actors involved (Botti et al., 2015) and also to improve gas measurement and monitoring processes.

Information systems and industrial automation systems are already widely used in confined space construction projects. As referenced by (Burlet-Vienney et al., 2015), sometimes a problem at the project level can explain the underlying cause of an accident.

A work by researchers from Pakistan has implemented an integrated solution based on BIM (Building Information Modeling) and Wireless Sensor Network (WSN) for confined spaces in civil construction environments. BIM, according to (Eastman et al., 2011), is a technology that allows to digitally create one or more accurate models of a building. These computer-generated models contain precise geometry and data needed to support construction, manufacturing and acquisition activities through which the building is done.

In the case of this Pakistani research, the solution, called CoSMoS, uses the Autodesk Revit Architecture software to map and visualize the confined spaces in specific constructions, while the environmental monitoring of these spaces is carried out by the commercial motto TelosB, which uses the TinyOS open-source operating system (Riaz et al., 2014).

In this solution, data from sensors present in the confined environments are read directly in Revit, enabling managers and occupational health and safety teams to more easily assimilate the places with higher accidents risks. The choice of TelosB for this project takes into account the motto's capacity to withstand aggressive and hostile environments, which is one of the main characteristics of confined spaces.

Regarding the identification of confined spaces and the assessment for entry permissions, some information systems propose more assertive and less subjective evaluation methods for risk prevention. In this scenario, in 2016 (Botti et al., 2016), a tool for the identification of such spaces in the industry has been developed. The goal was to create an effective mechanism in order to prevent workers from entering high risk areas. The tool was able to calculate a risk index to allow or prohibit workers from entering the space.

The measurement of gases in these environments also has several technological resources. Today, electrochemical and catalytic sensors can accurately measure hundreds of toxic gases. Selective filters are being better developed to increase the sensitivity of these sensors and reduce false alarms. The use of infrared sensors for measuring hydrocarbon gases has also been gaining ground, since there is no wear and tear for this type of sensor, unlike electrochemical and catalytic ones. Current technology also allows portable meters to be modular, where the user has the autonomy to change and replace the gas sensor cartridges according to the types of gases expected for each environment. Some specific detectors are already capable of detecting potential drops and automatically trigger an alarm for the competent authorities.

On robots in confined spaces and other non-human autonomous systems for entry into these places, present technologies focus on industrial robots and unmanned aerial vehicles. Among the case studies for inspection activities analyzed by (Botti et al., 2017) are the robots NERO (Nuclear Electric Robot Operator) and SADIE (Sizewell A Duct Inspection Equipment), which inspect reactors and ducts through non-destructive testing. Between the robots for cleaning in confined spaces, the study mentions the ReTRIEVER robotic arm, which is remotely controlled for waste removal in nuclear tanks.

As negative points of robotic arms in confined spaces, one can highlight the fact that the movements of these types of robots are mechanically limited in closed environments where the surfaces have several edgings and small radii of curvature, which increases the chances of collision. Another restriction arises from the passage of cables and hoses within the working space of the robotic handler, since these types of connections cannot be avoided to a great extent.

The research also states that, in all cases of analyzed studies, the applications of robots in confined spaces are limited and designed for specific applications. In this sense, it was found that of the cataloged automated entry technologies, none of the solutions simultaneously performs cleaning, inspection and maintenance tasks, but only one or two of these activities.

Thus, due to these limitations and also to the high costs of developing specific robotic systems, it is expected that other more affordable technologies with greater applicability will gain prominence in the new era of confined environments.

As referenced, these technologies tend to increasingly assist humans in these locations, so that the worker stays as little time as possible in the confined environment and their activity can be fast and efficient from available technological resources.

4 PERSPECTIVES

4.1 Mobile and Wearable Technologies

A good risk management program is needed to efficiently control the hazards to which workers are exposed in confined spaces. In this sense, metrology is a fundamental pillar in helping with this task: measuring and monitoring are important and fundamental actions for the adoption of preventive measures.

