An innovative integrated smart system for the safe management of de-energization in maintenance activities of assemblies of machinery

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In the Machinery Directive 2006/42/EC the risk management of the maintenance activities is particularly important, because the operators face several hazardous situations. The safe entrance into the danger zones of the machinery assemblies often requires the isolation from energy sources and the dissipation of stored energies to assure the avoidance of release of energy, the unexpected start-up of the machinery and harmful incidents. In this context conventional well-known procedures, such as Lock Out/Tag Out (LOTO), are widely exploited by the employer. Their actual effectiveness in terms of prevention of incidents depends strongly on the correct application by the operators and currently several dramatic events still occur. So, we present a novel smart system, based on the paradigm of Industry 4.0, which supports the operators and guides the procedure step-by-step with the aim of mitigating the error probability and the consequent risk.
The proposed smart system exploits the Radio Frequency IDentification (RFID) technology to measure the real-time position of workers through a synthetic-array method. A cloud-based software supervises and manages all activities. Based on the tracking results, it communicates step-by-step to the operators the safe procedures on remote devices such as smartphones and receives feedbacks about the right execution. In this way the de-energization procedure can be carried out in safe way with low level of error risks for all operators involved in the maintenance activity.

Keywords: Lock Out Tag Out, Industry 4.0, smart device, hazardous energy, maintenance safety, RFID localization

1. Introduction

Currently in the workplaces a very frequent hazardous situation for the operators concerns the execution of manual maintenance activities on machineries, assemblies and large production plants. The operators are physically in strict contact with the hazardous parts of the machinery and their tasks typically require the access to zones where some energy sources and stored energies can be present during normal operations. The guards and protection must be disabled to assure the free entrance of the operator within the hazardous zone. In this situation the machinery must stay in still condition and every energy supply or stored energy must not induce the start-up of the machinery and not produce hazardous situations for the operators. It is necessary to avoid that the machinery starts by itself due to problems in the control system or due to the erroneous command by the user that could energize the system when the operators are still working within the hazardous zone. In such events, the actual consequences of possible incidents are evidently dramatic with high probabilities of fatalities. Moreover, the operators could work on electrical equipment

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and evidently the isolation from the electricity supply must be maintained for all duration of the work.

The issue of assuring the worker safety during these hazardous tasks is particularly critical when we consider assemblies of machineries, integrated manufacturing systems and large production plants. In this context the presence of many machineries makes the problem very challenging. Together with this risk, we need to mention the risk of operator entrapment, i.e. the risk to restart the production line when operators are still in hazardous zones. When the spatial configuration of the production system is very complex, the risk of entrapment is not negligible. Typically, there are several hidden work areas and it is very difficult to assure the safe access of the operator into the work zones, which are in strict contact with hazards and to monitor their actual presence before deciding to restart the system.

The problem of the unexpected start-up due to release of the energy sources and residual stored energy in the system is explicitly considered within the health and safety requirements in the Annex I (clause 1.6.3 "Isolation of energy sources") of the Machinery Directives (EU, 2006). The manufacturer shall provide the machineries with technical solutions and define specific procedures within the user instructions to assure high level of safety during maintenance activities. Nowadays the respect of this requirement can be obtained assuring the possibility by the user to adopt the well-known procedure Lock-Out/Tag-Out (LOTO) (OSHA, 2002). Then, the employer is responsible to organize the effective application of the procedure in the workplaces (Directive 89/391/EEC, 1989). In large operation plants the problem of the safe de-energization is even more complex when the plant is not considered as single assembly, the energy sources are multiples under different distribution devices, the workplaces are several and located far from each other. So, there are multiple manufacturers and the equipment are energized using multiple and independent devices. In such context the information for the de-energization process are available in different sources and so it can be difficult for the employer to define a safe procedure.

