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Development Of Novel Integrated Smart System Based On Artificial Intelligence For Management Of Operator Safety In Production Processes

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Abstract

This paper addresses safety challenges due to errors and misbehaviours of the operators in complex production systems when malfunctioning and failures must be manually solved by the operators or when defeating of the machine safety devices is carried out. To this purpose, in this paper a novel integrated supervision system is proposed. The system uses various technologies, including RFID tags capable of detecting both personnel and object positions to gather information from the working area, computer vision (CV) technology to observe and analyse the behaviour of both the operator and the machine and Artificial Intelligence (AI) module. The comprehensive dataset which is collected by the RFID and CV systems together with the knowledge of the current operative state of the assembly is transmitted to the AI module, which, following a period of thorough training, is expected to identify potential risks to personnel. Then, the AI module will trigger safety functions, predetermined by the machine manufacturer, in response to deviations from established safety standards. Output signals may include warning notifications to the workers on portable mobile devices, advising against proceeding with production. The whole integrated system is completed by a front-end software for its management by the responsible of the assembly. To demonstrate the efficacy of this novel concept, we plan to develop a prototype connected to a production system comprising a lathe and a collaborative robot (cobot). This production system will integrate data pertaining to work phases, machine and cobot status. In this collaborative process, the cobot and lathe work together to automate the turning process, adhering to stringent safety conditions. To validate the effectiveness of the supervision system, rigorous testing will be conducted in common risk scenarios associated with the turning activity of the prototype. The main goal of this innovative device is to increase the workplace safety reducing the effects of human errors and misbehaviours.

Keywords: artificial intelligence (AI), safety, computer vision, RFID system, human misbehaviour

1. Introduction

The workplaces are fraught with safety challenges, encompassing issues such as an excessive presence of personnel within hazardous work zones, tampering with machine safety devices, malfunctions and failures during the working phase and human errors (Braglia et al., 2018). These concerns contribute to increase the risk of incidents and to present significant obstacles to maintaining a safe workplace. The presence of an excessive number of individuals in hazardous work areas, for example, raises the potential for collisions, increased confusion, and ineffective emergency response. Open machine guards during unsafe work phases due to defeating of the protective devices expose operators to the risk of contact with moving components, increasing both the probability and severity of objects ejection accidents. Operators, seeking to streamline specific work phases, may choose to disable safety devices. This practice introduces high risks and compromises the overall safety integrity of the operational environment (INAIL, 2021). Deliberate interference with these devices compromises the built-in safety mechanisms designed to protect operators from potential harms. Moreover, all possible failures can introduce an additional layer of risk. The possibility of human errors and misbehaviours during manual tasks can largely affect the safety level of the workers.

Addressing these challenges requires a comprehensive approach that includes enhanced supervision of the workplace and machines. Maintenance of machines is a delicate operation that necessitates qualified personnel and adherence to a set of procedures outlined in the machine's instructions of use. Therefore, it is crucial for the employer to oversee that these operations are carried out according to the manufacturer standards. In order to perform a supervision activity of the workplace, a smart system based on RFID technology (Buffi et al., 2021; Landi et al., 2021; Montanaro et al., 2022), Computer Vision (CV) solutions (Hwang et al., 2023; Phatangare et al., 2023; Xu et al., 2015) and Artificial Intelligence (AI) algorithms (Gallina et al., 2023; Garyaev and Garyaev, 2023) has been designed. The aim is to put the assembly in safe conditions (i.e., to stop the hazardous movements) and to advise the employer and the workers whenever a non-compliant situation occurs with the recommendation not to continue with production until the anomaly has been resolved. In the same way, according to the new Machinery Regulation 2023/1230, an autonomous technology equipped with AI module can be used to ensure Safety Functions (SF). For this reason, a supervision system could help the manufacturer of the production system (or of a single machine) to apply additional SF. The proposed solution aims to increase the likelihood of preventing incidents related to abnormal or challenging usage conditions that are difficult to foresee during the design phase and could, therefore, theoretically escape the normal conventional technical solutions envisioned during the design phase. The enabling condition to reduce the occurrence of incidents linked to the described issues lies in the choice of adopted technologies. The main features that have contributed to the selection of the technologies constituting the system architecture are listed below.