In regards to the measurement and monitoring of gases in confined spaces, the main national and international health and safety agencies suggest minimum and maximum levels of concentrations of these elements within these environments, which must be maintained and monitored throughout the worker's occupation time.

Nowadays, these measurements are carried out almost exclusively by portable meters known as explosimeters, done either by the employee who occupies the space or by third parties who supervise the service outside the entrance for rescue operations.

The main problem with the use of these portable meters is that they require certain efforts from users and the OHS team for their full utilization: Before entry, it is necessary to inspect the equipment, configure it, calibrate it and provide it with power. Afterwards, it is necessary to display and table the collected data, validate results and perform other actions that make the measurement and monitoring process tiring.

According to (Bolzani, 2004), this interaction with portable measuring devices is, in a way, a poor form of integration of computer systems, not being the most ideal for this type of operation. Furthermore, when using portable meters in confined spaces, the operator loses some of his mobility, not being able to work with his hands completely free in some cases, as shown in the example in Figure 1.

Figure 1: Gas measurement by portable meters: measurement performed by the worker himself (left) and measurement performed by the watchman (right). Source: Author, adapted from (Vale, 2015).

For the next coming years, it is expected that the gas monitoring in confined spaces will be done by wearable devices and wearable computers coupled to the workers' personal protective equipment. A smart safety helmet with methane gas and carbon monoxide sensors, for example, has already been developed to alert workers in underground coal mines when the concentration of these harmful gases exceeds a certain limit (Hazarika, 2016).

This form of monitoring in these environments will allow direct and instant access to information through data that will be directed to smart panels developed for managers and work safety teams and transmitted in real time. The equipment will also be able to send autonomously send requests for help and issue evacuation signals in case of emergency.

Even though this type of monitoring is more physically tied to the body of the employees, it is less intrusive than handheld computing, since it will not require the user's complete attention to manage it. Mobility with wearable devices is also better when compared to portable devices. The tendency is that wearables and smart protective equipment will present decreasing weights in the future, so that the user will not notice or be bothered by their use.

In addition, such computers coupled to the uniforms will also allow real-time monitoring of the employee's vital signs in the confined space through several biosensors, including body temperature sensors, heart rate monitoring sensors, blood pressure sensors and blood glucose and oxygen level sensors. Since gas meters can provide false alarms due to cross-sensitivity of the sensors, monitoring of workers' vital signs by wearable devices can, for example, help in the detection of oxygen insufficiency inside a confined space, according to the psychophysiological effects evidenced by the equipment.

4.2 Communication in Confined Spaces

All these sensors and equipment must be connected to low power wireless networks created exclusively for confined and underground environments, where traditional communication signals such as radio and 3G or 4G mobile phone networks will not be available nor be allowed due to the possibility of causing explosions.

Wireless mesh networks are likely to be present in the future of confined spaces due to their robustness, ease of scheduling and high integrity. In this sense, the wearables themselves will have embedded repeater systems and amplifiers to support communications in the adopted networks. Data routing between devices will also have robust and consistent algorithms for merging data into smart messages.

An emerging technology pointed out by (Kennedy, 2006) and that has practical application for technological use in confined spaces is the LR-WPAN (Low-Rate Wireless Personal Area Network) communication network associated with the IEEE 802.15.4 and Zigbee standards. Parameters such as low power consumption and low data rate in a wireless mesh network have been observed in several tests carried out by the researcher in underground mines.

In confined environments where 5G networks are already implemented and where this type of communication signal is available and suitable for use, it will be possible to transmit photographs and videos in real time with high image definition.

In China, mining companies have successfully deployed 5G-based underground stations to promote smart mining in coal mines. These bases may be part of the future of confined spaces according to the particularity of each environment.

The gains are countless with these technologies. The thick dust underground, for example, naturally interferes with the signal from traditional video and infrared cameras, but in 5G-based equipment the interference is little.