The effectiveness and correctness of execution of procedures for the managing of worker safety strongly depend on many aspects, such as its correct preparation, the right training of the operators, the effective supervision during the execution, the real commitment and involvement of the operators, their capability and performance in terms of avoidance of errors. Moreover, the occurrence of errors and the consequent presence of misbehaviours, which must be considered by the manufacturers during the procedure design, are particularly relevant. Notwithstanding this provision, the human errors due to, for example, stress, communication problems, inexperience, inattention, shift handover, unclear instructions, excessive confidence, still occur. Recent statistics report that the LOTO standard is one of the most violated procedure in the USA (OSHA, 2020).

In this context the current digitalisation of the machineries carried out under the Industry 4.0 paradigm plays an important role. The manufacturers are increasing the automation and intelligence of the machineries by reducing drastically the necessity of strict contact of the operators with the hazard zones recording and using many digital data for their optimized operation. Their deep automation will progressively reduce the contribution of the operator presence in the hazard zones during the normal operative activities. The operators are more and more becoming supervisors of automatic machineries and their tasks are mainly carried out far from the hazardous zones with an overall improvement of the safety level in the workplaces. This high level of automation is not able to improve safety performances during maintenance, which is still strictly related to manual activities by the operator. The Key Enable Technologies of Industry 4.0, such as Radio Frequency IDentification (RFID), can be effectively adopted for the safe use of machineries and give a useful contribution to this problem.

In the scientific and technical literature no contribution is present about the automatization and digitalisation of the de-energization/re-energization procedure. Several proposals to implement the localization of the operators and their personal protective equipment (PPE) for safety purposes have been proposed (Amicucci and Fiamingo, 2017). The most part deals only with the automatic localization of the operators within the working areas in order to monitor their hazardous presence and to command the stop of machinery movement, such as bridge cranes or laser guided vehicles.

In this paper, in the framework of the paradigm of Industry 4.0, we present a novel smart integrated system that exploits the RFID technology for the real-time monitoring of the operators positions that are involved in the de-energization procedure during maintenance activities. A cloud-based software for the smart management of the procedure supervises and manages all activities supporting the workers during their tasks. The smart system here proposed does not aim to modify the safety related parts of control system of the machineries but wishes to reduce risk at organizational level in accordance with the provisions of the legislation of health and safety of workplaces (Directive 89/391/EEC, 1989) as protective measures implemented by the user as specified in Figure 2 of ISO 12100:2010. When the interaction between this smart integrated system and the machinery safety system is required, a specific mode selector shall be provided by the machinery manufacturer and included in the intended use as described below.

So, the present paper is structured as follows. In section 2 the features of the novel smart system are described. In section 3, its operation is shown in detail. Finally, in section 4 some comments and future activities are outlined.

2. The novel smart system for the safe management of the de-energization/re-energization activities

The novel smart system for the safe management of the de-energization tasks is composed by several components as described below (Figure 1).

1. The maintenance operators must wear their working coverall and PPEs for the authorized entrance into the workzones where it is necessary to execute the tasks. Several ultrahigh frequency-radio frequency identification (UHF-RFID) passive tags are mounted on

the coverall and PPEs in order to assure the operator detection and then its effective localization. So, the tags can be located in correspondence of head, arms, legs, chest, hands and feet. The passive tags have been selected since are cheap and battery-free, consequently, it is possible to use many of them by increasing the system reliability at low cost.