1.1. RFID technology

RFID, which stands for Radio-Frequency Identification, is a system that allows the identification and data collection from objects, animals, or people using RFID tags containing a microchip and an antenna communicating via radiofrequency with an RFID reader. This technology is widely used in various sectors for various purposes, including:

- tracking individuals and verifying their motion state (stopped or in movement) using tags equipped with accelerometer;
- verifying the presence of objects and their orientation thanks to the tags integrated with accelerometers;
- incident detection by integrating tags into workwear, enabling the assessment of whether an operator is in a potentially hazardous zone.

1.2. Computer Vision based camera

Cameras equipped with CV are devices that integrate advanced image processing capabilities and intelligent analysis directly into the camera itself. These systems combine traditional camera technology with sophisticated computer vision algorithms, enabling the cameras not only to capture images or videos but also to interpret and understand what is being displayed. This technology is widely utilized in various sectors for various purposes (Ahmed et al., 2023; Zhong and Meng, 2019), including:

- real-time Image Analysis enables an immediate response to specific events or situations. For example, they can detect suspicious movements, identify specific objects, or report anomalies as they occur, enhancing safety and responsiveness;
- recognition of position/status of devices on machine thanks to the application of QR codes arranged in specific positions, the CV system can recognize the position of specific devices;
- tracking the movement of objects or individuals within their field of view. This functionality is very useful for monitoring and recording events.

1.3. Artificial Intelligence module

An AI module is a specific component of a larger system, focused on the ability to make decisions autonomously or with assistance by incorporating advanced artificial intelligence algorithms to analyse complex data, learn from past experiences, and producing consistent decisions tailored to specific scenarios. The AI-based system is able to receive input information and to process them properly through a previous phase of training and test.

In our system IA module is used to identify situations with potential risks, correlating them with specific conditions or states of input signals. In response, the module can generate precise output signals that other subsystems can utilize to mitigate the risks associated with a recognized hazardous situation, such as stop commands and emergency stop signals.

Hence, the aim of this study is to develop and implement an integrated and intelligent supervision system for machine assemblies, as defined in new Regulation (EU) 2023/1230, to monitor and evaluate the safety status of the working environment. The system aims to recognize risky conditions for operators due to faults, malfunctions, or incorrect behaviours carried out by them. The proposed control system is designed to be implemented in any type of production system within industrial environments, thanks to its versatility and ability to adapt to various machine configurations. The paper is organized as follows. Section 2 outlines the description of the proposed system. In Section 3, some possible case studies of the test rig under development are described in order to show and demonstrate the potentialities of the novel concept here proposed. Finally, Section 4 concludes the paper and outlines necessary future research activities.

2. General description of the system

Figure 1 illustrates the main components of the supervision system; a generic production system labelled as "1" (assembly of machinery), identification module "2", computer vision "3" module (CV) and the management system "4". In this figure signal exchange and physical connection of subsystems are draw as a dashed line, the arrowhead shows the direction of the signal (I/O). Additionally, to conduct more effective controls of activities in the working area, thanks to the communication between the assembly of machinery control system and the AI module, comprehensive information to the AI module is conveyed, including details about the machine status, and possible maintenance requests. The AI module represents, therefore, the system capable of making decisions and avoiding the occurrence of hazardous situations based on received signals and information. Signals are sent to the AI module at intervals that depend on the machine status and on the data processing capability of each subsystem. The signal reception time interval is also a subject of study in relation to the system's reaction time, which depends on the specific monitoring issues.

