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Analysis and testing of an online solution to monitor and solve safety issues for industrial systems

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Abstract

One of the main issues addressed in the context of the well-known fourth industrial revolution (also called Industry 4.0) is the theme of operators' safety at the workplace. To this end, several innovative solutions were proposed, aiming at reducing the likelihood of accidents. In line with these considerations, in this paper an online software solution for monitoring alarms and warning originated from equipment of industrial systems is presented and tested.
The solution is installed on a mobile device (i.e. a smartphone), and specifically its function is to alert the operators anytime an alarm is occurring through a simple notification, then to drive them to the instructions required to solve the problem. Tests were carried thanks to a Virtual Private Network (VPN) connecting a virtual machine where alarms are randomly generated and notifications are sent to the various connected devices. Results were analyzed from a usability perspective, by collecting the judgements expressed by four inexpert users, who were asked to rate four aspects of the tool usage; moreover, the System Usability Scale was adopted, whose score is higher than the acceptance value, demonstrating the effectiveness of the tool.

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Keywords: industrial systems; safety, industry 4.0; alarms management; food equipment

1. Introduction

At European level, the concepts of Smart Manufacturing and Industry 4.0 are becoming increasingly important as they propose the use of enabling methodologies and technologies (key enabling technologies, KET) capable of improving production systems from many points of view, for example improving safety levels, increasing productivity, increasing costs, etc.

An important issue dealing with Industry 4.0 and Smart Manufacturing is the ability to use synergistically multiple ICT methodologies and technologies to create a "connection" between the real world and a virtual world in which the analysis of problems and the relative solutions can take place by increasing the capacity of all the operators involved. This aspect is particularly important in the safety area, where, for example, the correct management of warning and early warning becomes crucial to avoid accidents that often cost the lives of the operators involved. However, the management of warning and early warning is not the only aspects to be considered in the field of work safety: it is also important to ensure that the communication between the operators themselves take place correctly (Bruzzone et al., 2016a). Safety also involves the protection and a proper training of the worker (Legislative Decree 81, 2008). There are many cases of accidents at workplace (even fatal) caused by an incorrect training of personnel (Court of Cassation - Penal Section IV - Sentence n.

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39765, 2015)[*]. It is noted that training personnel not only means transferring all those contents and procedures necessary to ensure safety, but also ensuring that operators understand their importance and operate correctly. This process is often more difficult when interacting with complex industrial systems, which, by their definition, are more and more integrated and involved and thus subject to greater security risks.

Based on these peculiarities, there is the need to define, develop and integrate solutions that can be adopted both in the training phase and in the usage phase, which are smart (able to interact intelligently and faster with the worker and with the machine), augmented (able to improve the information content available to the worker and the machine) and mobile (always available to the user while leaving him free to execute his personal causes) (Deepu et al., 2010; Magno et al., 2014; Lingg et al., 2014).

In this sense, the W-ARTEMYS project was launched with the ambitious goal of defining, observing and prototyping a system able to combine smart, augmented and mobile aspects to jointly use enabling and innovative technologies and methodologies that maintain and expand (for application potentials) the concept of Industry 4.0 and Smart Manufacturing applied to industrial systems, composed by different equipment connected to each other.

The development of the solution has obviously taken into account the key constraints related to the privacy of workers, often affected by invasive systems considering what is reported by the provisions of Law n. 300/1970 (Workers' Statute) and Legislative Decree no. 196/2003 (Code regarding the protection of personal data).

The main added value of the W-ARTEMYS project is to be found in the idea of integrating innovative and enabling methodologies and technologies for improving the safety of machine systems through an approach that incorporates and broadens the concepts of Industry 4.0 and Smart Manufacturing. In particular, the contribution that their correct application could make to improving workplace safety (especially when dealing with complex industrial systems such as industrial plants) is certainly relevant. However, an analysis of the scientific literature available up to now reveals that what has been proposed and developed in the context of Industry 4.0 and Smart Manufacturing for safety purposes is still of theoretical nature or highly experimental (Bruzzone et al., 2016b; Spanu et al., 2016; Bottani and Vignali, 2019). In this sense, there is a lack of research and development effort aimed at developing what already exists, overcoming the criticalities that arise when wanting to integrate the different methodologies and technologies made available by Industry 4.0 and Smart Manufacturing. The approach proposed in the W-ARTEMYS project evolves from the previous SISOM project, which has demonstrated the validity of some applications in augmented reality (AR) for security/safety purposes, through the extensive use of ICT and digital technologies that allow the interconnection of the real and virtual world. In particular, the W-ARTEMYS system proposes the joint use of methodologies and technologies based on the use of several enables key technologies on the real field.