2. A localization system based on the UHF-RFID technology detects the real-time position of the operators wearing the UHF-RFID tags. The system is based on a synthetic-array method (Buffi et al., 2015; Bernardini et al., 2021), which takes advantage of the relative motion of a reader antenna with respect to the tags. The reader antenna continuously moves along an assigned path by scanning the whole work area and by collecting the backscattering signals of the tags on the operators. Such signals are then elaborated to evaluate the relative position of the tags with respect to the reader antenna with a localization error of few decimetres provided that the antenna trajectory is known with low uncertainty. By generally speaking and by considering the encumbrance of the machinery assemblies at the ground, the antenna motion can be obtained by employing a suspended rope, an overhead travelling crane, a ceiling rail or a 3D cartesian movement system as proposed in this paper. The path of the reader antenna is specifically designed in accordance with the layout of the work areas which must be supervised. Wide beam reader antennas are typically employed, thus enabling the coverage of an area of about tens of m^2 with a single antenna. The position of the antenna reader in a local reference system within the factory and required as input data of the localization method, can be measured by encoders mounted on the rails. Thus, the operator positions are determined in the same local reference system and their relative positions with respect to the hazardous zones of the machines can be derived. If it is necessary to cover large plant areas, it is possible to adopt several moving reader antennas properly spaced along the cartesian system rails.
3. Tracking back-end is a software which is dedicated to the execution of safety checks to understand whether or not a generic operator is in safe position for the successive step of the de-energization process. Once the positions of the operators are measured thanks to the RFID-based localization system, it is necessary to assess whether the positions are safe or not for the next step. To this purpose a list where the responsible of the procedure enters the safe and unsafe areas for each phase via the Front End (see point 7th) is used for comparison. The tracking back-end records the current position of the operators and the outcome of the check.
4. An Android application (app) runs on mobile device, such as smartphone or tablet, and provides the maintenance operator with information about the de-energization/re-energization procedure. The app is used by the operator to send/receive information and confirmation about the de-energization process. It makes it possible for the operator to dialog in real time with the supervisor who could be present in front of the Front-end cloud server (see point 7th). Moreover, as described below, the operator can send commands to the control system of the machinery using the app.
5. Near Field Communication (NFC) tags are located at the work points, where the operators must execute the tasks of the de-energization procedure. Using his mobile device, the operators read the NFC tags and inform the Back-end cloud server about their position. The operators receive from the cloud server the confirmation about the right point where to execute the specific step of the procedure.
6. The Back-end cloud software based on the framework of Spring on java is the logic core of the smart system for the de-energization management. It coordinates the communication among all parts of the smart system and records every information about the de-energization procedure in specific database. It interacts with the Tracking back-end in order to obtain the consensus about the safe position of the maintenance operators before communicating him the next step.
7. The Front-end cloud server, which is developed with Angular platform, works as interface between the system and the maintenance supervisor, who executes the data entry about all information necessary for the operations of the smart system and can analyze all statistics about the completed procedures, such as, for example, the number of de-energizations performed procedures, the workers localized in safe and unsafe positions. Moreover, via the front-end cloud server the maintenance supervisor has the possibility to connect with the operator and to interact in real time with him as support sharing useful information about the task. His presence in the console is not mandatory but it is recommended for the execution of the operations. Obviously the operator has the right skill for the job, but the real time support can be considered an important added value in order to improve the success rate of the correct execution of the task.
8. The automatic machinery is able to interact with the Back-end cloud server to receive commands and information from the maintenance operator via the application on the mobile device. A particular smart maintenance mode selector is added to the standard mode selector in full compliance with the Machinery Directive (clause 1.2.5). When this selector is not activated the machinery is not able to receive/send command from/to the Back-end cloud server. When the selector is activated, the machinery is put in safe conditions and the commands through the console of the machinery are disabled and only the communication with the Back-end server is allowed.
9. Modbus TCP/IP module makes it possible the interaction between the Back-end cloud server and the control system of the automatic machinery. The former produces queries to the machinery about the status of sensors and process instrumentation and sends commands to the machinery such as, for example, the opening/closure of an automatic valve. For safety reason, the operator can send commands of operation via the Back-end cloud server only for equipment under its

view or in any case with any consequent unsafe implications (e.g. with guards surrounding valve closed).

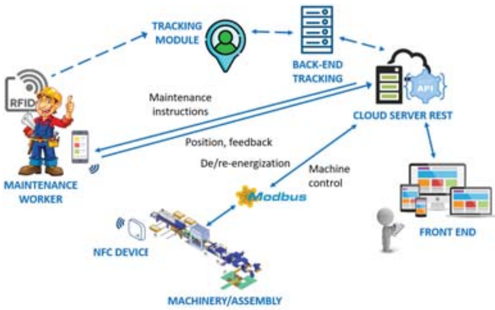

Fig. 1. Main components of the novel smart system for the safe management of the de-energization/re-energization process.

3. Operation of the novel smart system for the safe management of the de-energization

The operation of the novel smart system is based on the following steps (Figure 2).