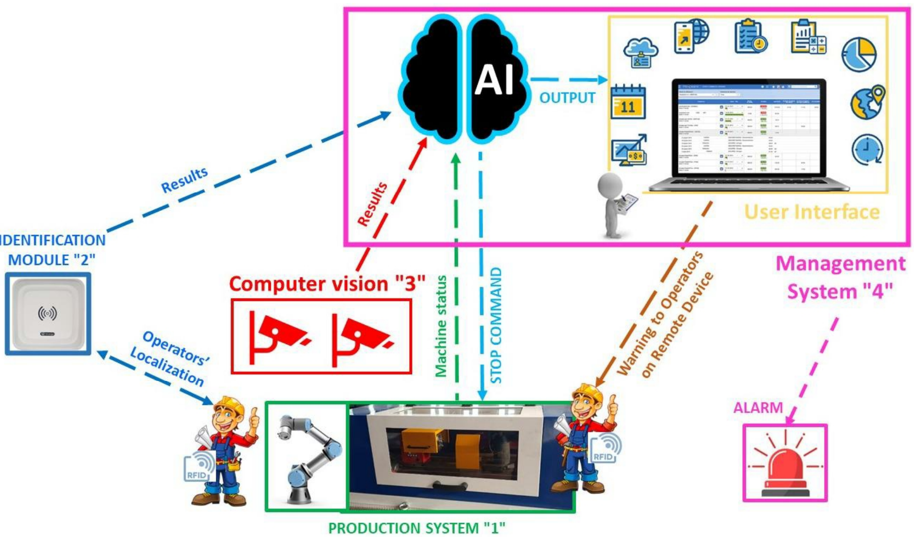

Fig. 1. Main components, architecture and signal exchange of the prototype.

In terms of safety and to address the outlined objective of managing conditions that are difficult to predict during the design phase due to actions taken by operators and machinery behaviour, the use of additional technologies and devices is also essential. Specifically, reference is made to the presence of an identification module, which uses RFID technology to pinpoint the locations of operators, verify the adoption of Personal Protective Equipment (PPE), and control the presence and position of both fixed and mobile safeguarding systems equipped on the assembly of machinery and other eventual equipment which are required to assure satisfying safety levels, such as specific tools for maintenance or containers of end items. The presence of the RFID system is crucial as RFID tags allow the identification module to recognize the presence/absence of objects and people, identifying them uniquely, and to recognize their orientation. Simultaneously, another technology envisioned to achieve the predefined objectives is a CV system, which observes the situation from various angles using at least three cameras so to cover all the necessary volume of the assembly (at least two cameras for full horizontal view and one vertical camera located on the top of the work area for top-down overview). The information captured by these additional devices converges in the management system, where AI algorithms are employed to evaluate and compare the input signals and make informed assessments.

Finally, the management system is characterized by the presence of a front-end user interface, allowing the Health, Safety & Environment (HSE) supervisor and line responsible to control and monitor the system's operation. In addition to enabling the viewing of the system status, the interface provides the authorized operators with the possibility to define and override safety commands for the machine when additional monitoring conditions are needed. A communication system using portable mobile device is used to inform the operators about the current risky situations and to recommend them proper behaviours as listed below.

The need to control the impact of the AI supervision system on machine safety during the execution of activities is directly specified at points 1 and 1.2.1 of Annex III of the essential health and safety requirements of the recent new Regulation (EU) 2023/1230 on machinery. This new regulation includes "the Safety components with fully or partially self-evolving behaviour using machine learning approaches ensuring safety functions" within safety components in Annex II. Whenever necessary, there must be the possibility to understand the reasons for certain decisions taken by the system. In conclusion, to adhere to the desired safety conditions, the management system must undergo comprehensive training to effectively identify anomalies that pose potential hazards to individuals. Whenever a hazard is detected (one or more input signals describe a deviation from safety standards), the main task of the AI module is to generate an output signal to improve the current safety of the production system, contingent upon the type of hazardous situation unfolding.

Several types of outputs will be implemented in the final prototype:

- warning signals to operator devices (smartwatch, smartphone, ...);
- warning signals to the employer and the recommendation not to continue with production until the problem is resolved;
- emergency stop signal;
- alarm: a general acoustic and visual signal of hazard applied in the interested area (flashing, siren, ...);
- stop command on the machines (stop of the production system operations to remove current hazards).