Based on these premises, one of the crucial points addressed in this work is to test Industry 4.0 solutions on real manufacturing systems, able to show alarms and warnings to the operators in real time, so as to evaluate their potential to improve safety at the workplace. Nowadays, one of the main issues of Industry 4.0 revolution is the need for less employees on the production lines for the plant to operate. This often implies enormous distances between the equipment and the operators, who have to act on it especially in case of failure. Although, in most cases, there is a central room where it is possible to online monitor the status of the manufacturing lines, it could happen that the same operators who have to check the status of the plant could work on a specific machine in order for example to restore it. In this case the absence of control on the status of the line could generate enormous safety issues, which can involve huge problems for the factory and the operators themselves. To solve this problem, one possible solution could be to adopt wearable ICT devices able to immediately alert the operators in case of safety issues involving a close equipment. The alarm and warning could be received by the operators on smartphones or smart-watches, which could also display possible solutions to them.

To this end, one of the specific activities of the W-ARTEMYS project was to develop a system able to link the alarms and warnings, which are displayed on the equipment monitor, with the solutions of these problems which are usually reported on the equipment manuals. At the end of this phase, the best tools to help the operators solve the problems have been already defined, showing that not always complex systems (such as AR ones) could be applied (Rosi et al., 2018). Difficulties now are instead related to connect the real data coming from the plant with the online software in order to have these systems interconnected.

This paper aims then at describing how to connect these two worlds and at highlighting the main difficulties that will be encountered when trying to doing so in a real industrial plant. Some testing procedures on the online system have been reported to check the effectiveness of the application developed.

2. W-ARTEMYS software

As explained in Rosi et al. (2018) and Vignali et al. (2019a; 2019b) the development of the W-ARTEMYS software concept started thanks to the collaboration of a work team composed of academies, institutions (INAIL) and industries with the aim to fulfil each request in term of usability, safety and regulatory issues. It has been chosen an aseptic filling line for a beverage packaging machine, with the aim of upgrade an old machine in line with industry 4.0 requirements and testing software's development.

In order to make the platform suitable for both developers and users, the software is composed by four levels in which,

[*] According to this sentence, an employer who fails to train a worker is liable as a specific fault for the accident which has occurred to him as a result of his negligent conduct, since this is a direct and foreseeable consequence of the failure to comply with training obligations.

each file can be allocated following a directory like the users can do using a personal computer.

In particular, the software nowadays is composed by four levels. The level 0 is named "Main object" and holds the first data required to create a box in which the other levels can be allocated. To clearly identify the main object, it is required to put on the system a description of what this box will contains.

The description represents also the name of the card created. At this level the developers can assign the reference image chosen to categorize each object, and a shortcut in the shape of a QR code, that allows the final user to have directly access at the object searched and connect it with the level 1 of the software structure. At this level it can be assigned a list of keywords that allow the search using the integrated Vocal Assistant.

The level 1, also named "Section" follows the same rules of field's compiling as the lower one, giving the change to upload files such as .pdf, 3D drawings, pictures, videos and audio, in order to completely define the object uploaded.

These levels are followed by the level 2, called "Aggregate" which requires a complete description of the object completed with elements useful to the voice assistant. It is also possible to create a QR code, as seen for the main object.

Level 3 consist on the files that can be uploaded on the platform in support of the corresponding aggregate.

2.1. The alarms management system

The alarms management system tool in W-ARTEMYS software consists of four levels, according to the description below (see Vignali et al. 2019a, 2019b for further details).