- Phase 1: a specific task of maintenance which requires the de-energization of the machinery is assigned to an operator. In general the state and the process phase are known and so the energy sources and the stored energy which shall be constrained and/or dissipated respectively are known, too. So, for example it is possible to know if an equipment is still hot or there is voltage on an equipment. The operator is informed on his app about all these hazardous energies that he has to manage. Consequently, the de-energization steps which are required to put in safe conditions the machineries are known and can be shared with the operator as described in the following. Hence, thanks to the safety measures provided by the machinery manufacturer the status of the machinery is well known (e.g., sensor, gauges).

- Phase 2: the operator, who wears his coverall and PPEs equipped with RFID tags, enters the hazardous zone to start the smart procedure of de-energization. This phase is divided in three sub-phases:

  - Phase 2.0: the operator enters the work zone taking his mobile device.
  - Phase 2.1: the operator reaches the point where he has to operate the de-energization. His current position is known thanks to the RFID-based localization system in a local reference system within the factory.

    At the same time the operator reads the NFC tag through his mobile device and confirms his position to the Back-end cloud software. In this way the NFC device assures a redundant information for the operator localization in addition to the RFID-based localization system. Thanks to the NFC, the operators can receive the confirmation to have reached the right position for the operation. The reliable functioning of the localization system has evidently important implications for the worker safety.
  - Phase 2.2: a check about the position of all operators who are involved in the operations of de-energization is executed using the localization system. Until they are not located in safe position in relation to the specific task to be executed it is not allowed to go on with the following step. If the control is not positive all people are invited by the Back-end system to move to safe position. Note please that the NFC is used only by the main responsible of the procedure to confirm the right location for task execution.

- Phase 3: Once all operators are in the right and safe position, it is possible to start the operation of de-energization (Figure 3):

  - Phase 3.1: the operator receives the sequence of tasks on his mobile device via the app. He has a complete overview of the de-energization process because he has at his disposal text instructions, photos, indications, short movies and audio files. The details of the operations appear on the app only one by one. The following step can be viewed only when the Back-end system has received the confirmation of the right execution of the task. All tasks can be carried out only if the positive consensus about the position of all operators involved. Indeed, after each step it is necessary to go back to Phase 2 in order to evaluate the position of the operators and to give the allowance for the step execution. The generic step cannot be evidently executed if it puts someone in unsafe condition. The consensus is sent by the Tracking Back-end to the Back-end system. The task of de-energization can be executed only by a single operator. If the procedure is already activated, a different operator can not activate the same procedure. This new operator can only participate to the procedure by using his own padlock if he is involved in the same maintenance task, thus by reading the steps without possibility of active interaction with the Back-end system.