3. Description of the application cases

As experimental test rig, the first attempt to realize and validate the proposed supervision system will be done to control and monitor the workspace which involves a lathe and a collaborative robot (cobot) working together to automate the turning process of various workpieces initially stored in a storage bin. The cobot performs a pick-and-place operation to position the workpiece near the operator, who manually places it in the chuck after the cobot opens the lathe door. Utilizing a wired connection linking the electric cabinet of the cobot to the lathe, a signal initiates the commencement of the machining phase after that the robot closed the guard.

It is imperative to specify that, to enable the lathe to start without direct operator consent, adherence to the requirements for conditions of interlocking guards with a start function is mandatory (see EN ISO 12100: 2010, paragraph 6.3.3.2.5). In addition, the safety distance between workers and the machine shall be monitored in real time. Similarly, the workpiece undergoes unloading and is automatically stored in a designated location based on the outcome of the machining process. The integration of the cobot and lathe constitutes the production system, denoted as "1".

This chapter outlines the operational scenarios, designed to test the prototype system's capability to detect potential hazards and prevent incidents. The application scenarios have been carefully devised to challenge the system's functionalities in various conditions, allowing for a thorough analysis of its capabilities to identify and respond to potential risks. Simulating hazardous situations is essential to assess the system's effectiveness in operational safety and ensure that it can prevent incidents through a timely and accurate response. This testing phase is crucial to ensure that the system is actually robust and reliable in real production conditions, contributing to providing a safe working environment for operators.

3.1. Defeating guards

In this scenario, an operator may defeat the interlocks on the interlocked movable guards (highlighted in red in Figure 2) or remove the guard if it is fixed at the machine (highlighted in green in Figure 2), causing the exposure of moving elements even during the execution of manual operations. For more information on defeating of guards see EN ISO 14119:2013. In order to recognize some kinds of tampering in our machine, the supervision system must monitor the lathe door's, the tool and chuck guard status (open/closed) through CV, verifying the presence of specially designed QR codes placed on both the guards and the machine frame, and determining their positions. When a mobile guard is open, the QR codes on the frame must be obscured and no longer visible to the CV. Those on the guard, on the other hand, will move, and the CV is able to recognize the change in their position. Meanwhile, the production system will indicate the ongoing operational phase, and the identification module, using RFID tags placed on the repairs themselves, will verify both their presence and orientation. This type of control must be performed whenever the work phase requires opening/closing of the guard and, in any case, repeated until a definite response is obtained. If a manumission action is detected, an immediate machine stop command (or emergency stop) is sent to the safety control system of the assembly of the machinery (this action can be considered as a SF of the manufacturer). If the absence of one or more QR codes or RFID tags is detected, the "guard removed" status is recognized with the same consequences.

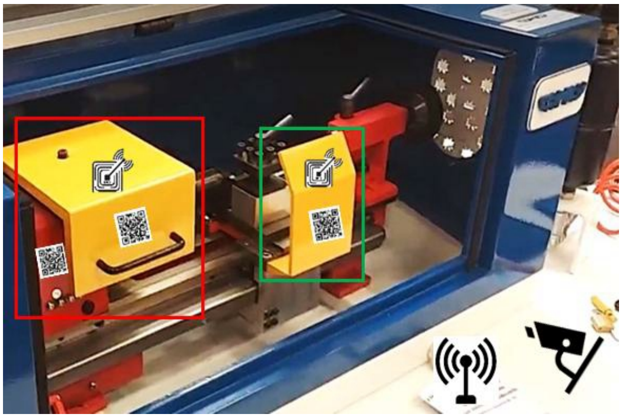

Fig. 2. Examples of movable and fixed guards in the proposed production system.