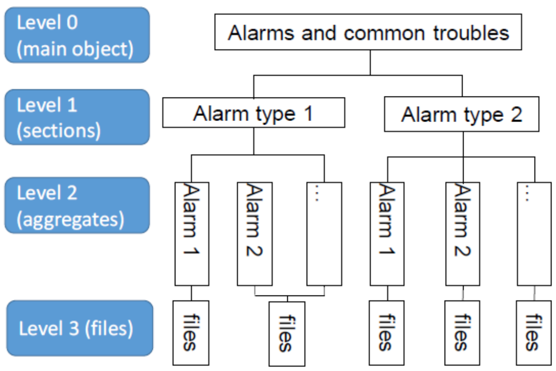

Fig. 1. Tree structure of the alarms management system.

Level 0 - Main object: for the purpose of this study, this level lists the alarms and common troubles;

Level 1 - Section: alarms have been divided into two sections, i.e.:

1. With specific on-screen warning;
2. Without specific on-screen warning.

Level 2 - Aggregate: the system has been implemented with a new "back-end card" that works in administrator mode on the W-ARTEMYS platform, to link the alarm tag with the main object, and the relating aggregate. To create a new "Alarm", the back end needs to connect the information generated by the machine, i.e.:

1. Alarm tag name;
2. Alarm description;

with the W-ARTEMYS components, namely:

I. Main object;
II. Sections;
III. Aggregate categories.

and to fill the fields required in the online platform.

Level 3 - Files: Each card represents a class of recovery procedures for the involved alarms. Different alarms can lead to the same part of a document, meaning that the related recovery procedure is explained in the same document (e.g. a manual), as shown in the flow-chart fig.3.

During this phase, the focus has been put on the alarms with specific on-screen warnings.

A set of alarms detected in a sample period of 90 days has been examined. Starting from this analysis, the main classes of alarm have been identified together with the relating troubleshooting procedure. Accordingly, an aggregate has been created in the W-ARTEMYS platform for each solution.

The sample of alarms has been analyzed in a statistical study, taking count of the following parameters:

- Appearance frequency;
- Alarm's duration.

At the same time, following a risk assessment-based procedure, the alarms have been filtered and categorized in some main classes. This filtering procedure has helped categorize each aggregate as a class of recovery procedures for the alarm. A further development has been to create a link between the alarm codes and the corresponding description in the manuals.

The alarms management systems, as designed in W-ARTEMYS, requires an internet connection, that allows to read the alarms status of the machine and, in the meantime, make the machine interactive, by allowing it to share information online. Obviously, this also require the company's commitment to unlock some connection ports of its internal server, where the database is located, and allow to navigate on its VPN.

Based on these considerations, a significant development has been done: a pop-up communication appears on the authorized devices (e.g. a tablet or smartphone), to intervene rapidly in case of need, even if the person in charge to solve the issues is far away from the machine.

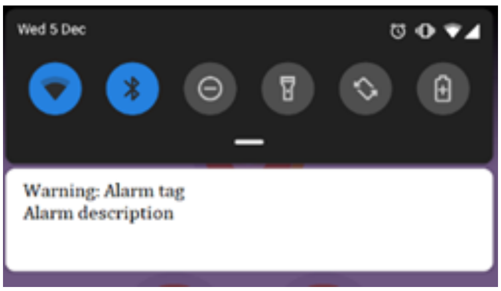

Fig. 2. Template of screen notification;

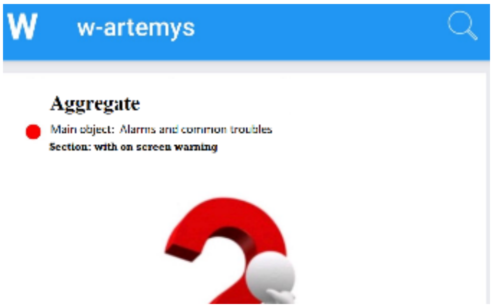

Fig. 3 Aggregate's card example

Following the pop-up Fig.2 the system links directly to the specific file that describes the alarm, the relating safety requirements, the risk involved in the operations, the cause of the alarm and the remedy to solve it, as shown in Fig.3.

This make it safer to operate on the line-production and on the whole production's department. Most importantly, it also ensures that the procedure is compliant with the manufacturer's prescriptions, which is relevant to preserve the safety of the finished products, based on the fact that these machines work in aseptic environment.