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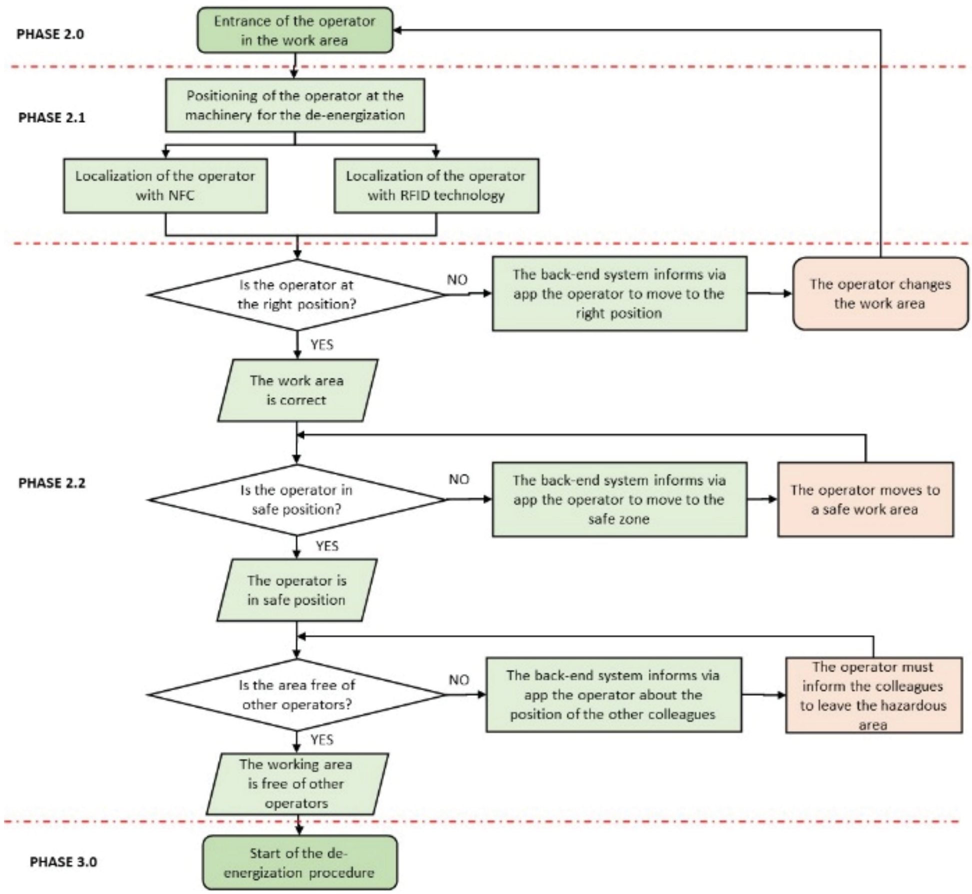

Fig. 2. Main phases of the operation start of the novel smart system for the safe management of the de-energization/re-energization process.