3.2. Counting the number of people

In this scenario (Figure 3), operators who are not authorized to perform set-up or machinery maintenance activities may enter the work area. Access to the area during critical operations such as set-up or maintenance, which require adequate training, by unauthorized operators could compromise their own safety and that of the other present colleagues. For this reason, it is necessary to develop a system that allows counting and identifying the operators present. To identify and count the number of people within the work area during the described tasks, the proposed solution includes:

- the CV system, utilizing specific Object and People Detection algorithms, performs the counting of the number of people simultaneously present in the work area;
- the RFID system, with tags placed inside operators' coverall, counts the number of operators present in the work area and identifies their identities to distinguish between authorized and unauthorized operators.

The machine control system communicates the ongoing operational phase to the AI module, which defines the maximum allowable number of operators for that phase. The monitoring of the system during this phase should occur within a time interval on the order of seconds. If, during the execution of any of the listed activities, the system detects a number of people exceeding the allowed limit, an alarm will be triggered until the number of people equals the defined limit specified in the machine user manual. If the number of counted people with the two methods is not the same, it means that an unauthorized person is in the area, or an operator does not wear the appropriate PPE. A warning signal will be sent directly to the HSE supervisor and line responsible to inform him about the problem. It is important to note that the operator identification carried out in this case study does not absolutely require the personal acquisition of any biometric personal data and so fully respects his own privacy.

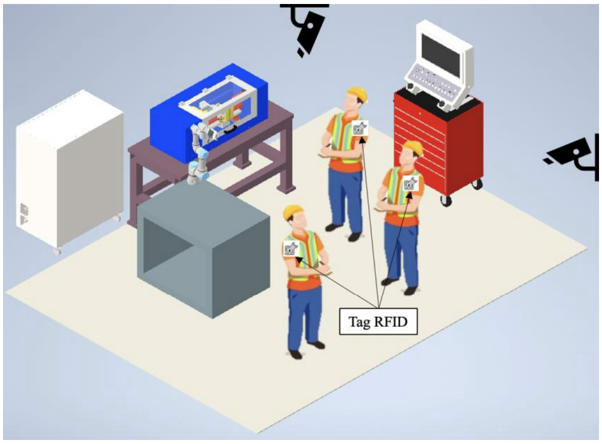

Fig. 3. Count of the number of people inside the working area by monitoring activity (CV) and tag identification (RFID).

3.3. Manumission of the cobot

In this scenario, the cobot may be susceptible to cyber, accidental, or intentional tampering, and it must be adequately protected for the already mentioned new machinery Regulation. The manumission of the program executed by the cobot could cause an unexpected movement of the device causing possible collision with operators. Specifically, the software and data must be safeguarded where a change in conditions could compromise the compliance of the quasi-machine/machine and the safety of individuals. To avoid possible hazards for people, the supervision system controls if the cobot movement is authorized by the operator, with the command console, or by the lathe control system. Therefore, it must be possible to determine if the behaviour of the cobot is suitable, i.e., it activates at specified times. In order to verify its behaviour, the following control activities can be carried out:

- the CV system checks the QR codes placed on the joints of the cobot, which, if the cobot is in a predefined still position, should assume a specific position;
- the machine control system communicates the ongoing operative phase, specifying whether the cobot is involved in the operation or not;
- the RFID system, through tags equipped with accelerometers, detects the current position of the cobot.

The goal is to ensure that the cobot movement is authorized either by the operator, through a control console, or by the machine itself, always supervised by AI, which must recognize any unexpected activations. The input signals from the machine, RFID, and CV are thus directed to the AI system. The system, by comparing the incoming information, must decide whether the behaviour of the cobot is “compliant” or not. If an anomaly is detected or a discrepancy occurs between at least two of the information received by the management system, the status of “Tampered Cobot” would be initialized, leading to the immediate stop command of the machine (or emergency stop depending on the risk) to the safety control system of the assembly (this action can be considered as a SF of the manufacturer).