3. Testing procedure

3.1. Technical and usability key performance indicators

In a recent publication, Bottani and Vignali (2019) have reviewed the literature related to the usage of augmented reality (AR) in industry in the last decade. This study has been taken as the basis for identifying an appropriate testing procedure for the solution developed in this paper, as the ultimate aim of the W-ARTEMYS project is to complement the software solution described in this paper by implementing an AR tool as a further support to the employee in carrying out his/her tasks. According to Bottani and Vignali (2019), testing of new technologies (such as AR) can be either aimed at evaluating the technical characteristics of the solution (*technical test*) or at assessing the performance resulting from its usage (*usability test*). The authors found that out of the 174 studies evaluated, 139 papers have carried out either a technical test or a user study, thus confirming that these tests are required to evaluate the effectiveness of the solution developed. Moreover, papers that described the application of AR solutions typically carried out a user study to evaluate the benefits generated when AR systems (instead of traditional methods) are used to assist the user in the execution of a task. The majority of papers describing the technical features of the AR solution, instead, carried out a technical test aimed at assessing the functioning of the technical solutions developed, while user studies are more limited in number.

The present paper is technical in nature, as it describes the main features of the solution developed to assist the employees in reacting to alarms and warnings in a real plant. Therefore, for the identification of the relevant key performance indicators (KPIs) to be used in evaluating the solution, particular attention has been paid to the analysis of those papers reviewed by Bottani and Vignali (2019) that carried out technical tests. Among these studies, the works by Ajanki et al. (2011), Verbelen et al. (2014), Wang et al. (2013) and Benbelkacem et al. (2013) appeared as particularly useful, as they evaluated both the software effectiveness (technical test) and usability of the solution (usability test).

Summarizing the KPIs proposed in these studies, the following list can be obtained:

- *technical KPIs*:
  1. correct functioning of the speech recognition feature;
  2. number of devices where the technical solution works correctly;
  3. time required for the intervention of the solution after a working/alarm is triggered (a maximum time is allowed for the system to intervene);
  4. capability of recognizing the marker located in the system, as a function of its shape and color;
  5. capability of the system to provide only the relevant information for the employee to intervene after an alarm/warning is triggered (redundant information is seen as an unnecessary burden and can confuse the employee);
  6. response time of the solution, depending on the fact that information is stored in the device (local memory) or on a server (cloud memory);
  7. memory required by the device;

- *usability KPIs*: to evaluate the usability of the solution developed, users were asked to answer questions similar to these ones (on a Likert scale):
  1. was it easy to use the software solution?
  2. was it useful to use the software solution for carrying out the task?
  3. do you think that you have correctly carried out the task?
  4. do you remember the instructions provided by the application?
  5. did you learn anything from the instructions provided by the application?
  6. did you enjoy the software application?
  7. which device did you prefer?

The proposed usability KPIs can also be integrated with those available in the systems usability scale (SUS), a simple, ten-item Likert scale giving a global view of subjective assessments of usability of technologies. This system was developed by Brooke (1986) as a tool to be used in usability engineering of electronic office systems. The list of the SUS items is below given:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.

6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

3.2. Testing phase

To measure the KPIs listed, a testing phase was set up at the University of Parma in November 2019 involving the company manufacturing the plant under examination (i.e. GEA Procomac S.p.A.). Because of the difficulties in testing the solution directly on the real plant, a simulated environment was created to reproduce the system (a virtual machine generates alarms similarly to a real plant); consequently, only some of the *technical* KPIs were applicable in this environment. As an example, the response time of the app was almost in real time because of a VPN connection; conversely, in case the connection is lost, messages will be displayed later on the mobile device. As far as the number of usable devices is concerned, in the laboratory environment only one device at a time can be connected to the VPN.

In line with these considerations, the aim of the testing phase was mainly to check the *usability* perceived by specifically four inexpert users (two men and two women, with a high level of education, aged between 25-45 years), who have never seen and above all tried the smartphone in which the software solution was installed. They were invited to hold the device for five minutes during which alarms and warnings were randomly triggered, generating their consequent notifies both with locked and unlocked screen.