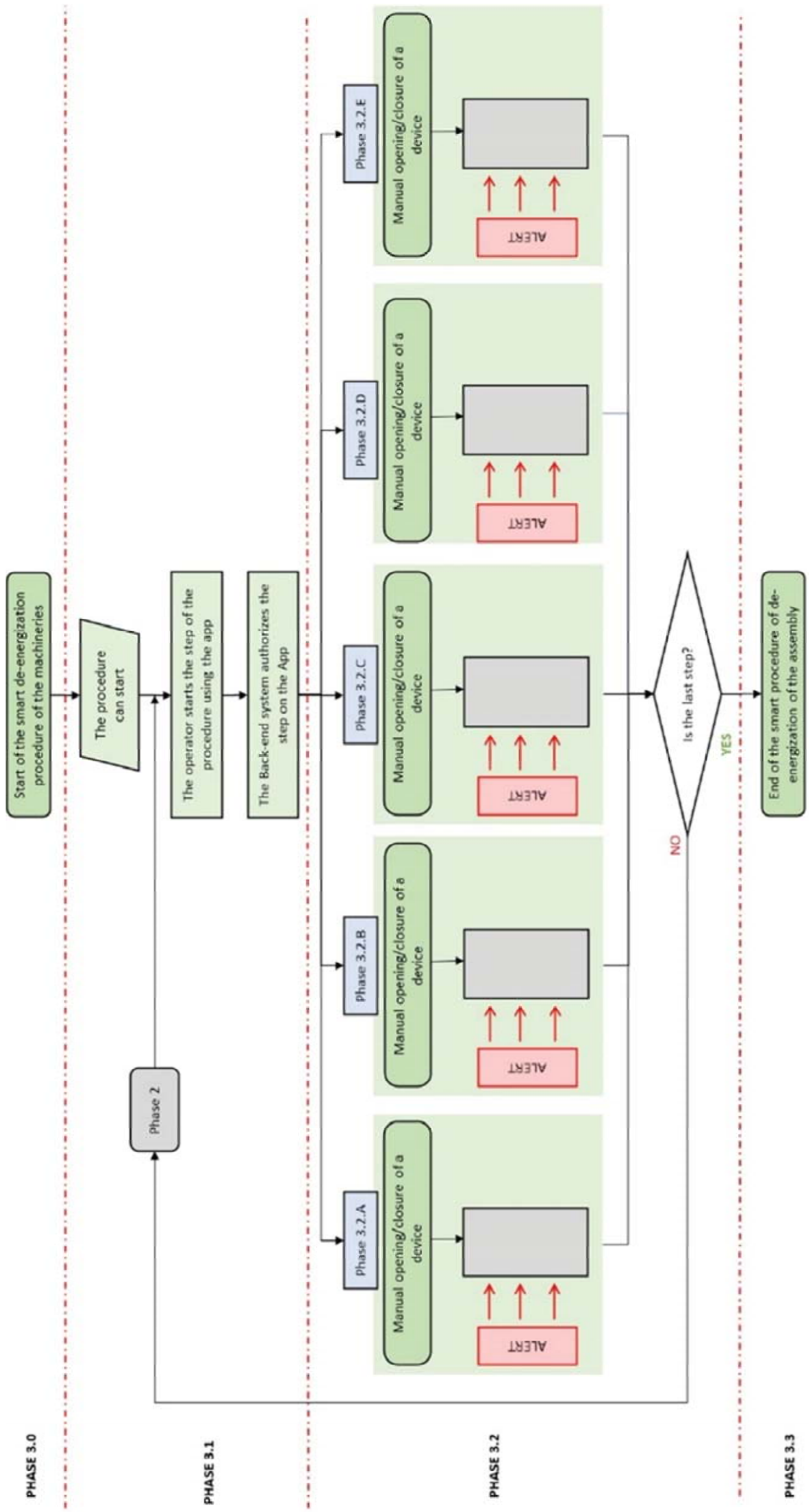

Fig. 3. De-energization tasks with the smart system.

- Phase 3.2: in this phase the operations of de-energization are carried out. In this paper we consider five kinds of tasks as described below:

  1. the operator manually opens/closes a device, such as a valve or an electrical disconnector, to stop the energy supply or to dissipate the stored energy. A limit switch produces a confirmation signal of right task execution for the control system of the machinery. The operator communicates via the app the task execution to the Back-end system that provides the following step only if it receives the same confirmation from the control system of the machine via the Modbus TCP/IP protocol. Then, the Back-end system informs via the app the operator about the right task completion. This signal is provided only for information about the progress of the maintenance procedure and not for safety reasons as intented in Machinery Directive. In current machineries there is not signal for the execution of this kind of task.
  2. The operator manually acts the specific mode selector on the machinery which excludes the local control of the machine and permits the control via industrial protocol in a “safe condition” for the operator. This mode selector shall also permit the de-energization of all possible hazardous actuators. The deep discussion of this part of the safe system is outside the general scope of the paper and it strongly depends on maintenance tasks to be performed on the specific machine. Hence, the safety of the machinery shall be reached using the specific mode selector cited above and the machinery safety is assured by the safety system of the machinery. Once the machine is in safe conditions, it is possible to command the operation of an equipment by mobile device. The operator sends the command of opening/closure of servo-controlled equipment, such as an electro valve, to the control system of the machine by using his app on the mobile device. First the command is received by the Back-end system which sends it to the machine via the Modbus TCP/IP protocol. The operator receives the confirmation of the completion of the task from the Back-end system once the machine communicates the task execution to the Back-end system.
  3. By using a radio control the operator activates the command on the control system for the opening/closure of an equipment under his view, such as an electro valve. Once the control system of the machine gives confirmation about the operation completion to the Back-end system, this informs the operator via the app on his mobile device.
  4. The operator manually closes an electric sm padlock (Master Lock, 2021) to block opening/closure of an equipment of an energy sou circuit, for example a valve of the pneumatic circ If the closing is correctly executed, the sm padlock produces a confirmation signal that can read via Bluetooth by the mobile device using specific application of the padlock. Then, operator sends his confirmation of task executior the Back-end system.
  5. The operator opens/closes an electric lock directly using his mobile device. Once opening/closing is carried out, the electric l produces a signal which is received via Bluetooth the mobile device. Then, the operator can send confirmation of right execution of closing/opening the Back-end system via the app.