4.3 Augmented Reality and Virtual Reality

The use of augmented reality (AR) and virtual reality (VR) in confined spaces will also enable special features to improve worker efficiency and safety. Equipped with smart glasses, employees will be able to assess all the information collected by the sensors in the confined space in a simple and intuitive way, without the handling of the measuring equipment itself, as shown in Figure 2.

The augmented reality in confined spaces will be mostly applied in maintenance activities, process monitoring, quality inspection and ergonomic evaluation. Virtual reality, on the other hand, should be mainly applied for training actions in confined spaces and in simulations of rescue processes in these places.

Still on the use of augmented reality in these environments, it will allow the visualization of work instructions for users according to the recommendations of the OHS team. Such equipment will allow remote collaboration between humans so that workers outside the environment collaborate with confined workers. Higher risk areas will also be signaled on the virtual glasses according to the elements found in the environment, as in the case of Figure 2, where a confined gas valve is highlighted to the operator.

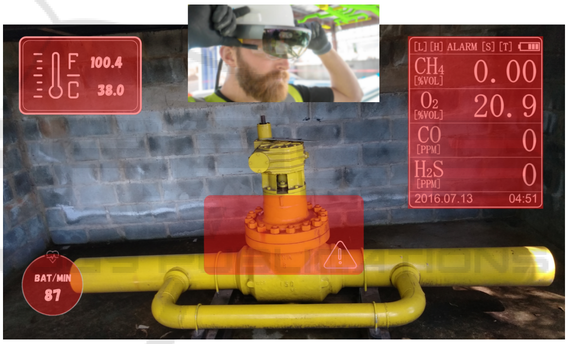

Figure 2: Using augmented reality to visualize sensed information in the confined space. Operator using Trimble Connect and Microsoft HoloLens. Source: Author, adapted from (Trimble, 2021).

Along with the glasses, video cameras will be integrated with the used protective equipment. Besides capturing images and videos in various situations, they will process computer vision algorithms to assist with measurement, equipment identification and environmental recognition tasks.

As an example of the use of cameras in underground mines, an application described by (Haas et al., 2016) can be highlighted, which uses a video camera connected to a dust monitor to automatically analyze the concentration of breathable silica in the air.

Neural networks can also be developed to quickly classify and detect venomous animals in dark parts of confined spaces. The detection and recognition of these animals by artificial intelligence will allow the use of appropriate tools for environmental risk removal and will enable more appropriate medical treatment should an accident with these animals occur.

4.4 Machine-human Collaboration

Regarding the future of robots in confined spaces, the most recent projects that are still in the development phase foresee humanoid robots transiting in these environments.

Some engineers and designers have already conducted relevant studies that allow this futuristic vision. While (Buchanan et al., 2019) proposes a hexapod robot that transits from the autonomous form to the body form in order to navigate in confined spaces, (Henze et al., 2017) proposes a humanoid robot with hands, feet, knees and elbows, which has the agility, the robustness and the balance required for these spaces.

Collaboration between robots and humans will also be a reality. Both will work together in a synchronized manner on routine and standardized tasks. In order to improve workers' safety in situations that require human-robot interaction, the use of augmented reality will allow the creation of visible paths for the robot's movement, avoiding collisions with objects and humans.

5 CHALLENGES AND LIMITATIONS

Imagining the future of confined spaces is a challenging task, since building equipment for these places represents a major challenge for the coming years, especially when the environment is confusing and complex. However, imagining solutions based on already existing tools is a first step towards making the great technological revolutions actually happen.

All the solutions cited above may at first seem simple, although promising, but the fact is that the construction and prototyping of these devices is not a reality due to high development costs, due to the equipment certification requirements for use in potentially explosive atmospheres, and due to the configuration of confined spaces.

In a search conducted in five academic search engines (IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink and Google Scholar), no history of an industrial wearable device developed exclusively for human use in confined spaces was found. The searched terms are listed in Table 1, with most of the similar equipment identified for these environments being developed for robots and unmanned aerial vehicles.

Table 1: Search strings.