3.4. Obscuring cameras

In this scenario, an operator attempts to obscure the computer vision system by placing a static image in the area captured by the camera system, preventing its acquisition of information. This manumission implemented by the operators would allow them to engage in improper behaviour that could potentially trigger hazardous situations. To assess whether the cameras have been obscured, the proposed solution includes:

- the CV system, which checks, through the comparison of information processed after image acquisition, whether the image has remained unchanged;
- the RFID system in conjunction with the Computer Vision system: the RFID system counts the number of people present in the work area through the placement of one or more RFID tags inside coveralls, while the CV system evaluates the movement or stillness of the operators captured, as the image placed in front of the camera system could depict an operator.

The monitoring of the system during this phase should potentially occur in a time interval on the order of seconds. If, following monitoring, the AI system receives a signal from the RFID system but receives no signal from the CV system, a tampering action of the CV is detected, and an immediate machine stop command will be sent to the control system.

3.5. Monitoring of components presence and position

In this scenario, it is anticipated to monitor the presence and correct positioning of the container used for collecting waste chips resulting from turning operations, as its absence poses a potential risk to the operator's safety due to the possibility to reach hazardous moving parts and to create a hazardous accumulation of chips on the floor. The assessment of object presence and their positioning can be carried out using CV and identification systems based on the use of RFID tags. It is necessary to place one or more specially designed QR codes on the objects to be identified in positions where they are always visible. It becomes imperative to define advanced CV algorithms capable of recognizing objects in the working area. To verify the presence of the chip container and its correct position, the proposed solution includes:

- the CV system, which will engage in monitoring the presence or absence of the container based on the successful or unsuccessful reading of QR codes placed on the lateral faces and the top surface of the container;
- the RFID system, thanks to the presence of tags on the container, will detect the presence of the container marked by the tags.

These checks shall be carried out regularly, approximately within a time interval of one minute. In the event of the absence or incorrect positioning of the chip collector, an alarm signal will be sent directly to the employer, in addition to the inability to proceed to the next processing step.

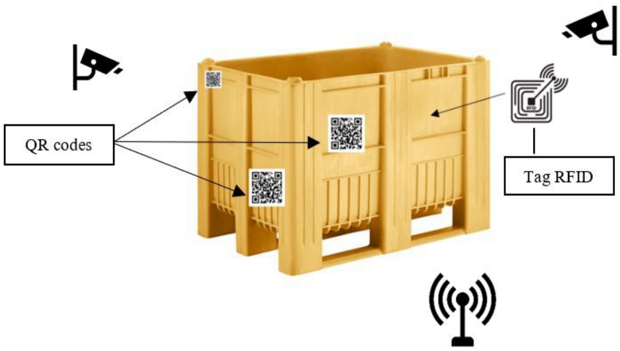

Fig. 4. Monitoring and identification activity of the chip container inside the working area.

4. Conclusions and future remarks

The supervision system here proposed as novel concept represents an innovative device designed for the safe oversight of a workplace environment hosting operators, machines, and other equipment. This novel system functions as a control system with the capability to ensure operator safety by identifying potential risk scenarios. Employing three parallel technologies for monitoring the work area offers redundancy in the AI evaluation, thereby minimizing potential errors in interpretation, particularly reducing the occurrence of false negatives that could pose significant risks to individuals. A robust training regimen for the definition of the AI algorithms is necessary to enhance its decision accuracy (Commission Report on safety and liability implications of AI, the Internet of Things and Robotics, 2020). The implementation of a supervision system should not substitute the internal safety functions of the machine which will help to guarantee a low probability of critical system malfunctions. In the next future, a detailed specific analysis about the performance levels of the safety functions related to the correct functioning of this novel smart system is planned (IEC TS 62998-1:2019). The next activity will concern the development and testing of a prototypal system to demonstrate the actual functionality and effectiveness of the present novel proposal. The system's responsiveness to various circumstances must be tested to assess its actual ability to intervene promptly. This responsiveness is contingent upon the complexity of the algorithms required for evaluating input signals. Another critical aspect will involve assessing the future efficacy of the smart system in appropriately managing operator safety following a period of self-evolution that will change its decision properties. The challenge will be to succeed in ensuring, and at the same time, demonstrating that the performance level of the safety functions of the prototype remains compliant over time.

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