For evident reasons of safety all these operations allowed only if they deal with devices that are under control and overview of the operator and if they do not other operators in unsafe conditions. When one of these t mandatory conditions could not be respected, the opera is promptly alerted on the mobile device to stop the energization procedure.
When the maintenance is completed, it is necessary to ca out the re-energization following the same proced presented above for the de-energization. The smart syste presented in the paper can be evidently used for support the re-energization procedures adopting the sa framework here described.

4. Conclusions and future works

A novel smart system for the safe management of the energization/re-energization in complex assemblies a industrial plants is proposed. It exploits the technologies the Industry 4.0 paradigm by assuring a good digitalisat and integration of the process within the control system. T operators are well supported during the procedure and probability of errors and its consequences are well mitiga thanks to the their knowledge of their real-time position a to the app at their disposal. The proposed system can considered an effective tool for the employers to organ and manage the health and safety procedures in workplaces related to the de-energization.
The effectiveness of the smart system in the s management of the de/re-energization processes stron depends on the actual adoption of RFID tags by maintenance operators, who could not wear the right PI with the necessary number of RFID tags due to a possi misbehaviour (an unsafe act which nowadays still occu In order to solve this problem, together with a w organized work supervision, the RFID tags can integrated within the mandatory PPE, such as safety sh

and work coveralls. Then, a gate access control system at the entrance of the assembly of machines zone could be used to check the presence of RFID tags and to give the entrance allowance only if the maintenance operators have the required set. In this way the operators are obliged by the check to wear the right PPEs. A critical discussion of this issue in relation with the recent ISO/TR 22053:2021 which is under development shall be carried out.
Another critical aspect of the novel smart proposed system concerns the reliability of the RFID-based localization system and the Back-end tracking which provides the Back-end cloud server with the information about the real-time position of the operators during their interaction with the machinery (EN ISO 13849-1, 2015; IEC TS 62998-1, 2019; ISO/DIS 14119, 2021). Indeed, errors in the position assessment and information communication could imply harmful conditions for the operators. In the next future a detailed specific analysis about this important issue is planned. We are planning a specific investigation to provide proof of its reliability. Anyhow the system here proposed could be considered only as an external support system for the end user without entering and modifying the safety related parts of control system of the assembly. Indeed, thanks to the smart selector it is possible to interact with the machinery in safe state. Another next activity concerns the development of each part of the system in order to design, build and test a prototypal device to demonstrate the actual effectiveness of the present proposal.

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References

Amicucci G. L., Fiamingo F. (2017). Usage of RFId in safety applications, *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe*, 1-6.

Bernardini F., Buffi A., Fontanelli D., Macii D., Magnago V., Marracci M., Motroni A., Nepa P., Tellini B., (2021). Robot-Based Indoor Positioning of UHF-RFID Tags: The SAR Method with Multiple Trajectories, *IEEE Transactions on Instrumentation and Measurement,* 70, 1-15, Art no. 8001415.

Buffi A., Nepa P., Lombardini F. (2015). A Phase-Based Technique for Localization of UHF-RFID Tags Moving on a Conveyor Belt: Performance Analysis and Test-Case Measurements. *IEEE Sensors Journal,* 15, 387-396.

Council Directive of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work (89/391/EEC)

Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on Machinery, and amending Directive 95/16/EC.

EN ISO 13849-1:2015 - Safety of machinery — Safety-related parts of control systems - Part 1: General principles for design.

IEC TS 62998-1:2019 - Safety of machinery. Safety-related sensors used for the protection of persons.

ISO/DIS 14119: 2021 - Safety of machinery - Interlocking devices associated with guards - Principles for design and selection.

ISO/TR 22053:2021 - Safety of machinery - Safeguarding supportive system, under development.

Landi L., Buffi A., Marracci M., Stecconi A., Di Leone P., Bernardini F., Di Donato L. (2021). Localization systems for safety applications in industrial scenarios, submitted, *31th European Safety and Reliability Conference*.

OSHA 3120 - Control of Hazardous Energy (Lockout/Tagout), 2002.

www.osha.gov/top10citedstandards, 2020.

www.masterlock.com/products/bluetooth-electronic-locks?personal, 2021.