#	Search String
1	”Confined Space” AND ”Wearable”
2	”Confined Space” AND ”Virtual Reality”
3	”Confined Space” AND ”Augmented Reality”
4	”Confined Space” AND ”Mixed Reality”
5	”Confined Space” AND ”Robot”

In the case of augmented reality glasses to be developed exclusively for use in these places, the operational requirements demand that the glasses do not block the operator's peripheral vision, allowing him to see both virtual and real objects. In this regard, the use of HMDs (head-mounted display) for these operations is an alternative. However, the high costs of these devices (ranging from US$ 700 to US$ 5000) are one of the main obstacles to the adoption of this equipment on a large industrial scale (D'Angelo, 2018).

For confined spaces, there is also the fact that the equipment certification for potentially explosive areas has, in itself, a high cost for building these prototypes. If the confined spaces are minimally classified as Zone 1 according to IEC 60079 (explosive atmospheres), then the possible protections for electrical and electronic equipment of this type should be *Ex d* (explosion-proof), *Ex i* (intrinsic safety), *Ex e* (increased safety) or *Ex p* (pressurized enclosures).

Currently, few companies develop wearable industrial computers suitable for use in classified areas, such as the intrinsically safe HMT-1Z1 equipment shown in Figure 3 and manufactured by RealWear. This shows that research and actions for the construction and adoption of these devices should be encouraged.

Figure 3: HMT-1Z1 equipment manufactured by RealWear and suitable for use in classified areas, in accordance with the ATEX and IECEx guidelines. Source: (RealWear, 2020).

Another barrier to be addressed regarding the use of wearable computing and wearables embedded in workers' uniforms in confined environments consists in weight reduction and better adaptability of wearables to the user's body so that the devices meet the ergonomic requirements of the application. As a main premise for a good user acceptance, wearable computing should not be invasive and, above all, it should provide freedom of body movements.

Finally, another challenge related to intelligent atmospheric monitoring in these environments by using technological equipment concerns the configuration of gases found in confined spaces. This is because some gases such as LPG and hydrogen sulfide are heavier than air and therefore accumulate at the bottom of the environment. Other lighter gases, such as methane, hover at the top of the space. And there are also gases with the same specific weight as air, as is the case of carbon monoxide, which is concentrated in the middle of the confined environment (Araújo, 2006).

Today, this situation requires operators to take gas measurements at all parts of the environment, having to frequently change the position of the measuring probes, which are flexible hoses connected to suction pumps for gas analysis by the sensors.

From an ergonomic point of view, the operation of moving the probe makes the monitoring process strenuous and tiring for the operators. This can be solved by coherently positioning the sensors on the user's body, as illustrated in Figure 4, so that the sensors' ability to detect the gas is more assertive, thus minimizing the production of false alarms due to cross-sensitivity.

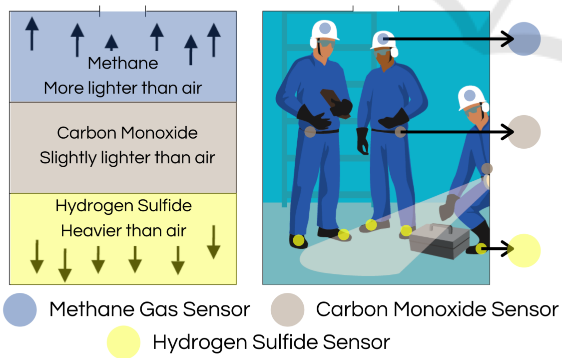

Figure 4: Sensors distributed on PPE can allow more assertive measurements. Source: Author, adapted from (Araújo, 2006) and (Vale, 2015).

6 CONCLUSION

This work investigated technologies used for work in confined spaces in the industry and described some promising solutions to support human activities in these locations. Under these perspectives, it is now intended to analyze and develop augmented reality devices for use in these environments. The current work in progress by the authors aims to display monitoring data in a more practical and intuitive way for confined workers. An example of an application under development is the computational coloring of naturally colorless gas concentrations in AR glasses for users.

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