Participants were asked to evaluate their experience with the software solution by expressing their level of agreement about respectively the abovementioned questions 1, 4, 5 and 6 on a 5-point Likert scale (from 1-totally disagree to 5-totally agree), expressed as statements. Questions 2 and 3 were properly excluded as the test did not consider the real intervention on the machine to stop the alarm; question 7 as well was not considered as we only had one device available at a time.

Moreover, the solution has been evaluated on the basis of the abovementioned SUS.

4. Results and discussion

Table 1 below shows the scores obtained by the four statements investigated. In addition, means (μ) and standard deviations (σ) were computed.

Table 1. Feedbacks by the four users.

Statement	User 1	User 2	User 3	User 4	μ	σ
1	4	3	4	5	4	0.7071
4	3	3	2	4	3	0.7071
5	4	4	5	4	4.25	0.4330
6	5	4	4	3	4	0.7071

Statement 5 got the highest mean and the lowest standard deviation, meaning overall participants felt they learned from this test and specifically from the application usage. On the contrary, statement 4 got the lowest mean; several justifications can be found for this result. One possible reason could be that the test was carried in laboratory environment and did not require the in-field implementation of the information provided by the app; hence, "learning by doing" mechanisms were not activated. A second reason could be that users were mainly focused on checking the right functioning of the app rather than on memorizing the information provided. In addition, some users could be less motivated in learning the instruction provided by the app because they are confident that these instructions are always available when needed. The remaining statements got satisfactory rates (μ=4).

The procedure for computing the SUS score is illustrated in Brooke (1986). The overall SUS score of the test is obtained through the mean of each single result, and in this case, it corresponds to 84.375. According to Bangor et al., (2009) and Brooke (2013), the minimum score for considering a technology acceptable is 70; we deduce that the software in question got a satisfactory result.

Table 2 reports results from the SUS (Table 2) indicate scores greater than 70 points for all the users (with a peak of 92.5 for some users).

Table 2. Feedbacks from the SUS.

Statement	User 1	User 2	User 3	User 4
1	5	4	4	5
2	1	2	2	1
3	5	4	5	4
4	1	2	3	1
5	4	3	3	4
6	2	2	2	1
7	5	4	5	5
8	1	2	1	1
9	5	4	5	5
10	2	3	1	2
SUS SCORE	92.5	70	82.5	92.5

5. Conclusions, limitations and future researches

As a result of the tests, the W-ARTEMYS system turned out to react quickly whenever an alarm was triggered by the virtual machine. Also, the correspondence between the alarm triggered and the solution provided by the aggregate in the app appeared as consistent, meaning that the system is able to provide the correct information to the user. Moreover, the notification system is intuitive and well displayed on the mobile device. In the current version of the system, each message is displayed every 10 seconds until the user clicks on it. This procedure helps the users detecting the alarms even when they are involved in other activities or absent-minded. However, even if more alarms can be triggered simultaneously, one notification at a time only is visible in the upper part of a mobile device display.

An issue when using the system is that the number of simultaneous alarms triggered by the system could be greater than the capability of the user to solve them. In the case, the number of repeated notifications could be excessive and stress the user. Moreover, because one notification only can be displayed on the mobile device, the user can actually read one notification at a time. If the user reads a second notification displayed after a previous one, the previous one disappears (although the user could always find it on the machine control panel). The solution procedure relating to the first notification disappears together with the message; nonetheless, when the user solves the problem related to the first alarm, the notification of the remaining alarms triggered reappear automatically on the mobile device. This help the user remember that further issues (related to the alarms previously generated) should be solved, following the troubleshooting procedures displayed on the mobile device.

Future research activities could be carried out to enhance the intelligibility of the notification system, e.g. by showing the full list of alarms simultaneously on the upper part of the display on the mobile device. Other problems that could be solved in future applications refer to the difficulties in the setting and maintaining the VPN connection with different mobile devices operating with the Android system. In fact, some manufacturers of mobile devices do not allow an inbound traffic of data coming by a server by means of a Hamachi Logmein VPN. Further development could be also related to the implementation of the software platform on IOS and other mobile operating system.

All these improvements will form part of future research activities with the ultimate aim to enable the implementation of the proposed platform in a real industrial system. In such implementation, the capability of the user to solve real problems will also be evaluated, applying some of the technical KPIs which were not measured is this study and discussing the relating outcomes.

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